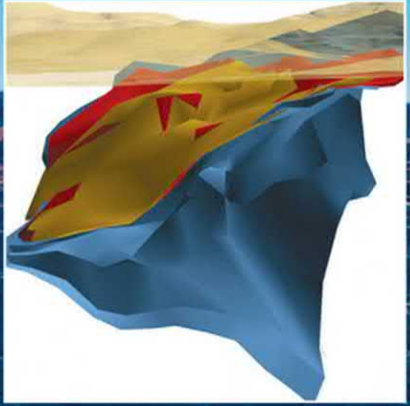
Second Edition

MINERAL EXPLORATION

Principles and Applications



Swapan Haldar

Mineral Exploration

Principles and Applications

Second Edition

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Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

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Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-12-814022-2

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Publisher: Joe Hayton
Acquisition Editor: Amy Shapiro
Editorial Project Manager: Tasha Frank
Production Project Manager: Nilesh Kumar Shah
Designer: Christian Bilbow

Typeset by TNQ Technologies

Dedicated to all my students in mineral exploration
—past, present, and future—
who taught me the art of teaching, motivated me to keep learning,
and galvanized me to write this book.
And
little Srishti and Srishta
who inspired me to love Mother Nature!

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Author Biography

Swapan Kumar Haldar has been a practicing veteran in the field of Mineral Exploration and Metal Mining for the past four and half decades. He received B.Sc. (Hons) and M.Sc. degrees from Calcutta University, and a Ph.D. from the Indian Institute of Technology, Kharagpur, India. The major part of his career since 1966 has been focused on base and noble metals exploration/mining with short stopovers at ESSO Standard Oil Inc., Hindustan Copper Limited, and Hindustan Zinc Limited, where he has undertaken various technical roles and managerial responsibilities. Since 2003 he has been Emeritus Scientist with the Department of Applied Geology, Presidency University, Kolkata, and has been teaching mineral exploration to postgraduate students of the department as well as at the University of Calcutta and Indian School of Mines (now IIT), Dhanbad. He has been a consultant with international exploration entities, namely, Goldstream Mining NL/IMX Resources Ltd., Australia, and Binani Industries Limited (BIL) Infratech Ltd., India. His profession has often required visits to mines and exploration camps in Australia/Tasmania, Canada, the United States, Germany, Portugal, France, Italy, the Netherlands, Switzerland, Saudi Arabia, Egypt, Bangladesh, Nepal, Bhutan, Jordan, and Israel.

He is a life fellow of the Mining, Geological and Metallurgical Institutes (MGMI) of India and the Indian Geological Congress. Dr. Haldar is recipient of the "Dr. J. Coggin Brown Memorial (Gold Medal) for Geological Sciences" by MGMI. He has authored 40 technical papers and four books:

1. *Exploration Modeling of Base Metal Deposits*, 2007, Elsevier, 227 pp.
2. *Mineral Exploration—Principles and Applications*, 1st Edition, 2013, Elsevier, 374 pp.
3. *Introduction to Mineralogy and Petrology*, 2014, Elsevier, 356 pp.
4. *Platinum-Nickel-Chromium Deposits: Geology, Exploration and Reserve Base*, 2016, Elsevier, 322 pp.

Dr. Haldar has a unique professional blend of mineral exploration, evaluation, and mineral economics with an essence of classroom teaching to postgraduate students of three celebrated universities over the past decade, and participates in executive teaching programs.

Preface

> *"You have a right to perform your prescribed action, but you are not entitled to the fruits of your actions. Never consider yourself to be the cause of the results your activities, and never be associated with not doing your duty."*
>
> (II-47) Bhagavad Gita.

September 2016, and my fourth book *Platinum-Nickel-Chromium: Geology, Exploration and Reserve Base* was released by Elsevier. I was completely exhausted by then, and we left to go abroad on November 5 to relax with our grandchildren. Our son-in-law and daughter had just moved to their new house with a nice garden having varieties of fruit and flower plants. I too love gardening, and that gave me ample opportunity to nourish the existing plants and add a few new ones.

Our return was scheduled on January 7, 2017. The same morning I received a mail from Ms. Amy Shapiro, Acquisitions Editor, Earth and Planetary Sciences, asking if was interested in working on a proposal for a second edition of *Mineral Exploration*. I was waiting for this opportunity to work together on a new edition of *Mineral Exploration* to give further all-inclusive coverage and a new look with recent updates, and to give my sincere thanks to Amy. Ms. Tasha Frank, Senor Editorial Project Manager, took over. I had a long work experience and understanding during my journey, and my sincere thanks goes to Tasha. My compliments to Nilesh Shah and team from Elsevier Chennai Camp for awesome page making that speaks in each page. Ashwathi Aravindakshan extended full support in copyright permission.

Prof. Martin Hale, formerly ITC, Netherlands, enriched me with a few valuable changes. Similar suggestions were received from Prof. E.C. Nehru, Emeritus, Brooklyn College, New York, Prof. B.C. Sarkar, IIT Dhanbad, India, Mr. Finn Barrette, Consultant, IMX Resources Ltd., Australia, and Dr. Tom Evans, Executive Manager, Lonmin Plc, UK. I am grateful to each one. Dr. D.B. Sikka from Canada, my friend, philosopher, and guide, wished to review the manuscript from his hospital bed, but when it reached him he had left for heaven. May his soul rest in peace! Appreciative suggestions and wishful gratitude from learned reviewers, professional colleagues from academia and industry, and finally from students have enriched the topics and inspired me in my long journey. I have critically reread the entire manuscript and made necessary edits to and additions of texts and 385 colored diagrams and images.

The new edition is an essential standard textbook for undergraduate university students taking modules in economic geology, and postgraduates specializing in mineral exploration. Practicing exploration geologists may well keep a copy as a ready reference. Students need a good insight into the way professionals work and the needs of the professions with which they interface. The chapters are planned with a comprehensive and holistic approach, and address the needs of students and professionals alike. The relevance is global with sufficient emphasis on regions/countries in which university education includes economic geology, and where mineral exploration is an important activity: the Americas, Australia, India, China, South Africa, and Western Europe.

The book is intended to become an industry standard, having comprehensive reference to study all aspects of mineral exploration, mining, and mineral processing/extraction, from the handling of run-of-mine ore to separation strategies and removal of waste products. The book incorporates state-of-the-art developments in the fields of engineering, chemistry, software applications, and environmental sustainability, and explains how these disciplines contribute to the ultimate goal of producing minerals and metals economically from ores. Eleven global case studies cover all aspects of activities, and are a practical reference for seasoned industry professionals interested in improving operational efficiencies.

All faculty members of the Applied Geology Department, Presidency University, extended full support over one and half decades for my academic growth. Students from Presidency and Calcutta University, IIT Dhanbad, and global readers from universities and exploration and mining/processing industries played a pivotal role in developing the interrelated subject in totality. A number of my students drafted more than 200 line drawings over one and half decades, which I finalized. I am avoiding individual names not to miss anyone. My best wishes are always with them for reaching their goal. My sincere thanks go to Dr. Snigdha Pal Chaudhury, Presidency University, for the description of chemical analytical methods.

I will be indebted forever to M/s Hindustan Copper Limited, Hindustan Zinc Limited, India, and IMX Resources Limited (Mr. Finn Barrett), Australia, for extending ample opportunity to enrich me with overall aspects of the mineral industry in general and mineral exploration in particular.

I am happy to mention that my two little grandchildren, Srishti and Srishta, never allow me to work when we meet, but infuse tremendous energy for my good health and mind. Srishti composed the poem *Our Earth* in this book, and Srishta created my website and all remote control computer support. Finally, I extend my whole-hearted love to my wife, Swapna, for making me what I am today, and lots of affection to Soumi and Surat for keeping me happy anywhere and everywhere.

> "I am a part of all that I have met;
> Yet all experience is an arch wherethro'
> Gleams that untravell'd world whose margin fades
> For ever and forever when I move."
>
> − Alfred Tennyson, Ulysses, 1842.

> "Oh Lord!
> Lead us from Ignorance to the Reality of Truth;
> Lead us from Darkness to the Light of Knowledge;
> Lead us from Fear of Death to the Immortality;
> Om (ॐ), Peace, peace, peace."
>
> Brihadaranyaka Upanishad, 1.3.28.

March 13, 2018
Swapan Kumar Haldar
Presidency University, Kolkata

List of Acronyms

GENERAL

BM	Bureau of Mines
CAPEX	Capital expenditure
GDP	Gross domestic product
GSI	Geological Survey of India
LBMA	London Bullion Market Association
LME	London Metal Exchange
JORC	(Australasian) Joint Ore Reserves Committee
MCDR	Mineral Conservation and Development Rules
MCR	Mineral Concession Rules
MMRD ACT	Mines and Minerals (Regulation and Development) Act
MPRDA	Minerals and Petroleum Resources Development Act
ML	Mining lease/license
MOE	Ministry of Environment
MOF	Ministry of Forest
MOM	Ministry of Mines
MSS	Multispectral scanner
MVT	Mississippi Valley type
NMP	National Mineral Policy
OB	Overburden
OMS	Ore man shift
OPEX	Operating expenditure
PL	Prospecting license
ROM	Run-of-mine
RP	Reconnaissance permit
SEDEX	Sedimentary exhalative
Sp. Gr.	Specific gravity
TM	Thematic mapper
tpa/tpy	Tonnes per annum/year
tpd	Tonnes per day
UNFC	United Nations Framework Classification
USGS	United States Geological Survey
USBM	United States Bureau of Mines
UTM System	Universal Transverse Mercator System
VCR	Vertical crater retreat
VHMS	Volcanic-hosted massive sulfide
VMS	Volcanogenic massive sulfide
VRM	Vertical retreat mining
WHO	World Health Organization

MINERALS

Cp	Chalcopyrite
Ga	Galena
Po	Pyrrhotite
Py	Pyrite
Sp	Sphalerite

METALS

Ag	Silver
Al	Aluminum
As	Arsenic
Au	Gold
Bi	Bismuth
Ca	Calcium
Cd	Cadmium
Ce	Cerium
Co	Cobalt
Cr	Chromium
Cu	Copper
F	Fluorine
Fe	Iron
He	Helium
Hg	Mercury
K	Potassium
La	Lanthanum
Li	Lithium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
Nd	Neodymium
Ni	Nickel
Pb	Lead
Pd	Palladium
Pm	Promethium
Pt	Platinum
Te	Tellurium
Rb	Rubidium
Rn	Radon
Sb	Antimony
Se	Selenium
Si	Silicon
Sm	Samarium
Sr	Strontium
U	Uranium
Zn	Zinc

TIME SCALE

AD	Anno Domini (year after Jesus Christ's birth)
BC	Before Christ (year)
Ga	Giga (10^9) or billion age (years)
Ma	Million (10^6) age (years)

CURRENCY

Country/Currency	Currency Code	Currency Image
Australia dollar	AUD	$
Canada dollar	CAD	$
Chile peso	CLP	$
Euro	EUR	€
India rupee	INR	₹
Saudi Arabia riyal	SAR	ريال
South Africa rand	ZAR	R
Tunisia dinar	TND	دينار
United Kingdom pound	GBP	£
United States dollar	USD	$
Zimbabwe dollar	ZWD	Z$

WEIGHTS

Bt	Billion tonnes
lb	Pound
kg	Kilogram
Mt	Million tonnes
t	Tonne

LENGTH

m	Meter
cm	Centimeter

Chapter 1

Mineral Exploration

Chapter Outline

> *Good exploration planning and decision making measure risk and reward; persist where the geology is encouraging and where the rewards will be large; recognize when you have failed.*
>
> Cameron R. Allen, Cominco Ltd.

1.1 INTRODUCTION

Minerals and metals are essential components for the growth of human society. The need to survive taught prehistoric Paleolithic men the use of stones as tools as early as 20,000 years ago. The discovery of minerals, their exploitation, and use became many-fold with the advent of civilization and is continuing today.

A mineral deposit is too small in size compared to the vast Earth's crust. Near-surface deposits have been discovered over the centuries, ores have been mined, and metals extracted. The future search for concealed types, rarely showing surface signatures, will be opportunities and challenges. New discoveries will require state-of-the-art exploration techniques, trained labor, scientific knowledge, adequate experience, high-end data processing systems, and interpretation skills.

1.1.1 Why Mineral Exploration?

Mineral reserves and resources, annual production versus consumption, demand versus supply, and index of per capita spending on commodities are measures that distinguish the rank of a country as developed, developing, and underdeveloped. Existing nonrenewable mineral reserve bases are limited and tend to reduce progressively with mine production. On the other hand, demand for minerals/metals gradually increases at ~10% with annual growth of the population and uplifting standards of living. However,

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00001-0

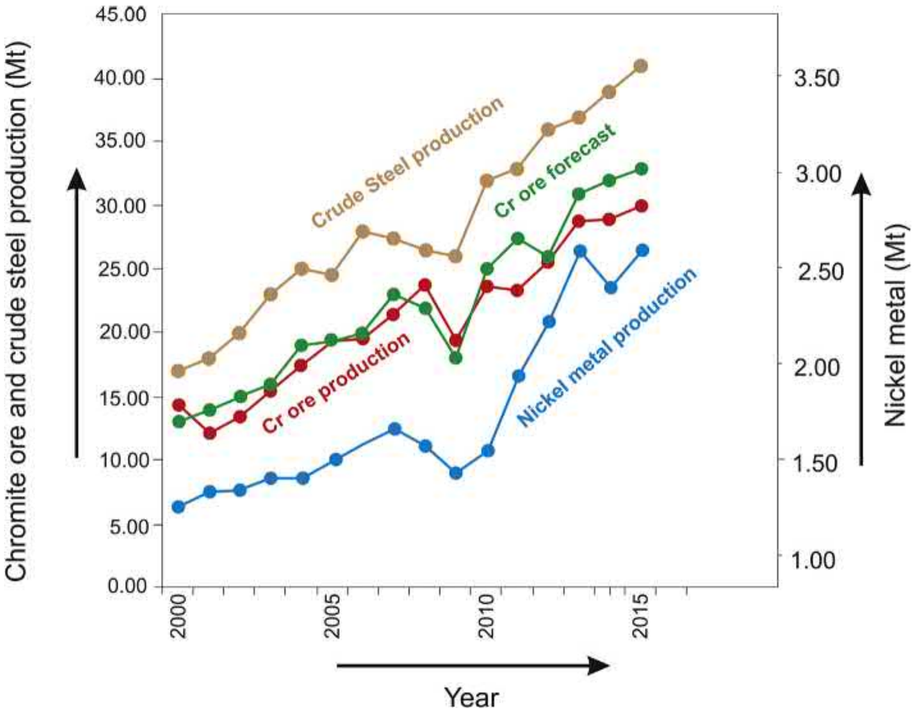

FIGURE 1.1 Global trend of chromite demand forecast and mine production, supply of primary nickel, and crude steel production (million tonnes/year) between 2000 and 2014 display a common growth pattern (USGS, 2017).

part of shortfall between demand and supply is partially substituted by recycling and reuse.

The demand for metals is interdependent of the finished product. The demand and supply of metals follows a common growth pattern. The increasing demand—production of iron ore will control the demand for zinc (galvanization), chromium (ferrochrome, hard steel, and chrome polish), and nickel (noncorrosive polish). Global chromite demand forecast, mine production, and supply of primary nickel and steel depicted a common trend between 2000 and 2014 (Fig. 1.1).

Policymakers in government and private sectors allocate funds for long- and short-term exploration programs guided by the past demand—supply trends of all commodities. Fund provision has special significance for strategic and deficient minerals. The existing demand—supply disparity can be reduced by expanding mining and smelting capacity with the on-hand ore reserves as a short-term ad hoc measure. The long-term standpoint would be continuous effort to enhance the reserve base. This is possible by new search, discovery, adequate exploration, economic mining, and smelting. The rate of reserve augmentation must be commensurate with the annual growth of a particular commodity, aiming at sustainable mineral resource development packages.

The process of mineral discovery and development to target production has a long gestation period of 5—10 years. Mineral sectors expect high-risk tolerance at all levels, extensive time, and rich sources for sustained cash flow. A small business unit in this field may often end its brief tenure with a total loss because of a failure to make a financial return. Many discoveries are not viable at current market prices, indicating the investment as a total loss. However, one discovery out of 100 or even 1000 attempts may pay back all the effort. The policymaker must plan timely allocation of funds for exploration and technology research of various mineral types, based on long-term demand—supply trends. An investment friendly environment, transparency, and political commitment of federal/state governments are essential for mineral development in any country (Evans, 2006; Haldar, 2013).

1.2 DEFINITION

1.2.1 Mineral and Rock

Mineral is a homogeneous inorganic substance that occurs naturally, usually in crystalline form with a definite chemical composition. It is generally in solid form, the exceptions being mercury, natural water, and fossil fuel. The common rock-forming minerals are quartz (SiO_2), orthoclase feldspar ($KAlSi_3O_8$), plagioclase feldspar ($CaNaAlSi_3O_8$), albite ($NaAlSi_3O_8$), and the mica group such as muscovite ($H_2KAL_3(SiO_4)_3$) and biotite ($H_2K(MgFe)_3Al(SiO_4)_3$). The common ore-forming minerals are hematite (Fe_2O_3), cassiterite (SnO_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS), baryte ($BaSO_4 \cdot 2H_2O$), gypsum ($CaSO_4$), and apatite ($Ca_5(PO_4)_3 \cdot (F,Cl,OH)$), among others.

Rock is an assemblage of mineral(s) formed under the natural process of igneous, sedimentary, and metamorphic origin. The common rocks are basalt, granite, quartzite, sandstone, limestone, marble, and mica schist.

1.2.2 Ore

In the past, the word **ore** was restricted exclusively to naturally occurring material from which one or more types of **metal** could be mined and extracted at a profit. The economic deposits comprising industrial minerals, rocks, bulk materials, gemstones, and fossil fuels were excluded from ore. The concept has undergone radical changes over the years. The Institution of Mining and Metallurgy, United Kingdom, currently defines ore as a "solid naturally occurring mineral aggregate of economic interest from which one or more valuable constituents may be recovered by treatment." Therefore ore and orebody include metallic deposits, noble metals, industrial minerals, rocks, bulk or aggregate materials, gravel, sand, gemstones, natural water, polymetallic nodules, and mineral fuel from land and the ocean bed (Fig. 1.2A–Z5). All ores are minerals or their aggregates, but the reverse is not true.

Minerals can be classified by commercial applications (Table 1.1).

1.2.3 Ore Deposit

An ore deposit is a natural concentration of one or more metallic, nonmetallic, and a combination of minerals within the host rock. It has a definite three-dimensional shape/size based on economic criteria with finite quantity (tonnes) and average quality (% grade). The shape varies according to the complex nature of the deposit such as layered, disseminated, veined, folded, and deformed. It may be exposed on the surface or hidden below stony barren hills, agricultural soils, sand, rivers, and forests (Fig. 1.3).

The worldwide important ore deposits include: Broken Hill, Mount Isa, McArthur, HYC, Century, Lady Loretta zinc-lead, Super Pit gold, Kambalda Ni–Cu–platinum-group elements (PGE), Mt. Keith nickel, and Olympic Dam copper-uranium-gold, Australia; Neves Corvo copper-zinc-lead-tin, Portugal; Sullivan zinc-lead, British Columbia; Sudbury nickel-copper-platinum and Lac Des Iles palladium, Canada; Red Dog zinc-lead, Alaska; Stillwater platinum and Eagle nickel, USA; Loma de nickel and Paguanta zinc-copper-silver, South America; Bushveld chromite-platinum and Venetia diamond, South Africa; Catoca diamond, Angola; The Great Dyke platinum-nickel-copper, Zimbabwe; Bou Jabeur zinc-lead-fluorite-barite deposit, Tunisia; Hambok copper-zinc and Bisha copper-gold, Eritrea; Noril'SK and Kola platinum, Russia; and Rampura-Agucha, Rajpura-Dariba, Zawar zinc-lead, Singhbhum, Khetri, and Malanjkhand copper, Bailadila, Kudremuk, Daitari, and Noamandi iron ore, Sukinda-Nausahi chromium-platinum, Byrapur chromite, Kolar gold, Jaisalmer limestone, Jhamarkotra rock phosphate, Makrana marble, and Salem magnesite, India. There is no preferential geographical location of ore deposits—they can be at a remote place or below a densely populated city. Ore deposits, being an exploitable nonrenewable asset, have to be used judicially so that they may be available for future generations.

1.2.4 Prime Commodity, Associated Commodity, and Trace Element

The **prime commodity** is the principal ore mineral recovered from mines. **Associated commodities** are the associated minerals recovered as by-products along with the main mineral. All ore deposits contain a number of valuable **trace elements** that can be recovered during processing of ore. The prime commodity of a zinc-lead-copper-silver mine is zinc; the associated commodities are lead and copper. The expected value-added trace elements are cadmium, silver, cobalt, and gold. The value of all main and secondary commodities and trace elements are considered collectively for valuation of the ore/mine.

1.2.5 Protore

The **protore** is an altered rock mass or primary mineral deposit having an uneconomic concentration of minerals. It may be further enriched by natural processes to form ore. These are low-grade residual deposits formed by weathering, oxidation, leaching, and similar physical and chemical alteration processes. The protore can turn into an economic deposit with advanced technology and/or increase in price. Examples are weathering of feldspathic granite to form kaolin deposits (Cornish kaolin, England) or mafic/ultramafic rocks like basalt/peridotite to form laterite (shoreline bauxite in South America, laterite iron ore in Northern Ireland, and Sukinda laterite nickel in India). It can be exploited for kaolin, iron ore, aluminum, manganese, and nickel due to sufficient enrichment of respective metals.

1.2.6 Gangue Minerals and Tailing

Ore deposits are rarely comprised of 100% ore-bearing minerals, but are usually associated with rock-forming minerals during the mineralization process. These associated minerals or rocks, having no significant or low commercial value, are called **gangue** minerals. Pure chalcopyrite having 34.5% Cu metal in copper deposit and sphalerite with 67% Zn metal in zinc deposit are hosted by quartzite/mica schist and dolomite, respectively. The constituent minerals of quartzite, mica schist, and dolomite

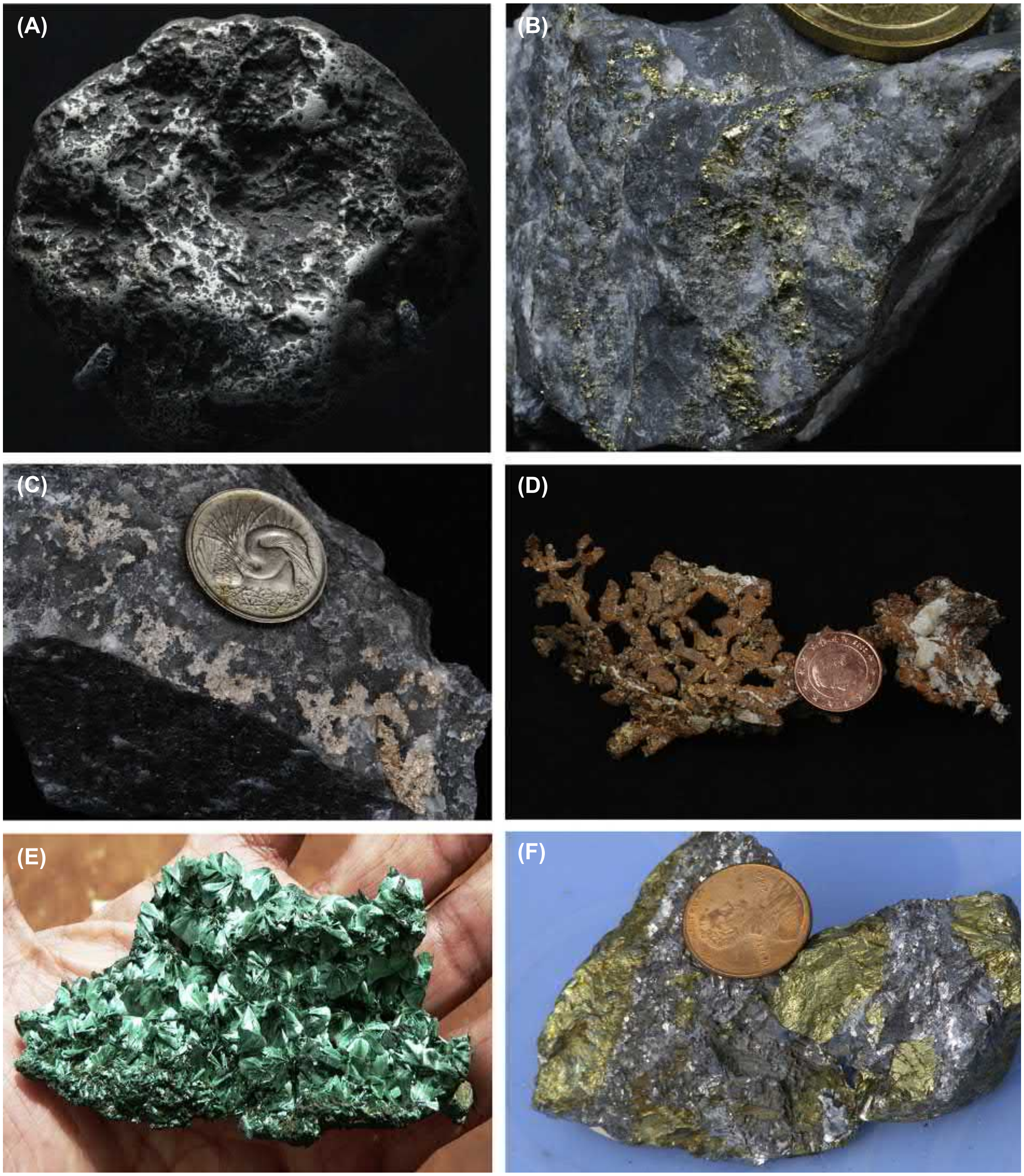

FIGURE 1.2 Common ore minerals: (A) native platinum, (B) native gold (Saudi Arabia), (C) native silver (Zawar, India), (D) native copper (Neves Corvo, Portugal), (E) malachite, (F) chalcopyrite (golden) and galena (steel gray) (Rajpura-Dariba, India)

FIGURE 1.2, cont'd (G) brown sphalerite (Zawar, India), (H) stratiform pyrite in graphite schist (Rajpura-Dariba, India), (I) massive pyrrhotite (Sindesar-Khurd, India), (J) wolframite (Degana, India), (K) crystalline chromite (Sukinda, India), (L) pisolite structure in bauxite (Bagru Hill, Jharkhand, India)

FIGURE 1.2, cont'd (M) hematite (steel gray) and jasper (red) (India), (N) rhodochrosite crystals with brilliant rose red color from South Africa, (O) azurite with distinct azure blue color is an excellent exploration guide, (P) cerussite or "white lead ore" (Megan, Germany), (Q) nickel-skutterudite (Schoenberg, Germany), (R) sperrylite crystal (~8 mm across) on weathered chalcopyrite mat (Broken Hammer deposit, Wallbridge Mining Co. Ltd., Sudbury Camp, Canada) (Dr. Tom Evans)

FIGURE 1.2, cont'd (S) krennerite (gold telluride) (Cripple Creek, USA), (T) cubic overgrowth and twinned crystals of fluorite (light rose) resting on crystalline twinned pyrite (black), (U) barite embedded with pyrite crystals (Preislar mine, Germany), (V) amethyst, (W) aquamarine, (X) ruby

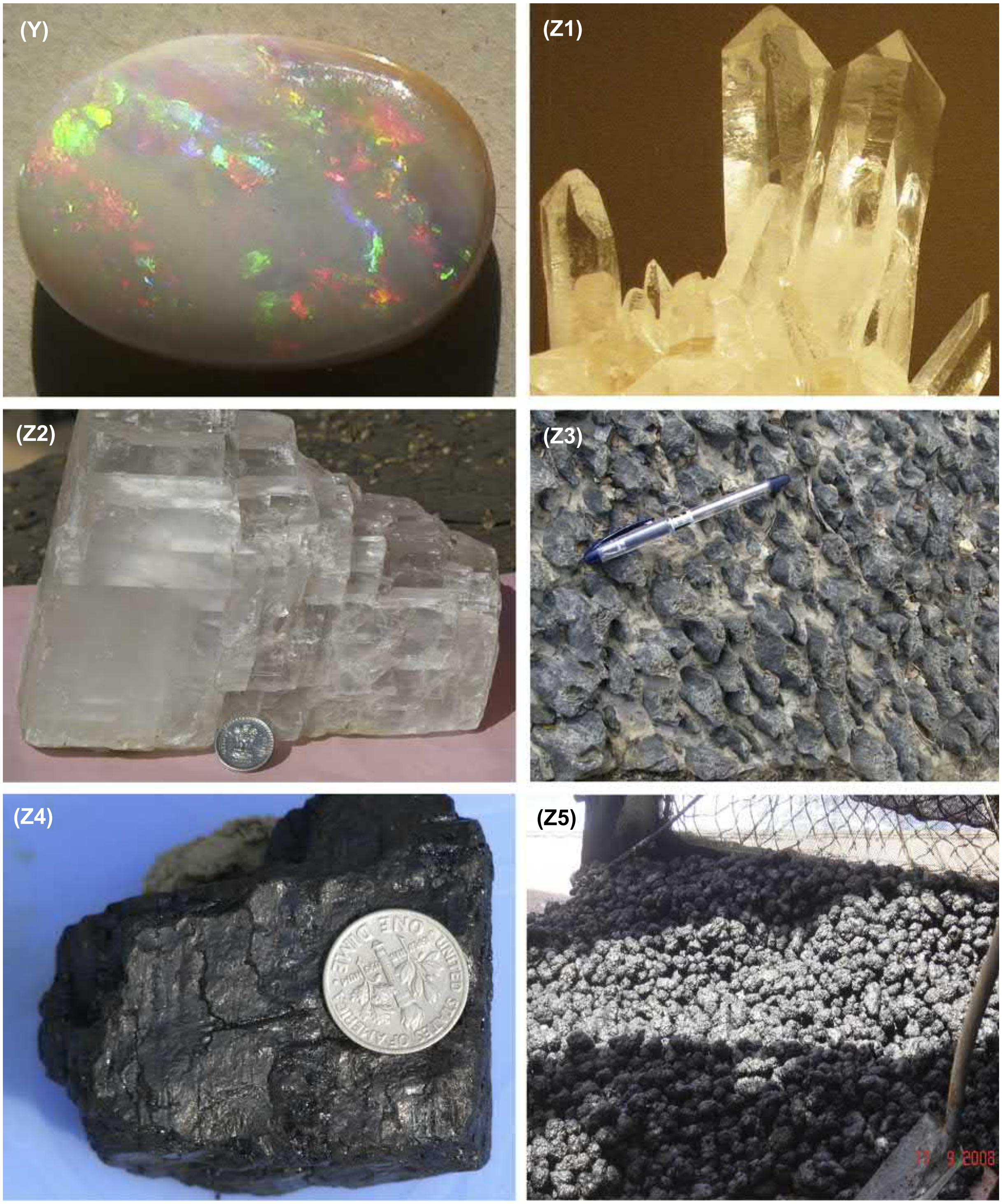

FIGURE 1.2, cont'd (Y) opal, (Z1) quartz crystal, (Z2) calcite, (Z3) rock phosphate (Jhamarkotra, India), (Z4) coal (Belatan, India), (Z5) polymetallic nodules (Indian Ocean).

TABLE 1.1 Classification of Mineral Deposits by Usage

Type	Minerals
Metallic	Native Pt, Au, Ag, Cu, chalcopyrite, sphalerite, galena, hematite, magnetite, pyrite, pyrrhotite, bauxite
Noble	Gold, silver, platinum, palladium
Industrial	Quartz, garnet, phosphate, asbestos, barite
Gemstones	Amethyst, aquamarine, diamond, emerald, garnet, opal, ruby, sapphire, topaz, zircon
Rock	Granite, marble, limestone, salt
Bulk/aggregate	Sand, gravel, mud, clay
Mineral fuel	Coal, crude oil, gas
Strategic	Uraninite, pitchblende, thorianite, wolframite
Life essential	Natural water
Rare earth	Lanthanum (La), cerium (Ce), neodymium (Nd), promethium (Pm)
Ocean	Polymetallic nodules, coral, common salt, potassium

are called the gangue minerals. The following is a list of common gangue minerals:

Quartz	SiO_2
Barite	$BaSO_4$
Calcite	$CaCO_3$
Clay minerals	All types
Dolomite	$CaMg(CO_3)_2$
Feldspar	All types
Garnet	All types
Gypsum	$CaSO_42H_2O$
Mica	All types
Pyrite	FeS_2
Pyrrhotite	$Fe_n \cdot S_{(n+1)}$

Mineral processing plants (beneficiation plants) are installed at every mine site to upgrade run-of-mine ore having ~1% Cu and ~8% Zn to produce an ideal concentrate of +20% Cu and +52% Zn. The run-of-mine ore is milled before separation of ore minerals from gangue by various beneficiation processes (Chapter 13). The concentrate is fed to the smelter and refinery to produce 99.99% metal in the purest form for the use of manufacturers and/or society in general. Rejects of the process plant are called **tailings**, which are composed of gangue minerals. The tailings are used as a support system by backfilling the void space in underground mines. Alternatively, they are deposited in a tailing pond and treated as waste. High-value metals can be recovered by leaching from tailings for future use. The tailings of Kolar gold mine, India, historically stored at a tailing dam, are being considered to recover gold by leaching without any mining and milling costs.

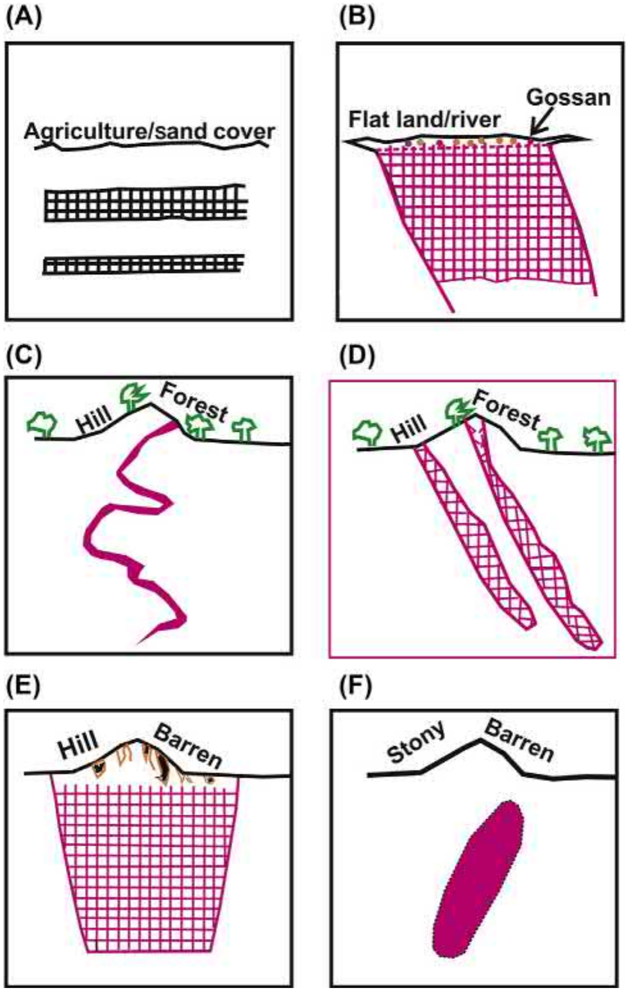

FIGURE 1.3 Mineral deposits with schematic shape and style: (A) subhorizontal lignite body under agriculture/sand cover at Barsingsar, (B) massive Zn–Pb–Ag orebody exposed to the surface at Rampura-Agucha, (C) intricately folded Pb–Cu deposit at Agnigundala, (D) en echelon Zn–Pb lenses under hilly terrain at Zawar, (E) unique gossans signature of sulfide deposit at Rajpura-Dariba, (F) concealed sulfide deposit under stony barren quartzite at Sindesar-Khurd, India.

1.2.7 Deleterious Substances

Metallic ore minerals are occasionally associated with undesired minerals that impose extra processing costs, and even penalties on the finished product. Arsenic in nickel and copper concentrate, mercury in zinc concentrate, phosphorus in iron concentrate, and calcite in uranium concentrate enforce financial penalties by a custom smelter for damaging the plant. Similarly, extra acid leaching costs are required for processing limonite-coated quartz sand used in the glass-making industry.

1.3 EXPLORATION

1.3.1 Discovery Type

The discovery of a mineral occurrence or a deposit is characterized by a measureable quantity and grade, which indicates an estimated amount of contained minerals or metals. The discovery can be immediately useful and exploitation profitable, in which case it is classified as a reserve or, more specifically, ore reserves. On the other hand, if the potential is known but is not immediately extractable or profitable, it is classified as a resource. The mineral explorer or exploration geologist must find the deposit first, and then engineers convert theoretical resources into producible reserves. The technology often exists, but toggles between one type and another with changes in market price. An uneconomic discovery now may become economic tomorrow, and vice versa. There are two types of discovery: greenfield and brownfield.

1.3.1.1 Greenfield Discovery

Greenfield discoveries are the findings from a broad base grassroots exploration program well away from known orebodies or known mineralized belts—in essence, pioneering discoveries in new locales. The term comes from the building industry, where undeveloped land is described as greenfield and previously developed land is described as brownfield. The knowledge base basin model discovery of the Kanpur-Maton-Jhamarkotra rock phosphate deposit in the Lower Aravalli formation during 1968 in Rajasthan, India, is a greenfield type (Chapter 15, Section 15.11). Similarly, the discovery of the world's largest and richest zinc-lead deposit at Broken Hill, Australia, during 1883 was also a greenfield type. All the mineral deposits in Australia and the nickel-copper deposits in Brazil, Columbia, China, Indonesia, the Philippines, and New Caledonia are examples of greenfield discoveries.

1.3.1.2 Brownfield Discovery

Brownfield discoveries are assigned where discovery is made by enhancing the reserve in strike and dip continuity of a known orebody or in the vicinity of an existing mine. In such cases the economics of development are improved by existing infrastructures. This is an important distinction in the analysis of discovery trends, though both types contribute to the rate of development and depletion. The rediscovery of Zawar Group (1943), Rajpura-Dariba Belt (1930), the world class largest and richest zinc-lead single orebody at Rampura-Agucha (1977), Khetri copper belt (1960s), Kolar gold field (first millennium BC), and iron ore deposits (1300 BC) in India are all examples of brownfield types of discovery. Many countries/continents, namely, Cyprus, Egypt, South Africa, the United States, and South America, depict ancient mining history for copper, gold, iron ore, diamonds, and gemstones. Any new deposit discovered in a known belt is grouped as a brownfield type.

1.3.2 Stages of Exploration

Any exploration program can be classified by successive stages: each stage is designed to achieve a combined specific objective within the time schedule and allocated fund. The outputs of each stage provide inputs to the next successive stage. The stages for major and limited application for minor minerals are placed in ascending order with respect to increasing geological confidence in the context of any exploratory procedure.

1.3.2.1 Reconnaissance (G4)

Reconnaissance is **grassroots** exploration for identifying the existence of mineral potential or initial targets on a regional scale. Preparations at this stage include literature survey, acquisition of geophysical data, if any, synthesis of all available data and concepts, and obtaining permission (reconnaissance license/permit [RP]) from the state/provincial/territorial government. Activities incorporate remote sensing, airborne and ground geophysical survey, regional geological overview, map checking/mapping on 1:250,000 and 1:50,000 scales, geochemical survey by chip/grab sampling of rocks and weathered profiles, broad geomorphology and drainage, pitting, and trenching to expose mineralized zones at ideal locations, and limited scouting/reverse circulation/diamond drilling to identify the possible existence/extent of mineralization. Petrographic and mineragraphic studies will help to determine principal host and country rocks and mineral assemblages. The prime objective is to study the entire area under leasehold within a stipulated timeframe, and to identify probable mineralized areas (targets) worthy of further investigation. The targets are ranked based on geological evidence suggestive of further investigation toward deposit identification. Finally, the initial leasehold area is thus substantially reduced to smaller units. Estimates are preliminary resource status (G4). This focuses concentration on the maximum exploration efforts to the target area in the next stage. The total area and duration permissible for RP vary between states and countries.

TABLE 1.2 Work Program During Reconnaissance License (G4) by Years

Year	Proposed Work Program
Year 1	**1.** Regional geological check, mapping, and rock chip sampling **2.** Acquisition and interpretation of available airborne geophysical data from previous surveys **3.** Identification of prospective geological packages/structures **4.** Regional geochemical surveys: soil/stream sediment sampling as required **5.** Regional airborne geophysics and ground magnetic and electromagnetic traverses as required
Year 2	**1.** Integration and interpretation of geological, geophysical, and geochemical data to identify anomalies/targets (could be geological, geochemical, and geophysical) **2.** First pass follow-up of anomalies/targets by detailed mapping, infill soil/rock chip sampling, and ground geophysics **3.** Prioritization of anomalies/targets for drill testing **4.** Scout drilling of interesting targets
Year 3	**1.** Second pass follow-up and target definition **2.** Reverse circulation/diamond core drilling **3.** Down-hole geophysics and drilling, if required **4.** Reports/recommendations **5.** Prospecting license application if encouraging results obtained

A comprehensive work program by year during RP can be envisaged for execution in a sequential manner (Table 1.2). Subsequent activities are planned and suitably modified based on the results achieved. The definite physical targets of various exploration activities would depend on the end result.

1.3.2.2 *Large Area Prospecting (G4/G3)*

Large area prospecting, a blend of reconnaissance (G4) and prospecting license (G3), is initiated in some countries. This combines reconnaissance and prospecting activities, including general and detailed exploration. It is the systematic exploration of potential target anomalies after obtaining a large area prospecting license (LAPL) from the state/provincial/territorial government. Activities include detailed geological mapping, rock chip and soil samplings, close-spaced ground geophysics, diamond core drilling on wide-spaced section lines, and resource estimation of inferred or possible categories. Other information like rainfall, climate, availability of infrastructures, and logistic facilities, including health care and environmental implications, are collected. The prime objective is to identify a suitable deposit that will be the target for further definitive exploration. The permissible area and duration will be between reconnaissance and prospecting.

1.3.2.3 *Prospecting (G3)*

Prospecting is the systematic process of searching promising mineral targets identified during reconnaissance. The objective is to increase definitive exploration for developing geological confidence leading to further exploration. The program starts by obtaining a prospecting license (PL) from the state/provincial/territorial government within the framework of area and duration. PL is granted to conduct prospecting, general exploration, and detailed exploration. PL shall be deemed to include LAPL, unless the context requires otherwise. Activities include mapping on a 1:50,000—1:25,000 scale, linking maps with a Universal Transversal Mercator (UTM), lithology, structure, surface signature, analysis of history of mining, if it exists, ground geophysics, geochemical orientation survey, sampling of rock/soil/debris of background and anomaly area, pitting/trenching, reverse circulation and diamond drilling at a 100—1000 m section at one level depending on mineral type, core sampling, petrographic and mineragraphic studies, borehole geophysical logging, and baseline environment. Estimates of quantities are inferred, based on the interpretation of geological, geophysical, and geochemical results.

Yearly exploration activities are programmed similar to Table 1.3 with more emphasis on objective-oriented results for broad delineation of the orebody.

1.3.2.4 *General Exploration (G2)*

General exploration is the initial delineation of an identified deposit. Methods include mapping on a 1:25,000, 1:5000, or larger scale for narrowing down the drill interval along the strike(100—400 m) and depth (50—100 m), detailed sampling and analysis of primary and secondary commodities, value-added trace and deleterious penalty elements, ~10% check sampling, analysis for quality assurance/quality control, borehole geophysical survey, bulk sampling for laboratory and bench-scale beneficiation tests, and recoveries and collection of geoenvironmental baseline parameters. The objective is to establish the major geological features of a deposit, giving a reasonable indication of continuity, and providing an estimate of size with high precision, shape, structure, and grade. The estimates are in the Indicated and Inferred categories. The activity ends with preparation of **broad order of economic** or **prefeasibility** or **scoping** studies.

TABLE 1.3 Design of an Exploration Scheme With Identification of Work, Time, and Cost at Million US$ to Achieve the Anticipated Results

Phase	Drilling Interval (m × m)	Total Meter	No. of Holes	Time (Year)	Cost (m US$)	Objectives
1	400 × one hole	m_1	N_1	Y_1	$\$_1$	To establish the existence of target mineralization in space
2	200 × 50	m_2	N_2	Y_2	$\$_2$	To establish broad potential over the strike length and laboratory-scale metallurgy
3	100 × 50	m_3	N_3	Y_3	$\$_3$	To establish firm reserves, grade, bench-, and pilot-scale metallurgy and Detailed Project Report for conceptual mine planning and mine investment decision
4	50 × 50	m_4	N_4	Y_4	$\$_4$	To create database for detailed production planning and grade control
5	Close space near surface and wide space at lower levels	m_5	N_5	Y_5	$\$_5$	To delineate near-surface features like weathering limit and extension of orebody down depth
Total		m	N	1−5	mUS$	

1.3.2.5 *Detailed Exploration (G1)*

Detailed exploration is conducted before the start of the mining phase or mine development. It involves three-dimensional delineation to outline firm contacts of the orebody, rock quality designation (RQD) for mine stability, and planning and preparation of samples for pilot plant metallurgical test work. The works envisaged are mapping at 1:5000 and 1:1000 scales, close space diamond drilling (100 × 50, 50 × 50 m), borehole geophysics, a trial pit in case of surface mining, and subsurface entry with mine development at one or more levels in case of underground mining. The sample data are adequate for conducting three-dimensional geostatistical orebody modeling employing in-house or commercial software for making due diligence reports. The reserves are categorized as Developed, Measured, Indicated, and Inferred with a high degree of accuracy. The sum total of Developed, Measured, and Indicated reserves amounts to 60% of the total estimated resources for investment decisions and preparation of a **bankable feasibility study** report.

A mining lease (ML) is obtained at this stage for the purpose of undertaking mining operations in accordance with the Miners and Minerals (Development and Regulation) Act 2016 for major minerals. It shall also include quarrying concessions permitting the mining of minor minerals. The ML is granted by a competent authority, i.e., the state/provincial/territorial government, with clearance from the Federal Ministry of Mines, the Ministry of Forest and Environment, and the Bureau of Mines. The permissible area under the ML will be negligible and may be 1/100th of the reconnaissance area.

A total span of 15−50 years or more is needed for the closure of mining. Conditions may change, and it is a combination of foresight, steady perseverance, and agility in adaptation, along with a good measure of statistical providence to achieve project success.

1.3.2.6 *Ongoing Exploration*

Diamond drilling is a continuous process throughout the entire life of the mine to supplement the reserve of depleted ore. Exploration continues during mine development and production. This is primarily conducted by underground diamond drilling to enhance reserve down-dip in the strike direction. The aim of the mine geologist is to replace 1 tonne of depleted ore with 2 tonnes of new reserve at the end of each year. This will increase the life of the mine and continue mining operations. It also upgrades the category of reserve from Inferred to Indicated, Measured, and Developed. Drill information helps to precisely delineate the ore boundary, weak rock formation, and shear zones for mine planning. This also provides additional data on RQD. Geochemical sampling of soil, debris, and groundwater in wells, streams, and rivers within and around the mining license area is carried out at regular intervals to monitor environmental hazards. The process continues beyond the closure of the mine.

1.3.2.7 *Exploration Scheme*

The diamond drill is a prime exploration tool. It is expensive and the process of diamond drilling is carried out in a logical sequence. The scheme can be divided into a

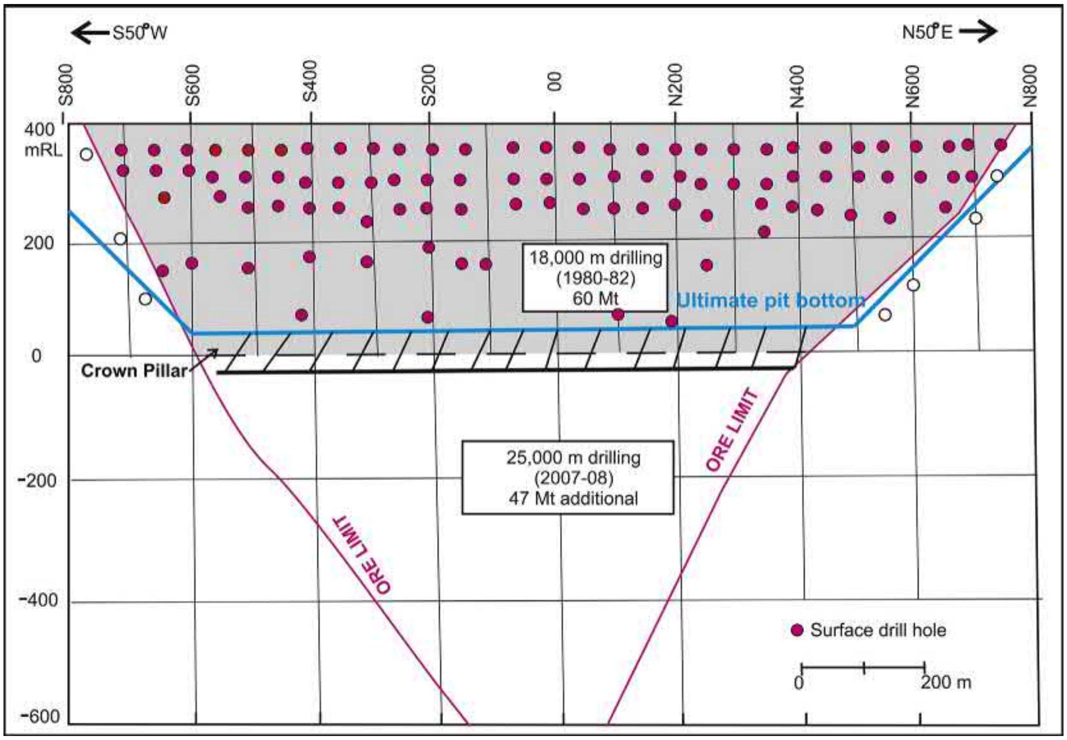

FIGURE 1.4 Longitudinal vertical projection of Rampura-Agucha zinc-lead-silver deposit in India showing phased and ongoing exploration program and resource update. The red color indicates the mineralized drill hole and separates boundary between orebody and waste rock on either sides. The blue color line demarcate the ultimate open pit limit and mining continues below by underground method.

number of phases depending upon the extension, size, and complexity of the mineral deposit. The activity in each phase is defined in a clear vision with respect to the interval of drilling, number of drill holes, meters to drill, time, and cost required to achieve the specified objectives (Table 1.3 and Fig. 1.4). At the close of each phase of activity the outcomes are reviewed with an economic benchmark. If necessary the activities of the next phase are momentarily modified or withdrawn from the project.

1.4 MINERAL POLICY AND ACT

Mother Earth is endowed with a variety of valuable mineral resources. These nonrenewable resources provide significant raw material for economic and overall growth of a country through the development of infrastructure, basic industries, and capital goods. Governments, particularly under federal and state structures, are committed to maintaining GDP at around 10%–15% from mineral sectors. The efficient management and scientific development of the mineral sector through integration of exploration, mining, beneficiation, extraction, and sustainable uses are to be guided within the framework of short- and long-term national goals, priorities, and prosperities.

The mineral policy or more precisely National Mineral Policy (NMP) is a reflection of that trend, taking care of public interest. The federal government requires development of minerals in the interest of the nation as a whole, and creates a mechanism to benefit the local population in particular. The policy ensures linkages between forward and backward states of union/federal government for the setting of mining projects. Individual states or regions can formulate their own policy under a national outline for the state's interest.

National policy is the principle, philosophy, vision, and mission for the development of mineral sectors. Rules, regulations, and Acts are the framework formulation of enforceable laws authorized by major legislation for legislative applications to pronounce efficient policy. The common legislations are the Mineral Concession Rules (MCRs), the Mineral Conservation and Development Rules, the Mines (Health and Safety) Rules, the Mines and Mineral (Development and Regulation) Act, the Mines Act, the Environment (Protection) Act, and the Forest Act.

The national goals and perspectives are dynamic and responsive to the changing needs of the industry in the context of domestic and global economics. Policy and Acts are amended as and when required. Reliable and transparent policy and Acts promote a focused and sustained investment climate in exploration and mining by national and foreign players. A favorable work environment by removing bottlenecks and red tape, which hinder long-term productivity and efficiency, must be reflected in the Act. Increasing competition on account of globalization, highest level of technology uses, and initiative growth in the mining sector has assumed critical significance. Mineral policy and Acts have to ensure the will, stability, sustainability, and internationality irrespective of the ruling government.

The policy and Acts as defined in developed and developing countries are discussed in brief next.

1.4.1 Australia

The commonwealth of Australia has the world's ninth highest per capita income. The country is comprised of the mainland surrounded by more than 8000 islands in the Indian and Pacific oceans, which includes Tasmania. The population is estimated at 23.78 million (2015). Australia follows a constitutional monarchy with a federal parliamentary system. It has six states and two major mainland territories. The Australian dollar is the currency (where 1 AU$ = 0.75 US$ as at April 2017).

Australia has significant mineral endowment supported by a strong advanced mineral exploration technology, mechanized mining tradition, technical institutions and vocational training centers, and well-trained engineers and workforces. The Australian exploration and mining companies are spread over the globe at different capacities. The mineral resource base industries are the key pillar of the Australian economy. Australia is the world's leading producer of bauxite, iron ore, rutile, zircon, and ilmenite, the second largest producer of alumina, gold, lithium, manganese ore, zinc-lead, the third largest producer of uranium, and the fourth largest producer of silver, nickel, and black coal.

Australian mineral policy instruments and regulations are aimed at rational development of the country's mineral resources. The wide goals of the government are to achieve community development, employment generation, a lower inflation, overall economic growth, and maintain high environmental standards and sustainability. The policy has been balanced to satisfy a company's perspective, i.e., the interests of its shareholders.

The mineral policy and mining legislation are largely provincial. Mines and minerals are a state subject in Australia and hence each of the six states and two major territories has its own mining legislation. Although there are many similarities, differences in legislation from state to state are also very significant. The policy framework and Acts are powerful, with clarity, efficiency, and competitiveness contributing to the country's prosperity. However, the system is quite complex on certain issues. The legislation as framed in Western Australia (Table 1.4) can be

TABLE 1.4 Western Australia: Tenement Type Summary (2009)

Tenement	Area	Term	Objective	Condition
Prospecting license	Not to exceed 2 km^2 for one license, eligible for more than one license	4 years from date of grant, discretionary renewal for one period of 4 years and further 4 years on license retention status	Prospecting for all minerals of economic interest	No significant ground disturbance other than drilling, pitting, and trenching
Exploration license	1–70 blocks, each block of 2.8 km^2	5 years, discretionary renewals for one period of 5 years in prescribed circumstances, and by further 2 years in exceptional circumstances	All minerals of economic interest—exploratory tenure—may extract up to 1000 tonnes of material	Applicant is technically competent and financial resources available, exploration reports to minister/geological survey
Retention license	Whole or part of primary tenement, eligible for more than one license	5 years, discretionary renewals for one period of 5 years in prescribed circumstances	Further exploration for all minerals of economic interest	Statutory declaration of identified resource, uneconomic and impracticable mining at present
Mining lease	Not exceeding 10 km^2, eligible for more than one mining lease	21 years, renewable as of right for one period of 21 years, discretionary thereafter	All minerals: may work and mine the land and remove, take and dispose minerals	Feasibility report, mineralization report prepared by a qualified person, approved mine plan, EMP, pay rent and royalties
General-purpose lease	≤ 0.10 km^2, eligible ≥ 1 lease	21 years: discretionary renewals for 21 years	Mining and related operations	Discretions of minister, registrar/warden
Miscellaneous licenses	–	5 years, renewals for 5 years and more	Rights for water	–

EMP, Environmental Management Plan.

considered as a model for discussion, with some deviation from other states and territories.

The Act may be cited as the Mining Act 1978, updated in 2009. The mining tenement or concession includes a PL, an exploration license, a retention license, an ML, a general-purpose lease, and a miscellaneous license granted or acquired under this Act or by virtue of the repealed Act. The Act includes a specified piece of land in respect of which the tenement is so granted or acquired. Application for all types of license in a prescribed format is submitted to the office of the mining registrar or warden of the mineral field or district in which the largest portion of the land to which the application relates is situated. The application must be accompanied by the following documents:

1. Written description of the area;
2. A map with clearly delineated tenement boundaries and coordinates;
3. Detailed program of work proposal;
4. Mining proposal or mineralization report prepared by a qualified person;
5. Estimated amount of money to be expended;
6. Stipulated fee and the amount of prescribed rent for the first year or portion thereof.

The mining registrar may grant the license if satisfied that the applicant has complied in all respects with the provisions of this Act and may refuse the license if not so satisfied. The holder of prospecting and exploration licenses will have priority for the granting of one or more mining or general-purpose leases or both in respect of any part or parts of the land while the license is in force. The license and lease are transferable.

1.4.2 Canada

Canada is the world's second largest country. The country consists of 10 provinces and three territories with a total population of 35.15 million (2016). Canada is a federal state, governed by a parliamentary democracy and a constitutional monarchy. It follows English and French as official languages. The currency is the Canadian dollar (where 1CA$ = 0.73 US$ as at April 2017). Canada ranks in the top five countries in the global production of 13 major minerals and metals: first in potash, second in uranium, nickel, and niobium, third in cobalt, aluminum, and platinum group metals, fourth in salt, sulfur, and tungsten, and fifth in diamonds, graphite, and gold.

The MMP was formulated in 1996 after extensive participation and deliberation between the federal government, provincial and territorial mines ministries, industries, environmental groups, and labor and aboriginal communities. The policy aimed at:

1. Promoting economic growth and job creation;
2. Affirming provincial jurisdiction over mining;
3. Delineating a new role for the federal government in minerals and metals that is tied to core federal responsibilities;
4. Meeting the challenges of sustainable development of minerals and metals at the international level;
5. Committing the government to pursue partnerships with industry, the stakeholders, the provinces and territories, and others in addressing issues within its jurisdiction;
6. A green environment; and
7. Globalization of the Canadian mineral sector through active, effective, and influential partnerships on the international stage.

The policy plays an essential role in the country's economy. It enjoys leadership in exploration and mine production within the country and the export of mining technology and equipment all over the world. Canada has become one of the world's principal venture capital markets for mineral exploration and development with the globalization and liberalization of investment regimes. The mineral and mining Act and regulation can be grouped as follows:

1. Mineral rights in Canada are primarily owned by the provincial or territorial government.
2. An individual or a company is entitled to apply for exploration, development, and mining rights in prescribed format, fees, and documents comprising of maps, descriptions, annual work plan, and anticipated expenditures. The lease is granted by the state department authority under its statutes and regulations.
3. The mining legislations for each of the 13 Canadian jurisdictions are separate, except for Nunavut. Nunavut is a newly formed territory covering the east and north portions of Northwest Territories. Nunavut exploration and mining activities continue to be regulated by the Department of Indian Affairs and Northern Development's office based in Northwest Territories.
4. The surface and mineral rights on the same property can be held by different owners for different minerals/end products.
5. There is no competitive bidding for mineral exploration rights in Canada.
6. Locations for mineral rights are selected by companies or individuals according to their choice in freehold land.
7. Individuals and companies must obtain a prospector's license before engaging in exploration for minerals. This is applicable in Northwest Territories, British Columbia, Manitoba, Ontario, Quebec, New Brunswick, and Nova Scotia.
8. However, one can conduct prospecting or exploration without a license in other states. A license will be required later to acquire mineral rights to protect a

claim of discovery. A special permit is required to obtain the right to fly an airborne geophysical survey over an area not covered by a mineral claim.

9. PL and recording fees are imposed at variable rates across jurisdictions.
10. It is expected that the leaseholder carry out a certain amount of assessment work each year to keep the claims in good standing. Technical activities include geological mapping, geochemical sampling, diamond drilling, assaying, and related work of certain value. Copies of geological maps, reports, drill logs, and assay values must be submitted to the mining recorder. The reports are kept for future access by any interested party, after the end of a confidentiality period.
11. Mining claim units are normally 0.16—0.25 km^2, with a maximum individual claim dimension varying between 2.56 and 5.00 km^2. It can be even larger, especially where claims are registered by way of **map staking**, the process of recording the claims on a surveyed map directly at the mining recorder's office without visiting the location.
12. Holders of claims in good standing must obtain a ML to develop the property into a mine. MLs require that claim boundaries be surveyed by a registered land surveyor. Mining rights are valid in most provinces/territories for 21 years and renewable until the ore persists.

1.4.3 Chile

The republic of Chile, a stable and prosperous nation in South America, occupies a long narrow coastal strip between the Andes Mountains in the east and the Pacific Ocean in the west. The country is populated by a multiethnic society of 18 million Spanish speaking inhabitants (2015). The currency is the Chilean peso or CLP (where1 US$ = 670.41 CLP as at April 2017). Chile is divided into 15 regions. The northern desert contains great mineral wealth, primarily of copper (production and export), molybdenum, iron ore, gold, and nitrates.

The destination for worldwide investment in exploration and mining became trade and industry friendly for Latin America (Chile, Peru, Argentina, and Bolivia). These countries formulated massive legal reform to safeguard the private investment players in the mining sector. In addition, emphasis was given to protect the environment, human rights, community development, and sustainability in mining. The exploration and mining Acts are framed as follows:

1. The provisions of the legal framework are derived from the Constitution of Chile and by basic constitutional laws, codes, and regulations that apply specifically to the mining industry. Legal framework guaranties assuring ownership of mineral holdings for both exploration and mining concessions.
2. The Mining Code provides state ownership and mineral rights. The state has absolute, exclusive, inalienable, and regulatory ownership of all mines, including coal and hydrocarbon, except surface clays.
3. Surface clay, sand, rocks, and similar materials, which can be used as such directly for construction, are not considered mineral substances and are not governed by the provisions of this Code.
4. The mining lease requires property rights of natural or legal individuals over lands where the minerals may be found. All individuals and companies may file exploration and mining concessions and acquire the rights after they are granted.
5. However, applications are debarred for justices, judges, secretaries, registrars, officials, and employees of appellate and civil courts, state agencies, or companies that, because of their positions, office, or duties, participate in granting mining concessions or have access to geological discoveries of minerals and related information or mining data. This restriction is limited up to 1 year after they have ceased to hold their position. The spouse and legitimate children of any of the aforementioned individuals are not entitled because of reasons based on considerations of national interest.
6. A mining concession may be granted for exploring and/or mining a mineral deposit. Any person is entitled to drill test holes and take samples during exploration irrespective of surface rights over the tenement. However, any damage to crops or buildings shall be compensated to the private land owner and prior permission obtained for government land.
7. Mining concessions may be granted on claimable mineral substances, including discarded mine production, tailings and slag of earlier mining, and smelting within the lease boundary.
8. In the event that any new mineral is found in the leasehold in significant quantities, which can be technically and economically mined and beneficiated, the state shall be informed. The new product shall be sold on behalf of the state. The cost incurred by the producer shall be reimbursed by the state.
9. A concession shall be comprised of a north—south-oriented parallelogram with coordinates of intersection in most precised UTM systems. The sides of the exploration tenement shall be measured at a minimum of 1000 m and multiples thereof. The area of exploration concession shall not exceed 50 km^2. The legislation contemplates two periods for expiration. The first period is for 2 years followed by a discretionary renewal for an additional 2 years reducing 50% of the initial area. Annual taxes must be paid to maintain the property rights in good standing.

10. The right to mine mineral substances is the legal continuity of exploration concessions. The sides for mining concession shall be at a minimum of 100 m or multiples thereof. The area of mining concessions shall not exceed 0.10 km^2. Once the filing process for mining concession has been completed and granted, and as long as the annual property tax payments have been made, the system provides the legal tools to maintain the concession until mine closure.

1.4.4 India

The Federal Constitutional Republic of India is the largest democracy in the world, with 1.327 billion people (April 2017). India consists of 29 states and seven union territories. It is the fourth largest economy by purchasing power parity (PPP). The first official language is Hindi. English is equally recognized. The currency is the Indian rupee (₹) (where 1 US$ = 66.75 INR (₹) as at April 2017). India is the leading producer and exporter of chromium, iron ore, manganese, bauxite, alumina, coal, and zinc. Nonmetallic minerals include limestone, rock phosphate, kaolin, and dolomite.

The Indian mining history dates back more than 5000 years and has naturally gone through various processes of change over the years. In ancient times the king was the supreme authority. The mine owners had limited freedom. Safety and the environment were not matters of concern. Subsequently, British-ruled states formulated the Indian Mines Act to take care of the safety and welfare of miners. However, the rulers of princely states were unconcerned with the Act, and the government was satisfied with indirect returns. The nation witnessed major developments after the postindependence era (1947) by abolition of the princely states. The first Industrial Policy Resolution and Industrial Development Act were formed in 1948 and 1951, respectively, with the active role of the state for the development of industries in a socialistic pattern. MCRs were formulated in 1963 and amended up to 2003 (IBM, 2003). The participating agencies were federal and state sector public enterprises for major and strategic minerals. The private sectors were entrusted with minor minerals. NMP was formulated in 1990 with following salient features:

1. Exploration and mineral identification on land and offshore;
2. Mineral resource development at national and strategic considerations to ensure adequate supply for present and future needs;
3. Linkage for smooth and uninterrupted development of the mineral industry to meet the needs of the country;
4. Promotion of research and development in minerals;
5. Ensuring establishment of appropriate education and training facilities for Human Resource Development to meet labor requirements in the mineral industry;
6. Minimizing the adverse effects of mineral development on forest, environment, and ecology through protective measures;
7. Ensuring mining operations comply with the safety and health care of all concerned;
8. State government to grant and renew licenses and leases;
9. Federal and state enterprises primarily responsible for mining and processing of 13 minerals of basic and strategic importance:
   - **a.** Iron ore
   - **b.** Chromium
   - **c.** Gold
   - **d.** Copper
   - **e.** Zinc
   - **f.** Tungsten
   - **g.** Platinum group of metals
   - **h.** Manganese
   - **i.** Sulfur
   - **j.** Diamond
   - **k.** Lead
   - **l.** Molybdenum
   - **m.** Nickel
10. Mining and processing of minor minerals by private sectors;
11. Geological Survey of India (GSI) responsible for regional mineral resource assessment;
12. Detailed exploration by state Directorate of Mines and Geology (DMG), state and central undertakings, and seabed exploration, mining, and processing by the Department of Ocean Development;
13. National mineral inventory: creation, updating, and dissemination by Indian Bureau of Mines (IBM).

Globalization of the Indian economy (1991) brought about a revision of NMP in 1993 to de-reserve the foregoing 13 minerals, and to give access to domestic and foreign private Mineral Exploration Groups. The NMP 1993 aimed at encouraging the flow of private investment and the introduction of state-of-the-art technology in exploration and mining. Eligibility for the granting of concessions is open to such a person of Indian nationality or a company incorporated in India under the Company Act 1956, and has registered him/herself with IBM or the state DMG. Such person or company shall undertake any reconnaissance, prospecting, general exploration, detailed exploration, or mining in respect of any major and minor minerals under reconnaissance license, LAPL, PL, or ML. Finally, the National Mineral Policy 2008 (MOM, 2008)

TABLE 1.5 Summaries of Mineral Rights Applicable in India (2011)

Tenement	Objective	Area	Term	Requirements	Conditions
Reconnaissance licence/permit	Grassroots exploration to identify mineral targets at regional scale for further prospecting, preliminary resource	Not to exceed 10,000 km^2 within a state	Between 1 and 3 years, nonrenewable	Indian national or company incorporated in India under Company Act, prescribed application	Well-defined work program, technically competent and financially strong, 100% FDI permissible
LAPL	Exploration and identify deposit, Inferred resource	Between 500 and 5000 km^2	Between $\geq$3 and 6 years, discretionary renewal for 2 years	Ditto	Ditto
PL	Systematic searching of deposits, outline Inferred resource	Between 1 and 500 km^2	Between 2 and 3 years, discretionary renewal for 2 years	Ditto	Ditto
General exploration	Indicated	Under PL		Ditto	Ditto
	Inferred				
	Prefeasibility				
Detailed exploration	Measured	Under PL		Ditto	Ditto
	Indicated				
	Inferred				
	Feasibility				
ML	Feasibility, mine development, production: • Developed • Measured • Indicated • Inferred	Between 100 and 0.10 km^2	Between 20 and 30 years, discretionary renewal for 20 years at a time, ensure full ore utilization	Ditto Mine plan, EMP complete, forest clearance, land detail	Ditto

EMP, Environmental Management Plan; *FDI*, foreign direct investment; *LAPL*, large area prospecting license; *ML*, mining lease; *PL*, prospecting license.

has been revised with fine tuning and transparency. A summary of the mineral rights (Table 1.5) and additional salient features is as follows:

1. The Mineral Policy (2008) aspires to develop a sustainable framework for optimum utilization of the country's natural mineral resources for the industrial growth of the country. At the same time it improves the life of people living in the mining areas that are generally located in backward and tribal regions.
2. The policy aims at strengthening the framework/institutions supporting the Indian mining sector, which include the IBM, GIS, and state DMG.
3. Government agencies will continue a nationwide survey, exploration, and mineral resources assessment.
4. The IBM will maintain a database in digitized form comprising a resource inventory in United Nations Framework Classification system and Tenement Registry that will be available at a cost.
5. A major thrust will be the development of infrastructural facilities in mineral-bearing remote areas.
6. Removal of restrictions on foreign equity holding in the mining sector will enable any company registered in India irrespective of foreign equity holding to apply for a reconnaissance and PL or ML. Foreign direct investment (FDI) or direct foreign equity participation is raised to 100%.
7. The policy is aimed at attracting large FDI in reconnaissance and large area prospecting and right of entry to improved technology in scientific and mechanized mining.
8. The policy emphasizes security of tenure along with transparency in allocation of concessions, seamless transition from prospecting to mining, and transferability.

9. The policy promotes competitive auction of orebodies fully prospected at public expense.
10. A cluster approach will be adopted by grouping small deposits within a single lease.
11. Relief and rehabilitation of displaced and affected persons will be extended with humanity.

1.4.4.1 Lease Amendments

The following Amendments have been made to the Indian Mines and Minerals (Development and Regulation) Act 2015:

1. There will be two types of license/lease: an ML and a composite license (CL), which will be electronically auctioned under the Mines and Minerals (Development and Regulation) Amendment Act 2015. This is as per the Mineral (Auction) Rules 2015 notified by the Ministry of Mines, Government of India.
2. While the ML will be for areas with proven reserves of minerals, the CL (prospective-cum-mining) will be for areas where preliminary exploration has been done by the government, and further exploration is required by mining companies.
3. The state governments will be required to specify the reserve price for auctioning MLs, which will be the mineral dispatched in a month multiplied by its sale price, as published by the IBM for the month of dispatch. The rules make it clear that auctioning will be done on a forward auction basis where the highest bid above the reserve price wins.
4. Similar to the e-auction of coal blocks, there will be a two-stage bidding process, where bidders will have to give an initial price offer at the technical stage. The initial price offer will have to be higher than the reserve price.
5. The highest such initial price offer will be the floor price (starting price) for the e-auction in the financial bid stage.
6. Auctioning for a CL will follow a similar pattern, but with additional requirements. State governments will be required to share the findings of the preliminary exploration of an area and the details of the land, including that under forest and land not owned by the state government.
7. The winner will have to undertake exploration in the area. If the winner fails to find mineral content, the license will lapse and the ML will be cancelled.
8. To be eligible for participation in the auction of either the license or the lease, the mineral reserve should not exceed more than 1.25 times the requirement of the bidder for its specified end use over 50 years. The bidders will need to furnish performance bank guarantees, which will be linked to the milestones in the mining plan.

1.4.5 Portugal

Portugal or the Portuguese Republic extends north–south in a rectangular fashion and includes continental Portugal, the Azores, and the Madeira Islands. The country is located in the southwest corner of Europe. Portugal has a population of 10.34 million (2015 estimate) with 95% literacy. The official language is Portuguese. The currency is the euro (€) at an exchange rate of 1 EUR = 1.1005 US$ as at April 2017.

The 85 km-long Iberian Pyrite Belt (IPB) exists between Portugal in the west and Spain in the east. IPB is one of the rich mineralized geological provinces of Western Europe and hosts number of deep-seated volcanogenic massive sulfide and gold deposits in the Portuguese part. The production of metallic minerals includes copper (Neves Corvo, refer to Chapter 15, Section 15.6), tungsten (Panasqueira mine, sixth largest in the world), lead, zinc, lithium (sixth largest), tin (10th largest), silver, and gold. Portugal is one of the leading producers of copper metal and tungsten concentrate in Europe. The mineral industry represents ~1% of GDP. The country also owns important uranium deposits, with ~4200 tonnes of U_3O_8 produced between 1950 and 1990.

The new mineral policy (amended in 2003) on spatial planning was created at the national level for a sectorial planning for minerals that must be produced by the national government. The legal nature of this plan is considered as policy guidance to assist in the decision-making process for both preparation and approval of low-level plans (all minerals) and total operation.

The prime target for exploration activities is focused around the IPB because it appears to have a good potential for success on the basis of the large sulfide deposits discovered so far. The IPB is a focal point of interest for mining companies. Several gold and base metal projects are under feasibility studies. Portugal is also known for its lower cost of production in Europe and Asia. These factors attract significant opportunities for FDI.

1.4.6 South Africa

The Republic of South Africa with parliamentary democracy is divided into nine provinces. The population is 54.96 million (2013 estimate). There are 11 official languages, two of which are Afrikaans and English. The South African currency is the rand (R) with the code ZAR (where 1 ZAR = 0.075 US$ as at April 2017). South Africa remains a cornucopia of mineral riches. It is the world's largest/leading producer of chrome (11 million tonnes), PGE (75.115 tonnes), gold (160 tonnes), iron ore (63 million tonnes), diamond, manganese, vanadium, and vermiculite.

Prior to May 2004 mineral rights in South Africa were owned by individuals or legal entities. Since then the government enacted the Minerals and Petroleum Resources Development Act, and all minerals now vest in the state as a long-term objective. The Act defines the state's legislation on mineral rights and mineral transactions. The Act also emphasizes that the government did not accept the dual state and private ownership of mineral rights. The government has entrenched a "use it or lose it" principle that is applied to leaseholders who own mineral and prospecting rights but are not making use of them. Privately held mineral rights had to be transferred under the provisions of the Act into licenses to prospect and mine that are granted by the state. Ultimately, all minerals in South Africa vest in the state.

The Act encourages that government policy furthers Black Economic Empowerment (BEE) for mineral industries within the country. It encourages the mineral exploration and mining players to enter into equity partnerships with BEE companies. The Act made provision for implementation of social responsibility procedures and programs. Details of these criteria are required to be provided in applications for permits and licenses under Schedule II (Transitional Arrangements). Existing prospecting and mining rights continued in force for a period of 2 and 5 years, respectively, from May 1, 2004. Holders of any unused old order rights had the exclusive right to apply for a prospecting or a mining right within 1 year of the Act coming into effect, failing which the right ceased to exist.

The state has confirmed its commitment to guaranteeing security of tenure in respect of prospecting and mining operations. The Act states that a company has 5 years (due date April 30, 2009) to apply for a new order mining license and the new order mining license will be granted for a maximum of 30 years. A summary of minerals rights applicable in South Africa is given in Table 1.6.

1.4.7 Tunisia

Tunisia is a small country located on the Mediterranean coast of Africa, between Algeria and Libya. The capital, government, head of state, and languages are Tunis, republic, president, and Arabic-French, respectively. Tunisia, with a population of 11 million (2014), is considered the most liberated in the Arab world, and has peaceful relations with both Israel and Palestine. State investment in

TABLE 1.6 Summaries of Minerals Rights Applicable in South Africa

Tenement	Objective	Duration	Requirements	Condition
RP	Exploration at grassroots level	2 years (nonrenewable)	Financial ability, technical competency, and well-defined work program	Holder does not have the exclusive right to apply for a prospecting right
Prospecting right	Exploration at target definition stage	Initially 3 years. Renewable once for 3 years	Ditto + Economic program and environmental plan	Payment of prospecting fees
Retention permit	Hold on to legal rights between prospecting and mining stages	3 years initially	• Prospecting stage complete; • Feasibility study complete; • Project currently not feasible; and • EMP complete	May not result in exclusion of competition, unfair competition, or hoarding of rights
		Renewable once for 2 years		May not be transferred, ceded, leased, sold, mortgaged, or encumbered in any way
Mining right	Mine development	30 years initially. Renewable for further periods of 30 years. Effective for LOM	• Financial ability; • Technical ability; • Prospecting complete; • Economic program; • Work program; • Social, labor, and environmental plan	Payment of royalties
				Compliance with Mining Charter and Codes of Good Practice on BBBEE
Mining permit	Small-scale mining	Initially 2 years, renewable for three further periods of 1 year at a time	Life of project must be < 2 years, area not to exceed $<0.01\ \mathrm{km}^2$, and environmental plan completed	Payment of royalties
				May not be leased or sold, but is mortgageable

B-BBEE, Broad-Based BlacK Economic Empowerment; *EMP*, Environmental Management Plan; *LOM*, Life of Mine; *RP*, reconnaissance license/permit.

infrastructure for the last 10 years has ensured that, despite inhospitable terrain, there are 20,000 km of good-quality paved roads linking all parts of the country. Fuel is cheap and readily available. The mineral resources are phosphates, iron ore, zinc-lead, and salt. The rail system is good, regular, and reliable. There are six international airports, and the national airline, Tunis-air, flies to Europe and the Middle East. There are eight commercial seaports and 22 smaller ports. Power is generated by the state-owned Société Tunisienne de l'Electricité et du Gaz. The Tunisian dinar (TND) is a soft currency (where 1 TND = 0.41 US$ as at April 2017).

All exploration and mining activities in Tunisia are governed by the Directorate General of Mines (DGM), and regulated under the Mining Code (Code Minier) promulgated under Law 2003-30, April 28, 2003. All mineral resources belong to the public domain of the state of Tunisia with full rights. All exploration and mining rights are vested in the state as represented by the Minister of Mines.

All prospecting, exploration, or exploitation rights are granted to natural Tunisians or foreign persons on the basis that they can demonstrate adequate financial resources and technical capacity to undertake the proposed activities in an optimal manner. All rights are granted provided that written permission has been obtained from the land owner (Article 79 Code Minier) and in case of dispute, final authority is vested in the state. The holder of a mining right is responsible to mark out the perimeter.

The following rights are granted by the DGM:

1. PL: granted to permit applicants to conduct the investigation necessary to prepare application documents for exploration permits but precludes drilling or mining activities. A PL grants access to areas covered by an exploitation concession or exploration permit for substances covered in the existing rights.
2. Exploration permit: initially granted for 3 years (Article 30 Code Minier), renewable twice thereafter, with each renewal period for a maximum of 3 years. A work program and detail of financial commitment by the permit holder are required on application, and renewals are contingent upon successful completion of the commitment and fulfillment of conditions set out in the Code Minier.
3. An exploration permit can be renewed for a further 2-year period after the expiry of the second renewal period and such a renewal is referred to as a special renewal and is granted to the permit holder to enable it to complete prefeasibility studies. At the end of the special renewal period, the permit holder has to apply to convert the permit into an exploitation concession (mining license) or relinquish the property. Exploration activities must commence within 12 months of the approval of the right. The permit holder is obliged to submit progress reports as a number continuing obligations.
4. Exploitation concession: granted by the Minister of Mines after approval of the Mining Consultative Committee. The concession is granted for a period consistent with the quantity of mineral reserves and the holder is required to commence development work no later than 2 years after authorization of the concession. The holder is responsible for rehabilitation liabilities and has social obligations in terms of the training and employment of Tunisian employees.
5. The holder of the foregoing rights is required to furnish the DGM with annual progress reports, as well as monthly statistical reports of employees, production, revenue, and equipment.

1.4.8 Royalties and Taxation

The fiscal policy related to application and registration fees, royalty, income tax, compensation to land owners, rehabilitation cost, and annual and dead rent applicable to holders of mineral exploration and mining rights varies between countries and even states. Mineral royalties are exclusively state/provincial/territorial earnings and constitute a significant revenue source for the state/provincial/territorial government. Mineral-rich states like Queensland, Western Australia, California, Ontario, Northern Province of South Africa, and Rajasthan receive more than 10% revenue from the mineral sector. Neither the rates nor the methods of calculating royalty are uniform. The rate of royalty in respect of copper, zinc, and gold ore, removed or consumed by the leaseholder or his/her agent, is compared in Table 1.7. The royalty and taxation rates vary as amended by the federal government from time to time.

1.4.9 Lease Application

Mineral concessions in general are the responsibility of the state/province/territory with the approval of the federal government. The model format of lease application pertaining to reconnaissance, large area prospecting, prospecting, mining, and all other lease-related matters can be obtained from the state/provincial/territorial Department of Mines and Geology. Applications are submitted to the state/provincial/territorial Department of Mines and Geology along with supporting documents (reports, work plan, proposed expenditure, map marked with tenement borders and coordinates, etc.) and stipulated fees. It must be within the framework of Mineral Concession Rules (MCR) 2016

TABLE 1.7 Summary of Comparative Royalty Rates in Various Countries

	Commodity		
Country	**Copper**	**Zinc**	**Gold**
India	4.2% of London Metal Exchange Cu metal price chargeable on the contained Cu metal in ore produced	8% or 8.4% of London Metal Exchange Zn metal price on ad valorem basis chargeable on contained Zn metal in ore or concentrate produced respectively	2% of London Bullion Metal Association price chargeable on the contained Au metal in ore produced
Australia	Royalty rates are fixed at 30 cents/tonne (aggregate, clays, dolomite, gravel, gypsum, construction limestone, rock, salt, sand, and shale) and 50 cents/tonne (building stone, metallurgical limestone, pyrophyllite, silica, and talc). All other minerals are rated as a % of the realized value at 2.5% (Co, Hg, platinum-group elements, Ag), 7.5% (bauxite, calcite, diamond, gems, precious and semiprecious stones, iron ore, manganese, and quartz crystal), and 5% for all other minerals with some minimum value per tonne for garnet, ilmenite, leucoxene, rutile, nickel, and zircon		
Canada	Mining tax/royalty varies between provincial/territorial regime at 12%–20% of net profits after full cost recovery		
Chile	Progressive royalty rates that range between 5% and 14% levied on the margin of profits obtained on sales of nonrenewable mining products		
South Africa	Royalty tax rates = 0.5% + X/9.0 (maximum 7%) for metals in concentrate or 0.5 + X/12.5 (maximum 5%) for refined metals. X = EBIT/gross sales × 100 EBIT = Earnings before interest and taxes. Royalties will be paid biannually in accordance with the Minerals and Petroleum Resources Development Act and the Mineral and Petroleum Resources Royalty Bill.		
Tunisia	Mining royalty equal to 1% of the gross revenue from extracted ore, paid biannually during the 2 months following the previous quarter		

and Mines and Minerals (Development and Regulations) Act 2016 of the home country. The lease is granted or denied with reasons within a specified time by the state department with concurrence from the federal government.

1.4.10 Cyclical Nature of Mineral Industries

The mineral industry undergoes the expected process of "cyclical natural ups and down" as a consequence of global slowdown in all major economies, with disinclination in the demand for metals and minerals. The average life cycle of nonrenewable minerals and metals reach the pick and then decline. The cycles of ascending and descending vary between 10 and 15 years. These trends in customer demands are creating new challenges and opportunities for today's metals organizations. Emerging markets in the near future will grow significantly due to the source of raw materials from both ever-growing China and India with higher PPP. Mineral exploration activity is an ongoing process within the context of the cyclical nature of the mineral industry to contest the supply chain in a changing demand scenario. Therefore a blend of exploration innovation, recycling, substitution, as well as reduced consumption of metals will help to sustain the global population in terms of mineral commodity supply for the years to come (Gandhi and Sarkar, 2016).

1.5 MINERAL TO METAL: A FULL CIRCLE

The significant and salient steps from discovery of mineral deposits to delivery of finished products to end users have been articulated in a cycle of 1–13 with emphasis on the cyclical nature of the mineral industry:

1. Mineral exploration to discover a deposit: reconnaissance, prospecting, and modeling—Chapters 1, 2, and 10.
2. Exploration via geology, geochemistry, geophysics, photogeology: remote sensing and geographic information system—Chapters 3–6.
3. Sampling, reserve/resource estimation, and precision by geostatistical applications—Chapters 7–9.
4. Feasibility study to prove commercial viability—Chapter 13.
5. Mine development, infrastructure, and extraction of ore from the ground—Chapter 11.
6. Mineral processing: milling and separation of ore from gangue to produce concentrates, refinement of industrial mineral product—Chapter 12.
7. Smelting: recovery of metals from mineral concentrate—Chapter 12.
8. Refining of metals to 99.99% purity—Chapter 12.
9. Marketing: shipping the product (concentrates, metals, and minerals) to the buyer (in-house or custom smelter and manufacturer)—Chapter 13.

10. Caring for the ecosystem and ensuring a sustainable future—Chapter 14.
11. Experience from exploration and mine case studies—Chapter 15.
12. The continuing search for minerals—Chapters 1−15.
13. Cyclical natural of global mineral industries creating new challenges and opportunities for today's metals organizations.

Knowledge of key geological field techniques is essential for exploration geologists involved in the search for metallic mineral deposits. The techniques, skills, and tasks include collection of all possible surface and subsurface field information, storage, analysis and presentation of geological data and their uses to locate new exploration targets, and identification of ore deposits (Roger, 2010).

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Chapter 2

Economic Mineral Deposits and Host Rocks

Chapter Outline

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00002-2

> *Economic strength of a country is known by its mineral wealth.*
>
> Author.

2.1 DEFINITION

A mineral deposit becomes economic when it has a profitable commercial value attached to it. The concentration of minerals and/or metals in deposits varies widely, and ranges from a few parts per million (1—10 ppm or g/t) for noble metals like platinum, palladium, gold, and silver, to a low percentage (1%—10%) for copper, zinc, lead, and to a higher grade (40%—60%) for aluminum, chromium, and iron ore. A mineral is termed economic or uneconomic depending on its industrial uses. The mineral quartz is economic as silica sand used in the glass or optical industry. The same mineral is uneconomic when it hosts gold as an auriferous quartz vein or occurs as a constituent of rocks hosting copper, zinc, and iron ore. It is processed and discarded as gangue, tailing, or waste. Ore deposits are generally composed of a main product, one or more coproducts, and trace elements such as zinc-lead-silver, copper-gold, and chromium-nickel-platinum-palladium. Sometimes a single mineral forms the valuable deposit such as calcite in marble. The same mineral can be designated as metallic or industrial depending on its use. Bauxite ore is **metallic** when aluminum is produced and **industrial** when used directly for refractory bricks and abrasives. An ore deposit can be composed of metallic and nonmetallic minerals, mined together, and processed to produce separate products. An example is Bou Jabeur deposit, Tunisia, containing galena and sphalerite along with fluorite and barite.

Economic minerals occur in various forms such as native elements to compounds of oxide, carbonate, silicate, sulfide, sulfate, sulfosalts, and phosphate (Table 2.1).

There are millions of metallic, polymetallic, and nonmetallic economic mineral deposits located all over the world with variable features with respect to host rocks, mineral composition, and near surface to deep seated, with high variation in volume and grade. Some of the commonly known examples include:

1. The Bushveld platinum, palladium, chromium deposit is the largest in the world and is hosted by the mafic/ultramafic igneous intrusive complex (Bushveld Igneous Complex), South Africa.
2. The Sudbury nickel, copper, platinum, palladium deposit is the largest deposit hosted by the mafic/ultramafic meteoritic impact complex (Sudbury Igneous Complex), Canada.
3. The Super Pit is the largest gold deposit in Western Australia, hosted by shear golden dolerite.
4. The Olympic Dam is a large polymetallic underground mine located in South Australia, 550 km north-northwest of Adelaide. It is the fourth largest copper deposit and the largest known single deposit of uranium in the world.
5. The Ok Tedi is an open-pit copper and gold deposit/mine in Papua New Guinea located near the headwaters of the Ok Tedi River.
6. The Red Dog is the world's largest known sediment-hosted zinc, lead, and silver deposit/mine located in a remote region of the Arctic in the US state of Alaska.
7. Rampura-Agucha is a world class, near-surface zinc, lead, silver deposit hosted by graphite mica schist and calc-silicate rocks, India.

TABLE 2.1 Forms of Occurrences and Common Minerals

Forms	Minerals
Native element	Copper (Cu), gold (Au), silver (Ag), platinum (Pt), palladium (Pd), antimony (Sb), sulfur (S), graphite (C)
Oxide and hydroxide	Quartz (SiO_2), hematite (Fe_2O_3), cassiterite (SnO_2), chromite (Cr_2O_3), bauxite ($Al_2O_3 \cdot 2H_2O$), gibbsite ($Al(OH)_3$), goethite ($FeO(OH)$), psilomelane (MnO_2), magnetite (FeO, Fe_2O_3)
Carbonate	Calcite ($CaCO_3$), magnesite ($MgCO_3$), dolomite ($CaMg(CO_3)_2$), ankerite $Ca(Fe,Mg,Mn)(CO_3)_2$, smithsonite ($ZnCO_3$), cerussite ($PbCO_3$), rhodochrosite ($MnCO_3$), azurite $\{Cu_3(CO_3)_2(OH)_2\}$
Silicate	Andalusite-kyanite-sillimanite (Al_2SiO_5), beryl ($Be_3Al_2Si_6O_{18}$), amazonite ($KAlSi_3O_8$), garnet group—pyrope ($Mg_3Al_2(SiO_4)_3$), almandine ($Fe_3Al_2(SiO_4)_3$)
Sulfide	Chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS), pyrite (FeS_2), pyrrhotite ($Fe_{(1-x)}S$ ($x = 0$ to 0.2))
Sulfate	Barites ($BaSO_4 \cdot 2H_2O$), gypsum ($CaSO_4$), anglesite ($PbSO_4$)
Sulfosalts	Bournonite ($PbCuSbS_3$), tetrahedrite ($Cu_{12}Sb_4S_{13}$), tennantite ($Cu_{12}As_4S_{13}$)
Phosphate	Apatite $\{Ca_5(PO_4)_3(F,Cl,OH)\}$, rock phosphate

8. Escondida copper mine in the Atacama Desert in northern Chile is currently the world's largest copper mine by reserve.
9. The Carajás iron ore deposit is the world's largest mine located in northern Brazil.
10. Guinea bauxite deposits are the world's largest reserves located in Western Africa.
11. Jubilee (Yubileyny) diamond mine, located in Sakha (Yakutia) in the Russian Republic, is the biggest diamond mine in the world.
12. The North Antelope Rochelle coal mine in the Powder River Basin of Wyoming, USA, is currently the world's largest coal mine by reserve.
13. The Ghawar oil and gas field in Saudi Arabia occupies an anticline above a basement fault block dating to Carboniferous sediments.

2.2 COMMON ECONOMIC MINERALS

A list of common economic metallic and nonmetallic ore-forming minerals, with their chemical formulae, % content, and major uses (Gaines et al., 1997; Chatterjee, 2007; Haldar and Tišljar, 2014), can be found in Table 2.2.

2.3 CLASSIFICATION OF MINERAL DEPOSITS

The understanding of various types of mineral deposit can help to formulate appropriate and successful exploration programs from grassroots to detailed stages. To assess a deposit type more effectively, it is divided into groups. The classification can be based on single or multiple criteria, e.g., geographic localization, depth of occurrence, relation to host rocks, structural control, nature of mineralization, morphology, genetic features, and contained metal. It is unlikely for two mineral deposits to be exactly identical, but in a broad sense it will fall into one or another group or class, perceivable and comparable. Therefore a largely acceptable physical description is attempted that can serve to design an exploration scheme (Chatterjee, 2004; McQueen, 2009).

2.3.1 Geographic Localization

Mineral deposits can be broadly described based on geographic location and dimension.

TABLE 2.2 List of Common Metallic and Nonmetallic Ore Forming Minerals and Uses

Principal Ore Mineral	Mineral Formula	% Content	Major Uses
Amethyst (Fig. 1.2V)	SiO_2	46.7 Si	Gemstone, purple variety of quartz, often used in jewelry
Andalusite	Al_2SiO_5	63 Al, 37 silica	Gemstone, porcelain spark plug
Apatite	$Ca_5(PO_4)_3(FClOH)$	41–42 P_2O_5	Fertilizer, occasionally gemstone
Aquamarine (Fig. 1.2W)	$Be_3Al_2Si_6O_{18}$	Beryllium aluminum silicate	Gemstone, greenish-blue variety of beryl, used in jewelry
Argentite	Ag_2S	87.0 Ag	Jewelry, photo processing
Arsenopyrite	FeAsS	46.0 As, 34.3 Fe	Herbicide, alloys, wood preservative, medicine, insecticide, rat poison
Asbestos group	$CaMg_3Si_4O_{12}(OH)_2$	–	Building and pipe material
Azurite (Fig. 1.2O)	$\{Cu_3(CO_3)_2(OH)_2\}$	55.31 Cu	Intense color is suitable for pigments, decorative stone, jewelry. Azurite is an excellent surface guide for exploration
		0.58 H	
Barite (Fig. 1.2U)	$BaSO_4$	65.7 Ba	Drilling mud, fillers, paper, rubber industry, radiology
Bauxite (Fig. 1.2L)	$Al_2O_3 \cdot 2H_2O$	39.0 Al	Construction, transport, consumer durables, packaging, electrical, machinery, refractory bricks, abrasives
		73.9 (Al_2O)	
Bentonite	$Al_2O_34SiO_2H_2O$	66.7 silica	Drilling mud, geotechnical, pellets, metal casting and medical
		28.3 alumina	
Beryl	$Be_3Al_2Si_6O_{18}$	Be	Gems, alloys, electronics, ceramics
Bismuthinite	Bi_2S_3	81.2 Bi	Alloys, pharmaceuticals
Bornite	Cu_5FeS_4	63.3 Cu	Source of copper metal
Braggite	(Pt,Pd,Ni)S	Variable	Source for Pt and Pd

Continued

TABLE 2.2 **List of Common Metallic and Nonmetallic Ore Forming Minerals and Uses—cont'd**

Principal Ore Mineral	Mineral Formula	% Content	Major Uses
Calcite (Fig. 1.2Z2)	$CaCO_3$	56 CaO	Dimension stones, mortar, sculpture, flooring, tiles, architecture, acid neutralizer, medicine, antiaircraft weaponry, index mineral of Mohs hardness scale
		44 CO_2	
Cassiterite	SnO_2	78.6 Sn	Tin plate, solder, alloys
Cerussite (Fig. 1.2P)	$PbCO_3$	77.5 Pb	Minor source for lead
Chalcocite	Cu_2S	79.8 Cu	Rich copper content
Chalcopyrite (Fig. 1.2F)	$CuFeS_2$	34.5 Cu	Main source of copper used for electric cable, alloys, currency, utensils, machinery, architecture, nutritional supplements, medicine, fungicides in agriculture
Chromite (Fig. 1.2K)	$FeCr_2O_4$	46.46 Cr	Hard rustless steel, chrome plating, refractory bricks, pigments and dyes
Cinnabar	HgS	86.2 Hg	Primary source of mercury, pigment
Coal (Fig. 1.2Z4)	C, O, H	60–91 C	Fuel and energy
		2–34 O	
Cobaltite	CoAsS	35.5 Co	Strategically and industrially useful metal, high-temperature alloys, steel tools
		45.2 As	
Copper native (Fig. 1.2D)	Cu	100.0 Cu	Electricity, alloys, currency, medicine
Corundum	Al_2O_3	52.9 Al	Gemstones, abrasives, grinding media
Covellite	CuS	66.4 Cu	Insecticides, computer chips
Cuprite	Cu_2O	88.8 Cu	Source of copper metal
Diamond	C	Pure carbon	Gems, abrasives, cutting tools, drill bits
Feldspar	$NaAlSi_3O_8$	18.4 alumina	Ceramics, glass manufacture, fillers, paints, plastics, rubber
	$KAlSi_3O_8$	16.4 potash	
Fluorite (Fig. 1.2T)	CaF_2	51 Ca, 49 F	Flux in steel manufacture, opalescent glass, enamels for cooking utensils, hydrofluoric acid, high-performance telescopes, camera lenses
Galena (Fig. 1.2F)	PbS	86.6 Pb	Batteries, electrodes, ceramic glazes, stained glass, shielding radiation
Gold native (Fig. 1.2B)	Au	100.0 Au	Bar and coinage for standard international monetary exchange, jewelry, dentistry, electronics
Graphite	C	70–85 C	Steel making, crucibles, refractory bricks, foundries, pencils, electrodes
Gypsum	$CaSO_4 \cdot 2H_2O$	23 Ca	Plasterboard, cement, insulation
Halite	NaCl	39.4 Na	Salt and preservatives, soda ash for glass, soaps, bleaching industry
Hematite (Fig. 1.2M)	Fe_2O_3	70.0 Fe	Iron and steel industry
Ilmenite	$FeTiO_3$	31.6 Ti	Alloy for high technologies in space and medical applications, pigments
Kaolin	$Al_4Si_4O_{10}(OH)_8$	46.5 SiO_2	Paper, rubber manufacture, coating clay, linoleum, paints, inks, leather, refractory bricks, pottery, insecticides, plastics, fertilizers
		39.7 alumina	
Krennerite (Fig. 1.2S)	$(AuTe_2)$	43.56 Au	Minor sources for gold
		56.44 Te	
		± Ag	

Continued

TABLE 2.2 List of Common Metallic and Nonmetallic Ore Forming Minerals and Uses—cont'd

Principal Ore Mineral	Mineral Formula	% Content	Major Uses
Kyanite	$(Ru,Ir,Os)S_2$, $3Al_2O_3$, $2SiO_2$	63.2 alumina 36.8 SiO_2	Heating elements, electrical insulation, ceramic industry, gemstones
Laurite	$(Ru,Ir,Os)S_2$	61.18 Ru 38.82 S	Primary source of ruthenium and associated with sperrylite and chromite
Lepidolite	Li-mica	3.58 Li	Batteries, coloring of glass
Magnesite	$MgCO_3$	47.6% MgO 52.4% CO_2	Refractory bricks, cement industry, fluxes/purifies iron ore by slag former in steelmaking furnaces
Magnetite	FeO, Fe_2O_3	72.4 Fe	Iron and steel industry
Malachite (Fig. 1.2E)	$\{Cu_2CO_3(OH)_2\}$	57.48 Cu 0.91 H	Pigment in green paints from antiquity, decorative vases, ornamental stones, gemstones, excellent exploration guide
Marcasite	FeS_2	46.6 Fe	Iron and steel industry
Marmarite	(ZnFe)S	46–56 Zn	Source of zinc metal
Millerite	NiS	64.7 Ni	Source of nickel for stainless steel, superalloys, electroplating, alnico magnets, coinage, rechargeable batteries, electric guitar strings, green tint in glass
Molybdenite	MoS_2	60.0 Mo	Corrosion resistance ferroalloy, alloy in stainless steels, electrodes
Monazite	$(CaLaTh)PO_4$	29.17 Ce 14.46 La 4.83 Th	Sources for cerium, lanthanum, thorium, and phosphorus, gaslight mantles
Niccolite/Nickeline	NiAs	43.9 Ni 56.1 As	Minor source of nickel, deleterious to smelting and milling
Opal (Fig. 1.2Y)	$SiO_2 \cdot nH_2O$	Water content range 3–21	All forms of jewelry, especially as pendants and ring centerpieces
Palladium native	Pd	100.0 Pd	Substitute for silver in dentistry and jewelry. Pure metal used as delicate mainsprings in analog wristwatches, surgical instruments, and catalysts
Pentlandite	$(Fe,Ni)_9S_8$	22 Ni, 42 Fe	Primary source of nickel, tarnish-resistant stainless steel, superalloys, electroplating, coinage, rechargeable batteries, microphone capsules
Platinum native (Fig. 1.2A)	Pt	100.0 Pt	Catalytic converter in vehicle emission control, electrical contacts, electronics and electrodes, laboratory equipment, dentistry, medicine, jewelry, currency, trading and investment
Psilomelane	MnO_2	50.0 Mn	Drier in paints, steel making
Pyrite (Fig. 1.2H)	FeS_2	46.6 Fe	Sulfur for sulfuric acid
Pyrolusite	MnO_2	63.0 Mn	Batteries, coloring in bricks, decoloring in glass, pottery
Pyrrhotite (Fig. 1.2I)	Fe_nS_{n+1}	60.4 Fe	Sulfur source, often nickel bearing
Quartz (Fig. 1.2Z1)	SiO_2	46.7 Si	Gemstones and building materials, porcelains, glass, paints, mortar, acid flux in smelting furnaces
Rhodochrosite (Fig. 1.2N)	$MnCO_3$	61.7 MnO 38.3 CO_2	An ore of manganese, aluminum alloys, brilliant transparent varieties as decorative stones, jewelry
Ruby (Fig. 1.2X)	Al_2O_3	52.93 Al 47.07 O	Gemstone variety of corundum, jewelry

Continued

TABLE 2.2 **List of Common Metallic and Nonmetallic Ore Forming Minerals and Uses—cont'd**

Principal Ore Mineral	Mineral Formula	% Content	Major Uses
Rutile	TiO_2	68.0 Ti	Source of titanium
Sheelite	$CaWO_4$	80.0 W	Electric bulbs, alloys, cutting material, defense purposes
Silver native (Fig. 1.2C)	Ag	100.0 Ag	Jewelry, electrical/electronics, photography, dentistry
Skutterudite (Fig. 1.2Q)	$(Co,Ni,Fe)As_3$	17.95 Co 5.96 Ni 76.07 As	Strategically and industrially useful, high-temperature superalloy, steel tools, batteries, pigments, radioisotopes, electroplating, often source for nickel
Smithsonite	$ZnCO_3$	52.0 Zn	Same as sphalerite
Sperrylite (Fig. 1.2R)	$PtAs_2$	57.0 Pt	Major source of platinum group of metals, catalytic converter in petrol/diesel vehicles, and jewelry
Sphalerite (Fig. 1.2G)	ZnS	67.0 Zn	Galvanizing, alloys, cosmetics, pharmaceuticals, micronutrient for humans, animals, and plants
Stannite	$Cu_2S \cdot FeS \cdot SnS_2$	27.5 Sn 29.5 Cu	Source for tin and copper
Stibnite	Sb_2S_3	71.8 Sb	Textiles, fibers, alloys with lead
Sulfur native	S	100.0 S	Sulfuric acid, fertilizer
Sylvite	KCl	52.4 K	Source of potash as fertilizer
Sylvanite	$(AuAg)Te_2$	24.5 Au 13.4 Ag 62.1 Te	Source of gold, silver, and tellurium
Talc	$3MgO, 4SiO_2H_2O$	31.7 MgO 63.5 SiO_2	Cosmetics, paints, plastics, paper, rubber, ceramics, pharmaceuticals, detergents
Uraninite	UO_3	88.0 U	Nuclear fuel, military
Wolframite (Fig. 1.2J)	$(Fe \cdot Mn)WO_4$	76.0 W	Electric bulbs, alloys, cutting material, national defense purposes
Wollastonite	$CaSiO_3$	48.3 CaO 51.7 SiO_2	Principal ingredient in ceramics industry, paints, paper, polymers, metallurgical applications
Zircon	ZrSiO4	49.8 Zr	Alloy in nuclear reactors, ultrastrong ceramics, abrasives, geological dating
Dolomite[a]	$CaMg(CO_3)_2$	21.7 Ca 13.2 Mg	Building stones, refractory bricks, cement, ornamental stones, ore of metallic magnesium, glass making, fluxes/purifies iron ore by slag former in steelmaking furnaces
Limestone[a]	$CaCO_3$	+50 $CaCO_3$, CaMg $[CO_3]_2$	Cement industry, fluxes/purifies iron ore by slag former in steelmaking furnaces
Marble[a]	$CaCO_3$	<56 lime	Building and decorative stone
Silica sand[a]	SiO_2	<100 SiO_2	Building, glass manufacture
Rock phosphate[a] (Fig. 1.2Z3)	$3Ca_3(PO_4)_2.CaR_2$	15–35 P_2O_5	Fertilizer, phosphoric acid
Seabed nodules (Fig. 1.2Z5)	Polymetallic-polynodule	~1.25 Ni ~1.00 Cu ~0.20 Co ~30 Mn	Sources for copper, nickel, cobalt, and manganese

[a] *Dolomite, limestone, marble, and silica sand are rocks/aggregates with variable composition. These deposits are mined for specific enrichment of elements of economic value. Similarly, rock phosphate is a natural lithified stromatolite rock and mined for phosphorus. It has no definite chemical composition and is formed due to algal bloom of phosphorus and calcium along with other chemical sediments in the sea floor.*

2.3.1.1 Province

The **province** or **metallogenic province** is a large specific area having essentially notable concentrations of certain characteristic metals or several metal assemblages or a distinctive style of mineralization to be delineated and developed as economic deposits. The metallogenic province can be formed on various processes such as plate tectonic activity, subduction, igneous intrusives, metal-rich epigenetic hydrothermal solution, and expulsion of pore water enriched in metals from a sedimentary basin. Examples of metallogenic provinces are Zn−Pb−Ag-bearing McArthur-Mt. Isa Inlier in NT, Australia, gold province in the Canadian shield, Pt−Pd−Ni−Cu−Au deposits in the Sudbury Basin, Canada, Bushveld Igneous Complex with Pt−Pd−Cr deposits, South Africa, Katanga and Zambian copper province, tungsten province of China, Zn−Pb−Ag deposits of Aravalli Province, and diamond-bearing Kimberlite province of Wajrakarur-Narayanpet, India.

2.3.1.2 Region

A **region** is similar to a province but is relatively smaller in size and controlled by stratigraphy and/or structure for the occurrence of specific mineral(s) at commercial quantity. Examples are Kalgoorlie Goldfield-Esperance region of Western Australia, Zn−Pb region of Mississippi Valley, copper region of Chile and Peru, diamond-bearing region of northern Minas Geraes, Brazil, Sudbury Basin, Canada, for nickel, platinum-group elements (PGE), lead and zinc, Bushveld region for chromite and PGE mineralization, diamond-bearing region of Kimberley, South Africa, Pacific and Central coal-bearing region of the United States, and rubies in high-grade metamorphic rocks of Kashmir region, India.

2.3.1.3 District

A **district** is comprised of one geographical area popularly known for the occurrence of a particular mineral, e.g., eolian soils of Blayney district, NSW, Australia, Baguio mineral district in the Philippines for copper deposits, New Mexico for uranium deposits, and Singhbhum district for copper and Salem district for magnesite, India.

2.3.1.4 Belt

A **belt** is a narrow linear stretch of land having series of deposits of associated minerals, such as Colorado gold-molybdenum belt, USA, Grants uranium mineral belt, New Mexico, and Khetri copper belt and Rajpura-Dariba-Bethumni zinc-lead-silver belt, Rajasthan, and Sukinda chromite belt, Orissa, India.

2.3.1.5 Deposit

A **deposit** is a single or a group of mineral occurrences of sufficient size and grade separated by a natural narrow barren parting, e.g., Broken Hill North zinc-lead silver deposit, Australia, Red Dog zinc-lead deposit, Alaska, Rampura-Agucha, Rajpura-Dariba, and Zawar zinc-lead silver deposits, India, OK Tedi copper-gold deposit, Papua New Guinea, Super Pit gold deposit, Western Australia, Olympic Dam copper-gold-uranium-silver deposit, South Australia, Neves Corvo polymetallic deposit, Portugal, Stillwater group of platinum deposits, USA, Victor nickel PGE deposit and Sudbury meteorite impact basin, Canada, Impala PGE chromite deposit and Bushveld Intrusive Complex, South Africa, Noril'sk-Talnakh PGE nickel deposit, Russia, Great Dyke PGE chromite deposit, Zimbabwe, Jinchuan nickel copper deposit and Kempirsai massif chromite deposit, Kazakhstan, Koniambo laterite nickel deposit, New Caledonia, Kiruna iron ore deposit, Sweden, Daitari iron ore deposit, India, Alkoa bauxite deposit, Australia, North Antelope Rochelle coal deposit/mine in the Powder River Basin of Wyoming, USA, Jhamarkotra stromatolites rock phosphate deposit, Rajasthan, India, and the heavy mineral sand (ore) deposit, Chennai coast, India.

2.3.1.6 Block

A **block** is a well-defined area having mineral concentration wholly or partly of economic value, such as Broken Hill main, Australia, and Bailadila deposit-14 and Central Mochia, India. The blocks in underground mining are subdivided to **levels** (e.g., upper level and lower level, 500−700 mRL and 300−500 mRL, respectively). The levels are further split into **stopes** (e.g., west 301 stope, north 101 stope, and valley stope). These terms are convenient to use locally for the attention and allocation of work activities in mineral exploration and sequencing mine production blocks.

2.3.2 Depth of Occurrence

2.3.2.1 Exposed to Surface

Mineral deposits like iron ore, bauxite, chromite, copper, limestone, and magnesite are exposed to the surface and are easy to explore/mine. Significant deposits of Rampura-Agucha zinc-lead-silver, India, Red Dog zinc-lead, Alaska, OK Tedi copper-gold, Papua New Guinea, and Olympic Dam copper-gold-uranium-silver, Australia, have been discovered and exploited based on surface exposure. There are ample possibilities of finding new deposits under

FIGURE 2.1 Massive chromite orebody exposed to surface near Karungalpatti village at Sitampundi belt, Namakkal District, Tamil Nadu, India, (Finn Barrett, Goldstream Mining NL, Australia, during reconnaissance.)

glacial or forest cover. Prospecting efforts should look for fresh rock exposure and newly derived boulders. Examples are Adi Nefas Zn—Cu—Au—Ag deposit, Madagascar, El Abra Cu deposit, Chile, and chromite deposits in Orissa, Tamil Nadu, India (Fig. 2.1).

2.3.2.2 Shallow Depth

Deposits like base metals, coal-lignite, and gypsum are covered by altered oxidized capping or exist at shallow depth or under thick overburden of bed rock. The deposits are Cerro de Maimon copper-gold, Dominican Republic, and Zawar zinc-lead-silver and Raniganj coal field and gypsum, India. Geochemical prospecting and ground geophysical survey will be useful to discover deposits at shallow depths.

2.3.2.3 Deep-Seated Hidden Deposit

The hidden polymetallic deposits discovered in the past were Neves Corvo copper-zinc-tin at 330—1000 m depth (Fig. 15.12), Portugal, and Sindesar-Khurd zinc-lead-silver at 130 m depth (Fig. 15.9), India. Near-surface deposits are mostly discovered. Deep-seated hidden deposits will be the future target of mineral exploration. The key exploration procedures suitable for the discovery of orebody at a depth of 300—700 m require clear understanding of regional structure, applications of high penetrative geophysical methods, and interpretation by simulation tools to identify, describe, and delineate. Exploration for such deposits is expensive and associated with considerable economic risk.

2.3.3 Relation to Host Rocks

2.3.3.1 Host Rocks

Mineralization is hosted by three types of rocks: igneous, sedimentary, and metamorphic. Examples of igneous rocks are porphyry copper deposits in granite, platinum-palladium-chromium-nickel deposits in dunite, and peridotite, gabbro, norite and anorthosite, tantalite, columbite, and cassiterite in pegmatite. Ore deposits can be exclusively formed under sedimentation processes such as iron ore formation (banded iron formations [BIF]/banded hematite quartzite [BHQ]), diamond in conglomerate, zinc-lead deposits in dolomite, and limestones. The deposits show bedded, stratabound, and often stratiform features having concordant relation with country rocks. Metamorphic rocks host important ore deposits generated as contact metamorphic aureoles. The ore deposits are garnet, wollastonite, andalusite, and graphite. The metamorphic equivalent of sedimentary and igneous rocks forms large deposits of marble, quartzite, and gneisses.

2.3.3.2 Identical to Host Rock

Mineral deposits like granite, limestone, marble, quartzite, and slate are indistinguishable from host rock. Examples are Keshariyaji green marble, Mekrana white marble, and Jaisalmer golden limestone, Rajasthan, India.

2.3.3.3 Different From Host Rock

The gold-bearing quartz veins act as an exclusive host for Au and are different from the surrounding rocks such as Kolar gold deposit, Karnataka, India.

2.3.3.4 Gradational Contact

The gradational deposits are often formed around the vein systems with characteristics of disseminated mineral distribution. The Bulldog Mountain vein systems, Colorado, show an abundance of fine-grained sphalerite and galena, with lesser tetrahedrite and minor chlorite and hematite. Mineralization becomes progressively richer with barite and silver with increasing elevation. Some mineral deposits, particularly those containing disseminated Cu, depict gradational contact to form an economic deposit. Sargipalli lead copper deposit, Orissa, India, is an example.

2.3.3.5 Metal Zoning

Metal zoning occurs in a multiple series of hydrothermal depositional sources. Mineralization zoning is characterized by Fe—Ba—Cu—Pb—Ag—Au. This is obviously a gradational transition of mineralization from vent-proximal mineralization to more distal mineralization. Metal zoning is an indication of metal deposition in relative order during primary crystallization or sedimentation. It may be modified by deformation and remobilization at a later stage. Metal zoning can be within a single orebody and between orebodies occurring in a group. Common metal zoning is in massive sulfide deposits: Cu → Zn/Pb → Pb/Zn → Fe or alternate rich → poor → rich bands, e.g., El Guanaco gold-copper in Chile, Zn—Cu—Au—Ag deposits of Scuddles, Golden Grove, Gossan Hill, Western Australia, and Rajpura-Dariba Zn—Pb—Cu—Ag and Zawar Zn—Pb—Ag deposits, India.

2.3.3.6 Wall Rock Alteration

Mineral deposits formed under epigenetic conditions, magmatic intrusion, and hydrothermal depositional environments cause changes in mineralogy, including the formation of new minerals, chemical compositions, colors, and textures of host rock in contact with and at some distance from the orebody. This alteration halo is known as the **alteration zone** or **zone of wall rock alteration**. The size of the alteration halo around the orebody varies from narrow to wide depending on the physical and chemical condition of the process of alteration. The common forms of wall rock alterations are silicification, chloritization, sericitization, and serpentinization. The presence of pyrite, siderite, titanium, manganese, potassium, lithium, lead, silver, arsenic, rubidium, barium, calcium, epidote, and carbonaceous material is common and a characteristic feature enveloping most of the sedimentary exhalative (SEDEX) type of copper-zinc-lead ± silver-gold deposits in the world. Correct identification of these alteration halos will add considerable value to mineral exploration in general, and planning for drill targets in particular. Good examples of ore deposits with alteration halos are Broken Hill, Mt. Isa, Hilton, Century, HYC, and Lady Loretta in Australia, Sullivan in Canada, and Rampura-Agucha, Rajpura-Dariba, and Khetri in India.

2.3.4 Structural Control

Structure, tectonics, and surface weathering play a significant role over geological time in the passage of hydrothermal flow of mineralized fluids, accumulation and concentration at suitable locations, and remobilization and reorientation of postgenetic activity. The features related to mineralization control are deformation, weathering, joints, fractures, folds, faults, breccia, and plate tectonics.

2.3.4.1 Undeformed

Most of the residual and placer deposits are of undeformed type such as East Coast Bauxite deposit, India.

2.3.4.2 Joints and Fractures

Many deposits show varied degrees of deformation, contemporaneous with formation or as an after-effect. **Joints** and **fractures** caused by regional stress break in the rocks along which little or no movement has occurred. Mineralization often concentrates along these regular and irregular planes. Magnesite accumulation can be seen along road cuttings near Salem Town, Tamil Nadu, India (Fig. 2.2). The Lennared Shelf zinc-lead deposit, Western Australia, is an example of a cavity filled along a major fault zone.

2.3.4.3 Fold

Directed compression of the crust, resulting in a semiplastic deformation, creates **folding** of strata (**fold**). The fold closure, limb in-flex zone, and axial planes are suitable for mineral localization. These mineral deposits are often folded during or after formation, e.g., Rajpura-Dariba zinc-lead-copper deposit (Fig. 2.3), Agnigundala lead-copper deposit, and Sukinda chromite belt, India.

2.3.4.4 Fault

The joints and fractures along which noticeable movements have occurred are called **faults**. Deposits can be faulted with displacement from millimeters to kilometers, thus creating challenges for exploration. Fault zones are favorable settings, and localization of mineralized solution for movement and concentration (Fig. 2.4). Mantoverde copper in Chile and many of the coal deposits are faulted.

2.3.4.5 Shear Zone

Shear is the outcome of rock deformation generating particular textures like intense foliation, deformation, and

FIGURE 2.2 Magnesite veins deposited along joints, faults, and fractures in ultramafic host rocks, Salem Road, Tamil Nadu, India.

FIGURE 2.3 Stratiform pyrite-zinc-lead mineralization folded with mineral concentration at crests presenting saddle reef structure, Rajpura-Dariba deposit, India.

microfolding due to compressive stress. A **shear zone** is a wide region of distributed shearing in crushed rock mass with widths varying between a few centimeters and several kilometers. The interconnected openings of the shear zone serve as excellent channelways for mineral-bearing solutions and subsequent formation of deposits. Many shear zones in orogenic belts host ore deposits. The Um El Tuyor gold deposit in Eastern Desert, Egypt, is a shear zone-related mineralization. The Lega Dembi Primary Gold Deposit in southern Ethiopia is related to the shear zone-hosted vein in the Neoproterozoic metamorphosed volcanosedimentary succession of greenschist to amphibolite-facies metamorphism. The Singhbhum shear zone, India, hosts copper-uranium mineralization, and has been mined since 1928. Fig. 2.5 shows chromite-magnesite veins developed in the shear zone of Sindhuvalli, Karnataka, India.

FIGURE 2.5 Layered chromite (black) and magnesite (white) veins developed in shear zones, Sindhuvalli, Karnataka, India.

2.3.4.6 Breccia

Breccia is commonly used for clastic sedimentary rocks composed of large sharp-angled fragments embedded in a fine-grained matrix of smaller particles or mineral cement. The breccia generated by folding, faulting, magmatic intrusions, and similar forces is called **tectonic breccia**. The tectonic breccia zones are represented by crush, rubble, crackle, and shatter rock mass. Breccia and conglomerate are similar rocks but with a difference in the shape of larger particles due to the transportation mechanism. **Igneous**, **flow**, or **pyroclastic** breccias are rocks composed of angular fragments of preexisting igneous rocks of pyroclastic debris ejected by volcanic blast or pyroclastic flow. An outstanding example would be intrusion of gabbroic magma within the preexisting ultramafic rocks hosting layered chromite at Nausahi, India (Fig. 2.6). The sharp-angled fragments of chromite in host rock form the angular fragments embedded in a matrix of fine-grained

FIGURE 2.4 Massive chromite lode depicting sharp faulted contact with barren ultramafic rock, Kathpal underground mine, Sukinda belt, India.

FIGURE 2.6 Pt–Pd-bearing magma (greasy white color gabbro) around sharp-angle chromite (black) from the tectonic breccia zone, Boula-Nausahi underground mine, Orissa, India.

FIGURE 2.7 Irregular fragmented chromite (black with white rims) in matrix of Pt–Pd-bearing gabbro from the tectonic breccia zone, Boula-Nausahi underground mine, Orissa, India.

gabbro containing PGE (Fig. 2.7). Zinc-copper-gold deposits of Saudi Arabia are hosted in volcaniclastic breccia. The Fossil Downs Zn-rich ore, Lennard Shelf deposit, Western Australia, is closely related to the major north–south-trending fault, brecciated cavity filled in limestone reefs.

2.3.4.7 Subduction

Subduction is the process of two converging tectonic plate movements. The plates of continental margin arcs, oceanic lithosphere, and volcanic island arcs collide and one slides under the other. In the process the heavier oceanic crust stoops under the lighter continental crust or the volcanic island arc forming a **subduction zone**. Formation of the subduction zone is closely associated with multidimensional tectonic activities like shallow and deep focuses, earthquakes, melting of mantle, volcanism, rising magma resulting in volcanic arc, plutonic rocks of ophiolite suites, platinum-chromium-bearing peridotite-dunite-gabbro-norite, movement of metal-bearing hydrothermal solution, and metamorphic dewatering of crust. The great belt of porphyry copper-gold that extends north from central Chile into Peru is a good example associated with the subduction of the Pacific Ocean floor beneath the South American plate. The main Chilean porphyry copper belt hosts some of the largest open-cut copper mines in the world.

2.3.5 Nature of Mineralization

The nature of mineralization is the expression of mineral formation as a natural process that includes disseminated, massive veins and stringers, ladder veins, stock work, morphology, and many more.

2.3.5.1 Dissemination

Disseminated types of mineralization are formed by crystallization of deep-seated magma. The early formed in situ valuable metallic and nonmetallic minerals are sparsely disseminated or scattered as fine grains throughout or as part of the host rock. Good examples are diamonds in kimberlite pipes in South Africa, porphyry copper deposits at El Salvador, Chile, porphyry tungsten-molybdenum deposit at Yukon, Canada, and Malanjkhond copper and Sargipalli lead-copper deposit, India.

2.3.5.2 Massive

Massive deposits with more than 60% sulfides (volcanogenic massive sulfide [VMS], volcanic-hosted massive sulfide [VHMS], or SEDEX) are formed due to accumulations on or near the sea floor in association with volcanic activity or hydrothermal emanations along with sedimentary deposition. Examples are the zinc-lead-silver deposit of Red Dog, Northwest Alaska, Neves Corvo, Portugal, and Gorubathan, India. Fig. 2.8 depicts massive chromite deposits hosted by an ultramafic complex with sharp contact.

2.3.5.3 Veins and Stringers

Veins, **fissure veins**, and **lodes** are tabular deposits usually formed by deposition of ore and gangue minerals in open spaces within fault, shear, and fracture zones. Veins often have great lateral and/or depth extents but are usually of narrow width that portrays veins and stringers. Veins frequently pinch and swell in all directions. The pinch and swell structure type of deposits pose problems during both exploration and mining. Proper delineation of the orebody, dilution control, and planning for large-scale mining are difficult.

FIGURE 2.8 Massive chromite ore, exposed on the surface as a classic surface guide for exploration, Tamil Nadu, India.

FIGURE 2.9 Sheeted veins and fine stringers of sphalerite in dolomite host rock at Zawar deposit, India.

FIGURE 2.10 Lead-zinc mineralized veins exposed to the surface at Rampura-Agucha deposit cutting at an angle to the host rock trend.

There are several examples, such as polymetallic deposits of Silvania, Silver Cup, Lucky Jim, and Highland Lass Bell in British Columbia, and sheeted veins in the underground mine of Zawar zinc-lead-silver (Fig. 2.9), Kolihan copper deposit, and chromite-magnesite deposit in Sindhuvalli, India. The mineralized vein or clusters of veins are exposed to the surface in many places, and are a good indicator of mineral exploration (Fig. 2.10). **Stringers** are large numbers of thin, tiny, and closely spaced mineralized veins originating from the main orebody and often described as the **stringer zone**.

2.3.5.4 Ladder Veins

FIGURE 2.11 Quartz-filled ladder vein structure in compact dolomite mass at the footwall of main lodes within greywacke rocks, Zawar group of mines, India.

Ladder veins are regularly spaced, short, and transverse fractures confined wall to wall within dikes or compact rock mass (Fig. 2.11). The fractures are nearly parallel to each other and occur for considerable distances along the host dike or rock. The fractures are generally formed by contraction joints and filled with auriferous quartz or valuable mineral matter to form an economic deposit. Examples of commercial ladder vein-type deposits are Morning Star gold mine in Victoria and molybdenite veins in New South Wales, Australia, and copper ladder veins in Norway.

2.3.5.5 Stock Work

Stock work styles of metalliferous deposits are characterized by a large mass of rock impregnated with a dense interlacing network of variously oriented irregular ore-bearing veins and grouped veinlets. The stock works are formed by a group of hydrothermal systems of metal-bearing fluids from hot mineralized solutions circulating through the fissured rocks and deposited in the basin. The veins contain metallic minerals. The stock work style of mineralization occurs in porphyritic plutonic igneous intrusions. These deposits are especially common with platinum-bearing sulfides, zinc, lead, copper, gold, silver, molybdenum, tin, tungsten, beryllium, uranium, mercury, and other metal ores. Stock work mineralization may occur as a separate body or in association with other styles. A system of working in the orebody, when it lies neither in strata nor in veins but in solid masses, can be done in chambers or stories. Examples of stock work are disseminated gold-bearing Trinity Mine, Nevada, USA, copper and tin-rich stock work at Neves Corvo mine, Portugal, and platinum-palladium-chromite mines at Boula-Nausahi and Sindesar-Khurd zinc-lead-silver mine (Fig. 2.12), India.

2.3.6 Morphology

2.3.6.1 Stratiform

Hydrothermal, volcanogenic, and SEDEX-type mineralization closely resembles stratification of sedimentary

FIGURE 2.12 Stock work formed by stratification and stringers of sphalerite, galena, and pyrite hosted by carbonaceous calc-silicate rock at Sindesar-Khurd orebody, India.

FIGURE 2.13 Stratiform sphalerite (honey-brown) mineralization in calc-silicate (bluish-gray) host rock at Rajpura-Dariba deposit, India.

formation. The stratification is formed by upward-moving metal-bearing hydrothermal solution through a porous aquifer and deposits ore minerals in the overlying pile of sedimentary strata of shale and dolomite. These deposits may contain a significant amount of organic matter and fine pyrite. Some of the world's largest and most famous stratiform base metal deposits are copper deposits at White Pine, Michigan, copper deposits of Zambia, lead-zinc-copper deposits at Sullivan in British Columbia, and zinc-lead-silver deposits at Rajpura-Dariba in India (Fig. 2.13), Broken Hills in New South Wales, Mt. Isa in Queensland, and McArthur River in NT, Australia.

2.3.6.2 Stratabound

Ore minerals in **stratabound** deposits are exclusively confined within a single specific stratigraphic unit. Stratabound deposits include various orientations of mineralization representing layers, rhythmic, stratiform, veinlets, stringers, and disseminated and alteration zones, strictly contained within the stratigraphic unit, but which may or may not be conformable with bedding. There are several world-class stratabound zinc-lead-silver deposits: they are Proterozoic Mt. Isa-McArthur Basin System of NT, Australia (Mt. Isa, George Fisher, Hilton, Lady Loretta, Century, and McArthur River), and the Proterozoic Middle Arravalli System in India (Zawar, Rajpura-Dariba, and Rampura-Agucha).

2.3.6.3 Layered, Rhythmic, and Bedded

Layered, **rhythmic**, and **bedded** types of deposits are formed generally by deposition and consolidation of sediments that may or may not be metamorphosed. The type of ore deposit will depend on the composition of the transported sediments. The deposits showing these features are iron ore (BHQ/BIF), lignite, and coal seam (Fig. 2.14).

Layered and rhythmic features are also developed during the differential crystallization and segregation of mafic and ultramafic magma in a huge chamber over a prolonged time. The early crystallization, settling, and consolidation of heavy metal-rich layers are composed of Cr—Ni—Cu—Pt—Pd and disseminated sulfides ± Au and Ag forming economic mineral deposits. The late crystallization and solidification of residual magma form alternate layers of dunite, peridotite, gabbro, and anorthosite. The process repeats with addition of fresh magmatic cycles. Examples are Bushveld platinum-chromite deposits, South Africa, and Sittampundi Cr—Pt—Pd (Fig. 2.15), Sukinda Cr—Ni, and Nausahi Cr—Pt—Pd, India.

2.3.6.4 Porphyry

Porphyry is a diversity of igneous rock consisting of large-grained crystals such as quartz and feldspar scattered in a

FIGURE 2.14 Alternate bands of coal (shining black color) and shale (brownish-gray), Belatan mine, Jharia coalfield, India.

FIGURE 2.15 Layers of chromite (black) and Pt—Pd-bearing gabbro (white), Sittampundi Igneous Complex, Tamil Nadu, India.

fine-grained groundmass. The groundmass is composed of indistinguishable crystals (aphanites as in basalt) or easily distinguishable crystals (phanerites as in granite). Porphyry refers to the texture of the igneous racks, and used as suffix after granite-, rhyolite-, and basalt-porphyry. The porphyry deposits are formed by differentiation and cooling of a column of rising magma in stages. The different stages of cooling create porphyritic textures in intrusive as well as in subvolcanic rocks. The process leads to a separation of dissolved metals into distinct zones responsible for forming rich deposits of copper, molybdenum, gold, tin, zinc, and lead in the intrusive rock itself. There are several large porphyry copper deposits in the world: Chuquicamata (690 Mt @ 2.58% Cu), Escondida, and El Salvador, Chile, Toquepala, Peru, Lavender Pit, Arizona, and Malanjkhand (145 Mt @ 1.35% Cu), India.

2.3.6.5 Lenticular

The magmatic segregation deposits are formed by fracture filling within the host rock, and are generally irregular, roughly spherical, and more often "tabular" or "lenticular" in shape. The width/thickness ranges between a few centimeters and a few meters. The length may exceed 1 km. Examples are Sukinda chromite deposits in dunite-peridotites and Balaria/Mochia zinc-lead-silver deposits in dolomite, India.

2.3.6.6 Pipe

Pipe-like deposits are relatively small in the horizontal dimension and extensively large in the vertical direction. These **pipes** and **chimneys** are orientated in vertical to subvertical positions. Pipes may be formed by infillings of mineralized breccias in volcanic pipes, e.g., copper-bearing breccia pipes of Messina, South Africa. Another common type of volcanic pipe is a deep narrow cone of solidified intrusive magma characteristically represented by kimberlite or lamproite. Kimberlite is high in magnesium, carbon dioxide, and water. Kimberlite is the primary source of diamond, precious gemstone, and semiprecious stones. The best example is the diamond pipe at Kimberley, South Africa, and Panna, India.

2.3.7 Genetic Model

2.3.7.1 Magmatic

Magmatic deposits are genetically linked with the evolution of magma that was emplaced into the continental or ocean crust (Fig. 2.16). Mineralization is located within the rock types derived from differential crystallization of parent magma. The significant magmatic deposits are related to mafic (gabbro, norite) and ultramafic (peridotite, dunite, pyroxenite [Fig. 2.17]) rocks originated from crystallization of mafic and ultramafic intrusive magma. Ore minerals are formed by separation of metal sulfides and oxides in molten form within an igneous melt. The deposit types include chromite-nickel-copper and PGE. There are several large magmatic deposits: Cr—PGE deposits at Bushveld Igneous Complex, South Africa, Ni—Cu—PGE deposits at Great

FIGURE 2.16 Field photograph of mantle peridotite tectonite from Manipur Ophiolite, Eastern India. Rocks are phanerocrystalline, coarse grained, and melanocratic. Color varies between dark (less altered) and pale green (more altered), intensely serpentinized, layered, and foliated. *Credit: Aparajita Banerjee.*

FIGURE 2.17 Pyroxenite is an ultramafic-layered igneous rock consisting essentially of minerals of the pyroxene group, such as augite and diopside, hypersthene, bronzite, or enstatite.

Dyke, Zimbabwe, Ni−PGE−Cr deposits at Sudbury, Canada, Ni−Cu−PGE deposits at Stillwater Igneous Complex, Montana, USA, and Cr−Ni ± PGE deposits at Sukinda and Nausahi Intrusive, India.

2.3.7.2 Sedimentary

Sedimentary rocks are formed by the process of deposition and consolidation of loose materials under aqueous conditions. The sedimentary deposits are a concordant and integral part of the stratigraphic sequence. They are formed due to seasonal concentration of heavy minerals like hematite on the sea floor. The structures consist of repeated thin layers of iron oxides, hematite, or magnetite, alternating with bands of iron-poor shale and chert. Examples are Pilbara BIF, Northwestern Australia, and Bailadila and Goa iron ore, India. The limestone deposits are formed by chemical sedimentation of calcium-magnesium carbonate on the sea floor. Coal and lignite are formed under sedimentary depositional conditions.

The evaporite deposits form through evaporation of saline water in lakes and seas, in regions of low rainfall and high temperature. The common evaporite deposits are salts (halite and sylvite), gypsum, borax, and nitrates. The original character of most evaporite deposits is destroyed by replacement through circulating fluids. Examples are sodium chloride and potassium salt deposits at Death Valley (Fig. 2.18), occupying an interface zone between the arid Great Basin and Mojave deserts of California and Nevada, USA, and gypsum deposit at Bikaner, India.

FIGURE 2.18 Death Valley formed on Manly Lake during the Pleistocene period in Eastern California. Surface elevation at the feet of the children is −279 ft (−85m) below the mean Sea Level (mSL). It is one of the hottest places on Earth, and known for salt mining for a variety of food-processing applications, including baking, cheese manufacturing, meat processing, seasonings, and prepared mixes.

2.3.7.3 Metamorphic

Metamorphic deposits are transformed alteration products of preexisting igneous or sedimentary materials. Reconstruction is formed under increasing pressure and temperature caused by igneous intrusive body or tectonic events. Metamorphic mineral deposits are formed due to regional prograde or retrograde metamorphic processes and are hosted by metamorphic rocks. Minerals like garnet, kyanite, sillimanite, wollastonite, graphite, and andalusite are end products of the metamorphic process. The copper deposits of Kennicott, Alaska, and White Pine, Michigan, are formed by low-grade metamorphism of organic-rich sediments resting over mafic or ultramafic rocks. The low copper values of underlying source rocks liberate during a leaching process caused by the passing of low-temperature hydrothermal fluids. The fluids migrate upward along the fractures and faults and precipitate high-grade copper in the rocks containing organic matter.

2.3.7.4 Volcanogenic Massive Sulfide and Volcanic-Hosted Massive Sulfide

VMS and **VHMS**-type ore deposits contribute significant sources of Cu—Zn—Pb sulfide ± Au and Ag, formed as a result of volcanic-associated hydrothermal events under submarine environments at or near the sea floor. They form in close time and space association between submarine volcanism, hydrothermal circulation, and exhalation of sulfides, independent of sedimentary process. The deposits are predominantly stratabound (volcanic derived or volcanosedimentary rocks) and often stratiform in nature. The ore formation system is synonymous with black smoker-type deposit. Kidd Creek, Timmins, Canada, is the largest volcanogenic massive sulfide deposit in the world. Kidd is also the deepest (+1000 m) base metal mine. The other notable VMS/VHMS deposits are Iberian Pyrite Belt of Spain and Portugal, Wolverine Zn—Cu—Pb—Ag—Au deposit, Canada, and Khnaiguiyah Zn—Pb—Cu, Saudi Arabia.

2.3.7.5 Black Smokers Pipe Type

Black smokers pipe-type deposits are formed on the tectonically and volcanically active modern ocean floor by superheated hydrothermal water ejected from below the crust. Water with high concentrations of dissolved metal sulfides (Cu, Zn, Pb) from the crust precipitates to form black chimney-like massive sulfide ore deposits around each vent and fissure when it comes in contact with cold ocean water over time. The formation of black smokers by sulfurous plumes is synonymous with VMS or VHMS deposits of Kidd Creak, Canada, formed 2.4 billion years ago on the ancient sea floor.

2.3.7.6 Mississippi Valley Type

Mississippi Valley-type deposits are epigenetic, stratabound, rhythmically banded ore with replacement of primary sedimentary features, predominantly carbonate (limestone, marl, dolomite, and rarely sandstone) host rocks. Mineralization is hosted in open space filling, collapse breccias, faults, and hydrothermal cavities. The deposits are formed by diagenetic recrystallization of carbonates creating a low-temperature hydrothermal solution that migrates to suitable stratigraphic traps like fold hinge and faults at the continental margin and intracratonic basin setting. The ore-forming minerals are predominantly sphalerite, galena, and barite. Calcite is the most common gangue mineral. Low pyrite content supports clean concentrate with high metal recovery of +95%. Some deposits are surrounded by a pyrite/marcasite halo. Prospects can be defined by regional stream sediment, soil, and gossan sample anomaly supported by aeromagnetic and gravity survey. There are numerous Zn— Pb—Ag sulfide deposits along the Mississippi River in the United States, Pine Point, Canada, San Vicente, Central Peru, Silesia, Southern Poland, Polaris, British Columbia, and Lennard Shelf (Fig. 2.19) and Admiral Bay, Western Australia.

2.3.7.7 SEDEX Type

SEDEX-type ore deposits are formed due to concurrent release of ore-bearing hydrothermal fluids into aqueous reservoirs, mainly oceans, resulting in the precipitation of stratiform zinc-lead sulfide ore in a marine basin environment. The stratification may be obscured due to post-depositional deformation and remobilization. The sources of metals and mineralizing solutions are deep-seated, superheated formational brines migrated through intracratonic rift basin faults, which come in contact with the sedimentation process. In contrast the sulfide deposits are more intimately associated with intrusive or metamorphic

FIGURE 2.19 Sphalerite (yellow) and galena (black) mineralization in calcite (white) bands indicating different fluid phase events, Lennard Shelf MVT deposit, Western Australia.

FIGURE 2.20 Massive sphalerite (iron-brown) and galena (shining) in carbonaceous calc-silicate host rock sedimentary exhalative deposition at Sindesar-Khurd SEDEX type in India.

processes or trapped within a rock matrix and are not exhalative. Formation occurred mainly during the Mid-Proterozoic period. SEDEX deposits are the most important source of zinc, lead, barite, and copper with associated by-products of silver, gold, bismuth, and tungsten. This type of deposit shows two mutual structures: (1) layered by the sedimentary-exaltation process and (2) veins by accumulation/remobilization/localization of hydrothermal fluid in fractures. Examples are zinc-lead-silver deposits of Red Dog, northwest Alaska, MacArthur River, Mt. Isa, HYC, Australia, Sullivan, British Columbia, Rampura-Agucha, Zawar Group, and Rajpura-Dariba (Fig. 2.20), India, and the Zambian copper belt.

2.3.7.8 Skarn Type

Skarn-type deposits are formed in a similar process to porphyry orebodies. Skarn deposits are developed due to replacement, alteration, and contact metasomatism of the surrounding country rocks by ore-bearing hydrothermal solution adjacent to a mafic, ultramafic, felsic, or granitic intrusive body. They most often develop at the contact of intrusive plutons and carbonate country rocks. The latter are converted to marbles, calc-silicate hornfels by contact metamorphic effects. Mineralization can occur in mafic volcanics and ultramafic flows or other intrusive rocks. There are many significant world-class economic skarn deposits: Pine Creek tungsten, California, Twin Buttes copper, Arizona, and Bingham Canyon copper, Utah, USA, OK Tedi gold-copper, Papua New Guinea, Avebury nickel, Tasmania, and Tosam tin-copper, India (reconnaissance stage).

2.3.7.9 Residual Type

Residual-type deposits are formed by a chemical weathering process such as leaching, which removes gangue minerals from protore and enriches valuable metals in situ or at a nearby location. The most important example is formation of bauxite under a tropical climate where abundance of high temperature and high rainfall during chemical weathering of granitic rocks produces highly leached cover rich in aluminum. Examples are bauxite deposit of Weipa, Gove Peninsula, Darling Range, and Mitchel Plateau in Australia, Awaso and Kibi, Ghana, East Coast, India, and Eyre Peninsula kaolin deposit, Australia. Basic and ultrabasic rocks tend to form laterites rich in iron and nickel, respectively. Nickel-bearing laterites may or may not be associated with PGE, are mined at New Caledonia, Norseman-Wiluna greenstone belt of Western Australia, Central Africa, and Ni-bearing limonite overburden at Sukinda, India. The other residual type deposits are auriferous laterites in greenstone belts (Western Australia) and Ni—Co and Cr in laterites on top of peridotites (New Caledonia and Western Australia, respectively), and Ti in soils on top of alkali igneous rocks (Parana Basin, Brazil).

2.3.7.10 Placer Type

Placer-type deposits are formed by surface weathering and ocean, river, or wind action resulting in concentrations of some valuable, heavy resistant minerals of economic quantities. The placer can be an accumulation of valuable minerals formed by gravity separation during sedimentary processes. The type of placer deposits are alluvial (transported by a river), colluvial (transported by gravity action), eluvial (material still at or near its point of formation), beach placers (coarse sand deposited along the edge of large water bodies), and paleoplacers (ancient buried and converted rock from an original loose mass of sediment). The most common placer deposits are those of gold, platinum group minerals, gemstones, pyrite, magnetite, cassiterite, wolframite, rutile, monazite, and zircon. The California Gold Rush in 1849 began when someone discovered rich placer deposits of gold in streams draining the Sierra Nevada Mountains. Recently formed marine placer deposits of rutile, monazite, ilmenite, and zircon are currently being exploited along the coast of eastern Australia, India, and Indonesia.

2.3.8 Grain Size

Rock-forming and ore-forming mineral grain size varies widely between very fine and very coarse. The different minerals are of different grain sizes under natural processes, and even the same mineral may show large variations in grain size influenced by the process of formation and postmineralization episodes like the effect of post-depositional structure, remobilization, and metamorphic grade. The grain size parameter contributes significantly to identification and liberation during crushing/grinding in the mineral processing plant and affects the recovery of concentrates. A change in grain size affects recovery due to the dislocations interacting with the grain boundary as they move. Particle size is a critical parameter for the selection of the process to be chosen from a variety of available operations during mineral processing. The appropriate process route is determined largely by the initial size of the mineral. Grain sizes are broadly grouped into three categories.

2.3.8.1 Fine Grained

The industry standard fine grain size is defined as <0.1 mm diameter. Excessive fine grain minerals by the natural process of formation or overgrind will create slimes hindering recovery of ore minerals (Fig. 2.21).

2.3.8.2 Medium Grained

Medium grain size is defined between 0.1 and 2 mm diameter. The minerals are easily identified showing all physical properties (Fig. 2.22). This is good for mineral beneficiation with optimum recovery.

2.3.8.3 Coarse Grained

The coarse grain size of minerals is >2 mm diameter. The large and very large size minerals are unique to identify (Fig. 2.23). These large size ore minerals can be separated following other routes to make a preconcentrate.

FIGURE 2.21 Massive fine-grained crystalline galena (shining gray color) and remnants of partially replaced quartz vein (white) at Rajpura-Dariba underground mine, India. The excessive fine grain size or overgrinding hinders better recovery. *Courtesy: Prof. Martin Hale.*

FIGURE 2.22 Medium-grained crystalline galena in dolomite host rock at Zawar underground mine, India. The limestone and dolomitic host rocks are favorable and create clean concentrates.

FIGURE 2.23 Coarse-grained galena crystal (shining gray color) with small patches of chalcopyrite (yellow) from SEDEX type of sulfide mineralization at Rajpura-Dariba underground mine, India. The sample is easiest to identify and unique in all respects. *Courtesy: Prof. Martin Hale.*

2.3.9 Contained Metal

Deposits can be classified on the basis of concentration of mineral or metal grade.

2.3.9.1 High Grade

High-grade deposits are economically the most encouraging type for the mineral industry, e.g., Red Dog (22% Zn + Pb), Alaska, Sullivan (12% Zn + Pb), Canada, Lady Loretta, (27% Zn + Pb), HYC (20% Zn + Pb), Broken Hill (15% Zn + Pb), Mt. Isa (13% Zn + Pb), Australia, and Rampura-Agucha (15% Zn + Pb), India.

2.3.9.2 *Medium Grade*

Medium-grade deposits are also equally important as sources of metal, e.g., Lennard Shelf (9.5% Zn + Pb), Australia, San Felipe (10% Zn + Pb), Mexico, and Rajpura-Dariba (10% Zn + Pb) and Sindesar-Khurd (10% Zn + Pb), India.

2.3.9.3 *Low Grade*

Large low-grade deposits are exploited on account of available existing infrastructure, e.g., Bou Jabeur (5.6% Zn + Pb), Tunisia, Scotia (5% Zn + Pb), Canada, Hambok (3% Zn + Cu), Eritrea, and Zawar Group (5% Zn + Pb), India. These deposits are workable with high mechanization for huge production and improved process recovery.

2.3.9.4 *Very Low Grade*

The very low-grade deposits like Suplja Stijena (2% Zn + Pb), Gradir, and Pering (1.4% Zn + Pb), South Africa, and Sindeswar-Kalan East (2.5% Zn + Pb), India, are explored and kept in abeyance for future resources with technology upgradation in low-cost mining and mineral beneficiation.

2.4 HOST ROCKS

Mineral deposits are an integral part of the parent rock bodies formed under certain physicochemical processes at a definite time and space. The mineral bodies, more specifically orebodies, are concentrations of particular minerals or metals or a group, which are technoeconomically exploitable from host rock mass. Therefore an exploration geologist must possess adequate knowledge of the favorable stratigraphy, structure, and rock association of the region to design the exploration program. For example, if the search is for coal the geologist's focus for prospecting will be on traversing rock formations of the Gondwana age. Similarly, if the search is for PGE, attention should be focused on layered mafic and ultramafic rocks with associated trace elements like nickel, copper, and chromium. If one is interested in a SEDEX-type zinc-lead-silver ore, then rocks like dolomite, a carbonaceous black schist of the Proterozoic age, should be considered. Ore-forming minerals, their broad affinity to host rocks, associated elements, and type of deposit, are given in Table 2.3.

TABLE 2.3 Host Rock of Common Economic Minerals and Type of Deposits

Element	Host Rock	Associated Elements	Deposit Type	Example
Ag	Dolomite, carbonaceous schist	Pb, Cu, Zn, Cd, Ba	Base metal	Penasquito polymetallic deposit, Mexico
Al	Residual sediments, weathered mafics/ultramafics	Fe, Mn, Ni, SiO_2	Bauxite	Western and central part of Guinea, Africa
As	Schist, greywacke	Au, Fe	Base metal	El'brusskiy arsenic mine, North Caucasus region, Russia
Au	Quartz reefs, veins, carbonate rocks	Ag, Cu, As, Sb	Gold	Super Pit gold, Western Australia
C (graphite)	Schist, khondalite		Graphite	Heilongjiang province, northeast China
C (diamond)	Kimberlite pipe, conglomerate	Cr	Diamond pipes and placer	Venetia diamond deposit/mine, South Africa
C (coal)	Shale and sandstone	Pyrite, methane	Coal	Wyoming's Powder River Basin, USA
Cr	Layered ultramafic intrusive	Cu, Ni, Au, PGE	Chromite	Bushveld Cr–PGE, South Africa
Cu	Granite, schist, quartzite	Au, Ag, Ni, Zn	Copper	Bingham Canyon Cu–Au–Ag–Mo deposit, Utah
Fe	BHQ, BIF	SiO_2	Iron ore	Carajas iron ore mine in northern Brazil
Mn	Veins and nodules	Fe	Manganese ore	Woodie Woodie deposit, Western Australia, Indian Ocean

Continued

TABLE 2.3 Host Rock of Common Economic Minerals and Type of Deposits—cont'd

Element	Host Rock	Associated Elements	Deposit Type	Example
Ni	Mafic and ultramafic	Cu, Cr, Co, PGE	Nickel	Sudbury Ni–PGE, Canada, Kambalda Ni, Australia, Jinchuan Ni, China
Pb	Dolomite, carbonaceous schist	Zn, Cu, Ag, Cd	Base metal	Southeast Missouri Lead Belt, USA
P_2O_5	Dolomite	–	Phosphate	Jhamarkotra stromatolites rock phosphate, India
Sn	Pegmatite and granite	W	Tin	Bangka and Belitung islands, Indonesia
U	Black shale, sandstone, hematite breccias, quartz, and pebble conglomerate	Cu, Mo, Fe, Au, Ag, Re	Uranium	McArthur River Uranium Mine, northern Saskatchewan, Canada
Zn	Dolomite, carbonaceous schist	Pb, Cu, Ag, Cd	Base metal	Rampura-Agucha mine, India, Broken Hill, Australia, Red Dog, Alaska

BHQ, banded hematite quartzite; *BIF*, banded iron formations; *PGE*, platinum-group elements.

2.5 INDUSTRY SPECIFICATIONS

Mineral sectors in general work with standard industrial specifications (Sinha and Sharma, 1993; Evans, 1998; Chatterjee, 2008). If required the raw material is processed for a market-finished commodity. Some minerals can be directly sold, involving negligible processing, such as quartz, feldspar, and limestone. Others may require processing through a few steps with intermediate saleable goods. Zinc (4%–10%), lead (1%–2%), and copper (0.5%–2.0%) ore at run-of-mine grade can either be transferred to an in-house beneficiation plant as a separate profit center or sold to a third-party process plant to produce respective concentrates (see Chapter 13). The average concentrate grades are +50% for zinc and lead, and +20% for copper. The bulk concentrate (copper + zinc + lead) is of lower grade produced from a complex type of mineralization. The concentrate is further processed either in-house or by a third-party smelter and subsequently refined to produce 99.99% metal grade. This refined metal is the input for the manufacturing industry for making consumer serviceable goods. Specifications for a number of minerals are generalized and described as follows:

(1) Bauxite
- (a) Metal grade : $>50\%$ Al_2O_3, $<5\%$ SiO_2
- (b) Refractory grade : $>55\%$ Al_2O_3, $<3\%$ SiO_2, Fe_2O_3 each
- (c) Chemical grade : $>58\%$ Al_2O_3, $<3\%$ Fe_2O_3

(2) Chromite
- (a) Metallurgical grade : $>48\%$ Cr_2O_3, Cr:Fe = $>2.8:1$
- (b) Refractory grade : 38%–48% Cr_2O_3, $Cr_2O_3 + Al_2O_3 > 60\%$
- (c) Chemical grade : 48%–50% Cr_2O_3, Cr:Fe = 1.6:1
  - Fe as FeO : $<15\%$
  - MgO : <12–16%
  - SiO_2 : $<5\%$
  - P as P_2O_5 : <0.005–0.20%
  - CaO : <5–12%
  - S as SO_3 : 0.1%

(3) Copper ore
- Run-of-mine Cu grade : 0.50%–2.00%
- Concentrate grade : $>20.00\%$
- Refined copper grade : 99.99%

(4) Fluorite
- (a) Metallurgical grade : $>85\%$ CaF_2, $<5\%$ SiO_2, $<0.03\%$ S
- (b) Ceramic grade : $>95\%$ CaF_2, $<3\%$ SiO_2, $<1\%$ $CaCO_3$, entirely free from Pb, Zn, Fe, S
- (c) Acid grade : $>97\%$ CaF_2, $<1\%$ SiO_2, $CaCO_3$, entirely free from Pb, Zn, and Fe

(5) Graphite
- (a) Lumpy:
  - Lump—walnut to pea
  - Chip—pea to wheat grain
  - Dust—finer <60 mesh
- (b) Amorphous : $>50\%$ graphitic carbon
- (c) Crystalline flacks : $>85\%$ graphitic carbon (-8 to 60 mesh in size)

(6) Gypsum
- (a) Cement grade : $>70\%$ $CaSO_4 \cdot 2H_2O$
- (b) Fertilizer grade : $>85\%$ $CaSO_4 \cdot 2H_2O$, $<6\%$ SiO_2, $<0.01\%$ NaCl, no clay
- (c) Plaster of Paris : 80%–90% $CaSO_4 \cdot 2H_2O$

(7) Glass sand
- (a) Normal glass
  - SiO_2 : $>96\%$
- (b) Optical glass
  - SiO_2 : 99.8%

Iron oxide : <0.02%
CaO + MgO : <0.1%
Cr, Co, Al_2O_3, TiO_2 : <0.10%
Mn : <1 ppm

(8) Iron ore
(a) Grade classification
Very high grade : >65% Fe
High grade : 62%–65% Fe
Medium grade : <62% Fe
Unclassified : Inadequate sampling
Phosphorus <0.18%
(b) Size classification
Lump ore : Particles >8 mm
Sinter feed : Fines >100 mesh
Fines (pallet feed) : Fines <100 mesh

(9) Limestone
(a) Cement grade : 45% CaO, <3% MgO
(b) Blast furnace grade : 46%–48% CaO, <11.3% total insoluble
(c) Steel melting grade : >48% CaO, <4% total insoluble Conventional open hearth steel making: <4% SiO_2
Basic oxygen furnace : <1% SiO_2

(10) Dolomite
(a) Blast furnace grade : >28–33% CaO, >18–20% MgO, <7% total insoluble
(b) Steel melting grade : >29% CaO, >20% MgO, <4% total insoluble
(c) Glass grade : Consistent chemical composition, <0.2% Fe_2O_3

(11) Manganese ore
Manganese ore grade : >35% Mn
Ferruginous Mn ore : 10%–35% Mn
Manganiferous iron ore : 5%–10% Mn
Metallurgical grade : >44% Mn
Battery grade : >78% MnO_2, <4% HCl-soluble Fe
Chemical grade : >80% MnO_2

(12) Rock phosphate
P_2O_5 : >24% (preferably + 30%)
Si_2O_2 : <20%
Fe : <3%
Al_2O_3 : <7%

(13) Sillimanite and kyanite
Al_2O_3 : >59%
Si_2O_2 : <39%
Fe_2O_3 : 0.75%
TiO_3 : <1.25%
CaO + MgO : <0.20%

(14) Talc
Talc is classified according to its color and softness

Grade I	Pure white appearance with smooth feel and free from grit
Grade II	Tinted variety with smooth feel and without grit
Grade III	Off-color variety with smooth feel and without grit
Grade IV	White or colored with grit

(15) Zinc-lead ore
Run-of-mill grade : >8% Pb + Zn
Fe content as Py, Po : Lesser the better
Graphite content : Lesser the better
Zinc concentrate : >52% Zn
Lead concentrate : 56%–60% Pb
Refined metal : >99.99% Zn, Pb

(16) Coal
(a) Noncoking coal
Grade A : Useful heat value >6200 kcal/kg
Grade B : Useful heat value >5600 and <6200 kcal/kg
Grade C : Useful heat value >4940 and <3600 kcal/kg
Grade D : Useful heat value >4200 and <4940 kcal/kg
Grade E : Useful heat value >3360 and <4200 kcal/kg
Grade F : Useful heat value >2400 and <3360 kcal/kg
Grade G : Useful heat value >1300 and <2400 kcal/kg
(b) Coking coal
Steel grade I : Ash content <15%
Steel grade I : Ash content >15% and <18%
Washery grade I : Ash content <18% and <21%
Washery grade II : Ash content <21% and <24%
Washery grade III : Ash content <24% and <28%
Washery grade IV : Ash content <28% and <35%
(c) Semicoking coal
Semicoking I : Ash + moisture content <19%
Semicoking II : Ash + moisture content between 19% and 24%
(d) Hard coke
Premium : Ash content <25%
Ordinary : Ash content between 25% and 30%
Beehive premium : Ash content <27%
Beehive superior : Ash content between 27% and 31%
Beehive superior : Ash content between 31% and 36%

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Chapter 3

Photogeology, Remote Sensing, and Geographic Information System in Mineral Exploration

Chapter Outline

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00003-4

> *To see a World in a Grain of Sand*
>
> *And a Heaven in a Wild Flower,*
>
> *Hold Infinity in the palm of your hand*
>
> *And Eternity in an hour.*
>
> William Blake.

3.1 INTRODUCTION

Shepherds, hunters, traders, and travelers traditionally walked through vast areas of land in ancient days and discovered many deposits because of their natural inquisitiveness. The copper, zinc, lead, gold, and silver deposits of the princely states of India, the Early Dynastic Period of Egypt (3100 BC), Turkey, Israel, Iran, Iraq, Cyprus, and Saudi Arabia were discovered more than 3000 years ago. The Broken Hill zinc-lead-silver deposit was an accidental discovery in NSW, Australia, in 1883 by shepherds looking for tin in gossans. The Sudbury Basin, known for its large Ni—Cu—platinum-group element resources, was reported by a blacksmith in 1883 during construction of the first transcontinental Canadian Pacific Railway. The Bushveld Igneous Complex, the world's largest chromium and platinum group of resources, was discovered in 1897 on a routine geological mapping. The Sukinda chromite deposit, the largest chromium resource in India, was a chance discovery by a tribal villager working for Tata Steel in the early 1940s. Centuries ago explorers traversed the lands by walking or by riding on camels, elephants, and horses looking for geological studies. This involved physically touching/examining rocks and minerals. It was always a difficult mission to approach remote hazardous terrain and often imposed restrictions on precise locations and required detailed mapping.

This physical approach was replaced by remote sensing techniques over a century ago. Since 1920 use of aerial photographic interpretation in the field of Earth sciences became a fast and effective tool for the exploration of natural resources. The science further advanced with the launching of the Landsat-1 satellite in 1972. This made remotely sensed high-resolution digital imagery of the electromagnetic spectrum available for interpretation and use in the commercial exploration of minerals, oil, and gas in the shortest possible time. The first known use of the term "geographical information system" (GIS) was by Roger Tomlinson in 1968. The use of GIS in mineral exploration was the application aspects. The system allows integration of of dissimilar digital datasets into a single and unified database. The recommended approach was to compile all types of available geoscientific data within the GIS envelope in the context of an exploration model to produce a mineral potential map.

Geoscientists had always been fascinated by the bird's eye view of Earth's surface. It helped them to understand and overview its geomorphology, lithology, vegetation, and structures. Geomorphology represents all facets of landform-related aspects. Lithology refers to the fundamental and broad distinction between soils and igneous, sedimentary, and metamorphic rocks. Vegetation focuses upon plant cover and the underlying soils and rocks on which it grows. Geological structures identify the kind of deformation the rocks had undergone such as fractures, shears, folds, faults, and lineaments. These attributes contributed several dimensions to the geological events generated during millions of years. This understanding guided geoscientists to search for minerals and fuels.

Data collection in remote sensing technology records information about an object, area, or phenomenon under investigation without coming in direct physical contact. There are two types of information collection system:

1. Still photographs snapped from space flights or airborne cameras; and
2. Continuous digital recording by multispectral electronic scanners or sensors from airplanes or satellites.

3.2 PHOTOGEOLOGY

Photogeology is the simplest approach to remote sensing techniques and their applications. It is the derivation of geological information from the interpretation of aerial photographs. Gaspard-Félix Tournachon (known by the pseudonym Nadar, a French photographer) was the first to suggest the use of aerial photographs taken from a captive balloon in 1858 for the preparation of topographic and cadastral maps. Albert Heim (1898) made a balloon flight over the Alps. He expressed that the structures were more clearly defined in the aerial view. Wilbur Wright took the first photograph from an airplane in 1909 and opened the door to photogeology. World War I (1914—18) had a tremendous influence on the development of aerial photography and its adaptation to common reconnaissance and the needs of surveillance. The science of photointerpretation was born. Many of its basic techniques were developed during the 1920s and expertise improved during World War II (1940—45). Development continued through the 1940s and 1960s approaching its highest capabilities. Growth finally assimilated into the newly developing geological remote sensing.

The camera has come a long way through the process of evolution since it was first invented in the early 1800s. It used direct sunlight that penetrates through a pinhole forming a conical shape in reverse to the object on the opposite wall of a dark room. This was modified and the pinhole was replaced by a lens. The image was recorded on a glass plate in the box. The first black and white (B&W)

photograph was reported in 1814. The crucial starting point in the history of the camera began in 1837 with a permanent photograph using visible light or rays. The first color photograph was produced on a glass plate in 1907. In the early 1940s commercially successful color photographs were produced on film. The quality of photographs was improved by introducing wide angle lenses and filters. The digital single lens reflex camera was first produced in 1981 and is the most recent addition to the world of high-resolution cameras, which provide more features than any other camera ever produced. Digital cameras hold photographs on a memory card, which allows one camera to hold over 100 photographs. Digital cameras have become increasingly popular over the last few years and are being continuously modified to be smaller (mounted on a cellular phone) and faster with 12.4 million pixels, like that mounted in NASA's space shuttle in 2008.

Aerial photography started with cameras fitted on hydrogen-filled balloons, pigeons, kites, parachutes, helicopters, fixed-wing aircraft, and the space shuttle. The camera takes photographs of the ground from a higher horizon without any ground-based support. The cameras may be handheld or firmly mounted on a stand or board. The images taken may be triggered remotely or automatically. Aerial photographs are usually taken between mid-morning and mid-afternoon when the sun is high with minimal shadow effect.

3.2.1 Classification of Aerial Photographs

Aerial photographs are classified on the basis of camera axis, i.e., oblique and vertical, type of film emulsion, and scale.

3.2.1.1 Oblique Photographs

Photographs can be snapped at either a high or low angle oblique camera position to the objects. The high angle oblique photographs include the horizon. The oblique photographs are handy to obtain permanent records of inaccessible mountain cliffs, canyons, gorges, steep angle quarry faces, dam sites, and similar features. These photographs can be studied to identify stratigraphy, rock color and texture, erosion, fold, fault, and linear structures. The information is valuable during mineral search and while attaining corrective measures of structural failures.

3.2.1.2 Vertical Photographs

Vertical photographs are taken by a camera pointing vertically downward, and the axis of the camera/lens is perpendicular to the ground. Aerial photographs show a perspective view due to the effect of distortion on account of image motion, displacement, change in topography, and effect of parallax. The principal point/plumb point/nadir or geometric center has no image displacement. It is the point on the photograph that lies on the optical axis of the camera and is determined by joining the fiducial marks recorded on the photograph (Fig. 3.1).

Flight lines are the paths that an aircraft takes to ensure complete coverage of the area to be photographed. The flight lines are arranged to give a succession of overlapping photographs (Fig. 3.1) to minimize distortion. The photographs overlap within and between the flight lines. The overlaps in these two directions are called forward overlap (end lap) and side lap. The forward overlap along the flight line between two adjacent photographs (stereo pairs) is about 60% to provide complete coverage and a stereoscopic view of the area. The forward overlaps between the first, second, and third adjacent photographs are 60% and 30%, respectively. The side lap between flight lines is usually about 30% to ensure that no areas are left uncovered. A nadir line is a line traced on the ground directly beneath an aircraft while taking photographs of the ground from above. This line connects the image center of the successive vertical photographs. The nadir line is rarely in straight line format due to changes in flight travel course, and needs necessary correction. The title strip of each photograph frame includes flight, line, and photograph number, date and time of the exposure, bubble balance, sun elevation, flight height, and focal length of the camera.

3.2.1.3 Film Emulsion

Aerial photos are coated with unique film emulsion and can be grouped as:

1. Panchromatic black and while (B&W).
2. Infrared black and white (IR).
3. Color (true).
4. IR color or false-color composite (FCC).

A true-color image of an object is the same color as it appears to human eyes—a green tree appears green and blue water appears blue. True color for B&W images perceive lightness of the object as the original depiction. A false-color IR image of an object depicts complementary colors that differ from original colors as appears to human eyes: vegetation, forest, and agricultural land depict red in lieu of original green color.

3.2.1.4 Scale

There are four broad groups of scale to distinguish aerial photographs: small, medium, large, and very large. A large-scale map indicates that the representative fraction (RF) is large, i.e., the RF's denominator is small. 1:10,000 and 1:2500 maps are large scale. Small-scale maps have a small RF. 1:250,000 and 1:50,000 maps are small scale.

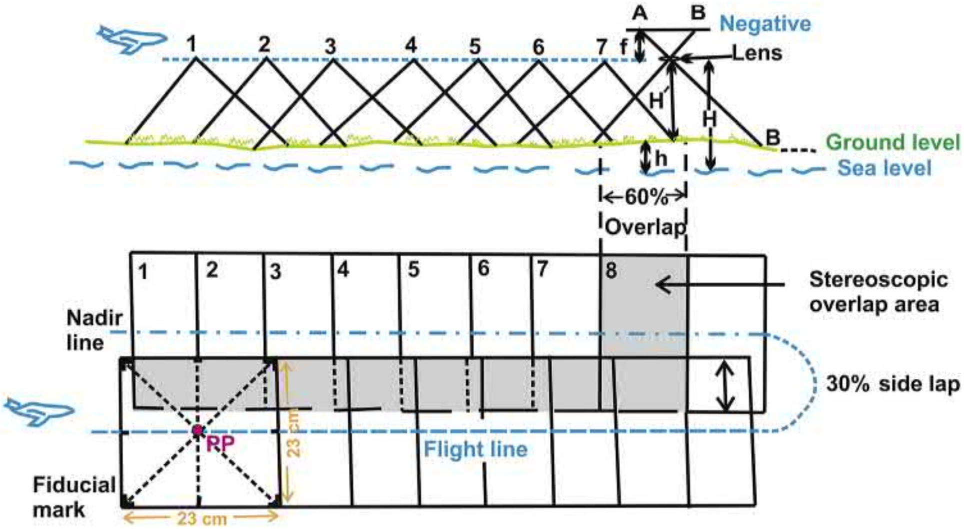

FIGURE 3.1 Schematic typical photograph coverage over flat terrain showing forward overlap and side lap, nadir, flight line, principal point, and fiducial mark.

1. Small scale: ≥1:50,000−1:250,000: reconnaissance
2. Medium scale: 1:10,000−1:50,000: prospecting
3. Large scale: 1:2000−1:10,000: detail exploration
4. Very large scale: ≤1:2000: mine exploration

The rule of thumb is "the larger the scale of map, the larger the objects with more detail features and better resolution."

Scale is the ratio between a distance of two points on the aerial photograph and the distance of the same points on the ground. The unit of scale is expressed as an equivalent (1 mm = 1000 mm) or dimensionless fraction (1/1000) or dimensional ratio (1:1000). In a vertical aerial photograph the scale is a function of the focal length (f) of the camera and the flying height above the average ground level (H′) of the aircraft. The aircraft flies at a nearly constant height. The scale will be constant as and when the plane flies over a flat terrain. In the case of flying over undulating mountainous terrain the scale will vary rapidly across the adjacent photographs. Therefore the scale of aerial photography is a function of terrain elevation.

$$\text{Scale (S)} = f/H'$$

where H′ is the difference between the terrain elevation (h) and height of the aircraft above a datum (H), usually the mean sea level value available from the altimeter in the aircraft.

Following Figure 3.1,

Focal length (f) = 50 cm.

Aircraft height above datum (H) = 5500 m.

Terrain height (h) = 50 m.

Scale (S) = 50 cm/(5500−500) m = 50 cm/500,000 cm = 1/10,000 or 1:10,000.

3.2.2 Parallax

Parallax is an apparent displacement or difference of orientation of an object viewed at two different locations during vertical aerial photography. The objects at a higher height lie closer to the camera and appear relatively larger than similar objects at a lower elevation. The tops of the objects are always displaced relative to their bases. Parallax can be measured by the angle of inclination between those two lines. Nearby objects have larger parallax than distant objects when observed from different positions. This difference in parallax gives a three-dimensional effect when stereo pairs are viewed stereoscopically.

3.2.3 Photographic Resolution

The resolution of aerial photographs depends on various factors such as:

1. The effect of scale is closely related to ground distance from the camera, i.e., the closer the distance, the higher the resolution.
2. Correct exposure time will give higher resolution while using slow and fast film.
3. Higher resolving power of the camera lens will give better results.
4. Movement of the camera lens during exposure must be minimized.
5. Vibration of the camera and aircraft should be minimal for better resolution.
6. Resolution will also change depending on atmospheric conditions at the time of filming and quality of film processing.
7. Precise film processing.

3.2.4 Problems of Aerial Photography

There are a few inherent problems particularly related to aircraft movement. An aircraft usually deviates from the line of flight, altitude, and tilting of wings resulting in drifting of photographs, change of scale between adjacent frame, distortions, and resolution of photographs.

3.2.5 Photographic Interpretation

The mirror stereoscope, color additive viewer, and electronic image analyzer are widely used equipment for aerial photographic interpretation.

A set of two photographs (23 × 23 cm), shot from two successive points, is viewed using the stereoscope. A three-dimensional (3D) mental model is perceived when the two images merge into each other. This enables a viewer to see a two-dimensional (2D) image that is actually two separate images printed side by side with common overlapping areas in three dimensions. The features in the photographs are verified with field observations.

Modern instruments are the color additive viewer and the electronic image analyzer. In the case of the color additive viewer, multispectral photographs are taken simultaneously using three or four cameras in a narrow spectral band of 0.4—0.5 (blue), 0.5—0.6 (green), 0.6—0.7 (red), and 0.7—0.9 (IR) μm. An FCC is generated by superimposition of multispectral photographs. The human eye will differentiate and interpret color composite more so than gray tones. The electronic image analyzer scans B&W aerial photographs and produces close circuit video digital images for interpretation.

3.2.6 Application in Mineral Exploration

Systematic evaluation, interpretation, and identification of key parameters from aerial photogeology have applications for society in general and mineral exploration in particular. The key information and applications include:

1. Topography, surface erosion, land distribution, drainage system, and land-use pattern that support urban and agricultural planning.
2. Soil and rock types (host environment), texture, structures (fold closure, faults, shears, and lineaments), and surface signatures (weathering profile, gossans, and old mining/smelting remnants) contribute to conceptualize the existence of near-surface/deep-seated deposits as possible exploration targets (Fig. 3.2).
3. Vegetation with prolific/scanty growth, anomalous colors, and toxic effects along with drainage pattern guide planning geochemical sampling.
4. Approach is more significant for mineral deposits occurring at remote inaccessible areas.

FIGURE 3.2 A typical aerial view of the Colorado River in the background from a height of 7000 feet from Southern Rim, Grand Canyon, Natural Wonders of the World, Arizona.

3.3 REMOTE SENSING

3.3.1 Definition and Concept

Remote sensing is an emerging expertise that has undergone phenomenal development over aerial photography and interpretation. It is a comprehensive process of collecting information about an object, area, and phenomenon without coming in direct contact or touching itself. The information is acquired by a remotely placed sensor far away from the source object. Remote sensing implies data acquisition by electromagnetic radiation from sensors flying on aerial or space platforms and interpretation of physical attributes of ground objects (Campbell, 2007). The fundamental difference between photogeology and remote sensing is the same as between photographs and images. Photographic data are the reflection of natural light recorded on a light-sensitive emulsion-coated base film (negative) and printed on light-sensitive emulsion-coated paper (positive/paper print) for interpretation. Image data are the reflected and emitted multispectral electromagnetic energy recorded directly in digital form on a magnetic tape or disk. The soft copy is processed and interpreted. The remote sensing data captivate the maximum capability, liberty, and flexibility for manipulation of multispectral responses over photogeology.

The remote sensing technique involves each type of object reflecting or emitting a certain intensity of energy as and when in contact with a different range of wavelengths of the electromagnetic spectrum, depending on the physicochemical attributes of the object. The multispectral images in green, red, and near-IR bands can distinguish between different types of objects like water, soil, rocks, surface weathering, and vegetation (Lillesand and Kiefer, 2003; Gupta, 2003; Evans, 2006).

3.3.2 Energy Sources and Radiation

3.3.2.1 Electromagnetic Energy

Visible light, one of the many forms of electromagnetic energy (EME), with wavelength (λ) varying between 0.4 and 0.7 μm, is sensed by the human eye. The human brain receives color impulses of visible objects from the eyes via three separate light receptors in the retina. These receptors respond to blue, green, and red light, and are known as additive primaries or primary colors. The receptor systems stimulate equally to white visual effects if these three colors overlap. A relative mixing of three primary colors reflected from the object changes to a full range of rainbow colors, i.e., violet, indigo, brown, green, yellow, orange, and red. The eyes perceive "a bowl of fruits" as visible light by synthesizing.

The other wavelengths ranging between 0.7 and 300 μm are longer than visible ray, and known as IR. IR is divided into various components with respect to increasing wavelength. These are near IR (NIR λ 0.7–1.1 μm), middle IR (MIR λ 1.1–3.0 μm), far IR (FIR λ 7–17 μm), and thermal IR (TIR λ 3.0–5.0 μm). Color NIR beams generate three supplementary colors, namely, cyan, magenta, and yellow.

There are two principal types of energy (EME), namely, light energy as reflected and heat energy as emitted from the object after partial absorption. Data acquisition in remote sensing technology works on this concept of transmitting rays/energy at various wavelengths and receiving the relative reflectance and emitted energy to distinguish the characteristic attributes of objects under investigation.

The ultraviolet ray (λ 3 nm–0.4 μm) transmits heat energy that burns human skin and affects the eyes. The transmission of IR energy at λ 8–14 μm emits less than 200°C and is suitable for a thermal spring. Similarly, IR energy at λ 3–5 μm emits more than 200°C and is suitable for volcanic study. Microwaves with 0.8–100 cm wavelength can penetrate into cloud and even the subsurface. Various rays/energies and their characteristic wavelengths can be found in Table 3.1.

TABLE 3.1 Various Rays/Energies and Their Characteristic Wave Lengths

Ray	Wavelength	Ray	Wavelength
Gamma ray	<0.03 nm	Photographic IR	0.7–3 μm
X-ray	0.03–3 nm	NIR (magenta, cyan, and yellow)	0.7–1.3 μm
Ultraviolet ray	3 nm –0.4 μm	MIR	1.3–3.0 μm
Visible ray	0.4–0.7 μm	FIR (thermal and emissive)	7–17 μm
Blue	0.4–0.5 μm	TIR (forest fire)	3.0 –15.0 μm
Green	0.5–0.6 μm	Microwave	0.3–300 cm
Red	0.6–0.7 μm	Television/radio waves	1.5 km
Infrared	0.7–300 μm	Electromagnetic radiation	0.74 –300 μm

1 nm = 10^{-9} m, 1 μm = 10^{-6} m. *FIR*, Far infrared; *MIR*, mid-infrared; *NIR*, near infrared; *TIR*, thermal infrared.

3.3.2.2 Electromagnetic Radiation

Electromagnetic radiation is a phenomenon that takes the form of self-propagating energy waves as it travels through space (vacuum or matter). It consists of both electric and magnetic field components. The energy waves oscillate in phase perpendicular to each other and perpendicular to the direction of energy propagation. It is observed that the longer the wavelength involved, the lower would be the frequency as well as the energy. Electromagnetic radiation is classified into several types according to the frequency of its wave. These types include (in order of decreasing frequency and increasing wavelength) cosmic radiation, gamma radiation, X-ray radiation, ultraviolet radiation, visible radiation, IR radiation, terahertz radiation, microwave radiation, and radio waves. A small and variable window of frequencies is sensed by the eyes of various organisms. This is known as the visible spectrum (λ 0.4–0.7 μm) or light. Electromagnetic radiation carries energy and momentum that may be imparted to matter with which it interacts.

A black body is an inclusive part of electromagnetic radiation, and is an idealized theoretical radiator that absorbs 100% of all electromagnetic radiation that hits it (Box 3.1).

Electromagnetic radiation propagation travels the path length twice between the source, object, and sensor through the total thickness of the atmosphere. The compositional nature of the atmosphere affects the propagating energy by partial absorption and scattering. Atmospheric absorption results in the effective loss of energy to atmospheric constituents. The most efficient atmospheric absorptions are water vapor, carbon monoxide, carbon dioxide, and ozone. The unpredictable diffusion of radiation by particles within the atmosphere is called atmospheric scattering. Atmospheric windows are the ranges of wavelength in which the atmosphere is particularly transmissive.

3.3.2.3 Electromagnetic Spectrum

The electromagnetic spectrum is a collective term referring to the entire range and scope of frequencies of

BOX 3.1 Black Body

A black body is a perfect theoretical radiator that absorbs 100% of all electromagnetic radiation that hits it. No electromagnetic radiation passes through it and none is reflected. The object appears completely black when it is cold because no light (visible electromagnetic radiation) is reflected or transmitted. There is no material in nature that completely absorbs all incoming radiation. However, graphitic carbon absorbs 97% incoming radiation, and is the perfect emitter of radiation. A black body emits a temperature-dependent spectrum (thermal radiation) of light, and is termed black-body radiation. A black body emits the maximum amount of energy possible at a particular temperature.

electromagnetic radiation. The behavior of radiation depends on its wavelength and is inversely proportional to frequency and wavelength, i.e., higher frequencies have shorter wavelengths and vice versa. The electromagnetic spectrum of an object is the characteristic distribution of electromagnetic radiation emitted or absorbed by that particular object. The complete range of the electromagnetic spectrum is elaborated in Fig. 3.3.

3.3.2.4 *Spectral Reflectance/Response Pattern*

The difference between the intensity of electromagnetic radiation reflected or emitted by an object at different wavelengths is called spectral response or signature. The curve generated by the intensity of energy versus wavelength is called the spectral response curve. A single feature or a response pattern can be diagnostic in identifying an object.

3.3.2.5 *Data Acquisition*

Data detection and acquisition are performed either photographically or electronically. The process of photography relies on chemical reaction on light-sensitive film. The electronic process administers electromagnetic signals to the objects. The electromagnetic signals are fed back to the sensors with a broader spectral range of sensitivity and are capable of storing and transmitting as and when required. Most of the data acquisition in remote sensing is synonymous with multispectral satellite imagery as detailed in Table 3.2. These images received from satellites are readily available to exploration agencies at a cost.

3.3.3 Remote Sensing System

For better understanding and utility a model remote sensing system comprises the following components:

3.3.3.1 *Platform*

Platforms are vehicles or carriers that carry the remote sensor. Typical platforms for remote sensing data acquisition are terrestrial (ladders and trucks for ground investigations), aerial (kites, balloons, helicopters, and aircraft for low-altitude remote sensing), and space-borne (manned or unmanned rockets and satellites from high altitude). The key factor for the selection of a platform is altitude, which determines the best possible ground

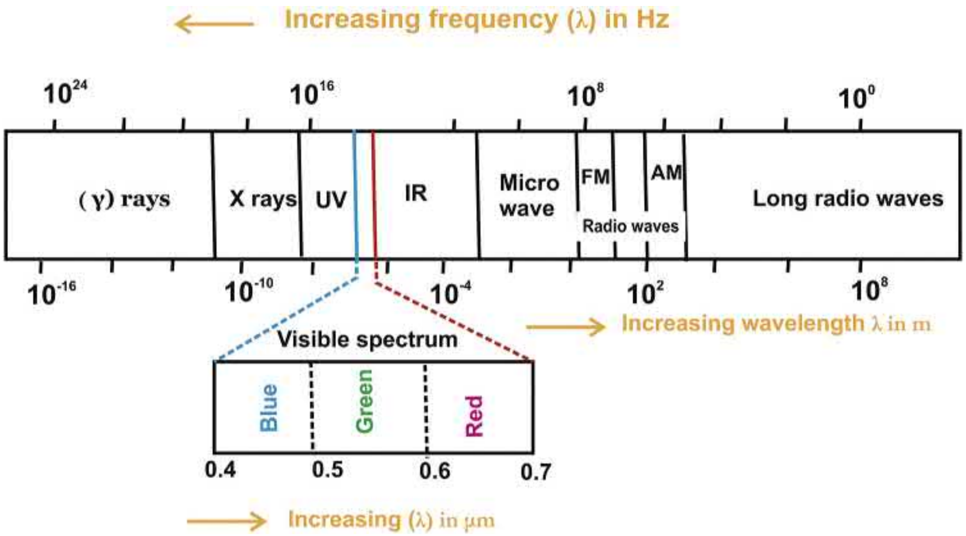

FIGURE 3.3 A complete possible range of electromagnetic spectrum with increasing frequency.

TABLE 3.2 Salient Features and Chronological Development of Major Landsat Type Earth-Resources Satellite Platforms Over Four Decades

Satellite	Country	Year	Nature	Altitude (km)	Sensor
Landsat-1	USA-NASA	1972	Sun Sys	919	MSS, RBV
Landsat-2	USA-NASA	1975	Sun Sys	919	MSS, RBV
Landsat-3	USA-NASA	1978	Sun Sys	919	MSS, RBV
Landsat-4	USA-NASA	1982	Sun Sys	705	MSS, TM
Landsat-5	USA-NASA	1984	Sun Sys	705	MSS, TM
SPOT-1	France	1986	Sun Sys	832	HRV
IRS-1A	India	1988	Sun Sys	904	LISS-1
IRS-1B	India	1991	Sun Sys	904	LISS-2
Landsat-6	USA (EOSAT)	1993	Sun Sys	705	ETM
SPOT-3	France	1993	Sun Sys	–	HRV
IRS-1C	India	1995	Sun Sys	817	LISS -3
IRS-1D	India	1997	Sun Sys	817	LISS -3
SPOT-4	France	1998	Sun Sys	832	HRV IR
IRS P7	India, ISRO	2007	Sun Sys	–	LISS-4
Landsat-7	USA-NASA	1999	Sun Sys	705	ETM+
Terra	USA–Japan	1999	Sun Sys	713	ASTER, etc.
RADARSAT-2	Canada	2008	Sun Sys	798	SAR
Landsat-8	USA-USGS	2013	Sun Sys	705	TIRS
SPOT-7	France	2014	Sun Sys	660	HRV IR
Cartosat-2E	India, ISRO	2017	Sun Sys	505	IRS

IRS, Indian Remote Sensing Satellite system; *NASA*, National Aeronautics and Space Administration (USA); *SPOT*, Satellites Pour l'Observation de la Terre (France).

resolution and which is also dependent on the instantaneous field of view (IFOV) of the sensor on board the platform.

The first Landsat-1 satellite was launched in July 1972 by NASA, USA. This was originally named Earth Resources Technology Satellite and provided multispectral imagery for the study of renewable and nonrenewable resources. Landsat-4 (1982) incorporated Thematic Mapper, which scanned in seven bands, two of which (5 and 7) were specifically opted for geological purposes. A great variety of satellites were built for monitoring various environmental conditions on land and at sea. Satellites can view Earth in vertical, side, or limb modes. The new methodology of Earth science is based on satellite data that allows a whole Earth approach to study the environment. The remotely sensed satellite data and images of Earth have four important advantages compared to ground observations, such as synoptic view, repetitive coverage, multispectral capability, and low-cost data.

India began development of an indigenous Indian Remote Sensing (IRS) satellite program to support the national economy in the areas of agriculture, water resources, forestry and ecology, geology, water sheds, marine fisheries, coastal management, weather forecasting, natural calamities, and disaster management. IRS satellites are the mainstay of the National Natural Resources Management System, for which the Department of Space is the nodal agency, providing operational remote sensing data services. Data from the IRS satellites are received and disseminated by several countries all over the world. New applications in the areas of urban sprawl, infrastructure planning, and other large-scale applications for mapping have been identified with the advent of high-resolution satellites. The salient features of some important Landsat-type Earth resources satellite platforms of the 20th century are given in Table 6.2.

The path of a celestial body or an artificial satellite as it revolves usually in an elliptical path around another body is called an orbit. Earth satellites make one complete revolution in 12 h. There are two types of orbit, i.e., polar and equatorial orbits.

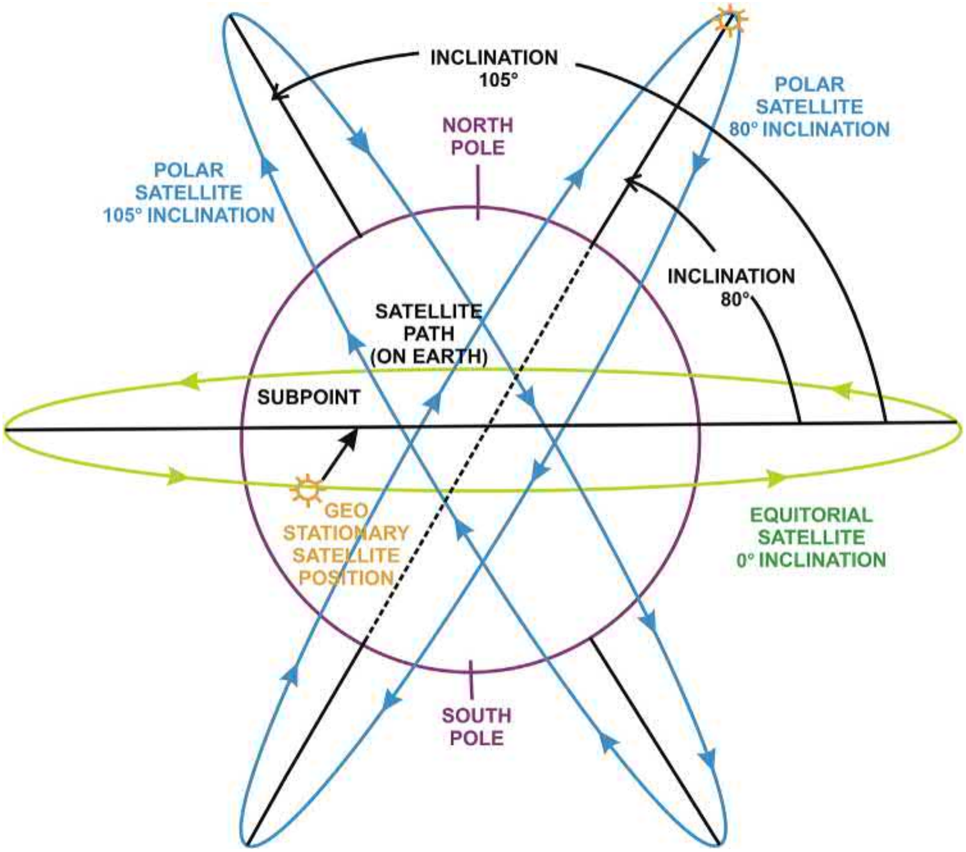

FIGURE 3.4 Diagram showing the typical elliptical orientation path of Earth's satellites, known as polar and equatorial orbits.

In the case of a polar orbit the satellite travels over both North and South Poles at about 850 km altitude above Earth at an angle of 80 and 105 degrees from the equatorial plane (Fig. 3.4). North to south rotation is called descending and south to north rotation is called ascending. The satellites take about 100 min for a complete revolution in polar orbit. They can see a small portion at a time covering the whole globe at high resolution. The polar orbit is essentially sun synchronous and geostationary. A satellite in such an orbit can observe all points on Earth during a 12-h day. This type of orbit is useful for spacecraft that perform mapping or surveillance.

In the case of an equatorial orbit the satellite flies along the line of Earth's equator (Fig. 3.4). A satellite must be launched from a place on Earth close to the equator to achieve equatorial orbit. Equatorial orbits are useful for satellites observing tropical weather patterns because they can monitor cloud conditions around the globe.

A sun-synchronous orbit (heliosynchronous or dawn-to-dusk orbit) is a geocentric orbit that combines altitude and inclination in such a way that an object on that orbit ascends or descends over any given point of Earth's surface at the same local mean solar time. The surface illumination angle will be nearly the same every time. This consistent lighting is a useful characteristic for satellites that image Earth's surface in visible or infrared wavelengths and for other remote sensing satellites, e.g., those carrying ocean and atmospheric remote sensing instruments that require sunlight.

A geostationary orbit is a geosynchronous orbit directly above Earth's equatorial orbit (0 degree latitude and 36,000 km altitude) and stays over the same spot with a period equal to Earth's rotational period. Geostationary objects appear motionless in the sky from Earth's surface, making the geostationary orbit of great interest for communication purposes and weather forecasting. It observes an evolving system with lower spatial resolution. The satellites in geostationary condition differ in location by longitude only, due to the constant 0 degree latitude and circularity of geostationary orbits.

3.3.3.2 Sensors

Sensors are devices like photographic cameras, scanners, and radiometers mounted on suitable platforms to detect and record the intensities of electromagnetic radiation in various spectral channels. Sensors are of two types: passive and active.

Passive sensors are designed to record data using an available naturally occurring energy source reflected,

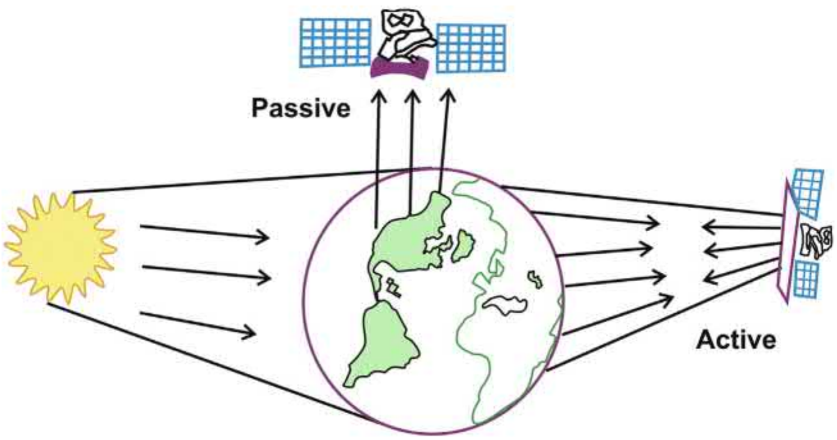

FIGURE 3.5 Schematic diagram showing the position of a data collecting device with respect to Sun and Earth to designate it as a passive or active sensor.

emitted, and transmitted by parts of the electromagnetic spectrum. They rely on the solar illumination side of Earth or natural thermal radiation for their source of energy (Fig. 3.5). The detection of reflected solar energy can only proceed when the target is illuminated by the Sun. This restricts visible light sensors on satellites from being used during a nighttime pass. Examples of passive sensors are Landsat Multispectral Scanner, Landsat Thematic Scanner using additional wavelengths to produce superior spectral and spatial resolution, the airborne scanning system SPOT with stereoscopic capabilities, and the space shuttle.

Active sensors use their own illumination as source of energy and can make observations on both the sunlit as well as the dark side of Earth regardless of the time of day or season (Fig. 3.5). The sensor emits radiation that is directed toward the target to be investigated. The radiation reflected from the target object is received and recorded by the sensor. An active system requires the generation of a fairly large amount of energy to adequately illuminate the targets. Some examples of active sensors are a Synthetic Aperture Radar (SAR) and laser fluorosensor.

3.3.3.3 Sensor Resolution

Remote sensing sensors have four types of resolution, namely, spatial, spectral, radiometric, and temporal:

1. Spatial resolution includes the geometric properties of the ground covered under the IFOV of the sensor. IFOV is defined as the maximum angle of view in which a sensor can effectively detect electromagnetic energy (imaging).
2. Spectral resolution is the span of the wavelength over which a spectral channel operates by the sensor. It is defined by the bandwidth of the electromagnetic radiation of the channels.
3. Radiometric resolution is the degree of intensities of radiation the sensor is able to distinguish.
4. Temporal resolution involves repetitive coverage over an area by the sensor and is equal to the time interval between successive observations. Repeated coverage will identify changes in the objects under study.

An ideal remote sensing system should fulfill the following criteria:

1. Uniform energy source of all wavelengths at a constant high level of output, irrespective of time and place.
2. Clean atmosphere between the source, target, and receiver for to and fro energy radiation.
3. Sensitive super-sensor for acquisition of data.
4. Real-time data processing and interpretation system.

Multidisciplinary users having adequate knowledge, skill, and experience of remote sensing geographical information system (RS-GIS) data acquisition and analysis and can extract their own information.

3.3.4 Characteristics of Digital Images

3.3.4.1 Pixel Parameters

In digital imaging, a pixel (picture element) is the smallest item of information in an image. Each pixel is represented by a number equivalent to average radiance or brightness of that very small area. Pixels are normally arranged in a 2D grid (x, y) and are often represented using dots or squares. The “z” value represents the grayscale value of 256 different brightness levels between 0 (black) and 255 (white). Each pixel is a sample of an original image, where more samples provide more accurate representations of the original object. Pixel size determines the spatial resolution. The intensity of each pixel is variable in a color system, and each pixel has typically three or four components such as red/green/blue or cyan/magenta/yellow and black. An image is built up of a series of rows and columns of pixels.

3.3.4.2 *Mosaics*

Each image has a uniform scale and resolution for a scan path with forward and side overlap. A mosaic is a set of images arranged to facilitate a bird's eye view of an entire area. This is done by cutting and merging each overlapping scene image.

3.3.5 Digital Image Processing

Multispectral satellite sensor data are collected and stored in digital form on computer compatible magnetic tapes at a ground station for processing. The mineral exploration data are upgraded to image restoration, enhancement, and information extraction.

3.3.5.1 *Image Restoration*

Image restoration is correcting defects/defiance in images during data collection and subsequent transfer to a ground station. The process involves replacing lost data (pixel and line), filtering of atmospheric and other noises, and geometrical correction.

3.3.5.2 *Image Enhancement*

Image enhancement is the procedure of improving the quality and information content of original data before processing. Common practices include contrast enhancement, spatial filtering, density slicing, and FCC. Contrast enhancement or stretching is performed by linear transformation expanding the original range of gray level. Spatial filtering improves the naturally occurring linear features like fault, shear zones, and lineaments. Density slicing converts the continuous gray tone range into a series of density intervals marked by a separate color or symbol to represent different features.

FCC is commonly used in remote sensing compared to true colors because of the absence of a pure blue color band because further scattering is dominant in the blue wavelength. The FCC is standardized because it gives maximum identical information of the objects on Earth and satisfies all users. In standard FCC, vegetation looks red (Fig. 3.6) because vegetation is very reflective in NIR and the color applied is red. Water bodies look dark if they are clear or deep because IR is an absorption band for water. Water bodies give shades of blue depending on their turbidity or shallowness because such water bodies reflect in the green wavelength and the color applied is blue.

3.3.5.3 *Information Extraction*

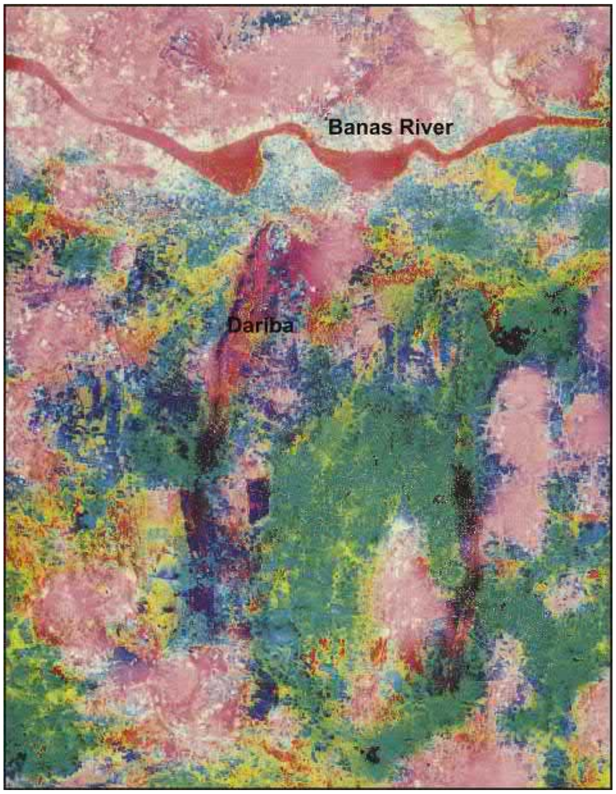

FIGURE 3.6 False-color composite image of aeromagnetic and satellite data over Rajpura-Dariba sulfide belt, Rajasthan, India.

Information extraction is carried out online by ratioing, multispectral classification, and principal component analysis to enhance specific geological features. The ratio is prepared by dividing the gray level of a pixel in one band by that in another to recognize ferruginous and limonitic capping (gossans) useful for identifying sulfide deposits. Multispectral classification generates small groups of pixels of different reflectance, and is marked by different colors or symbols to represent the same kind of surface signature. Principal component analysis is a commonly used method to improve the spread of reflectance by redistributing it. It is used to enhance or distinguish the difference in geological features (Fig. 3.7), e.g., elevation, land cover, lineaments, rock types, vegetation index, turbidity index, forest fire, flood, and archaeological features.

3.3.6 Interpretation

Remote sensing data interpretation or extraction of information from processed satellite images is usually done by photogeological or spectral approaches. Each frame of Earth cover image has its own spectral reflectance characteristics. The characteristics ("signature") are unique and make it possible to distinguish the objects of interest from their intermixed background. The final process is completed by the analysis of the data or images using image interpretation techniques. The techniques of remote sensing and image interpretation yield valuable information on Earth resources.

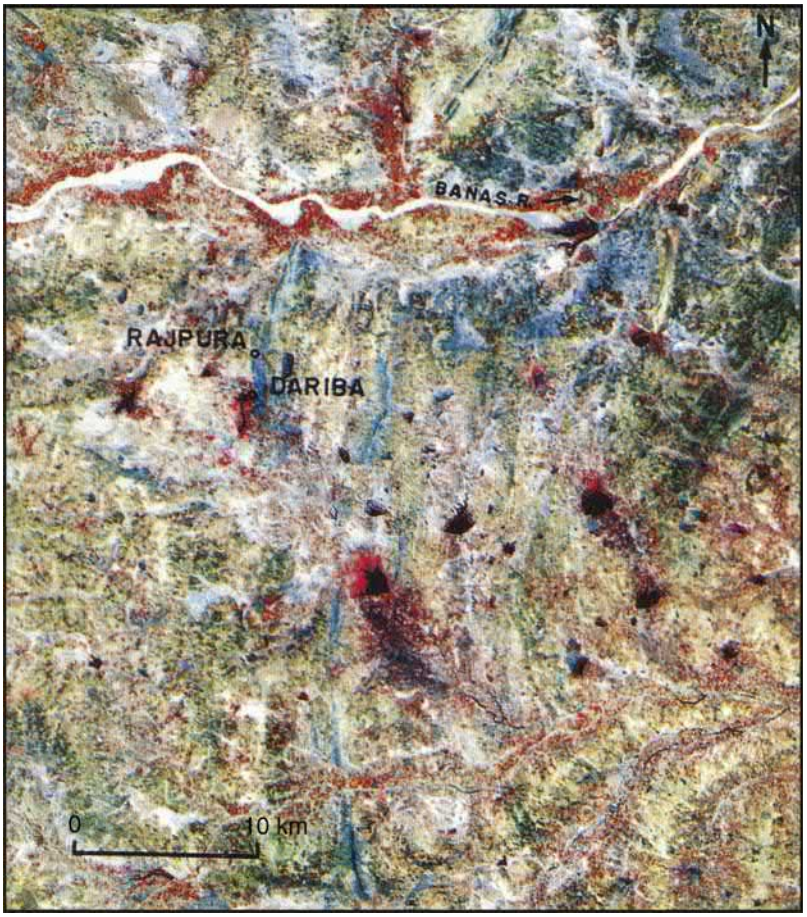

FIGURE 3.7 Principal component image of Rajpura-Dariba sulfide belt, Rajasthan, India.

3.3.7 Remote Sensing Application in Natural Resources

Multispectral remote sensing techniques have significant potential for multipurpose applications in all branches of Earth science, such as geomorphology, structure, litho mapping, and stratigraphic studies. Many applications are closely related to mineral exploration and resource estimation, and form a concept-based synoptic overview to locate and delineate mineral-bearing provinces, including hydrocarbon and water at reduced time and cost. Remote sensing applications play a significant role at all the sequential stages of exploration, starting from reconnaissance, large area prospecting, prospecting, detailed exploration, active mining, and geoenvironment to mine closure (Taranik, 2009). The applications are:

1. The most powerful data sources at the reconnaissance or preliminary stage of mineral search are satellite-based images at small scale (1:50,000 or 1:250,000). The objective is to identify metallogenic provinces out of an extremely large license area. The targets can be checked by limited test drilling. The explorer then moves to the prospecting stage using photogeology (1:25,000 or 1:50,000), supplemented by aerial geophysics to identify anomalies representing possible target(s) for systematic drilling. At this juncture thematic map generation is useful for prioritization of exploration targets. The prospecting activities lead to detailed exploration by detail mapping (1:10,000, 1:5000, 1:2,000), ground geochemistry, geophysics, and close space diamond or reverse circulation drilling to estimate the reserves and resources. The environmental baseline maps generated at the initiation of exploration can be useful and compared with the mine closure plan for environmental restoration of the ecosystem.
2. The remote sensing study of geomorphology reveals various types of land forms (tectonic, volcanic, fluvial, coastal and deltaic, aeolian, and glacial). The salient guides are predominantly surface indications like sustained weathering and erosion (residual and supergene enrichment), oxidation (gossans), remnants of ancient mining/smelting activities, drainage pattern (stream sediment sampling), placer deposits (diamond, gold,

ilmenite, and monazite) formed as a result of mechanical concentration of fluvial, aeolian, alluvial, eluvial, and marine processes. A long continuous belt of placer deposits around the east and west coast of India, Indonesia, and Australia are identified from remote sensing data.

3. The aerial and space base acquired data provide a completely new dimension to mineral exploration by integration of structural (rings, folds, faults, shear zones, and lineaments) data into a composite aerial view. These structures in many cases are the governing factors in localization of economic mineral deposits. The identification of rings, shear zones, and lineaments using RADARSAT images help to find areas with the probability of diamond pipe and base-metal mineralization. The final structure layer is prepared using visual interpretation and software processing.
4. The remote sensing data generate broad-scale litho maps, including mineral assemblages and formation of a stratigraphic succession model. Mineral deposits have a certain affinity to particular groups of host rocks, e.g., base metals with dolomite, calc-silicate and black schist, phosphorites with dolomite, iron with banded hematite quartzite, and coal with shale and sandstone. Similarly, some minerals are closely related to a certain stratigraphic age group, e.g., gold with Archean green schist horizon (>2500 Ma), coal with Permo-Carboniferous (248−360 Ma), and hydrocarbon with Cretaceous (65−144 Ma) ages. Some mineral deposits are preferentially confined to the genetic aspects of rock types, e.g., >60% of zinc-lead deposits is related to Proterozoic SEDEX type. The interpretation of remote sensing data serves as a useful guide during mineral exploration by identification of these critical features.
5. The dense vegetation masking the surface at remote locations may make mineral exploration difficult. Information collected from remote sensing platforms can reveal the reality below the ground. The relative geobotanical abnormalities in vast areas can be easily detected and mapped from aerial view. Two types of anomalies are common in the growth of vegetation. The morphological features include changes in the color of leaves and flowers, and dwarfing due to the toxic effect of metals in the soil. Taxonomic differences refer to relative abundance or absence of certain species.
6. The groundwater search requires identification of aquifers located a few meters to hundreds of meters from the surface. Surface features can be mapped by remote sensing leading to regional/local groundwater maps. Electromagnetic radiation and microwave can barely penetrate a few meters into the ground. This causes limitation of data acquisition and use of remote sensing as a direct guide for deep-seated groundwater exploration. Many of the surface features responsible for subsurface water conditions can be mapped by remote sensing leading to regional and local groundwater maps. The regional groundwater survey can be interpreted from a second-order indirect indicator, namely, landforms, rock types, soil moisture, rock fractures, drainage characteristics, and vegetation. The local exploration indicators are obtained from first-order direct signatures of recharge and discharge zone, soil moisture, and anomalous vegetations.
7. Hydrocarbons (oil and gas pools) exist kilometers below the surface and are confined to suitable stratigraphy and/or structural traps. Hydrocarbon exploration by multispectral remote sensing data acquisition depends on second-order indirect evidence like striking circular drainage anomalies, geobotanical and tonal anomalies due to seepage of underlying hydrocarbons, regional lineaments in oil-bearing regions, and films of oil slicks on ocean and sea water surfaces.

A remote sensing data interpreter has to rely on direct or indirect clues such as general stratigraphic setting, alteration and oxidation zones, favorable host rock assemblages, rings/folds/faults/shears/lineaments, morphology, drainage patterns, and effect on vegetation to guide the exploration rapidly. Alteration and structure along with other information layers, i.e., geo maps, geophysics, and geochemistry, are used to produce the primary exploration model in GIS. The best results are achieved by giving higher weights to the remote sensing layers. The quality of results is evaluated by field checking. Remote sensing interpretations are highly reliable in mineral exploration.

To conclude, mineral potential mapping is a systematic plan to collect, manage, and integrate various geospatial data from different sources and scales during multistage activity. GIS can describe, analyze, and interact to make predictions with models and provides support for decision makers.

3.4 GEOGRAPHIC INFORMATION SYSTEM

3.4.1 Definition

GIS is composed of three critical words.

Geographic refers to a known location of a primary database comprising observations of features, activities, or events defined in space as points, lines, or areas, and assay value, in terms of geographic coordinates (latitude, longitude, and elevation). The measuring units are either in degrees/minutes/seconds or the Universal Transverse Mercator (UTM) system. The various types of data are captured under a database management system (DBMS) or a relational database management system (RDBMS) in different layers.

Information means that the data are processed within GIS using high-speed powerful software tools for analysis of spatial data to yield useful knowledge, to make maps into dynamic objects and models, or as output when required by the user.

System implies a group of interacting, interrelated, or interdependent functions to reach the objectives of different users.

The sequence of activities in the GIS function is:

1. Data collection: measurement aspects of geographic phenomena and processes.
2. Storing: measurement stored in a digital database to emphasize spatial themes, entities, and relationships.
3. Retrieving: operate to create more measurements and discover new relationships by integrating.
4. Transformation: convert new representations to conform to uniform frameworks of entities and relationships.
5. Processing: a system for capture, storage, retrieval, analysis, and display.
6. Modeling: a system to store and maneuver geographic information.
7. Display: maps and reports.

GIS is a knowledge-based organized assemblage of hardware, software, geographic data, and professionals that capture, store, update, maneuver, analyze, and display all forms of geographically referenced information (Bonham-Carter et al., 1995; Sarkar, 2003).

3.4.2 Components of Geographic Information System

The main components of GIS involve five subsystems:

1. Hardware.
2. Software.
3. Geographic reference database.
4. Method.
5. People: professionals (multiusers from the same database).

The hardware component of GIS is the main input/output system and consists of computers or a central processing unit (CPU) for the storage of data and software. A high-capacity disk drive of the CPU is the storage unit for data and programs. The digitizer and scanner are attached for converting maps and documents into digital form. The output units consist of a monitor for online display a plotter, and a printer to see results as hard copy prints of maps, images, and other documents. The temporary and permanent storage devices are pen drive, compact disk, magnetic tape, and external disk.

The software is the key subsystem that includes the programs and interface for driving the hardware. It is responsible for total data management, storing, analyzing, maneuvering, and displaying the data or geographical information. Efficient, quality software must be user-friendly, compatible, well documented, and cost effective. There is much commercial software available, which can be tailor-made for specific uses. Some of the popular names are ArcInfo, ArcView, MapInfo, etc.

The data, or more precisely georeferenced data, are the most significant component of the GIS system. Data can be purchased from a commercial data provider or collected in-house and compiled to custom specification. The key functionality of GIS is integration of spatial and tabular data stored in standard formats of DBMS, RDBMS, and Structured Query Language (SQL).

The right method is significant for successful operation of GIS technology. A well-designed implementation plan with decision support and business rules is unique to each organization.

GIS technology cannot be useful without competent people. Specialists design the total system for a wide range of end users. The users belong to multidisciplines, e.g., computer science, agriculture, forest, town planning, industry, geology, etc. Each one can share a common database and generate results as required by them. The identification of specialists and end users is significant for proper implementation of GIS technology.

GIS is generally considered to be expensive and difficult to use. However, with the advent of new technology like graphical user interface and powerful and affordable hardware and software it is gaining ground and included in the mainstream.

A complete flow diagram of the GIS system is given in Fig. 3.8.

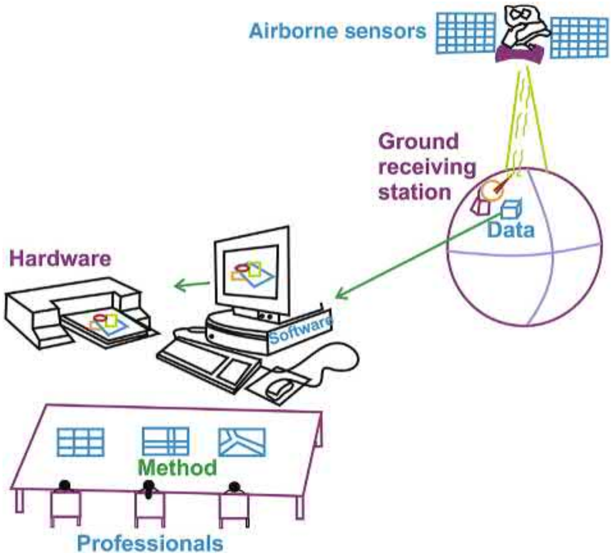

FIGURE 3.8 A typical functional aspect of geographical information system interfacing between major components from data collection to multiuser end results.

3.4.3 Capabilities

GIS has the capability of multiuser, multipurpose functions:

1. GIS is the high-tech equivalent of a quick and efficient map generator. It accesses and stores data in digital format and enables complex analysis and modeling.
2. It is capable of conducting the location analysis of various attributes stored at different layers, linking them to explain the causes and effects that yield results. The presence of surface weathering, topography, lithology, and structures at individual layers supported by geobotanical, geochemical, and geophysical evidences can lead to the discovery of massive hidden sulfide deposits/water bodies/oil and gas reservoirs.
3. It responds on query and displays results after satisfying certain spatial conditions. A well/drill site can be planned within a preset distance from a township by satisfying spatial conditions of possible aquifers, township, and existing pipeline.
4. It is capable of performing temporal analyses at time intervals over many years to derive relationships between changing land-use practices and future requirements.
5. It can evaluate different scenarios by applying sensitivity analysis and forecasting the best one. It can continuously monitor and revise decisions with changing assumptions and additional inputs.

3.4.4 Data Input

DBMS, RDBMS, and SQL software with error-checking facilities incorporate or import data from outside sources, and update and alter them if necessary. The data can be directly entered into the GIS platform manually or created outside in standard ASCII (American Standard Code for Information Interchange) files. GIS is also capable of importing data files that are created in other formats. GIS must provide the capability to export data to other systems in a common format (e.g., ASCII). Maneuvering the database to answer specific data-related questions is organized through a process known as database analysis. GIS must provide ways to modify, refine, revise, and update the database.

Two types of data are incorporated into GIS applications:

1. The first type consists of real-world phenomena and features that have some kind of spatial dimension such as a geological map (Fig. 3.9). These data elements are depicted mathematically in GIS as points, lines, or polygons that are referenced geographically or geocoded to some type of coordinate system. They are entered into GIS by devices like scanners, digitizers, Global Positioning System (GPS), air photographs, and satellite imagery.

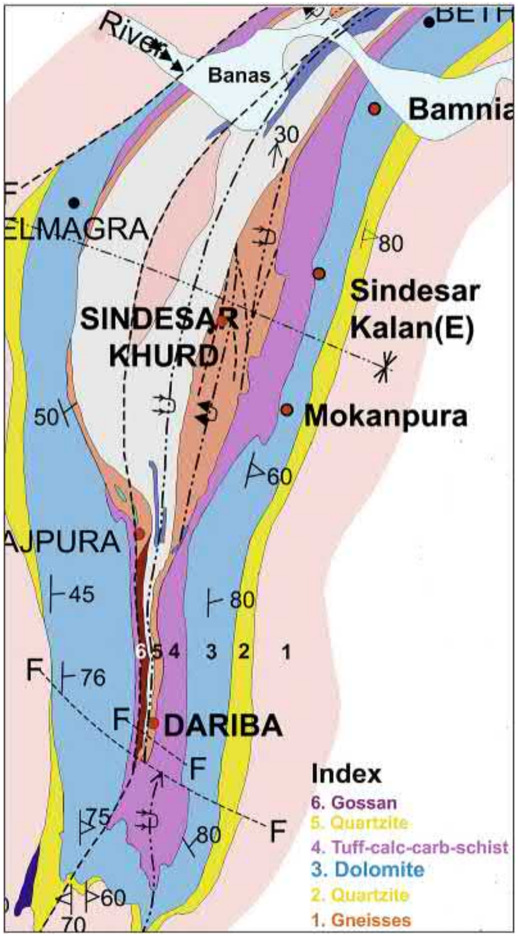

FIGURE 3.9 Data model of real-world phenomena and features having spatial dimension (e.g., geological map of Rajpura-Dariba base metal belt) usually incorporated into geographical information system (GIS) applications.

2. The second data type is often referred to as an attribute or point data such as soil profile. Attributes are pieces of data that are connected or related to the points, lines, and polygons mapped in GIS. This attribute data can be analyzed to determine patterns of importance. The attribute data are entered directly into a database where they are associated with element data. GIS uses one of the two primary types of spatial data, i.e., vector and raster, to represent the location component of the geographic information.

The vector data model is directional and represented by points, lines, and areas. Points are zero-dimensional objects (nodes) and represented by a single coordinate (x, y), e.g., sample, mine, house, city location. Lines are

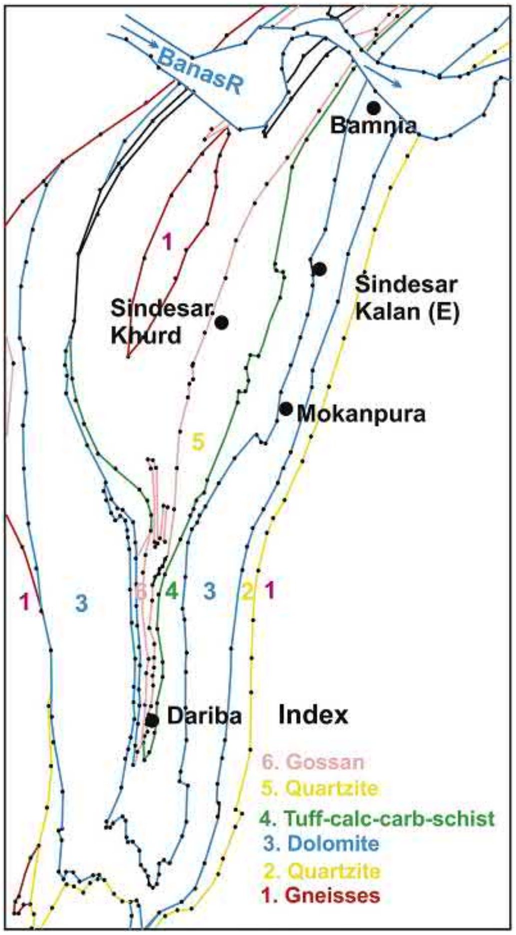

FIGURE 3.10 Data model by transformation of geographical phenomena of Rajpura-Dariba base metal belt into vector mode.

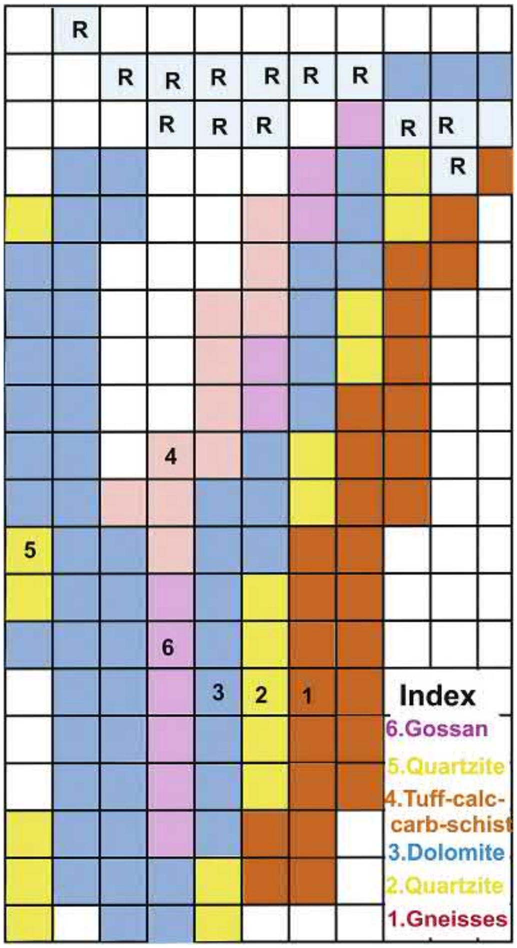

FIGURE 3.11 Data model by conversion of geological information of Rajpura-Dariba base metal belt to raster mode for geographical information system (GIS) applications in mineral exploration.

one-dimensional objects (line) and represented by a set of points or pair(s) of coordinates, e.g., roads, streams, faults, shears, lineaments, and drill hole paths. Polygons (2D areas representing dolomite or orebody) are bounded by a closed loop, joined by a set of line segments. 3D objects are embodied (x, y, z), where z is elevation, e.g., hills. The vector data model is particularly useful for representing discrete objects e.g., sample point, roads, streams, faults, and rock boundaries in the form of points, lines, and polygons, and stored as set of coordinates. The data in vector format are geometrically more precise and compact (Fig. 3.10).

The surface is divided into regular grids of cells represented by rows and columns or pixels of identical size and shape in the raster data model (Fig. 3.11). The location of geographic objects or conditions is defined by the coordinates of the cell position. Each cell indicates the type of object, class, category, measurement, condition, or an interpreted value that is found at that location over the entire cell. The smaller the cell size, the higher is the resolution with precision and detailed information. However, the data storage space will be enormous. On the contrary larger the cell size lesser data space will be required with approximate or less accurate information. In the case of a very coarse grid, several data types may occur in each cell, will be treated as homogeneous, and will generate inaccurate results during data analysis.

Merits and demerits between vector and raster data are modified after David (1997) and given in Table 3.3.

3.4.5 Projection and Registration

One often comes across maps of the same area containing different features (geology, geochemistry, and geophysics) and in different scale. GIS has the capability to maneuver the geocoded map information from different sources to common scale so that it can fit and register. Projection is a fundamental component of mapmaking in GIS. It is a mathematical function of transferring information from

TABLE 3.3 Salient Advantages and Disadvantages of Vector and Raster Data Models

Vector Data Model	Raster Data Model
Advantages	
Data storage at original georeferenced coordinates at higher spatial resolution, maintain and form without generalization	Geographic location of each cell is identified by its position in the cell matrix. Best resolution at smallest cell size
Graphic output is more accurate and realistic like cartographic representation	Data structure is simple and compact, storage in flat ASCII format for easy-to-use program and quick analysis
Most data, e.g., hard copy maps, are in vector form and no data conversion is required	Retrieval, updating, and generation of data. Grid-cell systems compatible with raster-based output devices—plotters and graphic terminals
Efficient encoding of topology and operations by network analysis	Topology can be completely described with network linkage
Data are less voluminous and technology is less expensive	Discrete data enable integrating two data types. Computational efficiency in overlay analysis
Disadvantages	
Location of each vertex needs to be stored unambiguously	Cell size decides resolution. The smaller the cell size, the more complex the data structure and the more expensive is the technology
Vector data conversion to topological structure is processing intensive and requires extensive data cleaning	Difficult to adequately represent linear features depending on the cell resolution. Network linkages are difficult to establish
Algorithms for analysis functions are complex, inherently limiting functionality for large data	Processing of associated attribute data is complex with a large volume of data
Elevation data are not effectively represented in vector form. Often require sizeable data generalization or interpolation of data layers	Most input data are in vector form and need conversion from vector to raster by escalating processing, generalization, and unsuitable cell size
Spatial analysis and filtering within polygons is not possible	Most output maps from grid-cell systems do not conform to high-quality cartographic needs

a 3D surface to fit in a 2D medium. The digital data may have to undergo other transformations like projection and coordinate conversions to integrate them into a GIS before they can be analyzed. This process inevitably distorts at least one of the following properties: shape, area, distance, or direction. Different projections are used for different types of map for specific uses. GIS has the processing power to transform digital information gathered from sources (digitized data, aerial photographs, satellite, and GPS) with different projections to a common frame.

3.4.6 Topology Building

Topology defines the mathematical representation of the spatial relationship between geographical features. It describes the relationships between connecting or adjacent coverage attributes. Topological relationships are built from simple elements into complex elements such as points (simplest elements), arcs (sets of connected points), and areas (sets of connected arcs). Three types of relationship exist in topology: connectivity, area definition, and contiguity. Storing connectivity makes coverage useful for modeling and tracing in linear networks. Storing information about area definition and contiguity makes it possible to merge adjacent polygons and to combine geographical features from different coverages with overlay operations.

3.4.7 Overlay Data Analysis and Modeling

Overlay analysis or spatial data analysis is a function in GIS applications to spatially analyze and interpolate multiple types of data streaming from a range of sources. Each type of data pertaining to the same area or similar objects is registered in vector or raster mode in individual files. New information can be created by overlaying or stacking (Fig. 3.12) of the related layers with common georeferences and analyzing through the GIS function. There are several different spatial overlays and manipulation operations to arrive at a specific model, which can be used on features of the user's interest.

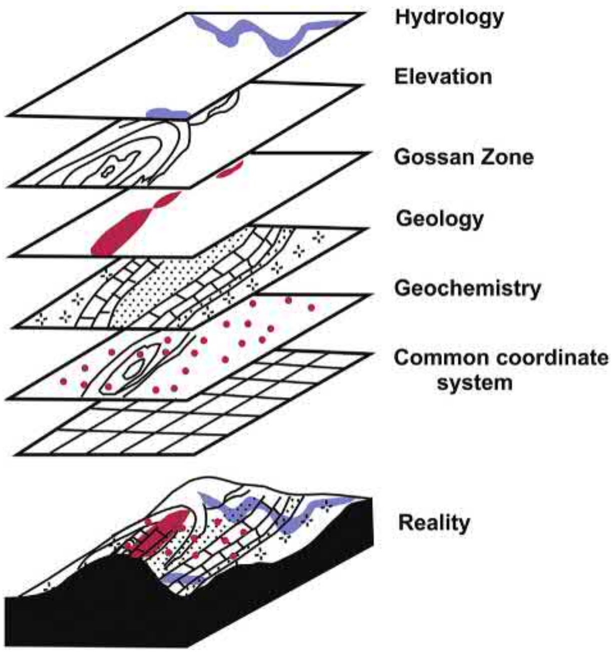

FIGURE 3.12 Concept of overlay analysis and integration of multilayer data of Rajpura-Dariba base metal belt for identifying drill targets: an example of geographical information system (GIS) application in mineral exploration.

3.4.7.1 Digital Evaluation Model, Digital Terrain Model, Terrain Evaluation Model, and Triangulated Irregular Network Model

The **digital evaluation model** (DEM) is a 3D representation of a surface topography using a raster or vector data structure. Any digital representation of a continuous surface of relief over space is known as DEM. It describes the elevation of any point in a given area in digital format. The **digital terrain model** or **terrain evaluation model** exhibits 3D spatial distribution of terrain attributes. It is a topographic map in digital format, consisting not only of a DEM but also types of land use, settlements, drainage, road networks and related features. The **triangulated irregular network** is a 3D surface model derived from irregularly spaced points and break line features. The basic unit is a triangle consisting of three lines connecting three nodes. Each triangle will have three neighbors except the outer periphery. Each node has an x, y coordinate and a z value or surface value. These models are created by digitizing contour maps along with point, line, and polygon data of related objects followed by vector-to-raster conversion and interpolation to derive the desired results. These are useful for road and rail line and dam site planning, reservoir capacity estimation, identifying ridge lines and valleys, visibility studies, and cut and filling problems.

3.4.7.2 Mineral Exploration Model

Overlay analysis is useful in mineral exploration for identifying targets. The example in Fig. 3.9 contains conceptual data from a range of source maps of Rajpura-Dariba base metal belt, Rajasthan, India. The files contain hydrology, elevation, surface signature, geology, and geochemistry. All source data have been geocoded and registered on a cell-by-cell basis from a series of land data files in individual layers. The analyst module of GIS manipulates and overlays simultaneously the information derived from various data files. The analyst uses the system to interrelate the geocoded source data files. The interpreted result is expected to define the target area for exploration of possible sulfide deposits. The example is a concept-based model attempting to generate thematic maps. The addition of remote sensing electromagnetic data and surface geophysics will certainly strengthen the model to forecast exploration targets.

3.4.8 Geographic Information System Application in Mineral Exploration

The applications of GIS in mineral exploration are widely used internationally. The GIS platform allows establishing a mineral deposit database for a region or country by integration of all available geoscientific data (even dissimilar) into a digital single and unified database. The recommended approach is to compile all of the available geoscientific data within GIS in the context of an exploration model. It will produce a brief report and mineral potential maps of a province, region, district, belt, deposit, and block. Careful consideration must be given to developing the model so that all of the relevant aspects of the deposit being sought are represented. The model is important in deciding the logical weight to apply by a geologist having adequate knowledge of the model and the deposit related to each of these aspects. The final map indicates the ranks and priority for exploration targets in the study area.

An extension of the GIS database is incorporation of exploration data consisting of deposit name, location, infrastructure available, parks and reserve forests, historic and current exploration details, drill hole location, summary logs, drill sample assay value, geochemistry, electromagnetic and gravity images, mineral occurrences, reserve and resource detail, and lease status like reconnaissance permit/prospecting license/mining lease. This mineral resource information system acts as an exploration guide to new targets and decision bases for free areas. It will be in SQL base system so that investors can design their objectives and search online for desired results.

3.5 GLOBAL POSITIONING SYSTEM

GPS is a universal satellite-based navigation system developed, replaced, monitored, and maintained by the US Department of Defense originally for military applications. Its official name was Navigation Satellite Timing and Ranging. The first global positioning space vehicle was launched in 1978. Total network satellite launching was completed in 1994 and the system became fully operational in 1995. Since then the system has been available for civilian use and works worldwide under any weather conditions, 24 h a day without paying any routine subscription or setup charges. The total number of satellites in the constellation today is 60 (16 for civilian use and the remaining for military use and spares). A GPS satellite weighs about 1000 kg. Precision for civilian use is in the centimeter scale and that for military purposes is in the millimeter scale. GPS consists of three major segments (Fig. 3.13). These are space segment, ground control segment, and user segment.

3.5.1 Space Segment

The space segment originally comprised 24 orbiting satellites (21 active and 3 spares), in six circular orbital planes with four satellites in each plane. The orbital planes are centered on Earth and have 55 degrees inclination relative to Earth's equatorial plane. The planes are equally spaced, separated 60 degrees apart along the equator from a reference point to the orbit's intersection. The satellites are orbiting at an altitude of approximately 20,200 km. Each satellite makes two complete orbits each day, i.e., a complete rotation around Earth in 12 h. The orbits are so arranged that at least six satellites are always within line of sight from almost anywhere on Earth's surface.

3.5.2 Ground Control Segment

The flight paths of the satellites are tracked by the ground control segment located at various monitoring stations of respective participative countries. In the event of any deviation of the space vehicle from its designed orbit the ground control station transmits the tracking information to the master control station. The master control station in turn uploads orbital and clock data to each GPS satellite regularly with a navigational update using ground antennas. These updates synchronize the atomic clocks on board the satellites within a few nanoseconds of each other.

3.5.3 User Segment

The user segment uses various types of receivers to compute the coordinates (X, Y), elevation (Z), velocity, and time estimates. GPS receivers are composed of an antenna tuned to the frequencies transmitted by the satellites, receiver-processors, and a highly stable atomic clock. The receiver computes its position and time by making simultaneous measurements to a number of satellites. A 2D position, i.e., latitude and longitude, can be computed by the signals of three satellites. Signals from at least four satellites are required for determination of 3D location, including elevation and clock bias. The receiver displays information comprised of a number of visible satellites, location, and speed to the user. The location works on both

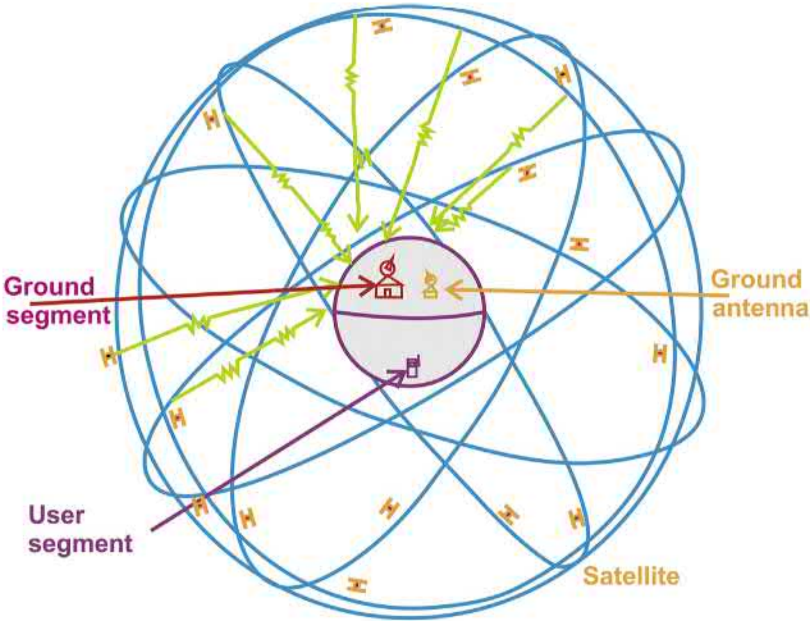

FIGURE 3.13 Conceptual overview of constellation of Global Positioning System (GPS) satellites in space, ground control, and user segments.

longitude and latitude, i.e., degrees/minutes/seconds, and UTM in a metric grid system. There are 60 zones to cover the entire Earth's surface. The receivers can include an input for differential corrections and relay position data to a computer. They can interface with other devices using different methods, including a serial connection, USB, or Bluetooth.

3.5.4 Signals

GPS satellites transmit low-power time-coded radio signals of 1575.42 MHz frequency in the UHF band. Signals travel by line of sight through semitransparent medium, but not through solids, metals, and electromagnetic fields, and are recorded by ground GPS receivers. The sources of error and interference of signal transmission include ionosphere and troposphere delay, signal multipath, clock, orbital, number of visible satellites, satellite geometry and shading, and international degradation of signals.

3.5.5 Types of Global Positioning System

The types of GPS receiver can be broadly classified on the basis of accuracy required and associated cost of the unit.

3.5.5.1 Handheld Global Positioning System

The handheld GPS is the simplest, cheapest, and easiest unit, consisting of a single receiver (Fig. 3.14). The technology is simple and reasonably accurate. The location position, computed from the signals, can be distorted by 10−30 m. Most mobile cell phones provide the name of locations and road maps, and show directions to destinations with precise distances in meters while traveling by receiving signals from local antenna.

FIGURE 3.14 Hand-held Geographical Positioning System (GARMIN GPSMAP 64s) capable of measuring 3D coordinate system and trace the traverse path, rock contacts, structural features, and many more. *Courtesy Prof. Sayad Rahaman.*

3.5.5.2 Differential Code Phase Global Positioning System

GPS measurements are prone to multiple errors on account of uncertainties in satellite ephemeris, atmospheric condition, quality of receiver, and multipath situation. The differential GPS works on simultaneous measurements by receivers at a reference station with precisely known location, clock time, and number of roving receivers moving from point to point. The positional introduced noises measured at the base station are used to compensate instantly the position measured by the rovers to attain greater accuracy. The base station may be a ground base facility or a geosynchronous satellite. In either case, the base station is known with precise location value. This known value can be compared with the signals received from GPS satellites and thus can find the international error introduced by each GPS signal. The correction can be immediately transmitted to the mobile GPS receivers (real-time Differential Global Positioning System [DGPS]) to compute a much more accurate position. The receiver position can also be corrected at a later time during processing by GPS software. The use of DGPS can greatly increase positional accuracy within 1 m.

3.5.5.3 Carrier Phase Tracking Global Positioning System

Carrier phase tracking GPS signals have resulted in the development of land surveying, geological mapping, and as a guide to reach the target destination. The positions can be measured up to a distance of 30 km from a reference location without any intermediate point. A small handheld unit allows positions and traverse routes to be downloaded to GIS software for geological mapping. A small unit can store more than 300 sample positions and tens of routes.

3.5.5.4 Electronic Total Station

An electronic total station (ETS) is an electronic/optical instrument used in modern all-purpose surveying. The total station is an electronic theodolite (total station theodolite) integrated with an electronic distance meter to read slope distances from the instrument to a particular spatial entity. Some models include internal electronic data storage to record surveyed points (x—northing, y—easting, and z—elevation), distance and horizontal and vertical angles. The data can be downloaded from the total station to a computer. The application software is used to process results and generate maps of the surveyed area.

A total station is used to record the absolute location, geological contacts (maps), results of geological, geochemical, and geophysical surveys, borehole program, and even underground working layouts and stopes. The recorded data are downloaded onto a computer, processed and compared to the designed layout. Control survey stations at regular intervals are installed underground to facilitate survey by ETS.

3.5.6 Global Positioning System Applications

GPS systems are versatile and widely used for military and civilian purposes, including mineral exploration. The common uses are:

1. GPS systems operate both for airborne, and ground base.
2. Applications in ground-based mineral exploration include vehicle and route tracking, instant and precise location (latitude, longitude, and altitude) on land and sea during field traverses, geological mapping, and checking litho contacts, structures, surface samples, and borehole collar location. GPS provides precise time references, including the scientific study of earthquakes and as a required time synchronization method for cellular network protocols.
3. Civilian uses are land surveying, land-use pattern, forest mapping, drainage, helping farmers harvest their fields, and a time synchronization method for cellular network protocols. The areas of interests are weather forecasting, aviation, and road/rail/shipping transport.
4. The military applications of GPS have many purposes like reconnaissance and route map creation, navigation of soldiers to locate them in darkness or in unfamiliar territory, and to coordinate the movement of troops and supplies. GPS helps in missile and projectile guidance for accurate targeting of various military weapons. GPS satellites also carry a set of nuclear detonation detectors consisting of an optical, X-ray, and electromagnetic pulse sensor. This forms a major portion of the US Nuclear Detonation Detection System.

3.6 SOFTWARE IN REMOTE SENSING GEOGRAPHICAL INFORMATION SYSTEM

RS-GIS technology captures basic electromagnetic radiance data of 3D georeferenced satellite images in WGS84 UTM 36N and 37N coordinates. These coordinates and attributes include multidisciplinary activities by multiend users. The data input is in RDBMS/DBMS format for combined procession by commercial software to generate 2D/3D models and hard copies.

The software modules represent total interface system, and are responsible for generating, storing, analyzing, maneuvering, and displaying results. The strength of the software is to maintain user friendliness, compatibilities, documentation, and to be cost effective. Mineral exploration and mining companies use RS-GIS to identify prospective areas for exploration, 3D orebody models, mining, infrastructure layout, and environmental management. Exploration and mining continues with estimation of reserves and resources with precision. The progress of GIS into three dimensions is a revolutionary change for the utility of technology in mineral exploration.

Available commercial GIS software is listed without any discrimination of superiority.

3.6.1 ArcGIS

ArcGIS is a group of GIS software developed by the Environmental Systems Research Institutes. It has two main modules: ArcInfo (Arc and Info) and MapInfo (Map and Info). Arc/Map means graphical entities and Info means attributes.

ArcGIS is a high-performance, dynamic software family that produces significantly better-looking accurate maps in the shortest time. It provides a review and responds to errors. It can preview documents, estimate rendering time, save to a map service definition format, and combine layers (referencing feature or raster data) into a single layer package comprising both layer file and data. It has the facility to share layers with itself and global groups via online ArcGIS or email. The main components of ArcGIS are ArcInfo, ArcView, and ArcReader.

ArcInfo is a comprehensive GIS within the ArcGIS family. It also adds advanced geoprocessing and data conversion functionality. ArcInfo builds and manages a complete intelligent GIS, including maps, data, metadata, geo-datasets, and workflow models. The key features include advanced spatial analysis, extensive database, multiuser editing, and high-end cartography in an exploration program.

ArcView is a fully featured GIS for visualizing, analyzing, and creating data with a geographic component. It consists of address, postcode, GPS location, city, local government area, etc. ArcView visualizes, explores, and analyses data, revealing patterns, relationships, and trends.

ArcReader is a simple desktop mapping application. It allows the viewing, exploring, and printing of maps, and possesses interactive mapping capabilities by accessing a wide variety of dynamic geographic information and viewing high-quality maps.

3.6.2 AutoCAD

AutoCAD Map, patented by Autodesk, is a powerful drafting tool used widely for engineering drawings with accuracy and 3D viewing. It works on 2D and 3D coordinate systems. It is user-friendly and available at a reasonable cost. It is extensively used by geologists for the preparation of maps, subsurface plans, and sections for estimation of resources and reserves by conventional methods.

3.6.3 IDRISI

IDRISI is an integrated GIS and image processing software solution developed by Clark Labs. It provides many modules for the analysis and display of digital spatial information. Land Change Modular provides land cover change analysis and prediction with tools to analyze, measure, and project the impacts of changes on habitat and biodiversity. It involves a set of feasible alternatives for multiple criteria group decision-making problems.

3.6.4 Integrated Land and Water Information System

Integrated Land and Water Information System (ILWIS) is developed by the International Institute for Aerospace Survey and Earth Sciences in the Netherlands. It is RS-GIS software for both vector and raster processing. The main features include digitizing, editing, analysis, and display of data, as well as production of quality maps.

3.6.5 MapInfo

MapInfo, developed by MapInfo Corporation, is a natural resources solution for mineral exploration, mining, engineering, infrastructure, and environment. MapInfo Vertical Mapper module has a wide range of analysis tools to reveal trends in datasets. It has unique prediction capabilities to specify a test location and identify areas with statistically similar attributes. The software executes 3D orebody modeling and estimation by all standard interpolation principles from existing point files or tables, regardless of data type. It performs triangulated irregular network with smoothing, inverse-weighted distance function, natural neighbor and rectangular (bilinear) interpolation, kriging, and custom point estimation. The advance module includes modeling options by overlaying multiple layers and applying a mathematical function, calculating steepness of slopes or the direction the slopes are facing in a grid, showing cross-sections, and displaying a 3D perspective view of the terrain with optional overlay of imagery and natural neighbor analysis.

3.6.6 Micro Station

Micro Station, developed by Bentley Systems, is an easy to access, powerful, and interoperable 3D CAD software platform for design, construction, operation, and dynamic viewing.

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Chapter 4

Exploration Geology

Chapter Outline

> *One discovery out of 100 or even 1000 attempts will pay back all the effort.*
>
> Author.

4.1 DEFINITION

Mineral exploration is a complete sequence of activities. It ranges between searching for a new mineral prospect (reconnaissance) and evaluation of the property for economic mining (feasibility study). It also includes augmentation of additional ore reserves and resources in the mine and total mining district. Various exploration techniques have been followed over the centuries. Exploration is conducted by one or a combination of multiple available global techniques and depends on the demand of the commodity being searched for, convenience of infrastructures, funds from the exploration institution, size and complexity of the deposit, price of end products, government policy, good will, and tax and royalty structures. Programs include multidisciplinary data generation in sequence. In addition to technical inputs, activities encompass collection of information about the infrastructure around the area, such as accessibility (road, rail, nearest rail-head, airport, and sea port), average rainfall, availability of potable and industrial water, power grid and supply system, local community, living conditions, health care, security, forests, and environmental issues. Background information about agencies from federal and state/regional/provincial governments and the public and private sectors, including multinational companies engaged in any mineral exploration program in the area, will be beneficial.

4.2 REGIONAL PLANNING AND ORGANIZATION

Perspective regional planning, involving resource development of all minerals for the nation as a whole and state/province in particular, is a continuous process. A multidisciplinary and multidimensional expert group from federal administrative services, technocrats, economists, statisticians, environmentalists, and human resource authorities collect information about past trends of consumption/supply, import/export, and strategic importance of the various mineral

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00004-6

commodities in a country from a global perspective. The trend of demand/supply is projected for future needs with respect to population growth to generate optimum resources for sustainable use of individual minerals (refer to Fig. 1.1). Activities are identified and responsibilities earmarked to respective organizations/institutions along with allocation of budgeting and funds. Governments continue routine monitoring, reconciliation, and corrective measures at appropriate stages. The following are key implementing organizations/agencies.

4.2.1 Bureau of Mines

The prime role of the Bureau of Mines is to create and maintain an up-to-date onshore and offshore mineral database, promote scientific development, encourage sustainable conservation, and protect the environment in mineral industries. The Bureau of Mines is responsible for the approval of mining plans and the regulatory inspecting authority is responsible for mining and environment management plans to ensure minimal adverse impact on the environment. The Bureau of Mines publishes a *Minerals Yearbook* every year highlighting total mineral-related statistics; this is disseminated free online and in printed form at a cost. The various institutions are the United States Bureau of Mines (USBM), Department of Mines and Petroleum (DMP), Australia, Bureau of Mines, Canada, Bureau of Mines, Chile, and Indian Bureau of Mines (IBM).

USBM was established in 1910 as a primary government agency with a mission to conduct scientific research to enhance mineral resources, safety, health care, and environmental impact, and disseminate information on mining, processing, extraction, use, and sustainable conservation of minerals. Since inception USBM was viewed as the nodal point for new and emerging science and technology in the mineral sector, both nationally and internationally. The government closed USBM during 1995–96 and merged certain functions with other interrelated federal agencies. The *Minerals Yearbook* of USBM is a cost-free pioneering effort for the collection, analysis, and dissemination of information about mining and processing of more than 100 mineral commodities across the nation and in more than 185 countries around the world.

DMP, Australia, ensures a stronger focus on the resources sector, maintaining a mining and petroleum regulatory role incorporating the safety and responsibilities of resources. DMP processes and provides an efficient and timely approval of mining title, which is essential for guaranteeing the sustainability of the resources sector and future prosperity of the states.

The Bureau of Mines in Chile is the major support for the national economy. Copper export alone contributes ~40% to the government exchequer.

IBM, established in 1948, is a multidisciplinary national organization with headquarters in Nagpur and several regional/district offices. It is responsible for mineral policy planning, conservation, and mining research. IBM is the custodian of total mineral statistics for the government of India. The functions of IBM include promoting conservation of mineral resources by way of inspection of mines, geological studies, scrutiny and approval of mining plans and schemes, conducting environmental audits, evolving technologies for mineral beneficiation, preparation of feasibility reports for mining and beneficiation projects, preparation of mineral maps and the National Mineral Inventory of mineral resources, providing technical consultancy services to the mineral industry, maintaining a data bank for mines and minerals, and preparing technical and statistical publications. IBM compiles and publishes a *Minerals Yearbook* covering statistics of total exploration, geological reports, mine production, export and import, price trends, and related matters of all minerals. It maintains a database of all reconnaissance permits, prospecting licenses, and mining leases in the country, available at a price. IBM has six technical divisions within its headquarters at Nagpur supported by a Modern Mineral Processing Laboratory and Pilot Plant. It has three zonal offices, 12 regional offices and two subregional offices, two regional ore-dressing laboratories, and pilot plants spread across the country.

4.2.2 Geological Survey

The Geological Survey is the national geoscientific and academic institution responsible for specialized multi-thematic mapping of the entire country, to develop basic research in earth science and to target new mineral discoveries that include water and energy resources to meet the demands of growing populations. The other functions are assessment of earth science-related environmental impacts and geological hazards like landslide, earthquake, flood, coastal zone instability, and desertification. It creates and updates a geoscientific database, reports, and maps for dissemination to government departments, user agencies, and individuals free or at cost as the case may be. There are several national geological institutions, namely, the United States Geological Survey (USGS), Geological Survey of Australia, Geological Survey of Canada (GSC), National Service of Geology and Mining, Chile, and Geological Survey of India (GSI).

USGS was established in 1879 as a scientific government agency. USGS headquarters is in Reston, Virginia, with major offices at Lakewood, Colorado (Denver Federal Center), and Menlo Park, California. The primary mission was to study landscapes, topographic mapping, natural resources, earthquakes and volcanic hazards, geomagnetism programs, and related matters. USGS has prepared

Geological Quadrangle Map, Geophysical Investigations Map, Hydrologic Investigations Atlas, Land Use and Land Cover Map, and Mineral Investigations Resource Map. The organization has four major science disciplines comprising biology, geography, geology, and hydrology. USGS is a fact-finding research organization with no regulatory responsibility.

The Geological Survey of Western Australia (GSWA) is a division within the DMP. Since 1880, the function of GSWA is to collect and synthesize information on a state's geology, exploration, and mineral/petroleum resources. GSWA publishes reports, maps, and a state-of-the-art database documenting all information to enable building blocks to design exploration programs. Reports, maps, and geographical information system data on geology, geophysics, geochemistry, geochronology, mineral exploration, resources, and reports of exploration companies can be downloaded free of charge from the Western Australia Mineral Exploration report system. Mineral deposit and mine information are available from Mines and mineral deposits. The department is critical of government decision making, particularly on economic and land-use issues. Every state, region, or province in Australia functions in a way suitable to that state, region, or province.

The Geological Survey of South Australia (GSSA) is an authority within the Department of State Development of the Government of South Australia, and is responsible for surveying and exploration of South Australia's geological resources. GSSA continues to discover new data, new insights, and new opportunities. GSSA collect, manage and deliver information, and knowledge of South Australia's geology, particularly for its mineral resources prospectively.

GSC was established in 1842. It is part of the Earth Science Sector of Natural Resources Canada. GSC is the premier agency for geoscientific information and research, with world-class expertise focusing on geoscience surveys, sustainable development of Canada's resources, environmental protection, and technology innovation.

GSI was established in 1851, with central headquarters at Kolkata and six regional offices and six training institutes. The regional offices are located at Kolkata (eastern), Shillong (northeastern), Hyderabad (southern), Lucknow (northern), Jaipur (western), and Nagpur (central). The Airborne Mineral Surveys & Exploration wing is located at Hyderabad. GSI is a premier institution imparting advanced training in earth science, photogeology, remote sensing, geophysics, and geochemistry, and is a center for geoinformation. GSI prepares and updates geological, geophysical, and geochemical maps, explores and assesses mineral and energy resources both onshore and offshore, develops and maintains national drill core libraries, performs research, and promotes the application of new knowledge. It creates and maintains an earth science database, acts as a national repository of data generated by various organizations, and disseminates to the public domain. It maintains national geological monuments, museums, and geological parks.

The Survey of India (SOI) was established in 1767 with its headquarters at Dehradun, Uttarakhand. The principal responsibilities of SOI are geodetic control (horizontal and vertical), geodetic and geophysical survey, topographical control, surveys, and mapping within India, mapping and production of geographical maps and aeronautical charts, and surveys for developmental projects. The organization prepares toposheets at 1:250,000, 1:50,000, and 1:25,000 scales for the entire country. The survey sheets, which are not of strategic importance (restricted), can be purchased by anybody from the SOI offices located at all state capitals. The restricted toposheets can be obtained by special permission of authorized central and state administrative officials and/or the Ministry of Defense.

4.2.3 State/Regional Department of Mines and Geology

The state/regional/provincial Department of Mines and Geology (DMG), located all over the world, is responsible for limited mineral exploration, granting of reconnaissance permits, prospecting licenses, and mining leases with approval/consent of the federal government, and the inspection and collection of royalties from various mining units.

4.2.4 Exploration Agencies: Public, Private, and Multinationals

The federal Geological Survey and state/regional DMG hold initial exploration maps to identify broad-based mineral provinces in a country. These maps are available at no/little cost for a selection of detailed exploration under a prospecting lease. The government/public sectors may continue detailed exploration and the results are available at cost for mining tenements.

Mineral exploration from reconnaissance to mine feasibility is also conducted by private sector companies within a country. These companies may continue processing/mining/smelting as a captive mine or sell explored property at any stage to a third party. The private companies are Osisko Mining, Argentina, Goldstream Mining NL and IMX Resources Ltd., Australia, Red Back Mining, Canada, Wesizwe Platinum, South Africa, Venturex Resources Ltd. and Vale, Zambia, ACC Ltd., Binani Zinc Ltd., Birla Corporation Ltd., Ferro Alloys Corp. Ltd., Sesa Goa Ltd., Tata Steel Ltd., and Vedanta Resources PLC, India.

The concept of globalization by open market policy gave way to a radical opportunity to multinational limited companies or multinational companies (MNC) worldwide. Any MNC registered in the host country, individually or as joint venture partner, is allowed to explore and mine all nonstrategic minerals with 100% foreign direct investment. The participation of MNC in the mineral sector has far-reaching effects and benefits to the receiving country by way of readily available, specialized, experienced, skilled technocrats and advanced technology. Multinational exploration companies are global players equipped for specific groups of minerals such as iron-ore-aluminum, copper-zinc-lead, platinum-nickel-chromium, gold, diamond, oil and gas, and coal-lignite-coalbed methane (CBM). Global MNC include Anglo American PLC (London), Rio Tinto Group (London), Vedanta Resource PLC (London), BHP Billiton Ltd. (Melbourne), CSR Limited (Sydney), Cameco Uranium (Canada), Goldcorp and De Beers (Johannesburg), Exeter Resource Corporation (Canada), Codelco Mining Corporation and Capstone Mining Corporation (Chile).

4.3 SURFACE GUIDE

Most mineral deposits display surface signatures like favorable stratigraphy and host rocks, surface weathering profile of metallic and nonmetallic mineralization, shear zone, lineaments, and the presence of earlier mining and smelting remnants that can be identified by experienced eyes. If these features are recorded during geological traverses in the field followed by exploration, a new deposit is likely to be discovered.

4.3.1 Favorable Stratigraphy and Host Rocks

The existence and identification of favorable stratigraphy and complementary host rocks are the essential prerequisites to initiate any exploration program for a specific mineral or group of minerals. Geological maps are available from Geological Survey, Bureau of Mines, or DMG. These can be downloaded free of charge or purchased at a small price. The layered ultramafic/mafic assemblage of the Archaean/Proterozoic age is the most suitable target for chromium-nickel-platinum-copper and gold association (e.g., Bushveld chromium-platinum in South Africa, Sudbury nickel-platinum in Canada, Stillwater palladium-platinum-chromium in the United States, Great Dyke platinum-chromium in Zimbabwe, and Sukinda-Nausahi chromium in India).

4.3.2 Weathering

The weathering and leaching of near-surface metallic deposits is an indicator of the likely existence of mineral deposits at depth. This has been described in detail at Sections 5.5.2.1−5.5.2.5 and (Figs. 5.4−5.12). Gossans above Broken Hill zinc-lead-silver deposit in Australia, Adi Nefas zinc-copper-gold-silver deposit, Madagascar, Rajpura-Dariba and Rampura-Agucha zinc-lead-silver deposit and Khetri copper deposit, India, are the best and most significant surface signature for a base-metal exploration guide. All these deposits have large reserves and resources with high metal grades after exploration, and have contributed to substantial annual production since their discovery.

4.3.3 Ancient Mining and Smelting

The copper, zinc, lead, gold, and silver deposits of the princely states of India, the Early Dynastic Period of Turkey, Israel, Iran, Iraq, Cyprus, Egypt, Saudi Arabia, North America, Spain, and Russia were discovered more than 3000 years ago. The ancient gold mines in Egypt are guiding modern miners toward a vast amount of mineral deposits, worth hundreds of billions of dollars. These deposits offer much information regarding ancient mining, processing, smelting, and usages of metals and became a guiding force for present-day exploration.

Ancient mining and smelting have been reported and supported by radiocarbon dating of woods from the Indus Valley (3000 BC for gold mining), along Lake Superior, North America (3000 BC for copper mining), Egypt (2613 and 2494 BC for Cu and gold mining), India (3000 BC for copper, 1400 BC for iron, 1000−100 BC for zinc-lead-silver mining), and Spain (AD 25 for gold mining). One can find ancient mine debris around open pits with wooden wall supports, entry systems to shallow and greater depths for underground mining, abandoned underground galleries with wooden ladders and platforms, in situ potholes, rock grinders at the surface for ore dressing, smelting furnaces, enormous heaps of slag and retorts reused for wall making, ruined places of worship, and deserted townships in and around the ancient mine-smelting sites. This evidence easily suggests the existence of rich ore deposits, and is a guide to modern-day exploration for depth and strike continuity in the region.

The remnants of ancient mines play a significant role in mineral exploration. The important surface signatures are the presence of fresh mineralized veins, gossans, and ancient open pits with wall supports as observed at East Lode of the Rajpura-Dariba mine, India. The miners follow the downward extension along the dip and pitch of narrow ore shoots making vertical or inclined entry (Fig. 4.1).The excavations are generally carried by fire setting and sudden cooling by water to create cracks in the ground. The entry system can be of multiple in nature in case of large exposed orebody and extends over great depth (Fig. 4.2).

Miners developed huge stopes and underground chambers within the rich part of mineralization. They

FIGURE 4.1 Ancient entry system to underground mine at shallow depth of orebody without any plunge during the 3rd–2nd millennium BC at Khetri copper belt, Rajasthan, India.

FIGURE 4.3 Ancient underground mining in rich zinc orebody at a depth of 172 m from the surface. Arching of the stope chamber shows high engineering skill. The wooden ladder (*left*) and platform (*right*) are still at an abandoned work site. Radiocarbon age dating indicates 3000 years from now at Rajpura-Dariba Mines, India.

demonstrated competent skills of engineering by making pillars with arches, and using wooden ladders and platforms, wooden launders for underground drainage, timber supports to prevent roof collapse, and clay lamps for mine illumination (Fig. 4.3).

The presence of small pits on the surface near to smelting sites and vast heaps of crushed debris near the mine opening indicate that zinc ore is crushed and richer fragments are handpicked and ground before smelting. Potholes of 30 cm diameter and 60–70 cm deep with rounded bottoms in hard calc-silicate outcrops are observed at Rajpura-Dariba, north of East Lode, India (Fig. 4.4).

The ancient zinc-smelting process was resolved through distillation and condensation technology (pyrometallurgy) of zinc ore using moderately refractory clay retorts. Archaeometallurgical excavation at Zawar discovered intact ancient zinc distillation furnaces containing their full spent charge of 36 retorts (Fig. 4.5). Each furnace is 60 cm in height and divided in two parts: a lower condensing chamber, separated by a perforated plate from the upper

FIGURE 4.2 Ancient entry system to underground mine at greater depth with orebody plunge to northeast at Rajpura-Dariba copper-zinc-lead-silver mine, India.

FIGURE 4.4 Ancient potholes at the surface used for crushing, grinding, and concentration of rich zinc ore are still preserved at Rajpura-Dariba Mines, India.

FIGURE 4.5 Ancient smelting furnace unearthed with 6 × 6 numbers of retorts placed in an inverted position for distillation of zinc by a heating and condensation process at Zawar Mines, India, during 2180 ± 35 years from today.

FIGURE 4.6 Ancient cylindrical distillation clay retorts from the smelting site at Zawar Mines area, India.

FIGURE 4.7 Ancient smelting retorts reused for the walls of a living shelter in the mining township at Zawar, India.

main furnace of the distillation chamber. Smelting was carried out at 1100–1200°C for 4–6 h. This site is recognized and preserved by the American Society of Metals as International Zinc Smelting Heritage in 1988.

A complete retort is cylindrical in shape with tappers at one end (Fig. 4.6), and fitted with an extended cylindrical hollow tube for channeling distilled hot zinc vapor from retorts in the upper chamber, which is condensed in the lower cooling chamber. The condensed zinc metal is dropped into a collecting pot. The exhausted retorts are either dumped or reused for making walls of hutments for the mining community (Fig. 4.7) in the township.

There is ample evidence of antique mining and smelting history as seen at the old deserted, ruined industrial township in the valley area of Zawar Mines, India. The presence of an abandoned mine entry system in the surrounding hills, clay and sand-covered intact smelting furnaces, parts of broken-down residential walls, and Hindu temples (Fig. 4.8) of the 13th century AD in the center of ancient zinc-smelting site were discovered. Some of these historical monuments are maintained by the Indian Archeology Department.

In 1988 the ancient mining/smelting village around the old Zawar area was recognized by the American Society of Metals (ASM International) with the installing of a plaque as accreditation of the oldest zinc-smelting site (180 ± 35 BC) in the world (Figs. 4.8, 4.9, and 4.11).

4.3.4 Shear

The shear zone is the result of a huge volume of rock deformation due to intense regional stress, typically in the zones of subduction at depths down to a few kilometers. It may occur at the edges of tectonic blocks, forming discontinuities that mark a distinct structure. The shear zones often host orebodies as a result of syngenetic or epigenetic hydrothermal flow through orogenic belts. The rocks are commonly metasomatized and often display retrograde metamorphism assemblage. An intense fractured or shear zone is a favorable structure to trap mineralization (Banerjee and Ghosh, 1997). The Hyde-Macraes Shear Zone, New Zealand, is a low-angle thrust system in which gold-bearing quartz veins have been deposited. The copper sulfide vein-type mineralization associated with migmatization in the southeastern part of Singhbhum Shear Zone, Jharkhand, India, is an example of shear-controlled copper-uranium mineralization.

4.3.5 Lineament

In general, mineral deposits occur in groups and follow a linear pattern along the fold axis, shear zone, and basement fracture traps (Roy, 2010). The linear alignment can be traced in a regional map of Aravalli Mountain, India, and McArthur-Mt. Isa province, Australia. Lineament mapping of different terrains using remote sensing images is capable of guiding groundwater flow. Analysis of surface lineament with the help of geoinformatics became significant in oil and

FIGURE 4.8 Ancient 13th century AD Hindu temple in the center of the ancient zinc-smelting site at Zawar Mines area, India.

FIGURE 4.9 In 1988 the ancient mining/smelting village around the old Zawar area was recognized by the American Society of Metals (ASM International) with the installing of a plaque as accreditation of the oldest zinc-smelting site (180 ± 35 BC) in the world.

gas exploration as at Sabatayn mature basin in Yemen. A satellite image Enhanced Thematic Mapper-based analysis was conducted for extracting surface and subsurface lineaments overlaying the seismic, magnetic, and gravity data.

4.4 TOPOGRAPHIC SURVEY

An accurate topographic map is essential for the long- and short-term purposes of any type of project. This is more relevant during all stages of mineral exploration, mine development, mining, and related activities. The simplest way to conduct a topographic survey is with a tape and compass; however, this method produces a low level of accuracy. Accurate topographic surveys are carried out using electronic total stations to capture 3D observation data (x, y, z) on site. The data are processed using commercial software to generate a digital terrain model (DTM). The DTM is capable of producing contours, volumes, sections, and 3D wireframe views and plots.

An accurate topographic map (toposheet) in 1:250,000 or 1:50,000 scales, marked with reference survey station or triangulation points, contours, and all other land-related features, is easily available at cost from National Survey departments. Toposheets can also be downloaded internationally from the US Army Mapping Service in the Universal Transverse Mercator coordinate system (UTM system, Box 4.1) at a nominal price. The sheets are base maps and significantly useful for geological mapping, sampling, and borehole locations. In the advanced stages of exploration and detailed mine planning, highest accuracy is maintained in topographic surveys (1:5000 and 1:1000 scales) by using Leica Total Station and Leica Global Positioning System (GPS) equipment. The underground mine survey is routinely cross-checked by closing the survey from and to the known surface station.

BOX 4.1 Universal Transverse Mercator Coordinate System

The Universal Transverse Mercator (UTM) coordinate system is a 2D GPS of grid-based internationally accredited mapping references. The UTM system is a set of 60 separate "transverse Mercator" projections covering 60 latitudinal zones each 6 degrees wide. The latitude/longitude-based coordinate system can be transformed to a UTM system and vice versa. The UTM uses a square grid, and values increase from left to right and bottom to top with no negative numbers. All UTM coordinates are measured in meters.

The Military Grid Reference System is derived from UTM, and is the geocoordinate standard used by NATO military personnel for locating points on Earth's surface.

4.5 GEOLOGICAL MAPPING

Mineral exploration is initiated by preparing a high-quality geological base map. The precision and scale of the map depends on the stages of exploration, technical infrastructure, and funds. A geological map is a record of geological facts such as occurrence of rocks in space and their contacts, weathering effects such as leaching or gossan, and structure in their correct space relations. There will be sharp distinctions between observations and interpretations of contacts represented by continuous and broken lines, respectively. The inferences are confirmed by opening through pits and trenches. It can be authenticated by subsurface information as obtained from drill holes and mine workings. The map must have a scale, direction, and index describing the various features shown on it.

4.5.1 Surface Map

Surface maps are prepared by taking traverses on the surface at various intervals, and plotting records like rock types, contacts, and all other observations, including strike, dip, and plunge. Government agencies prepare maps of entire countries on a regional and district scale for future planning purposes. The maps are becoming précised and meaningful with the advent of facilities like remote sensing technology.

4.5.1.1 Regional Scale

Regional scale mapping starts with study and interpretation of geological features from satellite images and aerial photographs. These base maps along with toposheets at 1:250,000 or 1:50,000 scales are used for the selection of boundaries for a reconnaissance license. The regional survey is based on widely spaced traverse and cross-verification of broad geological contacts, shear zones, and weathering features. The map represents an overall regional picture, including geomorphology, drainage pattern, and major structures. Regional scale maps are not for representing specific features. Soil, grab, and rock chip samples of rocks and weathered profiles are collected at this stage. The purpose is to provide a base map for further detailed study for searching for minerals and designing of roads, dams, and other infrastructures (Fig. 4.10).

4.5.1.2 District/Belt Scale

The district/belt map represents a part of the regional map having a cluster of mineral deposits. The features are recorded with closely spaced traverses and rock/soil sampling. The scale of the map is 1:25,000 and 1:10,000, using theodolite and GPS survey instruments. The map will be useful for selection of a prospecting lease and to formulate an exploration program. The map makes an assessment of correct stratigraphy, correct lithology, detailed structures, surface show of mineralization, and analysis of ancient history of mining and smelting (Fig. 4.11).

4.5.1.3 Deposit Scale

The deposit map contains maximum detail information and is focused at a large scale (1:5000 to 1:1000) with triangulation station benchmarks. The area is under a prospecting or mining license. The map helps to design a drilling program to delineate minerals or orebodies (Fig. 4.12), shows detailed surface geological features, extent of deposit, and location of trenches, pits, and boreholes, and helps to draw sections along and across the elongation of mineralization.

4.5.2 Underground Mapping

Surface geology related to lithology, structure, and mineralization can be correlated for down-depth continuity with subsurface features as the mine progresses through service and stope development. The walls and back of the mine entry systems such as adits, inclines, raises, winzes, and shafts, and level development in the form of drives and cross-cuts, are mapped in small scales of 1:200 or 1:50.

Survey stations are marked in the roof of the working, maintaining line of sight to guide successive development. The surface is cleaned by high-pressure water jet or compressed air. Cloth tape is stretched between two survey stations. Pocket metallic tape is used for taking offsets of working profiles, rock contacts, foliation, bedding, joints, fractures, shears, void fills, and mineralization (Figs. 4.13 and 4.14). Information is plotted on graph sheets underground and transferred to a master plan. These maps help in drawing rocks and orebody contacts with high confidence, planning underground drill holes, and finally stope design.

4.6 STRATIGRAPHIC CORRELATION

Geological maps of regional, deposit, and deposit scale can be analyzed and correlated to establish a comparative statement of lithological succession with the metallogeny of the region (Figs. 4.15 and 4.16). The study of isotope geochronology will fix the age of stratigraphic formation to anticipate the favorable host rocks and expected mineralization. This helps to generalize the ore-hosting horizon for future search in the in-between blocks and extensions on either side.

4.7 EXPLORATION ACTIVITY

Geological exploration can be divided into three broad groups, namely, regional scale, district scale, and deposit scale. The overall activities can be identified as follows.

4.7.1 Regional Scale

- Survey of existing literature, examination of aerial photographs and satellite images, acquisition of geophysical data, if any, and geological maps of the prospective region, understanding of the stratigraphic setting and

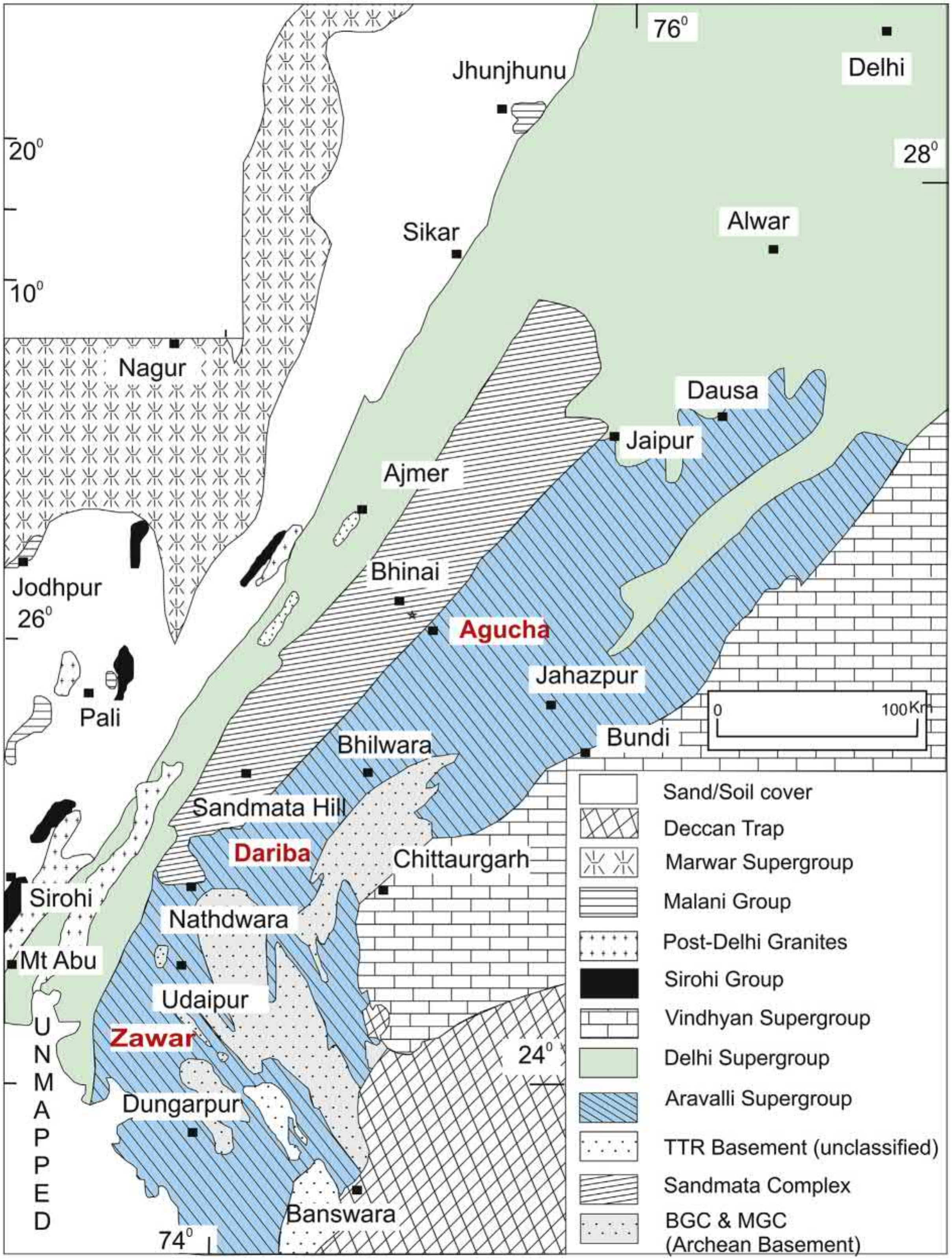

FIGURE 4.10 Regional geological map of the Aravalli Mountain showing major tectonostratigraphic units. BGC and MGC stand for Banded Gneissic Complex and Mewar Gneissic Complex, respectively.

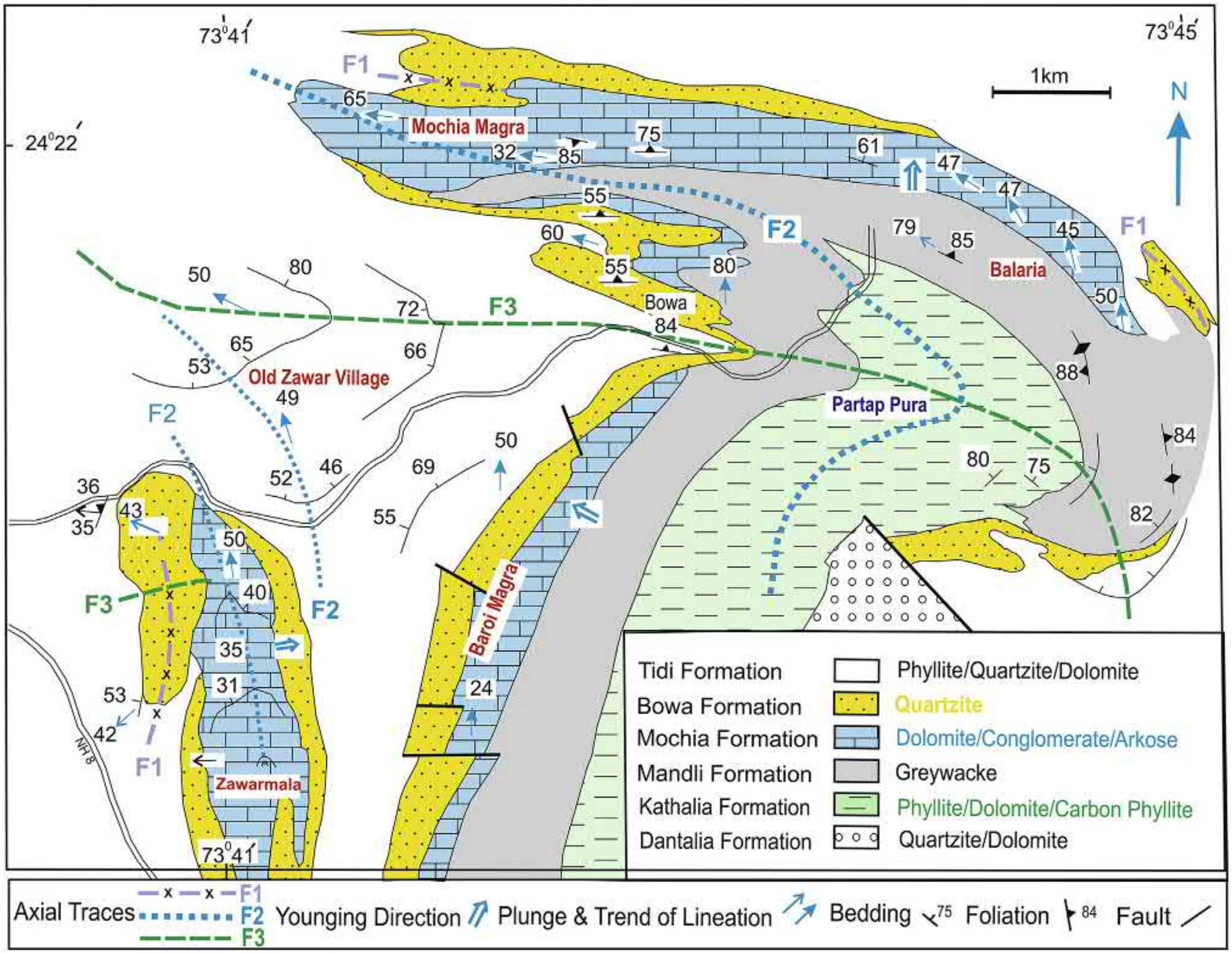

FIGURE 4.11 Surface map of Zawar group of deposits showing all mining blocks, namely, Balaria, Mochia Magra, Baroi, and Zawarmala, India.

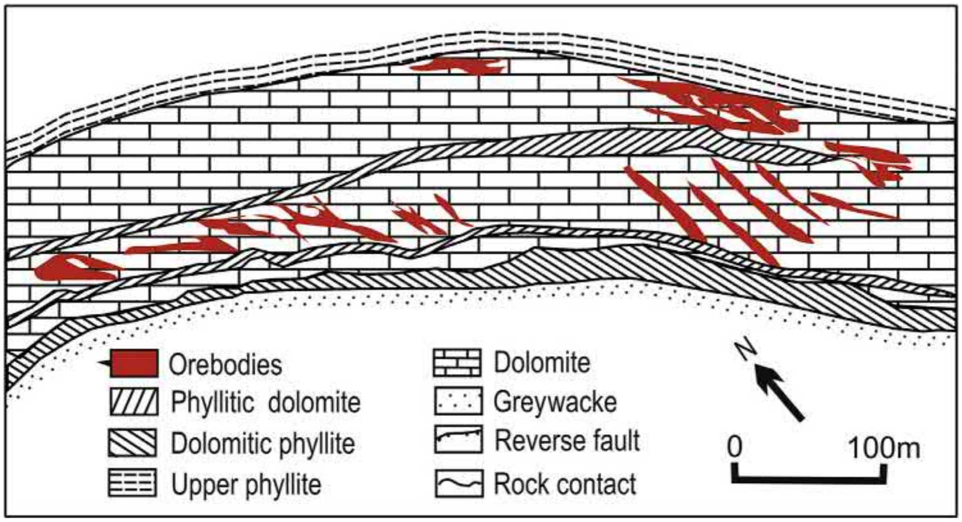

FIGURE 4.12 Surface geological maps showing stratabound en echelon orebodies of Balaria zinc-lead-silver deposit, Rajasthan, India.

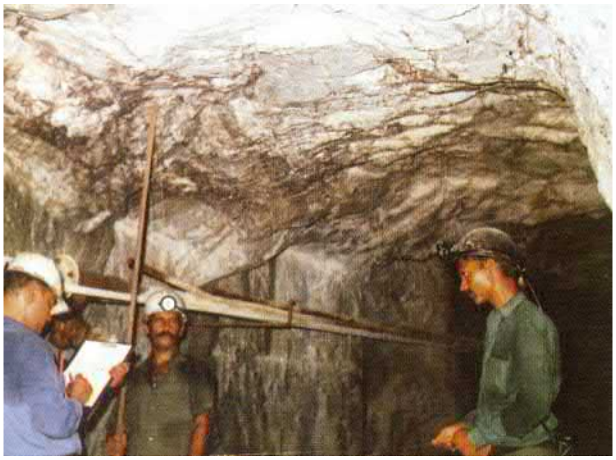

FIGURE 4.13 Scan line underground mapping of cross-cut at Balaria Mine, India.

structural architecture, synthesis of all available data and concepts, and submission of a reconnaissance permit. The resource at this stage is of a preliminary nature.

- Work plan, including preparation of an organization plan, exploration scheme with fund allocation and budgeting, and time schedule to achieve specific objectives (refer to Table 1.1).
- Tasks, including aerial geophysical and broad-based geochemical survey, ground check, wide-space soil and rock chip sample collection, pitting, trenching, a few scout drillings to establish the existence of mineralization, demarcation of priority, and ranking of targets.
- Investment decision for the next phase.

4.7.2 District Scale

- Submission of prospecting lease, study of district geological and mineral maps, and designing the exploration scheme with respect to work component, technology, type of exploration method, time, and fund requirement (refer to Table 1.2).
- Geological mapping of the target areas, recognition of surface signatures like the presence of weathering and alterations, identification of host rock, structural settings, and control.
- Ground geophysics and geochemistry, pitting, trenching, data synthesis, and interpretation for reinforcing the drill targets (refer to Fig. 5.2). Drilling continues to delineate proved and probable ore reserves and possible resources.
- Baseline environment plan.
- Investment decision for the next phase.

4.7.3 Local Scale

- Detailed geological mapping of host rock and structure controlling mineralization, closely spaced surface directional drilling (refer to Figs. 15.3 and 15.8) to compute reserves with high confidence, pitting, trenching, and entry to subsurface for level development, underground drilling for precise ore boundary, reserves of higher category, metallurgical test work, and environmental baseline reports.
- Scoping study, prefeasibility study, and feasibility study.
- Submission of mining lease application along with environment management plan.
- Ore production, mineral processing, and extraction of metal or saleable commodity.
- Cash inflow/outflow (Chapter 11, Fig. 11.3).

4.7.4 Exploration Components

- Sampling: soil, pitting, trenching, grab, chip, channel, directional drilling, sample reduction, check studies, and tests of quality control and quality assurance that are elaborated in Chapter 7.

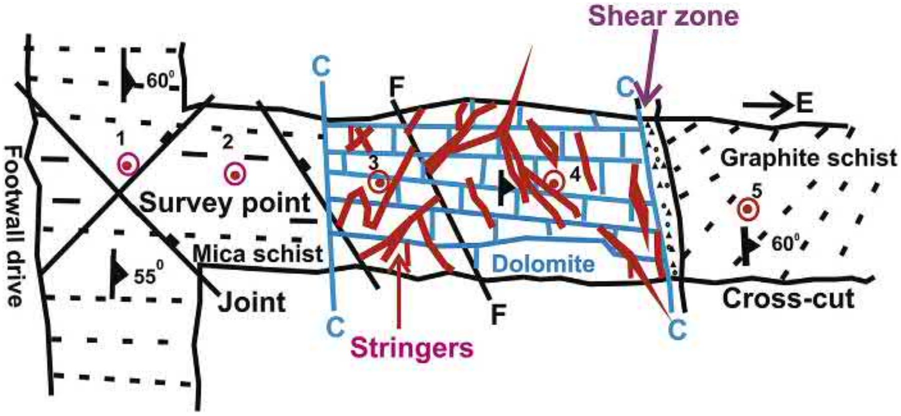

FIGURE 4.14 A typical underground map of development work showing survey stations (*points and circle*), rock contacts (C–C), structures, and mineralized stringers (red) in dolomite host rock (blue) at Balaria Mine, India.

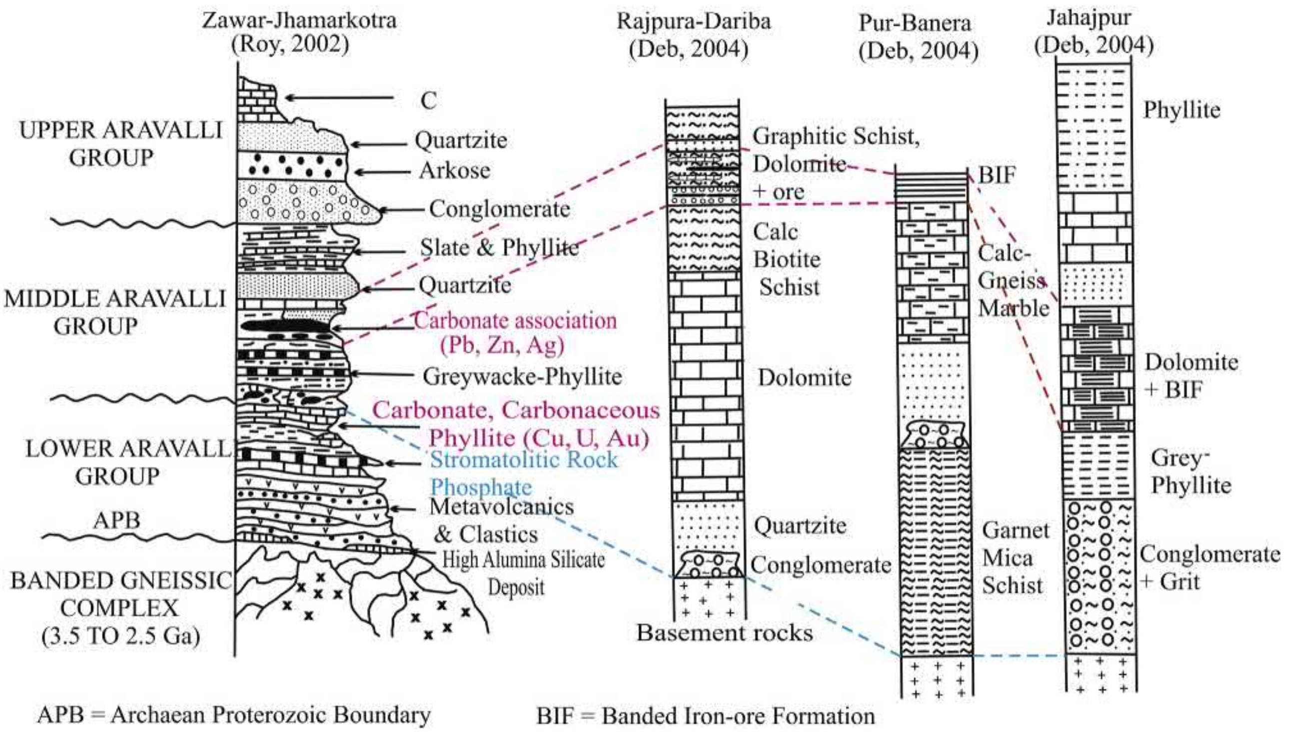

FIGURE 4.15 Lithostratigraphic correlations of Aravalli Province hosting rock phosphate, copper-uranium-gold, and zinc-lead-silver mineralization from lower to higher horizons (Haldar, 2007).

- Optimization of drilling.
- Preparation of cross-section, longitudinal vertical section, level plan, 3D orebody modeling, and estimation and categorization of reserves and resources (Chapter 8).
- Environment management plan.
- Sustainable development in mining (Chapter 14).

4.8 EXPLORATION FOR COAL-LIGNITE AND COALBED METHANE

Coal, the solid fossil fuel, is a flammable black to brown hard rock, mainly composed of high carbon associated with hydrogen, methane, sulfur, oxygen, and nitrogen. The ranks of coal (from most to least % of carbon content on a dry ash-free basis) are anthracite (+87−95), bituminous (77−87), subbituminous (71−77), lignite or brown coal (60−70), and peat (+60). Peat is the recent accumulation of plant matter and is partially carbonized.

Coal is stratified carbonized remains of plant material transformed over millions of years. It is formed first by extensive and voluminous growth of vegetable matter under high precipitation in swamp and river basin environments, followed by accumulation and in situ burial under sediments. The subsequent process is transformation to coal by chemical and thermal alteration of organic debris. Coalification can also happen by drifting of plant material to distant lakes or any water body, and submersion under sediments. Plant materials tend to alter progressively through peat → lignite → subbituminous → bituminous → anthracite coal during the transformation process (e.g., Wyoming coal deposit, Powder River Basin, USA, and Haerwusu coal deposit, Inner Mongolia, the largest open-pit in China). Water, carbon dioxide, nitrogen, and methane gas are produced along with coal in this process.

Lignite or **brown coal** is a soft brown combustible sedimentary rock formed from naturally compressed peat. It is considered the lowest rank of coal due to relatively low heat content (e.g., Tagebau Hambach lignite deposit, North-Rhine Westphalia, Germany, and Neyveli lignite deposit, Cauvery Basin, India).

CBM is a clean-burning fuel for domestic and industrial uses. Its extraction reduces explosion hazards in underground coal mines. These gases are part of the coal seam at different percentages. The energy that plants originally obtained from the Sun is stored in the form of chemical bonds in natural gas. This occurs as free gas within fractures or absorbed into the micropore surfaces in the matrix of the coal beds (Chapter 12, Figs. 12.17 and 12.18). The amount of methane held in a coal seam depends on the age, moisture content, and depth of the coal seam. The excess gas migrates into the surrounding rock strata and sand reservoirs that may overlie the deeply buried seams. The gas is tapped and sold in commercial quantities using suitable technology. It is identified as a cleaner natural gas form of energy than traditional coal and petroleum (e.g., Lupane CBM deposit, Matabeleland North province, Zimbabwe).

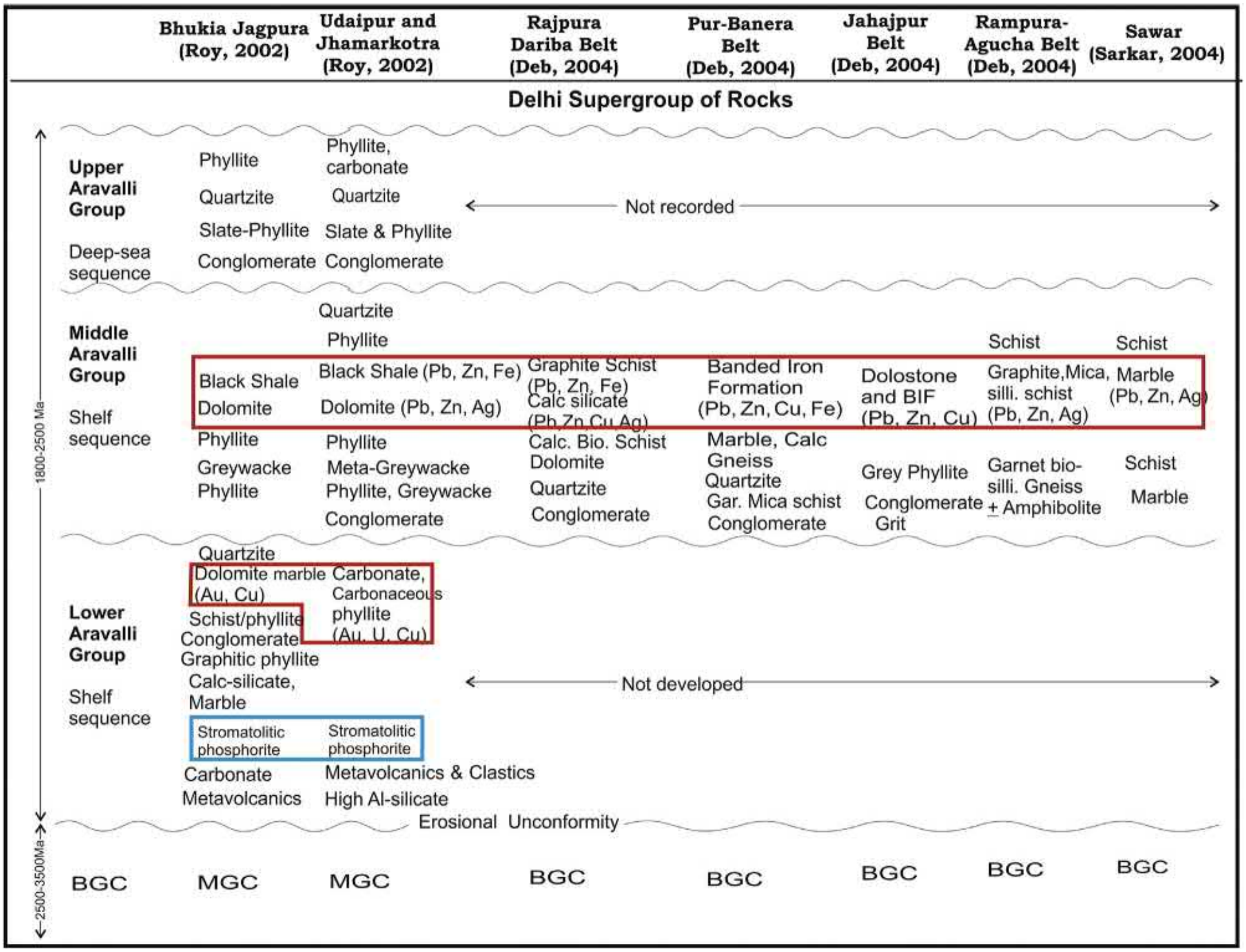

FIGURE 4.16 Lithostratigraphic correlations and comparative statement of the Aravalli rocks hosting rock phosphate, copper-uranium-gold, and zinc-lead-silver mineralization. *Bio*, biotite; *Calc*, calcareous; *Silli*, sillimanite. *Compiled after Haldar (2007), Deb and Pal (2004), Roy and Jakhar (2002) and Sarkar and Banerjee (2004).*

The key coal exploration program is to identify sedimentary packages of Carboniferous and younger in age. The most favorable coal-forming stratigraphy is the Carboniferous period between 360 and 290 Ma, (coal bearing), and lesser amounts continue to subsequent Permian (290—250 Ma) and throughout the Mesozoic Era (250—65 Ma). The Tertiary Era (<65 Ma) often forms lignite with less mature type. Examples of this include Paleocene coal (65—55 Ma) found in Columbia and Venezuela and Miocene coal (20 Ma) found in Indonesia.

Exploration for coal-lignite and CBM includes geological mapping, study of the geological setting of coal basins, interpretation of air photographs and satellite images, airborne and surface geophysics (gravity, magnetic, and seismic), core and noncore drilling supplemented by digital down-the-hole logging, use of GPS and microcomputers, and comprehensive chemical analysis. Remote sensing data can identify the major lineaments, faults, and other tectonic setups useful to explore coal-bearing areas. A high-resolution seismic survey can define the basin configuration, its tectonic style, thickness of coal-bearing formation, lateral continuity, and approximate depth of different coal seams.

The design and procedure for a core and noncore drilling program for a coal seam must be performed on a sequential approach by successively narrowing the drilling interval along with strike continuity of the expected coal seam. Downhole geophysical logging will be helpful in proving the continuity of a seam in strike and dip directions. The use of bentonite drill mud is substituted by high-density polymer foams to facilitate removal of cuttings and stabilize the side wall of the drill hole, thereby allowing ready conversion of drill holes to monitor wells. Over 85% core recovery in and around a coal seam should be achieved by using split tube core barrels. Samples of drill cuttings are taken at regular intervals for analysis.

Formal core descriptions are made and core is frequently photographed by digital cameras that are appended to computerized drilling reports.

In the case of CBM exploration the wells must be well maintained to prevent formational damage. Overpressure of gas/water kicks and high permeability are the primary concerns for drilling in CBM exploration. These concerns often lead to loss of circulation fluid, formational damage due to the nature of coal, and hole sloughing. The rigs commonly used are portable, self-propelled, and hydraulically driven. A major problem during drilling could be excessive water flow. The escape of large quantities of water from the coal seam generally obstructs drilling with pressure.

World total recoverable coal reserves as at December 2012 stood at 909 billion tonnes (Bt). This is shared by (in Bt): the United States (237.3, 28%), Russia (157, 18%), China (114.5, 13%), Australia (76.4, 9%), India (60.6, 7%), Germany (40.7, 5%), Ukraine (33.9, 4%), and Kazakhstan (33.6, 4%). Source: www.mining-technology.com.

World coal production during 2015 was 7861 million tonnes (Mt). The top 10 coal-procuring countries during 2015 were (in Mt): China (3747, 46%), United States (813, 12%), India (677, 8%), Australia (484, 6%), Indonesia (392, 5%), Russia (373, 5%), South Africa (252, 3%), Germany (184, 2%), Poland (136, 2%), and Kazakhstan (106, 1%). Source: www.minin-technology.com.

4.8.1 Uses of the Coal Group

The primary uses of coal, lignite, peat, and CBM are the following:

1. Coal has many important uses worldwide. The most significant uses of coal are in the generation of electricity, steel production, cement manufacturing, and as a liquid fuel. Steam coal (thermal coal) is mainly used in power generation.
2. The Lignite Energy Council reports that 79% of lignite is used to generate electricity, 13% is used to generate synthetic natural gas, and 8% is used to create fertilizer products like anhydrous ammonia and ammonium sulfate (May 15, 2017).
3. Peat is stacked to dry in rural areas. It remains harvested on an industrial scale for this purpose in countries such as Ireland and Finland. Peat has traditionally been used for cooking and domestic heating in many countries, including Ireland and Scotland.
4. CBM is an environmentally friendly natural gas, and is used as a cheap, clean energy source for motor vehicles and public transport and as a substitute for costly petrol and diesel fuel, which cause extreme pollution. It is considered a valuable energy resource with reserves and production having grown steadily since 1989.

4.9 EXPLORATION FOR OIL AND GAS

Petroleum or **oil** is a naturally occurring, yellow to black liquid found in geological formations mostly beneath Earth's surface. Crude oil is composed of carbon (83%−85%), hydrogen (10%−14%), nitrogen (0.1%−2%), oxygen (0.05%−1.5%), sulfur (0.05%−6.0%), and metals (<0.01%). The mother liquid splits into several constituents by fractional distillation, and refined components are used as various types of fuels.

Natural gas is a naturally forming complex hydrocarbon comprised primarily of methane associated with minor higher alkanes, carbon dioxide, nitrogen, hydrogen sulfide, or helium. It occurs as an independent gas reservoir or in close proximity as layers on top of petroleum pools/coal beds (Fig. 4.17). Natural gas is a clean fossil fuel used as a source of energy for heating, cooking, electricity generation, and in vehicles.

A fossil fuel, petroleum/natural gas is formed when large quantities of dead organisms, usually zooplankton and algae, are buried underneath sedimentary rocks, and subjected to decomposition under both intense heat and high pressure. The liquid is generally moved away from the place of origin and trapped in suitable highly porous geological structures/reservoirs between impervious beds. Hydrocarbon fossil fuels (coal, petroleum, and natural gas)

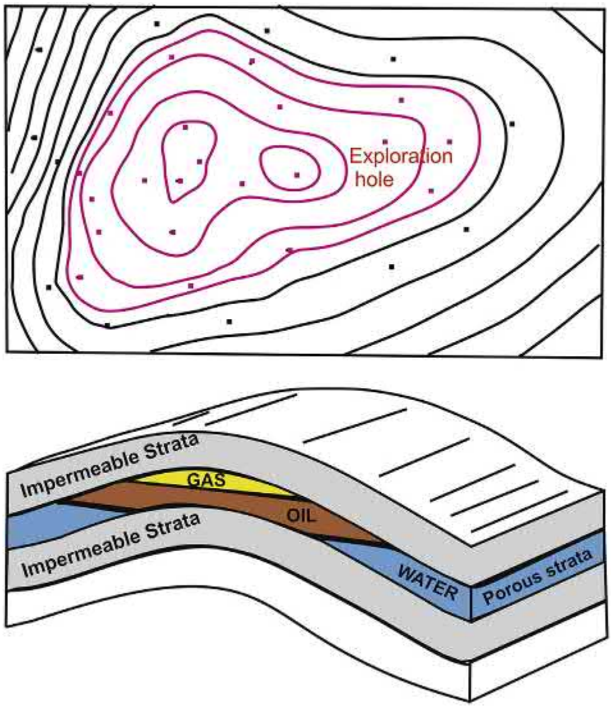

FIGURE 4.17 Conceptual diagram showing oil, gas and water accumulation in an anticline structure as interpreted through geological-geochemical-geophysical studies and supported by drill-holes (bottom). •/• are location of positive/negative drill holes (top).

are formed from dead and decaying plankton, plants, and organic matter (zooplankton and algae) that lived <360 million years ago (Carboniferous period). These organic lifeforms originated from ancient oceans, primordial swamps, lagoons, rivers, and fan-shaped deltas. The decaying organic matter decomposed under high pressure and temperature caused by sediments being piled on top of organic matter over time. Eventually, the dead organic matter heated and compressed sufficiently to form coal, petroleum, and natural gas over hundreds of millions of years.

Oil exploration is an expensive, high-risk operation, and is conducted primarily by national governments and/or large exploration companies. The following steps are custom-made for the exploration of oil and natural gas:

1. A high degree of knowledge is required of stratigraphy and source rock package from Carboniferous or younger ages when organic-rich rock such as oil shale or coal was subjected to high pressure and temperature over an extended period of time to form hydrocarbons. Sedimentary rocks are the most significant medium/source for oil and gas generation and accumulation in large quantities forming hydrocarbon basins/reservoirs. The primary components of the collector sedimentary rocks are originated from clastic and carbonate environment. The clastic forms include alluvial fans, tidal plains, deltas, sandbanks, underwater dunes, sand ridges, barrier islands in coastal marine environments (marine beaches and offshore), debrites, and turbidity fans. The carbonate environments entail carbonate platforms, high-energy shallows, restricted shoals, lagoons, inner shelves, bodies of organogenic reefs, perireef limestone, debrites and turbidites or allodapic limestone, and reef and perireef bioclastic limestone outside the carbonate platforms (Haldar and Tišljar, 2014).
2. The ideal sedimentary process includes building, destruction, accumulation, sedimentation, and cementation. Coarse-grained texture, graded bedding and structure, excellent porosity and permeability, the large presence paleoorganisms in the form of skeletal debris, shells of Corallinaceae algae, bryozoans, corals, sessile foraminifera (*Nubecularia*) and thick shells, bivalves, oysters, foraminifera, skeletons of cyanobacteria (blue-green algae), oncoids, and peloids are the outstanding indicators of hydrocarbon reservoirs. The cover pelites (silt, clay, and mud) and marls (evaporates) are significant insulator rocks that stop oil/gas from moving away (Haldar and Tišljar, 2014).
3. Hydrocarbons are squished from source rock by three density-related mechanisms: newly matured hydrocarbons are less dense than their precursors, which causes overpressure; hydrocarbons are lighter and so migrate upward due to buoyancy; and fluids expand as further burial causes increased heating. Most hydrocarbons migrate to the surface as oil seeps, but some will be trapped. Look for significant visible surface features such as oil and natural gas seeps (Fig. 5.19) and underwater shallow/deep seabed craters caused by escaping gas (Fig. 5.18).
4. Common reservoir rocks are gravels, conglomerates, breccias, porous sand/sandstones (clastic), and limestones and dolomites (carbonates). Strongly fractured igneous and metamorphic rocks (e.g., fractured granite) may be appropriate collectors under suitable conditions. Hydrocarbons are contained in a reservoir rock. Reservoirs must also be permeable so that the hydrocarbons will flow to the surface during production.
5. Hydrocarbons are buoyant and have to be trapped within a structural (e.g., anticline, fault block) or stratigraphic trap. A hydrocarbon trap has to be covered by an impermeable rock known as a seal or cap rock to prevent hydrocarbons escaping to the surface.
6. Exploration tools are highly sophisticated geophysical methods (gravity, magnetic, passing through passive or regional seismic reflection surveys) to detect the existence and determine the extent of these anomalies in large-scale features of subsurface geology. Detailed time domain seismic survey continues to identify the leads to create a profile of the substructure.
7. A prospect is identified and evaluated by exploration well drilling to conclusively confirm the presence/absence of oil and/or gas.
8. Finally, well drilling, geophysical well logging, analysis, interpretation, resource/reserve estimation, and economic evaluation continue to declare a reservoir for production planning.

World proven petroleum reserves as at early 2017 stand at 1,726,685 million barrels. The first 10 countries in order of rank are (in million barrels): Venezuela (300,878), Saudi Arabia (266,455), Canada (169,709), Iran (158,400), Iraq (142,503), Kuwait (101,500), UAE (97,800), Russia (80,000), Libya (48,363), and United States (35,230).

Source: www.en.wikipedia.org/wiki/List_of_countries_by_proven_oil_reserves.

Total oil production in 2016 averaged 80,622,000 barrels per day (bbl/day). The top 10 countries contribute ~68% of the total amount (in bbl/day): Russia (10,551,497), Saudi Arabia (10,460,710), United States (8,875,817), Iraq (4,451,516), Iran (3,990,956), China (3,980,650), Canada (3,662,694), UAE (3,106,077), Kuwait (2,923,825), and Brazil (2,515,459).

Source: www.en.wikipedia.org/wiki/List_of_countries_by_oil_production.

4.9.1 Use of Oil and Gas

The primary uses of oil and gas include the following:

1. **Petroleum products include transportation fuels, fuel oils for heating and electricity generation, asphalt, and road oil, and feedstocks for making chemicals, plastics, and synthetic materials that are in nearly everything we use.**
2. Liquefied petroleum gas or liquid petroleum gas (also called propane or butane) are flammable mixtures of hydrocarbon gases used as fuel in heating appliances, cooking equipment, and vehicles.

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Chapter 5

Exploration Geochemistry

Chapter Outline

> *Abnormality in the chemical signature on the surface is defined as a geochemical anomaly, which may show the way to the discovery of large mineral deposits.*
>
> Author.

5.1 DEFINITION

Exploration geochemistry deals with the enrichment or depletion of certain chemical elements in the vicinity of mineral deposits. Geochemical prospecting is conducted by systematic measurements of one or more chemical parameters, usually in traces, of naturally occurring material in Earth's crust. Samples are collected from rocks, debris, soils, weathering profile, including gossan, stream, or lake sediments, groundwater, vapor, vegetation, and living beings. At times, sampling results may show abnormal chemical patterns over the regional perspective. This abnormality is defined as a **geochemical anomaly**, which may reveal near-surface or deep-seated hidden mineral deposits with economically viable properties.

The intensity, spread, and size of a geochemical anomaly are influenced by the following natural factors:

1. Mobility power of elements in the physical and chemical milieu.
2. Depth of primary mineralization.
3. Wet and dry tropical climate.
4. Shape and size of mineralization.
5. Permeability, porosity, and mineralogical composition of host rock.
6. Local and regional topography.
7. Hydrologic regime.
8. Nature of weathered profile.
9. Tectonic movements.
10. Sampling media and density.
11. Precision and accuracy of the analytical procedure.

5.1.1 Elemental Dispersion

Dispersion is the natural process of outward movement of certain metallic elements from a source, i.e., a mineral deposit. The dispersing elements tend to form a zone (halo)

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00005-8

around/in proximity to/away from the source. The dispersing metallic values are less than those in the deposit, but significantly higher than the background values found in enclosing country rocks. These elements occur in traces and are found in soils, rocks, and groundwater. The degree of concentration of specific elements logarithmically diminishes away from the mineralization until it reaches a background value. Geochemical sampling can outline two types of **dispersion halos**: primary halo and secondary halo.

Primary dispersion halos refer to a geochemical envelope, which is an expression of alteration and zoning conditions surrounding metalliferous deposits. Formation of the primary halo is synchronous to mineralization as a result of moving hydrothermal fluid in rocks. It is essentially identical to the geochemistry of unweathered rocks and minerals, irrespective to how and where the orebody itself was formed. The halos are either enriched or depleted in several elements due to the introduction or redistribution related to ore-forming phenomena. The shape and size of the halo is exceptionally variable due to the diverse mobility characteristics of elements in solution and microstructures in rocks. The extremely porous or extensively fractured rocks develop widespread primary halos (Fig. 5.1A).

Secondary dispersion halos are the dispersed remnants of mineralization caused long after deposit formation by surface processes of chemical and physical weathering and redistribution of primary patterns. A secondary halo can be recognized in samples taken from soils, rocks, stream sediments, plants, groundwater, and volatile matter at a distance of meters to kilometers from the deposit.

Chemical weathering involves elemental breakdown of rocks and minerals in abundance of water, oxygen, and carbon dioxide. It can move considerable distances from the source. Multicolored laterite and gossan above mineral deposits at Broken Hill, Australia, and Sukinda (Fig. 5.5), Rajpura-Dariba (Figs. 5.10 and 5.11), Khetri (Fig. 5.12), and Malanjkhand in India are unique examples of chemical weathering. Physical weathering implies disintegration of rocks and minerals with little or no chemical and mineralogical changes. It may involve long-distance transportation from the source. These minerals are chemically resistant, namely, oxides (cassiterite, rutile, magnetite, chromite) and native forms of gold, platinum, and diamond. Favorable locations are **till** and **glacial** deposit environments.

5.1.2 Pathfinder Elements

Pathfinder or **indicator** elements are characteristic parameters in geochemical prospecting. The elements are relatively mobile due to physicochemical conditions of the solutions in which they are found, or may be in a volatile state (gaseous). They occur invariably in close association with the primary minerals being sought. These elements are easily identifiable as a broader halo around the deposit, or detected easily by simpler and inexpensive analytical methods. The pathfinder elements play a significant role in locating concealed deposits due to these special properties. The condition of the pathfinder necessitates that the element(s) used must occur in primary association with the element(s) being sought, for example, copper, nickel, and chromium as pathfinders for platinum-palladium group of deposits (Bushveld chromium-platinum-group element [PGE] deposit, South Africa, Sudbury nickel-PGE deposit, Canada, and Nausahi chromium-PGE deposit, India), zinc for lead-silver-zinc deposits, Rajasthan, and scheelite in Kolar gold field, Karnataka, India. The elements can also be derived from their parents by radioactive decay, such as use of radon as a pathfinder for uranium deposits. Some common pathfinder elements are listed in Table 5.1.

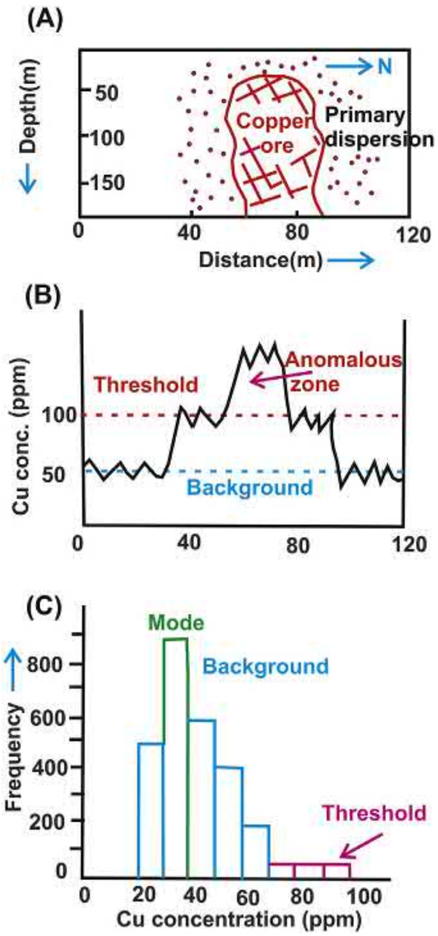

FIGURE 5.1 A typical illustration of (A) concealed copper deposit with primary dispersion halos, (B) geochemical profile of soil samples viewing background, threshold values, and anomalous zone, and (C) histogram of Cu values showing most frequently occurring samples.

TABLE 5.1 Common Pathfinder Elements in Geochemical Exploration

Type of Deposits	Pathfinder Element(s)
Gold-silver vein type, gold-silver-copper-cobalt-zinc and complex sulfide ores	As
W—Be—Zn—Mo—Cu—Pb skarns, Sn—Bo veins	B
Copper-zinc-lead-silver and complex sulfide deposits	Hg, Zn
Ba—Ag vein deposit, porphyry copper	Mn
Wolframite-tin contact metamorphic deposits	Mo
Porphyry copper, barium-silver deposits	Mn, Mo, Au, Te
Platinum-palladium in mafic/ultramafic rocks	Cu—Ni—Cr—Pd—Co
Uranium (all types)	Rn, Cu, Bi, As
Uranium sedimentary type	Se, V, Mo
Sulfide deposits of all types	SO_4

5.1.3 Background and Threshold Value

Background values are characterized by a normal range of concentration of elements in regional perspective rather than localized mineral occurrences. It is significant to establish the background value of the study area so that the anomalies due to economic mineral accumulations, if any, can be identified. A large number of samples comprised of rocks, soils, sediments, groundwater, and volatile matter are analyzed for multiple elements separately for each area before exploration begins. Each type of sampled material should be treated separately. The values may vary significantly between samples. Frequency distribution is usually positively skewed. The arithmetic average (mean) is evidently biased by a few scattered high values. The most frequently occurring values (modes) tend to lie within a relatively restricted range, and are considered to be the normal abundance or background for that particular element of the area (Fig. 5.1C).

Threshold value is defined as the probable upper or lower limit of background value (Fig. 5.1B) at some statistically precise confidence level. Any sample that exceeds this threshold is considered as possibly anomalous and belongs to a separate population. It may vary for each element, each rock type, different types of samples, and in each area (Fig. 5.1A).

5.1.4 Orientation Survey

The success of exploration geochemistry depends on the appropriate detection of pathfinder elements in primary and secondary environments. In practice, a first round **orientation survey** is conducted in every new area to draw a detailed work plan that adequately distinguishes anomalies from background values. The important parameters to consider in combination are:

1. Host rock environment.
2. Identify criteria that influence dispersion.
3. Possible local contamination.
4. Effect of topography.
5. Best sample medium.
6. Optimum sample interval.
7. Depth of soil sample.
8. Size fraction.
9. Analysis for group of elements.
10. Anomaly enhancement.
11. Analytical techniques for establishing the background and threshold value.

In the reconnaissance phase, regional geological knowledge, the possible presence of economic mineral association, and previous experience elsewhere will be guiding factors to plan an orientation survey. The activities are focused around probable targets with better knowledge of geochemical characteristics of the area for detailed exploration. The procedure should be simplified and finite. The orientation survey is always justified for any new area. It will optimize the sampling program and increase efficiency of interpretation with higher confidence. In turn, it saves considerable time and money in long run.

Anomaly enhancement techniques are commonly practiced during orientation surveys with weak anomalies, particularly for deep-seated mineralization. Value enhancement can be obtained by physical, chemical, and statistical means. The physical methods are enrichment of metallic, magnetic, and heavy minerals by panning, magnetic, and heavy media separation, respectively. The chemical methods include selective leaching of iron and manganese oxides in the host environment. The statistical means are anomalous to background and trace elements ratio and the additive and multiplicative halo concept. This technique highlights insignificant values of interest in locating concealed deposits.

5.1.5 Regional-, District-, and Local-Scale Geochemistry

Geochemical province is defined as a relatively large segment of area in which the chemical composition of the bedrocks is significantly different from the surroundings. It is manifested by a certain suite of rocks relatively enriched in certain specific elements, e.g., Southern Australia and southeastern Tanzania are favorable for locating copper, chromium, nickel, and PGE, Aravalli Mountain province for base metals, and Chattish Garh and Goa for iron ore, India. Similarly, **metallogenic province** represents a large area characterized by an unusual abundance of particular types of metals in country rocks, e.g., the copper-producing area of Peru Chile, Singhbhum and Khetri (India), lead-zinc-silver producing areas of Mt. Isa (Australia), Sullivan province (Canada), and Zawar, Dariba, Rampura-Agucha (India), tin in northwestern Europe, and Bastar in India. There is no definite or unique sample interval. Traditionally, low-density stream sediment surveys of one sample per 50−200 or 5−20 km^2 will be adequate for selection of a province depending on regional geological knowledge and terrain. The analysis is performed for 16 to 25 elements.

Mineral district is defined by the presence of known characteristic mineralization such as chromium mineralization in Jajpur-Keonjhar district, India. Stream sediment and limited soil and rock chip samples at 3−6 or even 1−2 km^2 grid intervals are followed during the prospecting stage depending on geological heterogeneity and signatures.

Local-scale geochemistry is aimed at outlining the location and broad extent of mineralization by detailed stream sediment sample at intervals of 30−300 m. Rock and soil geochemistry can be exercised in the absence of inadequate drainage systems. Once the target is identified, more closely spaced traverses at 100−300 m apart are sampled for soils and rocks at an interval 10−50 m across. The interpretation is further upgraded and précised by addition of pitting and deep trenching in a close grid pattern. The target is now ready for drill testing.

The mission and extent of geochemical exploration is generalized by progressively diminishing the size of the search area in which an economic deposit may exist. Activities continue from grassroots reconnaissance to detailed sampling until a target is defined that can be tested by drilling. The sequential program demands further detail and expensive techniques with a sole objective of maximum probability of discovery at the lowest possible time and cost.

5.2 FIELD PROCEDURE

Field procedure comprises sample collections of various types (solid, liquid, and gas) and sizes with precise locations. It includes the best sample material and optimum sampling design that identifies the presence of mineralization. Major sources of samples are from stream sediments, soils, rocks, groundwater, and volatile matter.

Each sample, weighing between 250 and 1000 g, is collected during field survey by hand, or with a plastic or aluminum scoop at specified intervals from unconsolidated soil. The rock chips are collected by chisel and hammer. Samples are kept in plastic bags for soil and cloth bags for rocks with code numbers indicating project name, location, and sample type with description. Geological observations and sketches are recorded in a field notebook. Grain size is preferred as fines, say (−) 80 mesh in the case of soil. The sample is reduced to 50 g by drying, screening, grinding, coning, and quartering at the camp site. The laboratory will need 1−5.5 g for chemical analysis. The remaining sample part is preserved for future reference. The quantity of the sample to be collected from surface water and groundwater varies between 100 and 1000 mL depending upon the number of elements and type of analysis. Water is collected in an exceptionally clean, hard, polyethylene sampling bottle as the elements are in the variation of parts per billion.

5.3 DATA INTERPRETATION

The multielemental sampling data (assay values) from geochemical surveys can be analyzed by standard statistical methods to express inferences of each element. The frequency distribution diagram will reveal median, mode, and mean of the sample population to identify and distinguish between background, threshold, and anomalous values. Trend surface analysis and moving average methods can produce a regional distribution pattern of the elements being investigated. An isograde contour map will guide the detailed exploration program such as drill testing around the most anomalous zone (Fig. 5.2). The multiple correlation coefficient matrix of multielement data will clearly display maximum affinity between coexisting groups of elements. Cluster analysis deals with mutually correlated elements and is greatest within group correlation relative to between group correlation, taking into account all possible combinations of given elements.

5.4 GEOCHEMICAL METHODS

Geochemical prospecting can be broadly classified into the following types depending on stages of the survey, nature of the terrain, surface weathering, climate, and signals associated with mineralization, type of analytical instrumentation available, and time and cost permissible for the program (Beus and Grigorayan, 1975; Govett, 1983; Hawkes and Webb, 1962; Hale, 2000; Horsnail, 2001; Levinson, 1974; Lett, 2007; Lett, 2009; Rose et al., 1983). Geochemical surveys are broadly addressed by 14 forms:

1. Pedogeochemical (soil survey).
2. Consolidated weathered cover prospecting.
3. Lithogeochemical (rock survey).
4. Drift or till geochemical survey.

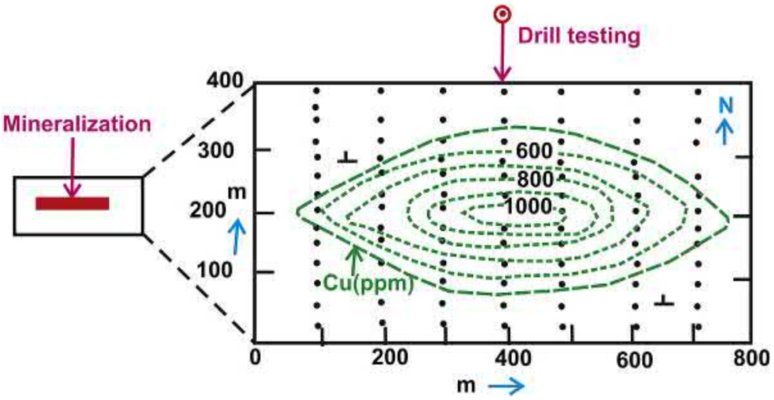

FIGURE 5.2 Data interpretation of soil and pit geochemical samples by contouring copper values to identify the best target for drill testing.

5. Stream sediment survey.
6. Hydrogeochemical survey.
7. Vegetation survey:
   a. Geobotany;
   b. Biogeochemical.
8. Geozoological/homogeochemical survey.
9. Atmogeochemical (vapor survey).
10. Electrogeochemical survey.
11. Radiogenic isotope geochemistry.
12. Heavy mineral survey.
13. Polymetallic polynodule survey.
14. Hydrocarbon geochemical survey.

5.4.1 Pedogeochemical (Soil Survey)

Pedogeochemical survey is also known as **soil survey**. The soil is the unconsolidated weathering product. It generally lies on or close to its source of formation such as residual soil. It may be transported over large distances forming alluvial soil. The soil survey is widely used in geochemical exploration and often yields successful results. The anomalous enrichment of indicator elements from an underlying mineralization source is likely to occur due to secondary dispersion in the overlying soil, weathered profile, and groundwater during the process of weathering and leaching (Cameron et al., 2004). The dispersion of elements spreads outward forming a larger exploration target than the actual size of the orebody.

The soils display layering of individual characteristic horizons differing in mineralogy and trace element composition. Therefore sampling of different horizons will present different results. The soil profile can be classified in three broad groups such as A, B, and C horizons (Fig. 5.3). Horizon "A" is composed of humus-charged top soil with minerals. Zone "B" represents accumulation of clays enriched with trace elements. Horizon "C" consists of bedrock fragments in various stages of degradation (C_1), and gradually changes to hard parent rock (C_2). The proportion of metallic elements in "B" horizon is generally higher than in "A" zone. The anomalous behavior of "C" zone is similar to the parent bedrock. Therefore samples from "B" layer enriched with trace elements are most preferred during soil survey.

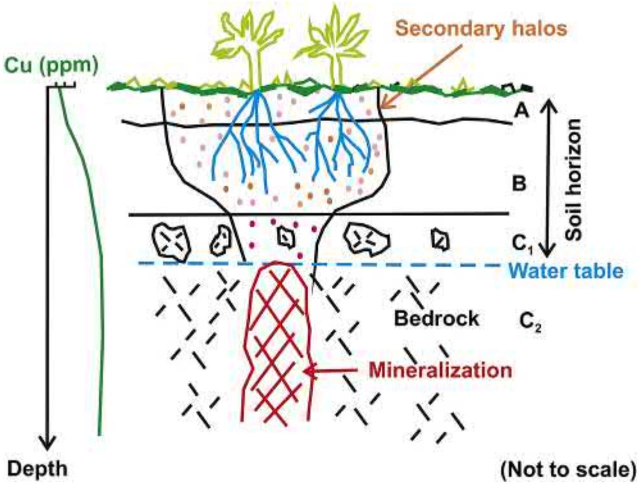

FIGURE 5.3 Diagrammatic presentation of soil horizons, relative vertical and lateral spread of secondary dispersion halos, and associated metal contents.

Soil samples from residual or transported material play a significant role during the reconnaissance survey (refer to Fig. 7.20). They can provide a quick idea about the presence or absence of target metals in the environment. Soil geochemistry as a successful exploration tool was demonstrated in the discovery and development of the Kalkaroo Cu—Au—Mo deposit, South Australia, and large PGE mineralization at the Ural Mountains, Russia. Soil sampling had extensively been used for locating base metal deposits in Khetri, Pur-Banera, Zawar, Rajpura-Dariba, and Agucha (Rajasthan), Malanjkhand (Madhya Pradesh), Singhbhum copper-uranium belt (Jharkhand), and Sukinda chromium-nickel deposit (Orissa), India.

5.4.2 Consolidated Weathered Cover

The weathering of cover sequence has undergone various types of chemical fractionation over millions of years due to the paleoclimatic setup of the region. The consequential resistant residual weathering component of rocks and soils consolidates to form landscape geochemistry. The weathered cover can broadly be classified into four types depending on their composition and type of weathering, and can guide in mineral search.

5.4.2.1 Calcrete

Calcrete is the weathered crust in arid and semiarid regions and is represented by a mixture of sand and silt cemented by calcite, dolomite, gypsum, halite, and ferric oxide. The process is simulated mainly by near-surface groundwater and vertical/lateral concentration of minerals like uranium, vanadium, potassium, calcium, magnesium, and base and noble metals. The economic calcrete-type uranium deposits occur typically in Australia, Namibia, South Africa, Botswana, China, and at the desert/semidesert terrains of Jodhpur and Bikaner, western Rajasthan (vast drainage area of Luni and extinct Saraswati river basin), India. The calcrete-type weathering indicates the presence of carbonates nearby that may be metalliferrous as in the case of Rajpura-Dariba base metal deposit in Rajasthan, India. This is also formed near ultramafic intrusions where carbonate nodules are common in soil along river banks like Subarnarekha, east of Singhbhum copper belt, India, indicating the presence of Cu—Ni—Co—PGE.

5.4.2.2 Silcrete

Silcrete is a surface crust of residual weathering where sand and silt are cemented by silica. This is formed in semiarid regions simulated by stable groundwater conditions. The silcrete is commonly found in association with gossan over the copper deposits of Khetri region, Rajasthan.

5.4.2.3 Ferricrete

Ferricrete (ferruginous concrete) is a hard erosion-resistant layer of sedimentary rock (conglomerate/breccia) cemented by iron oxides derived from the oxidation of percolating solutions of iron salts. The cementing materials are usually transported from distances and form a surface cover. The common types are alluvial and colluvial iron oxyhydroxide and manganocrete deposits. The ferricrete deposits occur around the Gulf and Atlantic coasts of the United States. Ferricrete is widely used in South Africa and in Orissa and Gujarat in India to create local roads in rural areas.

5.4.2.4 Laterite

Laterite is a surficial/near-surficial consolidated product of humid tropical weathering/oxidation and supergene enrichment as a result of physical and chemical processes on felsic/mafic/ultramafic/clay rocks. It is composed of goethite, hematite, kaolin, quartz, ±bauxite, nickel, and other clay minerals. The color is red or brown to chocolate at the top showing a hollow, vesicular, botryoidal structure. It changes progressively from a nodular iron oxide-rich zone at the top to a structureless clay-rich red-yellow limonite transition and finally merges with partially altered (saprolite) to unaltered bedrocks (Fig. 5.4). Laterite causes the concentration of metals/ore deposits of Ni—Cu—Co—PGE, Au, Al, Fe, and Mn by the action of a paleoclimatic environment, and occurs within the regolith (the layer of soft/fragile/loose, heterogeneous superficial material covering solid rock).

The deeply weathered profiles are widespread on continental landmasses between latitudes 35°N and 35°S.

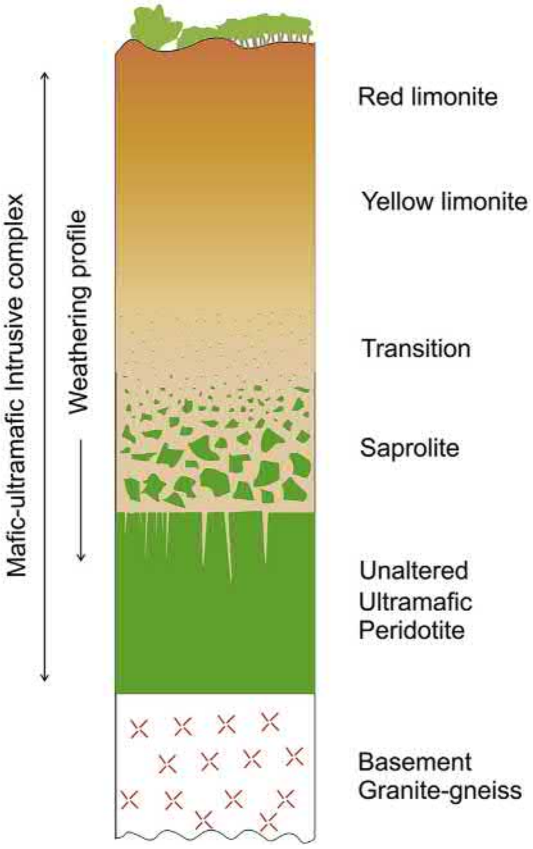

FIGURE 5.4 An ideal lateritic profile showing the formation of nickel-copper-cobalt-platinum group metals formed by the supergene enrichment process of physical and chemical weathering in humid tropical countries. Nickel-copper-cobalt metal enrichment is in the highest order in the saprolite/garnierite/serpentinite horizon and gradually diminishes to the up- and downside.

FIGURE 5.5 The older ultramafics have been extensively weathered to form laterite (yellow and red limonite) at the top of Sukinda intrusion. The nickel-bearing laterite has complex metallurgy for economic recovery and is stacked separately for future technology update.

The key controlling factors for lateritic formation are the presence of host rocks, a stable paleoclimate receiving more than 1000 mm annual precipitation, average cold month temperatures between 15 and 27°C, warm month temperatures between 22 and 31°C (Robert et al., 2012), deeply weathered profiles, widespread establishment on continental landmasses, topographically moderate relief and flat enough to prevent erosion, long periods of tectonic stability, tectonic activity, excess leaching of chemically weathering products, climate change that can cause surficial erosion, and essentially a prevailing humid tropical to temperate climate. The basic dominant extractable minerals/metals are:

1. Aluminous laterite (bauxite): large bauxite reserves include Weipa mine, Queensland, Australia, Guinea, Vietnam, Jamaica, and East Coast, India.
2. Ferruginous laterite (iron ore): Capanema deposit, Minas Gerais, Brazil, and Goa, India.
3. Nickeliferous laterite (nickel ore): eastern coast of Brazil, Madagascar, Indonesia, Papua New Guinea, Goro nickel, New Caledonia, Nonoc, the Philippines, Mutrin Murrin, Western Australia, Çaldağ deposit, Western Turkey, and Sukinda, India (Fig. 5.5).
4. Chromiferous laterite (chromite ore): Sukinda, India.
5. Manganiferous laterite (manganese ore), Uttara Kannada, India.

5.4.2.5 Gossans

Gossans are the signposts that point to what lies beneath the surface. Gossans are exceedingly ferruginous rock, which is the product of oxidation by weathering and leaching of sulfide mineralization. The colors significantly depend on mineralogical composition of iron hydroxides and oxides phases, and vary between red (hematite), yellow (jarosite), brown, and black (galena) with stains of azure blue, malachite green, and peacock (copper). The texture can be brecciated, cleavaged, banded, diamond mesh, triangular, cellular, contour, sponge, and colloform with box work of primary sulfides. The texture assumes a honeycomb pattern (box work) of various colors that exist in capping as sulfide grains oxidize and residual limonite remains in cavities. The characteristic relic textures and colors resulting from the weathering of certain primary sulfide minerals like sphalerite, galena, and chalcopyrite will be specifically diagnostic. Identification can be corroborated by microscopic observation and chemical analysis. Field observations make it easy to detect gossan in prospecting areas with good outcropping conditions. The study of color aerial photographs and satellite images is of much use to focus on certain dark reddish bodies, which have to be checked in the field. The depth of gossan may extend from a few centimeters to hundreds of meters.

The weathering of sphalerite above massive primary sulfide deposits usually depicts a yellow-brown color with coarse cellular box work and sponge structure (Fig. 5.6). The primary mineral sphalerite (ZnS) often changes to

FIGURE 5.6 The yellow-brown color, cellular box work, and sponge structure of a unique gossans formation above Rajpura-Dariba zinc-lead-copper-silver deposit indicate the presence of sphalerite underneath.

FIGURE 5.7 The dark chocolate color, crust radiate structure, and diamond mesh cellular box work of a unique gossans formation above Rajpura-Dariba deposit indicate the presence of galena and tetrahedrite underneath.

willemite (Zn_2SiO_4). Gossans of multisulfide deposits are often associated with typical contour box work from silver-rich tetrahedrite (copper-stibnite) and tennantite (copper-arsenic) minerals.

The dark chocolate color with cleavages, crust, radiate structures, and cubic diamond mesh cellular box work (Fig. 5.7) in gossan indicate the presence of galena and tetrahedrite as primary mineralization of sulfide deposit at depth (Bateman, 1962). Primary galena (PbS) often changes to anglesite ($PbSO_4$), cerussite ($PbCO_3$), pyromorphite ($PbS(PO_4)_3Cl$), and mimetite ($PbS(AsO_4)_3Cl$).

The chalcopyrite often changes into native copper, melaconite (CuO), azurite ($Cu_3(CO_3)_2(OH)_2$), and malachite ($CuCO_3Cu(OH)_3$). Dark shades of peacock blue, green, and black colors (Fig. 5.8) and triangular cellular structures are easily recognizable and associated with primary copper sulfide at depth.

FIGURE 5.8 The dark shades of multicolor peacock blue, green, brown, and black, and the tiny box work of a unique gossans formation above Rajpura-Dariba deposit indicate the presence of primary chalcopyrite, tetrahedrite, and tennantite ore deposit.

The massive sulfide deposits contain typically large quantities of iron sulfides and carbonates (pyrite, pyrrhotite, marcasite, siderite, and ankerite) that oxidize and produce an exceptional acidic environment in the above-ground water table, and induce the formation of characteristic gossan.

Geochemical studies of gossan have been successfully used in the exploration of Mo—Ni—Cu at Malanjkhand copper deposit, India, which shows complete alteration and enrichment profile (Fig. 5.9) to form a typical textbook gossan. The thin oxidized cap is represented by limonite with stains of malachite, azurite, and native copper. This is followed by a zone of secondary sulfide enrichment in the central and southern parts of the orebody with predominance of covellite, bornite, chalcocite, and chalcopyrite. This is the most copper-enriched horizon of the deposit. The secondary enrichment grades into primary orebody with gradual decrease in secondary minerals with predominance of chalcopyrite and pyrite.

More significant examples can be cited from the unique world-class textbook gossans formation at Rajpura-Dariba Zn—Pb—Cu—Ag deposit (Figs. 5.10 and 5.11) and Cu deposits of Khetri belt (Fig. 5.12) (India), Zn—Pb—Ag deposit, Broken Hill (Australia), Ashanti Cu—Au deposit (Ghana), Zn deposit at Togo (western Africa), Rouez gold deposit (France), Hassai Cu—Zn—Au deposit (Sudan), and Al Hazar Cu—Au deposit (Saudi Arabia).

All facies of the gossan have to be sampled because they may correspond to different types of primary mineralization. The weight of the sample is about a few kilograms scooped from the surface depending upon homogeneity and chips sampling in a grid pattern for consolidated mass. Multielemental analysis is appropriate during the reconnaissance stage. True gossan can be difficult to distinguish from ironstone and other iron oxide accumulations such as laterite.

5.4.3 Lithogeochemical Survey

Lithogeochemical survey (rock survey) is useful during regional work to recognize a promising geochemical province and favorable host rocks. The most epigenetic and syngenetic mineral deposits show primary dispersion around the mineralization by the presence of anomalous high-value target elements. Lithogeochemistry aims at identifying primary dispersion, other diagnostic geochemical features, and trace element association, which are different from country rocks. Some granite possesses above average contents of Mn, Mo, Au, and Te indicating a potential for hosting porphyry copper deposits (Malanjkhand, India). The rocks associated with tin deposits in the Tasman Geosyncline contain 3—10 times

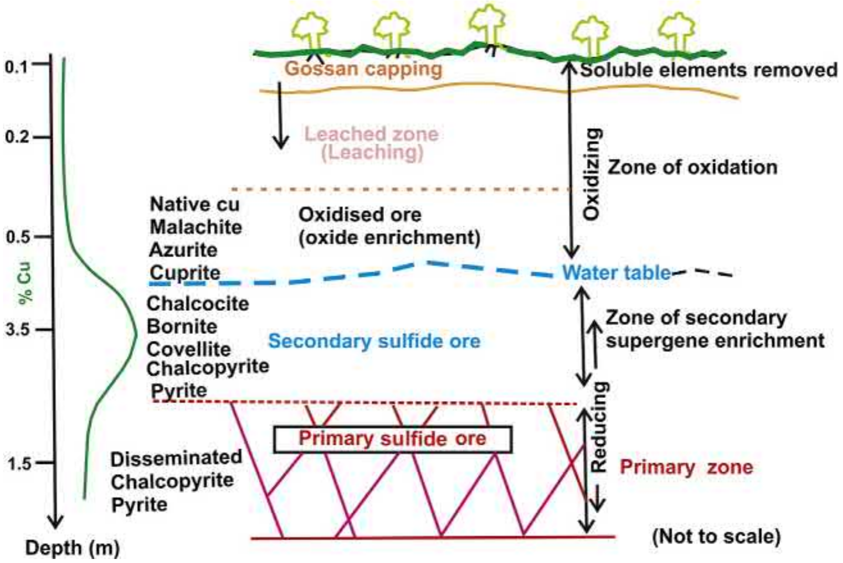

FIGURE 5.9 A generalized profile of gossans formation over massive copper sulfide deposits conceptualized after Malanjkhand copper deposit, India.

FIGURE 5.10 A unique world-class gossans hill above the massive silver-rich zinc-lead-copper deposit at Rajpura-Dariba. In 1977 the site was designated as a "National Geological Monument" by the government of India.

FIGURE 5.11 Part of the unique gossans collapsed in the eastern part of the hill during active underground mining operation leaving fresh exposure. *Photo January 2010.*

tin value than do country rocks. The sedimentary exhalative-type zinc-lead-silver deposits often show a primary pyrite halo.

The lithogeochemical survey is based on analysis of unweathered rock/individual mineral(s). Sampling on a uniform grid across a geological terrain includes several rock types from fresh outcrops, wall rocks, and drill cores. The rock chip consists of five to six small fragments that individually or collectively represent a sample. A sample weighing ~1 kg will be adequate. Primary halos play a significant role in discovering deep-seated hidden deposits, particularly having a supporting structure.

The key guiding factors in a lithogeochemical survey are:

1. Large concentration area with target elements ~10 times higher than background values.
2. Additive halo technique by adding all anomalous content of a group of indicator elements.
3. Multiplicative halo concept by ratio between the product of all economic elements and the product of impurity elements.
4. Vertical zoning of metal distribution.
5. Linear productivity, which is the product of width of anomaly with % content of economic element.
6. Anomaly ratio, which is the ratio of anomalous to background value.

FIGURE 5.12 Gossans are very common features as a surface exploration guide at Khetri copper belt, India. The dimension is small compared to Rajpura-Draiba belt.

5.4.4 Drift or Till Geochemical Survey

Drift prospecting is a broad term for sediments created, transported, and deposited under the influence of the moving ice of glaciers particularly in steep mountain terrain. The various sizes of rock fragments travel longer distances to form drift sequences. The size and shape of mineralized boulders along with stream sediments reveal the extent of transportation and to trace back the source of the parent deposit a few kilometers away at higher elevation. The deposits are classified as glaciofluvial gravels and sands, silts and clays, and till or moraine. Till is a favored sample medium for locating mineral deposits in glaciated terrain. The basal till sequence is studied for the presence of mineralized clasts, heavy minerals, and relative abundance of major, minor, and trace elements to assess potentiality. The sample density, depth, and method should be selected according to the needs of the exploration program. The concentration of oxidized ore minerals and their product of decomposition can be detected from fine fractions in the surface till. Portable reverse circulation drills are used for collection of till samples at depth and to determine the vertical and lateral variation in till geochemistry. The survey also traces the detrital dispersal of bedrock mineralization to the primary source. The activity components include collection of basal till sample, determination of ice flow history, and data interpretation.

Till geochemical exploration is extensively conducted in Canada (Thompson Ni—Cu—PGE and Bell copper deposit), North America (Eagle Bay Cu—Mo—Au—Ag deposit), Glenlyon and Carmacks Cu—Zn—Pb—Ag—Au deposits of Yukon-Tanana terrain, and Finland. Gorubathan massive multimetal deposit of Himalaya at Darjeeling district, India, was discovered by the presence of float-mineralized boulders in the downstream. The parent body was located a few kilometers uphill.

5.4.5 Stream Sediment Survey

The geochemical survey based on the chemical analysis of samples of an active stream sediment from drainage courses have long been used as an exploration tool. The composition of the stream sediment samples reflects the bedrock geology of the catchment area, overburden cover profile, and any contained metalliferous mineralization. The stream sediment survey is most widely practiced in all reconnaissance, prospecting, and detailed surveys of drainage basins. Many minerals, particularly sulfides, are unstable in stream/weathering environments, and greatly disperse as a result of oxidation and other chemical reactions. The greater dispersion means greater ability to discover an orebody from a greater distance.

The process motivates secondary dispersion of both ore and indicator elements. The elements move in solid and solution form to further distances within a drainage basin. The stream sediments usually comprise clastic and hydromorphic components that include clays, detrital fine-grained rock and mineral particles, inorganic colloids, organic matter, and iron and manganese coatings on clasts. The mobility of different elements will vary significantly. The detrital grains enriched in ore and indicator elements will be deposited downstream. The samples may lead to reach the mineralization target location following the "path" of increasing values upstream.

The samples represent the best possible composite of weathered and primary rocks of upstream catchment areas. The unconsolidated materials are in a state of mechanical transportation by streams, springs, and creeks. The initial sample density during reconnaissance survey will be as wide as sample 1 in 200 sq. km block size. The same will be planned as close as few meters during prospecting stage, following the course of natural stream. The initial location of the sample collection point upstream should be at least 50 m away from roads, habitations, and active and closed

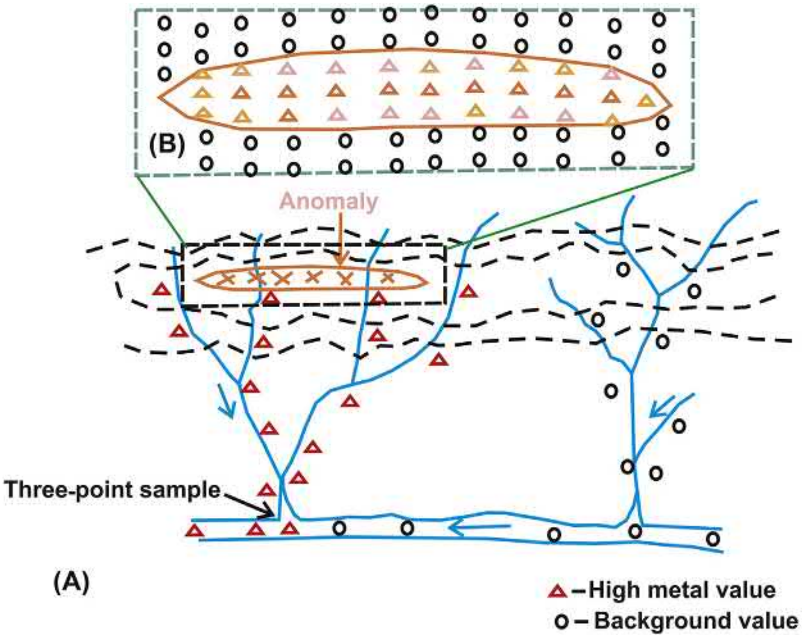

FIGURE 5.13 A schematic diagram showing (A) stream sediment sampling along the course of a water channel and three-point sample collection around the confluence and (B) detailed pit or soil samples for drill testing (*top inset*).

metal mine sites to avoid the obvious sources of contamination. The optimum size fraction varies in different environments and generally (−) 80 mesh size is recommended. The samples are collected in the dry season from natural sediment traps along stream courses (Fig. 5.13). The choice of samples from first-, second-, and third-order streams will depend on terrain, climate, and the nature of weathering of the region. Two sets of samples are collected at each location. One set undergoes panning for heavy mineral concentration. The other set is wet sieved at −200 mesh (−75 μm) or −80 mesh fraction. The second set is allowed to settle, and is decanted and transferred in high-quality plastic bags without any contamination, decanted again, and air dried before analysis.

The discovery of the large porphyry copper deposit of Bougainvillea, Papua New Guinea, gold deposits in British Columbia, lateritic nickel deposit of Sukinda belt, and diamond-bearing kimberlite deposit at Wajrakarur, India, by heavy mineral concentration are a few examples of a stream sediment survey.

5.4.6 Hydrogeochemical Survey

Groundwater and surface water signify distinctly different chemical and physical properties. Groundwater occurs in dug wells, springs, and boreholes indicating better potential in exploration geochemistry, particularly if it is acidic (low pH) to dissolve and transport metal elements like Cu, Pb, Zn, Mo, Sn, S,U, Ni, and Co caused by chemical weathering, oxidation, and leaching. Surface water from streams, rivers, and oceans has less dissolving power and fine-grained sediments adsorb much of the metal carried by water. Samples from stream water and sediments are collected simultaneously for analysis.

The water samples are easy to collect. About a liter of water is collected in a special quality container. Solubility of metals reduces with an increase of pH from 4 to 7. Therefore pH is recorded at the time of sample collection. Suspended solids are filtered before analysis. The elemental value changes with time and season. It is desirable to analyze samples within 48 h of collection. Samples cannot be preserved for future studies.

Hot springs are probable locations for B, Li, and Hg mineralization. Geochemical methods are applied to search for mineral deposits under sea water, e.g., manganese and phosphate nodules on the ocean floor. Water sampling is becoming a benchmark for information on the natural dispersion of toxic elements and for identifying pollution.

5.4.7 Vegetation Survey

A **vegetation survey** can broadly be grouped as (1) geobotany and (2) biogeochemistry. The vegetation survey will receive prominence as an exploration guide for the future as much of the world's mineral resources are hidden beneath vegetation (Colin, 2007).

5.4.7.1 Geobotany

Plants usually respond to the geological environment in which they grow, and may show characteristic changes with respect to form, size, color, growth rate, and toxic effects.

FIGURE 5.14 *Impatiens balsamina* or garden balsamor rose balsam (Balsaminaceae family) often grow over the outcrops of zinc-lead deposits and act as a natural geobotanical guide for mineral exploration as evidenced at Zawar belt, India.

Geobotany uses these environmental variations. It includes a survey to recognize the presence or absence of specific plant populations in a location, and is critically associated with particular elements. Alamine violet thrives only on zinc-rich soils in the zinc district of Central and Western Europe. *Viola calaminaria* sp. acts as an indicator plant for base metal prospecting. Prolific growth of *Impatiens balsamia* and *Nyctanthes arbor-tristis* (Seuli in Bengali) in rainy seasons, exactly over the outcrops of zinc-lead deposits at Zawar (Figs. 5.14 and 5.15), and *Leucas aspera* in the ancient mine dump of Rajpura-Dariba zinc-lead-silver deposit, India, are location-specific indicator plants. Sometimes the normal growth of certain plants sufferers from malformation or odd coloring caused by the excess presence of certain harmful toxic trace elements on or near the mineralization. The dwarfing of plants and the total absence of sal (*Shorea robusta*) over Kansa nickel deposit, India, are significant. In contrast, the same species is plentiful in the rest of the valley. Bryophyte moss has been a good indicator of uranium mineralization in the Siwalik sandstone of Himachal Pradesh, India.

FIGURE 5.15 Growth of *Nyctanthes arbor-tristis* or night jasmine or Seuli (Oleaceae family) often play the role of a geobotanical guide for the exploration of sulfide deposits at Zawar belt, India.

5.4.7.2 Biogeochemical

Biogeochemistry encompasses the collection and chemical analysis of whole plants, selected parts, and humus. The mobilized elements dissolve and enrich in soils during chemical weathering. As plants and trees grow, these dissolved elements, including metals, from soil are extracted by roots that act as a sampling agent. The elements migrate to various parts of the tree, such as roots, trunk, stem, and finally to leaves. The cycle is complete with leaves falling to the ground enriching the humus in metals (Fig. 5.16). Anomalies indicating buried mineralization can be detected by judicial selection of appropriate parts of plants (roots, bark, twigs, needles, and leaves) and subject to analysis.

The widely distributed plants of the same species, ages, and parts should be sampled from location to location and values compared for signs of anomaly. The samples should be washed thoroughly and dried before burning. The quantity should be large enough to generate adequate ash for trace element analysis. Artemisia (sagebrush) accumulates high copper in British Columbia and Pb, Zn, and Ba in Kazakhstan. *Curatella americana* L. is known to be a potentially reliable indicator tree for epithermal gold-quartz veins in Costa Rica.

5.4.8 Geozoological Survey

Humans and animals of certain territories suffer from specific diseases due to excess intake or deficiency of certain elements enriched in surrounding rocks and soils. The common transfer routes are through drinking water, milk, vegetables, and cattle feed grass from local areas. People suffering from arsenosis, arthritis, fluorosis, sclerosis, and goiter indicate anomalous trace elements of As, Cd, F, Hg, and I deficiency, respectively. The copper, zinc, and lead contents of trout livers have been used as pathfinder elements for mineralization.

5.4.9 Vapor Survey

Vapor surveys (atmogeochemical) help in locating buried deposits through detection of halos of mercury, helium, nitrogen, sulfur dioxide, hydrogen sulfide, hydrocarbon, radon, methane, and other gases and volatile elements, often at a considerable distance from the source of mineralization. The vapors can be detected from air, soils, and groundwater.

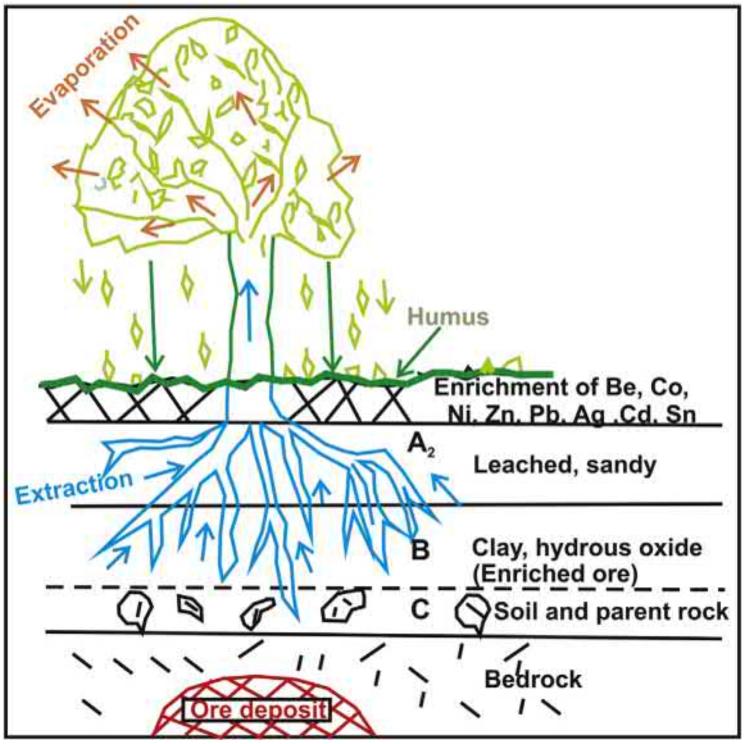

FIGURE 5.16 Schematic illustration showing growth of plants by extraction of metallic elements from soil and migration from root acting as a sampling agent to the leaves.

Volatile elements are released through oxidation of ore deposits. The common types of anomalies are as follows.

Mercury (Hg) vapor anomalies are determined over structurally controlled mineralization in arid terrain. Hg anomalies are associated with concealed deep-seated high-temperature geothermal systems, zinc-lead sulfide assemblages, hydrocarbon gas, and oil fields. Hg gas from soil can be sampled (Fig. 5.17) by precipitation of Hg as amalgam on extra pure noble metal foils (Ag) in a couple of hours and analyzed to suggest deep-seated sulfide mineralization (Talapatra, 2006).

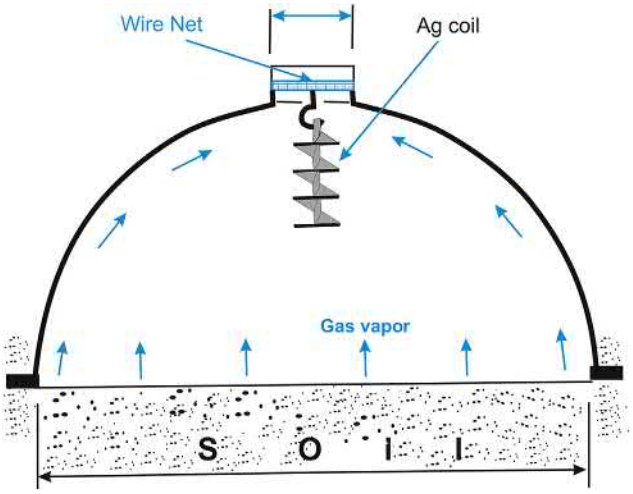

FIGURE 5.17 Vapor sampling instrument collecting subsurface metal elements from mineralization located at depth.

Helium (He) anomalies are produced by radioactive decay and are found over oil reservoirs, hot springs, porphyry copper, and uranium deposits. Samples from shallow depth of soil are collected and analyzed by mass spectrometry.

Nitrogen concentrations (anomalies) increase toward the center of hydrocarbon-bearing basins. Methane (CH_4), nitrogen, other natural gases, and asphalt (a sticky black and highly viscous liquid or semiliquid) are present in most crude petroleum basins and coal deposits. The bubbles of natural gases, crude oil, and hot asphalt from underlying oil and gas fields escape with high pressure to Earth's surface through fissures. The gas causes bubbles that make asphalt appear to boil. The release of gas and asphalt to the surface acts as a unique guide to locate and develop hydrocarbon (oil and gas) basins and coal fields. These features (Figs. 5.18 and 5.19) can be seen today at Rancho La Brea Lake Pits in front of Page Museum in the heart of Los Angeles, USA. The site represents one of the world's most famous fossil locations, trapped over 10,000 years ago, above the renowned 20th century petroleum-producing basin in Los Angeles County. Asphalt and methane appear under the surrounding buildings and require special operations for removal to prevent weakening the building foundations.

FIGURE 5.18 Oozing of hot methane and nitrogen gas bubbles from Rancho La Brea Tar Pits, Los Angeles County, one of the world's most famous fossil locations. The Pits are on the top of a crude oil basin discovered in 1900 followed by exploration and production from 1907.

FIGURE 5.19 Oozing of hot crude oil and shiny black asphalt to the surface (foreground) over the abandoned petroleum basin in front of Page Museum, Rancho La Brea, in the heart of Los Angeles County. The background is the lass green grass park for public recreation around the museum. *Author, Srishti and Srishta, reconnaissance tour, July 2010.*

SO_2, CO_2, and CS_2 are commonly found in soil over copper deposits and their wall rocks.

5.4.10 Electrogeochemical Survey

Electrogeochemical survey, CHIM (CHastichnoe Izvlechennye Metallov), in China, became well accepted during the 1970s for landscape geochemical prospecting around arid to semiarid regions with deeply weathered terrain (Keeling et al., 2006). The vertical dispersion of metal ions from deep-seated orebodies to the surface by electrochemical mass transport through rock capillaries can be identified by either soil or vapor sampling. However, the ionic concentrations are too feeble to be detected by traditional geochemical methods. The electrogeochemical technique is capable of collecting larger volumes of mobilized metal ions on electrodes placed in soil, and applying small currents for a sustained period (Fig. 5.20). The survey line set up over the expected hidden orebody is comprised of a series of specially coated carbon electrode pairs. The electrodes are placed at ~20 cm depth, ~60 cm apart, and covered by soil. The electrodes are connected with a 9 V DC battery and left for ~48−72 h. The electrode units are unearthed and absorbent coatings scaled out and digested in concentrated nitric acid for elemental analysis by inductively coupled plasma mass spectrometry (ICP-MS). Soil samples are collected from each electrode pit and analyzed by ICP-MS for comparison. Survey scan lines are shifted on either side along the strike direction of expected mineralization at intervals anywhere between 20 and 500 m depending on the stage of application.

This technique is often recommended to validate targets indicated by geophysical conductivity, prominence of Hg concentration, nonpedogenic calcrete anomalies, and shallow soil sampling before confirmation by expensive diamond drilling. It has successfully been tested for probing strike and depth extension for the concealed part of Challenger gold deposit in Australia and other deposits in the United States, Canada, and China. This method, together with Hg soil geochemistry, is effective for the selection of prospecting targets during reconnaissance for concealed ore beneath thick,weathered overburden. The technique has the advantages of being simple, rapid with high efficiency, and reproduced at relatively low cost.

5.4.11 Radiogenic Isotope Geochemistry

Radiogenic isotope geochemistry plays a significant role in modern-day scientific research for resolving the chronology of rock-forming events. Isotope geochemistry is an attribute of relative and absolute concentration of elements and their isotopes in Earth. Variations in the abundance of these isotopes can be measured by a **isotope ratio mass spectrometer**. The information reveals the age of rocks and minerals, or source of air and water. The study of isotopes is divided into: (1) stable isotope and (2) radiogenic isotope geochemistry. The stable isotopes are carbon (stable ^{12}C, ^{13}C, and radioactive ^{14}C), nitrogen (stable ^{14}N and ^{15}N), oxygen (stable ^{16}O, ^{17}O, and ^{18}O), and sulfur (stable ^{32}S, ^{33}S, ^{34}S, and ^{36}S).

Radiogenic isotope represents lead-lead isotope geochemistry. Lead has four stable isotopes, ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb, and one common radioactive isotope, ^{202}Pb, with a half-life of ~53,000 years. Lead is created in earth primarily via the decay of uranium and thorium. The most important ratio pertains to the daughter Pb isotope (^{206}Pb and ^{207}Pb) derived from the decay of radiogenic

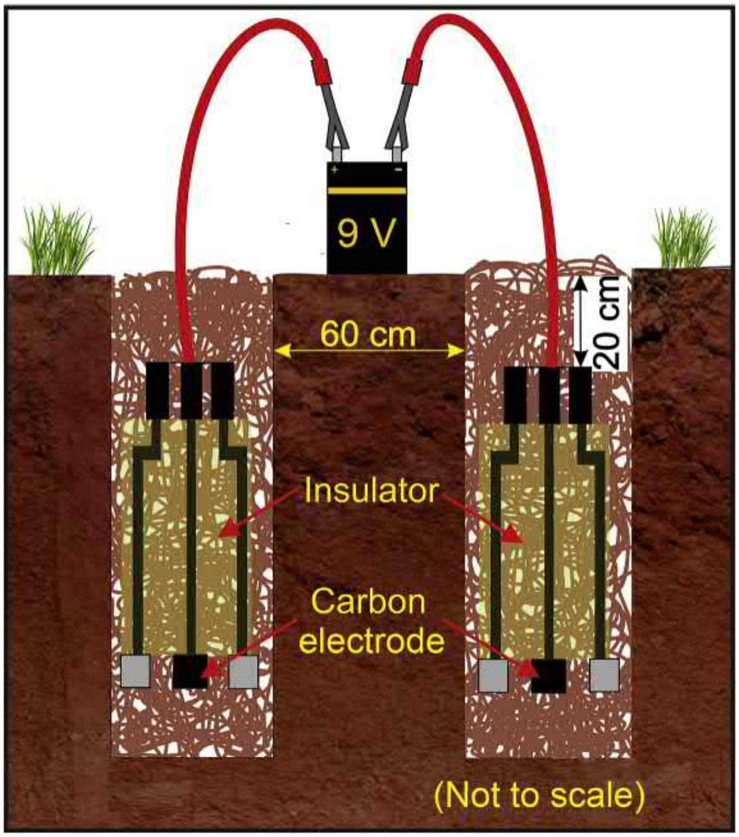

FIGURE 5.20 CHIM (CHastichnoe Izvlechennye Metallov) electrogeochemical survey is capable of collecting larger volumes of mobilized metal ions on electrodes placed in soil and applying small currents for a sustained period.

parent uranium (^{238}U and ^{235}U) and thorium isotopes (^{232}Th). The other radiogenic ratios are between Sm—Nd, Rb—Sr, and K—Ar systems. The samarium-neodymium isotope system can be utilized to provide a date, isotope signature, or fingerprint of geological and archeological finds (pots, ceramics). ^{147}Sm decays to produce ^{143}Nd with a half-life of 1.06×10^{11} years.

5.4.12 Heavy Mineral Survey

Heavy minerals like ilmenite, sillimanite, garnet, zircon, rutile, monazite, magnetite, titanium, chromite, cassiterite, diamond, gold, and platinum-palladium have a tendency to form onshore beach and offshore placer/ocean floor deposits. Prominent deposits occurring along the coastline of countries like India (Fig. 5.21), Indonesia, Malaysia, and Australia bordering the Indian Ocean are the largest marine resources in the world. The beaches in the east and west coasts of India are enriched with on- and offshore heavy mineral placer deposits, and are exploited economically. Sampling is conducted by collecting vertical columns of layered placer deposits at regular intervals. The isograde and isopach contours are drawn for the computation of reserves.

5.4.13 Polymetallic Polynodule Survey

"**Polymetallic polynodules**" (manganese nodules) are rock concretions on the sea floor formed by concentric layers of iron, manganese, and other high-value metals around a tiny core. The size of a fully developed nodule varies from a fraction of a millimeter to as much as 20 cm with an average size between 5 and 10 cm. Nodules are formed by precipitation of metals from sea water over several million years. Polymetallic nodules occur in most oceans of the world with the greatest abundance at the vast abyssal floor at depths between 4000 and 6000 m. Areas of economic interest have been identified in the north central Pacific Ocean, the Peru basin in the southeast Pacific, and the center of the north Indian Ocean. The most promising deposits with respect to resource and metal content occur between the Hawaii Islands and Central America in the equatorial Pacific Ocean.

Sample collection from prospective areas of the sea floor is discussed in Fig. 7.31. The worldwide resource has been estimated at 500 billion tonnes. The nodules are of greatest economic interest with metal contents varying between nickel (1.25% and 1.50%), copper (1.00% and 1.40%), cobalt (0.20% and 0.25%), manganese (~30%),

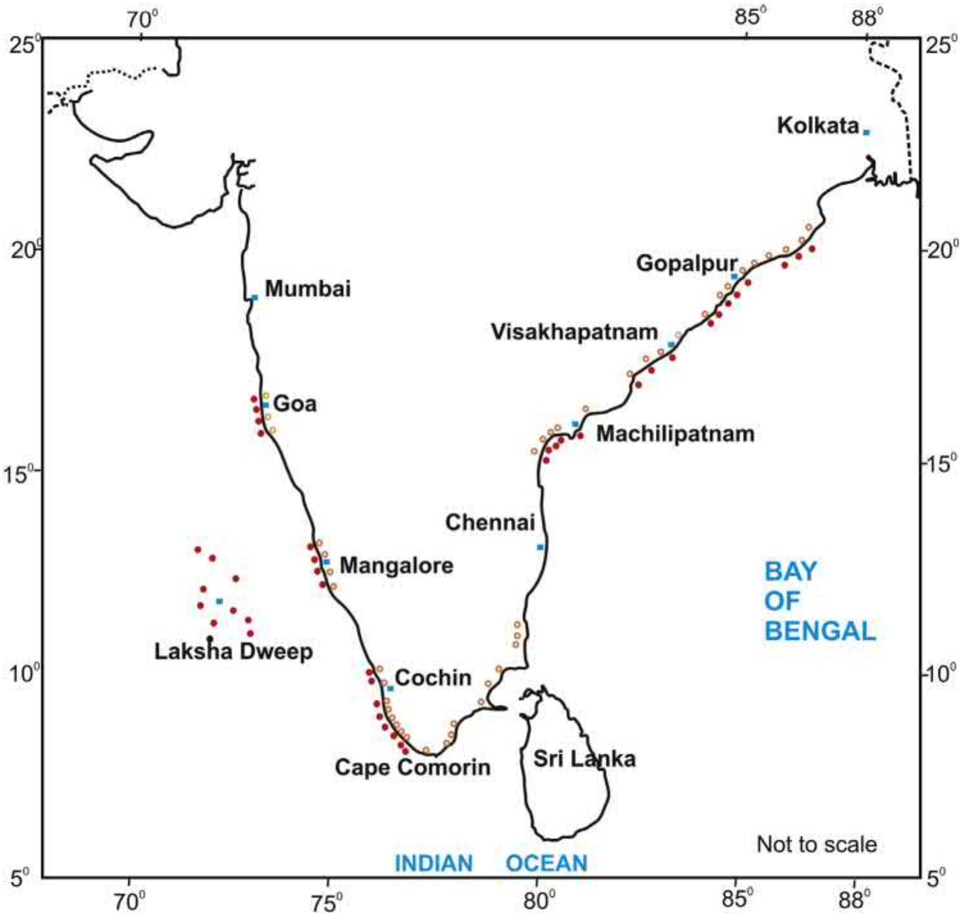

FIGURE 5.21 Heavy mineral placer deposits containing titanium, chromite, diamond, ilmenite, magnetite, monazite, rutile, zircon, garnet, and sillimanite along the Indian coastline.

iron (~6%), silicon (~5%), and aluminum (~3%), with lesser amounts of Ca, Na, Mg, K, Ti, and Ba.

Since 1970 research and development works were initiated to identify the best ocean bed nodule deposits, establishing mining and process route by prospective mining consortia comprised of federal and private companies from the UK, United States, Germany, Belgium, Netherlands, Italy, Japan, France, Soviet Union, India, and China. As a result many tonnes of nodules from abyssal plains (~5500 m depth) of the eastern equatorial Pacific Ocean were collected. Significant quantities of Ni, Cu, and Co were extracted from this ore using both pyro and hydro methods. However, the activities could not be commercialized due to excess availability of onshore nickel metal, anticipated ecological imbalance, and conservation of the natural resources for the future. The research continues.

5.4.14 Hydrocarbon Geochemical Survey

Oil and gas geochemical surveys are significantly suitable for surface exploration because the oil and gas fields are natural accumulations of volatile hydrocarbons. This is conceptually based on hydrocarbon genesis that originates mainly from degradation and thermal cracking of disseminated organic matter in sedimentary rocks (Ruan and Fei, 2000). The resulting liquid and gaseous hydrocarbons migrate and their accumulation in favorable geological traps (gas fields/reservoirs) is an inevitable product. The accumulated hydrocarbon is constantly dispersing laterally and vertically at slow speed.

Surface geochemical exploration presumes that oil or gas reservoirs leak petroleum and gas to the surface, and that these seeping hydrocarbons are likely to be related to possible reservoirs in the subsurface. The surface liquid and gas geochemical surveys along with available remote sensing and geological and geophysical data interpretation are effectively applied to surface lithology, including soil type and surface conditions as important indicators.

The surface geochemical survey of hydrocarbons is conceived in two broad-based sampling methods with focused objectives to detect and map seeps, and to relate them to prospects (Sundberg, 1994):

1. Microseepage survey method: where hydrocarbon seeping from a reservoir through a cap rock moves to the surface, and soil samples are collected, analyzed, and plotted as linear profiles or mapped in two dimensions for drill testing and programmed drilling.
2. Macroseepage characterization: where petroleum seepage is intense enough to allow a macroscopic quantity of hydrocarbon to be obtained, and offers a unique opportunity to characterize exploration targets prior to drilling.

The use of seeps and oozes in hydrocarbon exploration is widely accepted and practiced throughout the industry, mainly in the Philippines, Egypt, and North America.

5.5 REVIEW

Geochemical survey and sampling played a far-sighted role in mineral exploration long before the concept of mining, and continues much beyond the closure of mining operations. Baseline geochemical maps, at national and international levels, are generated by the multielemental study of soils and rocks at intervals on a scale of tens to thousands of kilometers covering Earth's surface (Carranza, 2006). The samples are analyzed for total range of trace elements (Ag, As, Au, Bi, Ca, Co, Cr, Cu, F, Fe, Hg, K, Mn, Mo, Na, Ni, Pb, Pd, Pt, Rn, Sb, Si, Te, Zn, etc.). The baseline maps depict regional spatial variation of elements, and aim at future mineral search and broad-based environmental issues. An entire range of geochemical techniques has been focused on with decision-making criteria based on site conditions, judgment, and previous experience during reconnaissance to closure of operations.

Geochemical exploration eventually works on real-time modeling—the ability to determine new sampling, drilling locations before moving the drill rig for target testing, infill drilling, need to redrill, and step-out decisions. This reduces lead times, which is especially important when the exploration season is short.

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Chapter 6

Exploration Geophysics

Chapter Outline

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00006-X

> *Neves-Corvo multimetal deposit, Portugal, hidden between 330 and 1000 m below the surface is an outstanding example of geophysical success in mineral exploration.*
>
> Author.

6.1 INTRODUCTION

Geophysics is a natural science that studies the physical process and properties of whole Earth from the deepest interior to the surface. The science of geology, geography, geochemistry, and geophysics together plays a significant role in earth science. The former two disciplines involve direct observations of rock exposures on surface, subsurface workings, and borehole cores. These are more often descriptive and qualitative. Geochemistry is partly a descriptive and mainly a quantitative study of elements. Geophysical tools often operate above the ground from aircraft or helicopters fitted with multisensors, or on the ground in general.

Geophysical studies are always quantitative relating to actual measurements based on the variation of response pattern or contrast of propagating waves passing through a non-homogeneous medium. The propagation parameters include seismicity, density, magnetic susceptibility, electrical conductivity, resistivity, and electromagnetic and radiometric radiance. The propagating wave reflects and refracts at the interface of rock types, structure, stratigraphic formation, and the presence of mineralization, water, oil, and gas. The measures of variation are with respect to either position of the objects, such as strength of magnetic field along a profile, or function of time, like the propagation of seismic waves. The data in both cases are presented as a graphical waveform (Fig. 6.1). The graphical waveform will represent physical variations in the underlying structure (“signal” of a mineral body) superimposed on undesired variations from nongeological features (“noise” due to the presence of electrical cables, rail lines, traffic vibrations, factories, and workshops). **Signal** is that part of the waveform that relates to the messages sought from geological features under investigation. **Noise**, random or coherent, is the other part of the waveform due to extraneous effects. **Anomaly** is a significant departure from the normal pattern of background values. The anomalies must be explained in terms of geological conditions indicating possible occurrences of causative bodies, rocks, structures, water, oil, gas, and mineral deposits.

The data collection, processing, interpolation, and interpretation of complex geophysical fields are cumbersome with computing limitations. The advent of digital computing during the second half of 20th century enhanced computing skills many-fold. The original data, generally a smooth continuous function of time or distance, need to be expressed in digital form by sampling the function at a fixed interval, and recording the instantaneous value of the function at each sampling point. The analog function of time f(t) or distance f(d) in its original form (magnetic, seismic, gravitational) can be converted to a digital function g(t) as shown in Fig. 6.2. The data in digital form can be easily processed by advanced software. The transformed digital data are represented by specified discrete values at a series of points at fixed intervals. The new waveforms are complex. Mathematical techniques, such as Fourier analysis, convolution, cross-correlation, and digital filtering, are applied to maximize the signal content making it useful for geological interpretation. Digital data processing and interpretation simulate an image or model of the subsurface structure.

Geophysical data are acquired from both airborne and ground bases. Airborne techniques operate from aircraft equipped with multiple sensors, e.g., cameras, gravitational, magnetic, electromagnetic, and radiometric antenna, an interfaced notebook computer, and using digital acquisition and automatic data quality control. Airborne methods

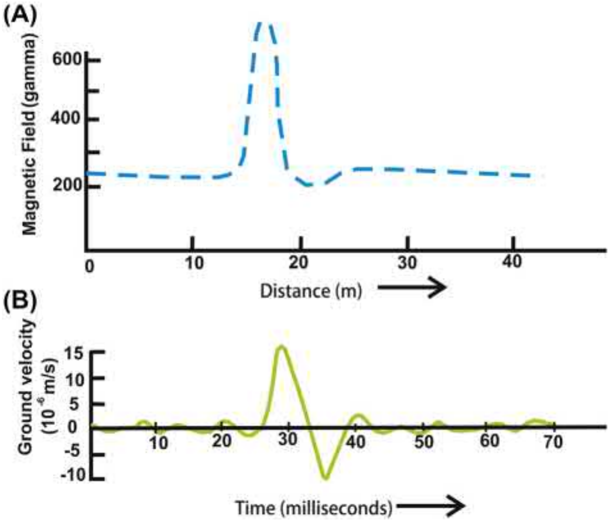

FIGURE 6.1 Graphical presentations of geophysical responses in waveform as a function of distance (A) or time (B).

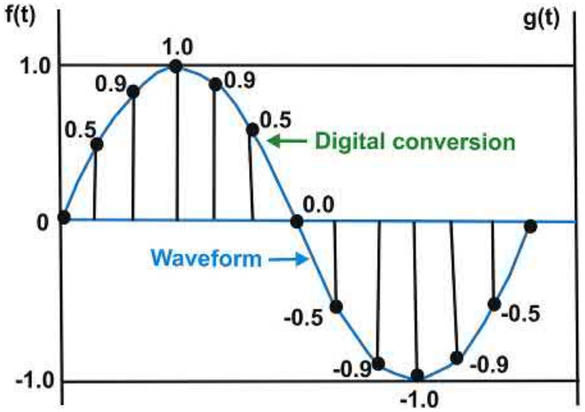

FIGURE 6.2 Digital transformation in waveform of geophysical responses for high-end computer processing.

TABLE 6.1 Geophysical Surveying Methods With Parameters and Properties Suitable for Type Deposits

Method	Measured Parameters	Operative Physical Property	Suitable Deposit Type
Seismic	Travel time of reflected and refracted seismic waves	Density and elastic mode	Coal, oil and gas, groundwater, layered sedimentary basin, Ni–Cu–PGE in volcanic basal flows (Dentith and Mudge, 2014)
		Velocity, acoustic	
Gravity	Gravity (measuring variation in Earth's gravitational field)	Density contrast between the surrounding host rocks	Massive sulfides, chromite, Ni–Cu–PGE, salt domes, barite, kimberlite pipes, concealed basins
Magnetic	Measuring spatial variation in Earth's magnetic field	Magnetic susceptibility	Magnetite-, ilmenite-, pyrrhotite-rich sulfides, Ni–Cu–PGE
Electrical			
1. Resistivity	Earth's resistance	Electrical conductivity	Groundwater, sulfide, Ni–Cu–PGE
2. Induced potential	Polarization voltage/frequency development of ground resistance	Electrical capacitance	Large sulfide dissemination, Ni–Cu–PGE, graphite
3. Self-potential	Electrical potential	Electrical conductivity	Sulfide veins, graphite, ground water, Ni–Cu–PGE
Electromagnetic	Response to electromagnetic radiation	Electrical conductivity and inductance	Sulfide, Cr–Ni–Cu–PGE ore, graphite
Radiometric	Gamma radiation	Gamma ray	Thorium, uranium, radium
Borehole geophysics and mise-à-la-masse	Downhole probe	All types	Continuity of sulfide, Ni–Cr–Cu–PGE in strike and depth

PGE, platinum-group elements.

in mineral prospecting begin with reconnaissance and large area prospecting outlining broad geological features for drill testing. Ground survey continues to the detailed prospecting stages to delineate probable shape size and prioritize the anomalies. Advanced geophysical borehole logging can establish orebody continuity in all directions during prefeasibility and mining operations.

Geophysical surveying is capable of providing a relatively quick and cost-effective way of locating subsurface hidden mineral deposits (Kavdia et al., 2015). However, it does not dispense with the necessity of drilling. The success of a mineral investigation program using geophysics will significantly depend on specialized training in instrumentation, capacity of depth penetration, mathematical interpretative skill, and experience of practicing geologists. It can optimize exploration programs by maximizing the rate of ground coverage.

Geophysical methods cover a wide domain of mineral investigation and are used in combination with geological and geochemical surveys for quality results. The various key procedures are listed in Table 6.1 and discussed in the literature (Sharma, 1986; Robinson and Coruh, 1988; Gerkens, 1989; Kearey et al., 2002; Ramakrishna, 2006; Dentith and Mudge, 2014).

6.2 SEISMIC SURVEY

6.2.1 Concept

Seismology is the science of earthquakes and studies the causes and effects from minute pulsations to the most catastrophic natural phenomenon inside Earth. The methods are classified into two divisions based on energy source of the seismic waves. **Earthquake seismology** is caused by natural shock waves of earthquakes and derives information on physical properties, composition, and the gross internal structure of Earth. **Explosion seismology** is the product of artificial blasts: (1) detonating a charge of dynamite (land) and (2) nonexplosive vibroseis or compressed air (marine) at selected sites to infer information about regional/local structures. This is extensively being applied to interpret the interfaces of rock boundaries, layered sedimentary sequences, location of water tables, and oil and gas exploration.

The survey works on the mode of propagation of waves in elastic media; more precisely, travel in rock media. The subsurface unit is assumed to be homogeneous and isotropic to simplify wave propagation resulting in basic interpretation of the measured effects at the plane of discontinuity.

6.2.2 Stress and Strain

The propagation of seismic waves causes redistribution of internal forces and deformation of geometrical shapes within a rock mass. The concepts of stress and strain are a result of these changes.

The internal forces appear inside a body and simultaneously try to recover the original configuration when it is deformed or strained. This balancing internal force or restoring force per unit area across a surface element "A" within the material created due to deformation is called **stress**. Stress is the force per unit area acting on a plane within a body.

Stress = (Internal or restoring force)/(Area) = F/A
The unit is dyne/cm^2.

Stress is **normal** when F is perpendicular to the plane of the area element. Stress is **tensile** or **compressive** depending on its direction from or into the object on which it acts. Stress is **shearing** when F is tangential to the area element.

Strain is the fractional change in length, area, and volume associated with deformation of Earth by tectonic stresses or passage of seismic waves. Strain is defined as the fractional changes in dimension being deformed per unit original dimension. It is unitless.

Strain = (Change in dimension)/(Original dimension)

The strain that causes only a change in shape with no change in volume is called a **shear or distortion strain**. A change in volume without a change in shape is **dilatation** or **contraction** strain. The strains that are associated with relative changes in length in the directions of respective stresses are called normal stress.

6.2.3 Elastic Moduli

The elastic properties of a material are described by certain clastic constants that quantitatively specify the relationships between different types of stress and strain. The velocity of an elastic wave traversing in homogeneous medium depends on a number of factors: Young's modulus, bulk modulus, rigidity or shear modulus, and Poisson's ratio. **Young's modulus** (E) is the ratio between longitudinal stress and longitudinal strain. **Bulk modulus** (K) is the ratio of uniform compressive stress to fractional change in volume. **Rigidity stress** (μ) is the measure of the stress/strain ratio in the case of a simple tangential stress. **Poisson's ratio** (σ) is a measure of the geometrical change in the shape of a clastic body.

6.2.4 Seismic Waves

Seismic waves from natural or artificial sources propagate outward as pulses. There are two groups of seismic waves: (1) **body wave** and (2) **surface wave**.

6.2.4.1 Body Wave

Body waves propagate through the internal volume of an elastic solid medium, and there are of two types: **compressional waves** and **shear waves**.

Compressional waves (longitudinal, primary, P-waves of earthquake seismology) are the fastest of all seismic waves. They propagate by compressional and dilatational uniaxial strains in the direction of wave travel through solid, liquid, and gas media. Body waves cause the compression of rocks when their energy acts upon them. A rock expands beyond its original volume when P-waves move past the rock, only to be compressed again by the next P-wave (Fig. 6.3A).

Shear waves (transverse, secondary, S-waves of earthquake seismology) carry energy through the earth in a very complex pattern. The particles of the medium vibrate about their fixed mean position in a plane perpendicular to the direction of wave propagation. They move more slowly than P-waves and cannot travel through the outer core because they cannot exist in fluids, e.g., air, water, and molten rock (Fig. 6.3B).

6.2.4.2 Surface Wave

Surface waves (Rayleigh and Love waves) travel only along a free surface or along the boundary between two dissimilar solid media. **Rayleigh waves** are formed when the particle motion is a combination of both longitudinal and transverse vibration giving rise to an elliptical retrograde motion in the vertical plane along the direction of travel. **Love waves** are a major type of surface wave having a horizontal motion that is shear or transverse to the direction of propagation.

The velocity of propagation of any body wave in any homogeneous, isotropic material is determined by the elastic moduli and densities of the material through which it passes. The traditional seismic survey uses only

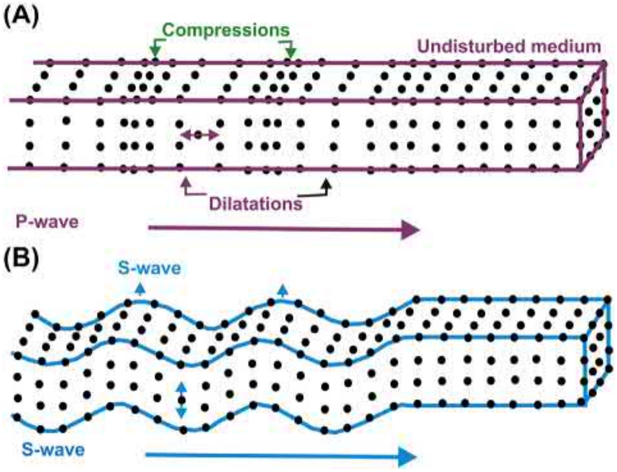

FIGURE 6.3 Propagation of (A) compressional or primary and (B) shear or secondary waves showing type of elastic deformation of ground particles.

compressional waves due to easy detection of the vertical ground motion in the detectors that becomes fast because of high-speed wave velocity. The recording of stress and surface waves provides greater information about the subsurface, but at a cost of greater data acquisition and consequent complex processing. The multicomponent survey is becoming more popular and useful.

6.2.5 Seismic Reflection and Refraction Method

Seismic reflection and refraction are frequently practiced methods for mapping subsurface structure in sedimentary formation in connection with coal, oil, and gas exploration. They follow the laws of reflection and refraction of optical waves in contact with two different media. Similarly, P- and S-seismic waves move uniformly from the source and reflect and refract on the boundary of a second medium with different elastic velocity. The energy is partly reflected and partly transmitted in a second medium (Fig 6.4).

A wave travels from source "S" and reflects at a point "R" of the interface at a thickness of "h_1" and arrives at the geophone "G" at a time interval of "T_x." The velocity "V_1" of the upper layer and depth "h_1" to the interface can be obtained mathematically by recording the reflection times at two distances (x, x′).

The information obtained by a single reflected pulse at one detector position is not enough to establish the existence of a reflecting horizon. In practice, stepwise shifting of the entire shot-geophone with a series of multitrack geophones placed at short intervals is used. A continuous mapping of the reflecting horizon is possible in this way (Figs. 6.5–6.7).

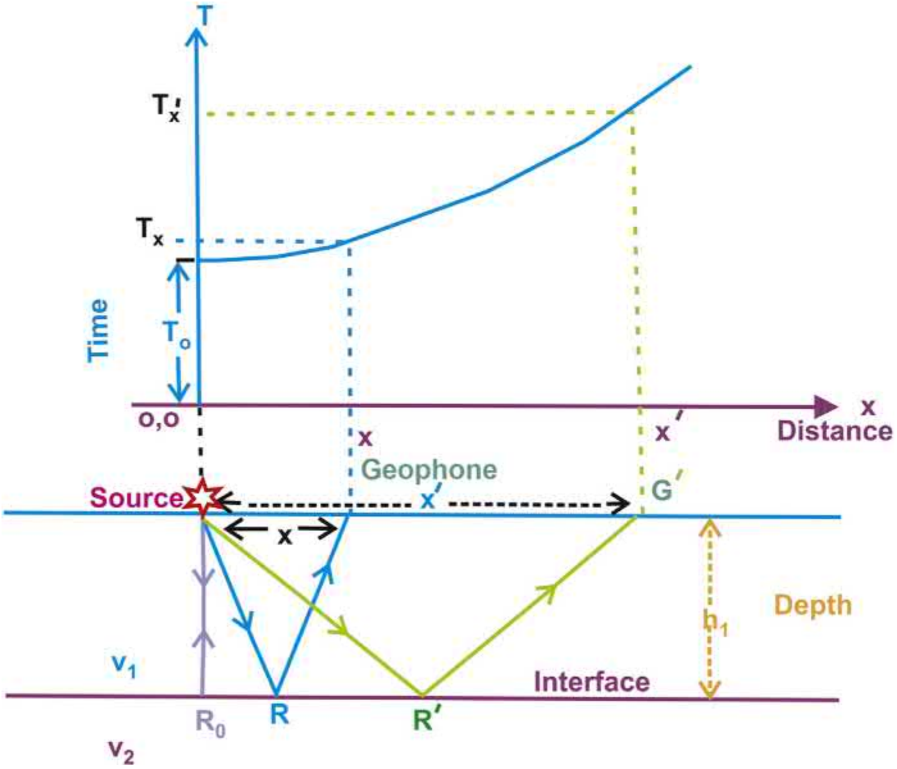

FIGURE 6.4 Method of seismic reflection profiling by time versus distance curve at media interface.

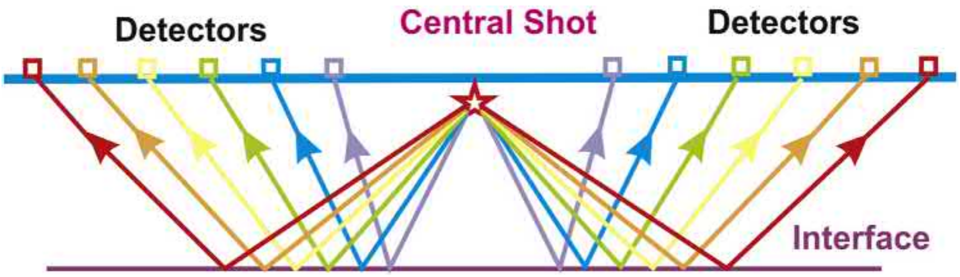

FIGURE 6.5 Multichannel seismic profiling between central shot and multiple detectors on either side.

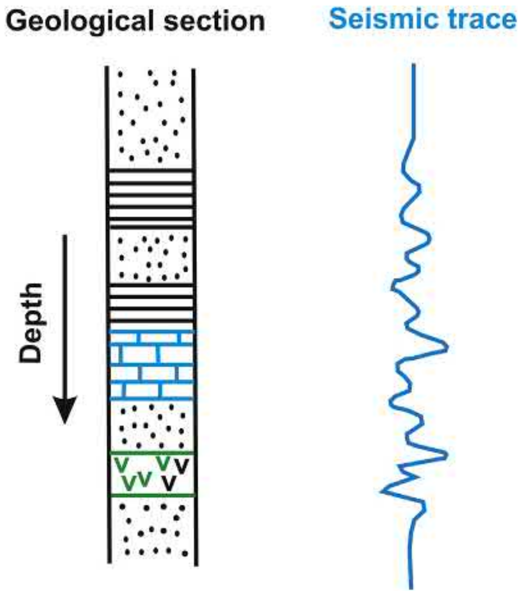

FIGURE 6.6 Seismic reflection profiling of subsurface geological formation.

The generation of artificial seismic waves involves explosion of a dynamite charge in a hole or a weight dropping. The truck-mounted mechanical vibrators (vibroseis) are used to pass an extended vibration of low amplitude into the ground with continuously varying frequency between 10 and 80 Hz. In marine seismic studies an electric or gas spark or air gun shot is used as energy source. The **seismometer** or **geophone** is a device to detect and receive seismic ground motion. It is an electromechanical device that converts mechanical input (seismic pulse) into electrical output, and finally produces a continuous graph (seismograph). The modern seismic survey simultaneously records ground motions received from all directions due to combinations of transverse and longitudinal waves by a three-component geophone (Fig. 6.8).

FIGURE 6.8 A three-component vertical 14 Hz "geophone" device for detection and recording of seismic reflection and refraction from subsurface interface.

6.2.6 Applications

The seismic survey can explain subsurface discontinuities, layering, and probable rocks/structures. It is suitable for the investigation of coal, oil and gas, groundwater, and massive metallic deposits. A 3D seismic survey outlined the basin configuration and resource estimate at Krishna-Godavari Basin, India, and a 2D seismic section mapping and establishment of a major structure for basement faults was applied successfully at Zeegt lignite coal mine in Mongol Altai coal basin. The other areas covered in metallic minerals are Munni Munni platinum-group element (PGE) deposit, Australia, Kevitsa Ni—Cu—PGE deposit, Finland, goldfields of Witwatersrand Basin, South Africa, and Bathurst zinc-gold Mining Camp, Canada. The ocean floor, otherwise unknown, was mapped precisely by marine seismic survey in the mid-20th century. The Mid-Atlantic Ridge at an average water depth of 5 km, and deep oceanic trenches in the Western Pacific, were discovered.

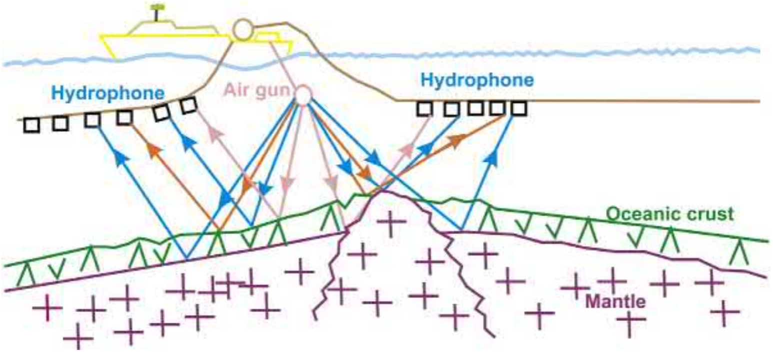

FIGURE 6.7 Schematic diagram of marine base underwater seismic reflection profiling.

6.3 GRAVITY SURVEY

6.3.1 Concept

The gravity survey investigates variation (gravity anomalies) in Earth's gravitational field generated by differences in density between subsurface rocks. Density variation is induced by the presence of a causative body such as salt domes, granite plutons, sedimentary basins, heavy minerals like chromite and manganese, and faults and folds within the surrounding subsurface rocks. The size of the anomalies primarily depends on the difference in density between host rocks and causative body, their geometrical form, and depth of occurrence. The method is capable of being surveyed from the ground, air, and in a marine environment.

6.3.2 Theory

Newton's law of universal gravitation states that a particle attracts every other particle in the universe using a force "F" that is directly proportional to the product of their masses (m_1 and m_2) and inversely proportional to the square of the distance (r) between their centers.

$$\text{Therefore } F \infty m_1m_2,\ F \infty 1/r^2.$$

$$F = (G \cdot m_1m_2)/(r^2)$$

$$G = (F \cdot r^2)/(m_1m_2)$$

where G is a universal gravitational constant (6.67×10^{-8} dyne cm^2/gm^2 in the centimeter–gram–second system), which is numerically equal to the force in dynes that will be exerted between two masses of 1 g each with centers 1 cm apart.

6.3.3 Unit of Gravity

The gravitational field is defined in terms of gravitational potential U. The potential U due to a point mass "m" at a given point "P" at a distance "r" from m is defined as the work needed by the gravitational force in moving a unit mass from infinity to the final position P. The measuring unit is Gal (after Galileo) (g/cm^3), which is strength of a gravitational field or unit of acceleration that will act upon a mass of 1 g with a force of 1 dyne. The value of gravity (g) has a worldwide average of 980 Gal on Earth's surface with a variation of 5.17 Gal from equator to pole. The field measuring unit used is milliGal (mGal*)* and the gravity unit = 0.1 mGal. 1 Gal is equal to 0.01 m/s^2.

Gravity anomalies result from the difference in density, or density contrast, between a body of rock and its surroundings. The density contrast $\Delta\rho$ is given by $\Delta\rho = \rho_1 - \rho_2$, for a body of density ρ_1 embedded in a material of density ρ_2.

6.3.4 Rock Density

The bulk density of a rock depends on its mineral composition, porosity, and fluid in pore spaces. The variation of one or all will change the density locally. Density is determined by direct measurement of samples in air and water. The difference in weight in air and water and volume of water displaced by immersing the sample provide the volume of the sample. The sample density is the weight of the sample in air divided by the weight of an equal volume of water. The densities of common rocks and ore minerals are given in Table 6.2.

6.3.5 Measurement Instrument of Gravity

The **gravimeter** is the measuring instrument of the gravitational field of Earth at specific locations. The instrument works on the principle of measuring constant downward acceleration of gravity. There are two types of gravimeters: absolute and relative. Absolute gravimeters measure the local gravity in absolute units (Gal). Absolute gravimeters are compact (Autograv CG-5 model) and used in the field. They work by directly measuring the acceleration of a mass during freefall in a vacuum. An accelerometer is rigidly attached to the ground.

TABLE 6.2 Densities of Common Rocks and Minerals

Rocks	Density (10^3 kg/m^3)	Minerals	Density (10^3 kg/m^3)
Alluvium	1.96–2.00	Cassiterite	6.80–7.10
Amphibolites	2.79–3.14	Chalcopyrite	3.90–4.10
Anorthosite	2.61–2.75	Chromite	4.30–4.80
Basalt	2.70–3.20	Coal	1.11–1.51
Clay	1.63–2.60	Galena	7.40–7.60
Dolomite	2.28–2.90	Gold native	19.30
Gabbro	2.85–3.12	Gypsum	2.30–2.80
Gneiss	2.61–2.99	Hematite	5.10
Granite	2.52–2.75	Magnetite	4.90–5.20
Limestone	2.60–2.80	Mercury native	13.60
Peridotite	3.10–3.40	Platinum naive	14.00–19.00
Quartzite	2.60–2.70	Pyrite	4.90–5.20
Rhyolite	2.40–2.60	Pyrrhotite	4.50–4.80
Sandstone	2.05–2.55	Silver native	10.10–11.10
Schist	2.50–2.90	Sphalerite	4.10–4.30
Shale	2.06–2.66	Quartz	2.59–2.65

Relative gravimeters are extremely sensitive, specially assembled, spring-based instruments carrying a fixed mass (m). The principle is that the changes in gravity will result in a change in weight of fixed mass g(m + δg) with change of location. Thus the length of the spring will differ slightly (Fig. 6.9) with change of location. The spring extension is recorded by suitable optical, mechanical, or electrical amplifications with high precision. The gravimeter is calibrated at regular intervals at a base station where the absolute value of gravity is known. Absolute gravity values at survey stations are obtained with reference to the International Gravity Standardization Network.

The progressive spacing of instruments in a gravity profile (Fig. 6.10) changes from a few meters in mineral investigation to several kilometers in a regional reconnaissance survey. In the case of rapid change in gravity field the station density must be increased for precise interpretation of gravity gradient. The data sheet contains date, time, location, elevation, water depth, and gravimeter reading for each survey station.

The Worden gravimeter is a widely used instrument. It is a compact temperature-compensated unit with a precision level <0.1 mGal. This shipborne system is extensively used in marine gravity surveys for mapping the ocean floor. Satisfactory tests of airborne helicopter gravity surveys are receiving prominence.

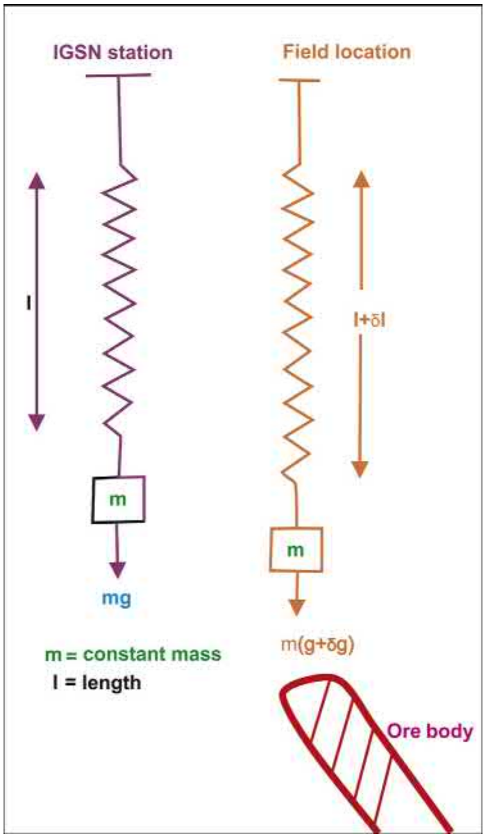

FIGURE 6.9 Schematic diagram showing the principle of a stable relative gravimeter survey in the field. *IGSN*, International Gravity Standardization Network.

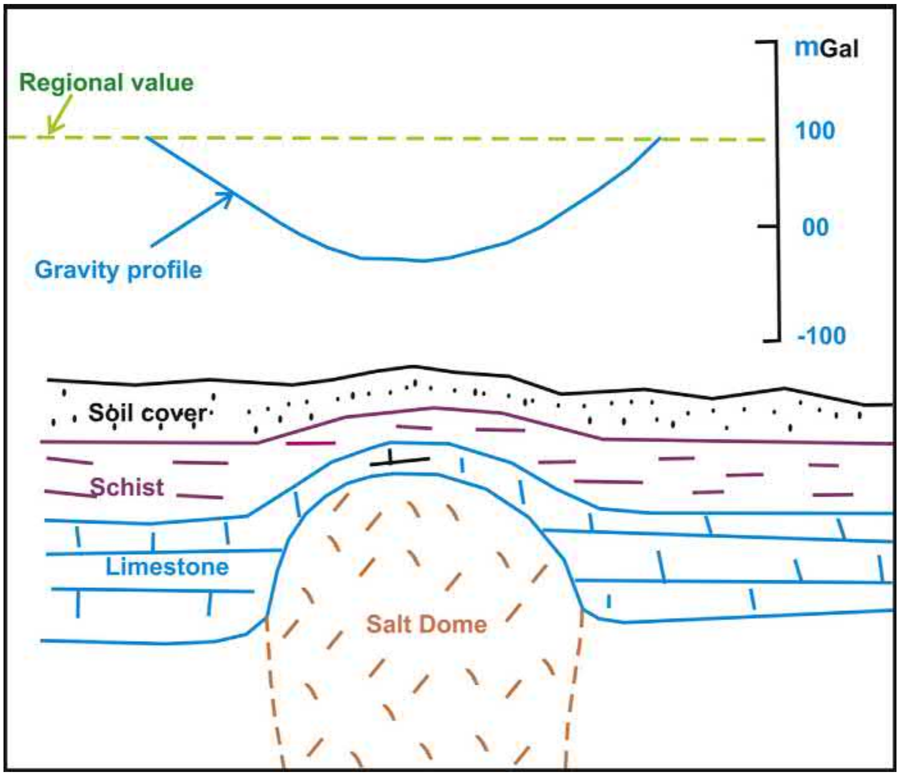

FIGURE 6.10 Gravity profile across a buried salt dome showing lower density compared to the surrounding country rocks.

6.3.6 Gravity Reduction

Gravity reduction is routine correction of field gravity contrast data between an arbitrary reference point and a series of ground stations influenced by extraneous effects not related to subsurface geology. No interpretation should be attempted before correcting field data.

6.3.6.1 Drift Correction

Drift correction occurs due to the poor quality of the spring and change of temperature during the recording period. Instrumental drift is corrected by repeated readings at a base station at a fixed time interval throughout the day. The drift correction at time "t" is "d."

6.3.6.2 Latitude Correction

Earth is a nonspherical body with equatorial bulging. Points near the equator are farther from the center of mass of Earth than those near the poles, causing gravity to increase from the equator to the poles. The correction is subtracted from, or added to, the measured gravity contrast, depending on whether the station is at higher or lower latitude than the base station.

6.3.6.3 Elevation Correction (Free Air)

Newton's law of inverse square dependence on distance causes the vertical decrease in gravity of the survey point with increase in elevation in air from the center of Earth. An amendment factor is used in gravitational surveys to decrease the force of gravity with increasing altitude. It assumes interference of air between the observation point and sea level, and is equal to -0.3086 mGal per meter above sea level. This correction is added to the measured gravity difference if the survey station lies above the datum plane and vice versa.

6.3.6.4 Elevation Correction (Bouguer)

Bouguer correction removes the effect of gravitational pull as a function of change in elevation by approximating the horizontal rock layer present below the observation point. The extra mass beneath an object located at a high elevation (on top of a mountain) causes a higher amount of gravitational force. If the strength of gravity at sea level is known, then its actual value at higher elevations can be approximated using the Bouguer correction. Bouguer correction is mathematically expressed as (0.4186 "g" "h"), where "g" is the assumed average density of Earth and "h" is the difference in altitude between the place where the gravity is known and where it is being measured. This value is added to the gravity at the lower location to yield an approximation of its value at the higher elevation.

6.3.6.5 Elevation Correction (Terrain)

Elevation correction or **terrain correction** accounts for the topographic relief in the vicinity of the gravity station. The effects are always positive. It is low in flat areas and high in steep-sided valleys and at the top of cliffs and summits of mountains.

6.3.6.6 Tidal Correction

The periodical gravitational effects of the Sun and Moon create Earth's tides in the same way as ocean tides behave due to celestial attraction. The effect is considerably smaller than the ocean tides. The distance between the observation point and the center of Earth will vary periodically by a few centimeters because of the combined effect of the Sun and Moon. This is known as tidal variation and needs correction for high-precision surveys.

6.3.7 Applications

Gravity surveys are used either alone or in combination with magnetotelluric, magnetic, and induced polarization and resistivity surveys to determine the location and size of the major source structures containing accumulations of hydrocarbons, massive base metal deposits, iron ore, salt domes, and hydrogeological aquifers.

An outstanding application of a gravity survey is the discovery of deep-seated Neves Corvo massive multimetal sulfide orebodies. There was no surface signature. The ground gravity survey during 1973 over the Portuguese part of the Iberian pyrite extension indicated strong positive anomalies that rapidly varied at regional background. The first few target drillings were discouraging, and operation was suspended. Exploration drilling renewed due to convincing Bouguer anomalies after a time gap of a year and a half. The fifth drill hole was successful and intersected four concealed Cu—Zn—Pb—Sn orebodies (Neves, Corvo, Graca, and Jambual) at a vertical depth of 330 m from the surface. Other examples include Bushveld Cr, South Africa, Kola Peninsula PGE, Russia, and Sukinda-Nausahi Cr—Ni, India.

6.4 MAGNETIC SURVEY

Magnetic survey is the oldest and most widely used geophysical tool in mineral exploration for investigation of iron ore, magnetite, ilmenite, pyrite- and pyrrhotite-rich sulfide, and Ni—Cu—PGE deposits. The magnetic method is a passive method since it only measures the existing magnetic field strength and does not amplify or modify it. The magnetic methods are more popular in mineral exploration because the magnetic data can be quickly recorded from the air in conjunction with other geophysical surveys. The airborne potential field surveys provide regional coverage of large areas at a comparatively low cost in the shortest time.

6.4.1 Concept

The investigation of subsurface geology based on anomalies in the geomagnetic field resulting from varying magnetic properties of underlying rocks and minerals is the basic principle of magnetic survey. The directional properties of magnetite-rich rock (lodestone) were discovered centuries before Christ. This was modified with knowledge of Earth's magnetic field or geomagnetism and its directional behavior between the 12th and 16th centuries. The quantification of directional properties of geomagnetism and local anomalies with growing sophisticated instrumentation became increasingly significant for mineral prospecting during the 18th century onward.

Magnetic surveying for mineral investigation with high-precision instruments can be operable in air (airborne), sea (marine), and land (ground). Airborne survey is appropriate for scanning large areas during reconnaissance to delimit target areas for detailed ground survey during the prospecting stage. The process is rapid and cost effective. A "bird" is used as a magnetic sensor fixed to a string in the tail of an aircraft. A "fish" is used to tow a sensor behind a ship to remove the magnetic effect of the vessel. It is effective for investigation of ocean floor polymetallic nodules. The ground magnetic survey is suitable for prospecting over relatively small areas previously defined as targets by airborne surveys.

6.4.2 Theory

A magnetic field or flux density develops around a bar magnet. It flows from one end of the magnet to the other. The flux can be mapped by sprinkling iron filings over a thin transparent sheet set over a bar magnet or by a small compass needle suspended within it. The curve orientations of iron filings or magnetic needle are called **lines of force** that converge to points at both ends of the bar magnet. These points are located inside the magnet, are referred as **poles**, and always occur in pairs. A freely suspended bar magnet similarly assumes a position in the flux of Earth's magnetic field. The pole that aligns to point in the direction of the geomagnetic north pole is called the **north-seeking or positive pole**. It is balanced by a **south-seeking or negative pole** of identical strength at the opposite end of the magnet. The lines of force always diverge from north or positive pole and converge to south or negative pole (Fig. 6.11).

The magnetic field "B" or flux density due to a magnetic pole of strength "m" at a distance "r" from the pole is expressed as the force exerted on a unit positive pole at point "P." It is defined as:

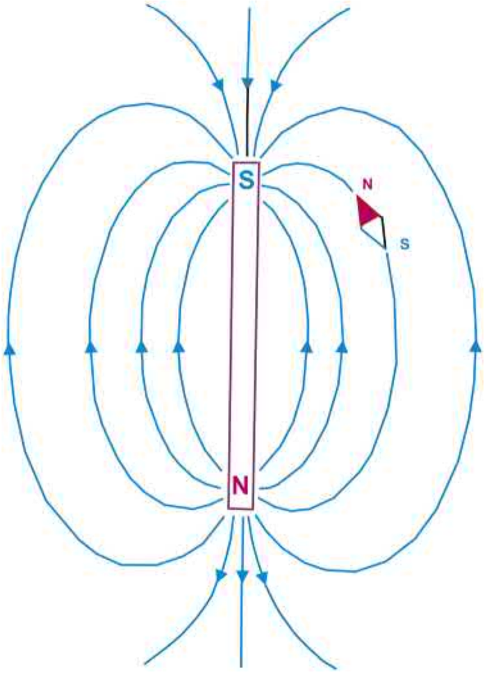

FIGURE 6.11 Lines of forces caused by a bar magnet always diverge from north or positive pole and converge to south or negative pole.

$$B = (\mu_0 \cdot m)/(4\pi \cdot \mu_R \cdot r)$$

where μ_0 is the constant corresponding to magnetic permeability of a vacuum and μ_R is the relative magnetic permeability of the medium separating the poles.

The unit of measurement of magnetic intensity is gamma (γ), which is equal to 10^{-9} T or nT (nanotesla). The total magnetic intensity of Earth in the polar region is 60,000 γ or 60,000 nT, and at the equator it is 30,000 γ.

6.4.3 Earth's Magnetic Field

Earth possesses the property of a huge magnet with north and south geomagnetic poles aligned 11.5 degrees away from the geographical North Pole (to the west) and South Pole (to the east). The orientation of a freely oscillating magnetic needle at any point on Earth's surface depends on the direction of the geomagnetic field at that point. The geomagnetic field, "F," at any point has few elements to represent its magnitude and direction. The components are a vertical (Z), horizontal (H), declination (D), and inclination (I) as shown in Fig. 6.12. Declination is the angle between magnetic north and true or geographic north. Inclination (I) is the angle of F with respect to the horizontal component H. Magnetic anomaly is caused by the superimposed presence of magnetic minerals and rocks on the normal geomagnetic field at that location.

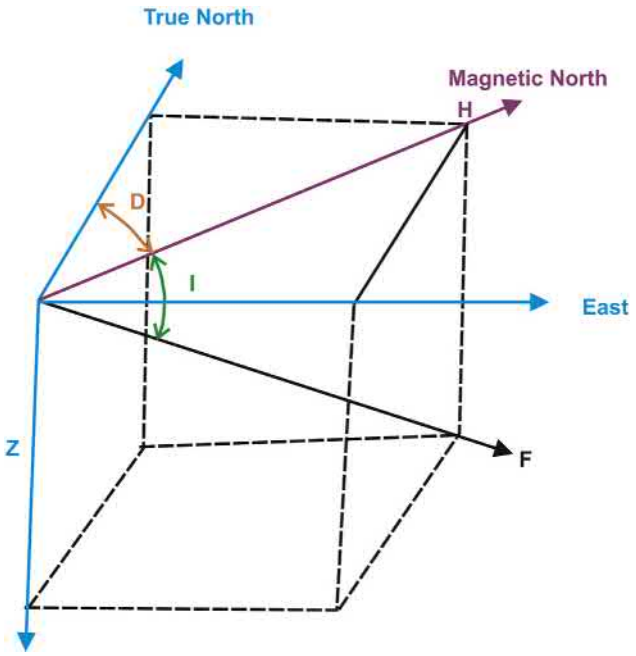

FIGURE 6.12 Schematic diagram of geomagnetic elements showing the declination (D) and inclination (I) of the total field vector F.

6.4.4 Rock Magnetism

The magnetic susceptibility of rocks depends mainly on the proportion of rock-forming minerals. The most common rock types are either nonmagnetic or very feebly magnetic. Rocks develop a susceptibility to magnetism with a higher proportion of magnetic minerals like magnetite, ilmenite, and pyrrhotite. Mafic/ultramafic rocks are usually more magnetic due to higher content of magnetite than acidic igneous rocks. Metamorphic rocks vary in magnetic property. Sedimentary rocks in general are nonmagnetic unless locally enriched with magnetite, ilmenite, and pyrrhotite-magnetite-bearing sulfide deposits.

The common causes of magnetic anomalies are intrusion of mafic and ultramafic dykes, sills, lava flows, and magnetic orebodies. Amplitude varies between as low as 20 nT in limestone and 800 nT in mafic igneous rocks to more than 6000 nT over sulfide orebodies. Magnetic susceptibility caused by variation of rocks or orebodies is superimposed on the geomagnetic field at that location. Magnetic anomaly is the response signaled by the causative body over regional trends of country rocks.

6.4.5 Survey Instruments

A magnetic survey instrument used during the early 1900s to measure geomagnetic elements was the **magnetic variometer**. It was essentially based on principles of a suspended bar magnet in Earth's field. Since then, instruments are updated to be user friendly and compatible with computer-based processing for easy interpretation with a precision of ±0.1 nT.

FIGURE 6.13 User-friendly proton magnetometer device compatible to high-end processing with precision.

The fluxgate magnetometer was developed during the 1940s and employs two identical ferromagnetic cores of high permeability that provide instantaneous measurements. The instrument is developed following either "nuclear precision" or "proton Precision" (Fig. 6.13), and consists of a container filled with liquid rich in hydrogen atoms surrounded by a coil. The next-generation instruments with higher precision are the optically pumped potassium or alkali vapor magnetometer and the magnetic gradiometer suitable for airborne, ground, and marine surveys.

6.4.6 Data Reduction

The reduction of magnetic data is essential to remove noises caused by other elements not related to subsurface magnetism. The effect of **diurnal variation** on ground surveying can be removed by periodic calibration of instruments at a fixed base station. Similarly, an aeromagnetic survey can alternatively be assessed by arranging numerous crossover points in the survey path (refer to Fig. 6.20). Geometric correction is computed by using the International Geomagnetic Reference Field, which defines the theoretical undisturbed magnetic field at any point on Earth's surface. Terrain correction is rarely applied in magnetic survey due to the negligible effect of vertical gradient of the geomagnetic field.

6.4.7 Applications

Magnetic survey is extensively used for metallic mineral investigation, particularly for iron ore with a higher ratio of magnetite to hematite. It is capable of locating massive sulfide deposits, especially in conjunction with the electromagnetic method (Section 6.6). Aeromagnetic surveying should preferably be programmed at a low-level flight path

(100−200 m above ground) avoiding excessive monsoon, peak summer, and foggy weather. The depth of penetration of an airborne survey will depend on the capacity of the instruments. In a ground survey, traverses are designed across a strike of the formations at a line interval less than the width of the expected causative body. Magnetic anomalies caused by shallow objects are more easily detectable than deep-seated targets. Airborne magnetic and geomagnetic surveys with advanced configuration systems, both in frequency and time domain, with high penetration capacity can identify deep-seated metallic bodies. Application of the system requires a considerable increase in bandwidth of both helicopter-borne frequency-domain electromagnetic and fixed-wing time-domain electromagnetic (TDEM) systems.

Depth estimates from aeromagnetic data can determine values for broad areas, such as the thickness of the sedimentary section in an oil and gas reservoir basin or at a limited number of points within the basin.

Interpretation of 2D and 3D isocontour maps of corrected magnetic data provides a qualitative existence of orebodies. The approximate location and horizontal extent of causative bodies can be determined by studying the relative spreads of the maxima and minima of anomalies. A comparison of gravity and magnetic interpretation of rich sulfide orebodies is given in Fig. 6.14. Similar studies will be applicable for the Ni-PGE-Cu belt, Sudbury Camp, Canada.

6.5 ELECTRICAL SURVEY

6.5.1 Concept

Geoelectrical methods of mineral investigation depend on the properties of conductivity and resistivity of subsurface rock mass to passing electric current. Methods include either introduction of artificially generated current through ground or the use of a naturally occurring electrical field within Earth. The current is propagated through a pair of electrodes connected to the transmitter terminal. The resulting ground potential distribution is mapped by using another pair of electrodes connected to a sensitive voltmeter. The potential distribution and lines of electrical flux can be measured by the magnitude of current introduced and the variation in the receiving electrodes in a homogeneous subsurface. The current deflects and distorts the normal potential in inhomogeneous conditions in the presence of electrically conductive or resistive objects. The better conductive causative mineral bodies are massive sulfide deposits, graphite-rich beds, and fractured/altered zones with confined water containing dissolved salts and clay. Massive quartz veins are highly resistive to current flow.

Three different types of geoelectrical methods are in use based on the type of current sources and response to subsurface rocks: (1) resistivity, (2) induced potential, and (3) self-potential.

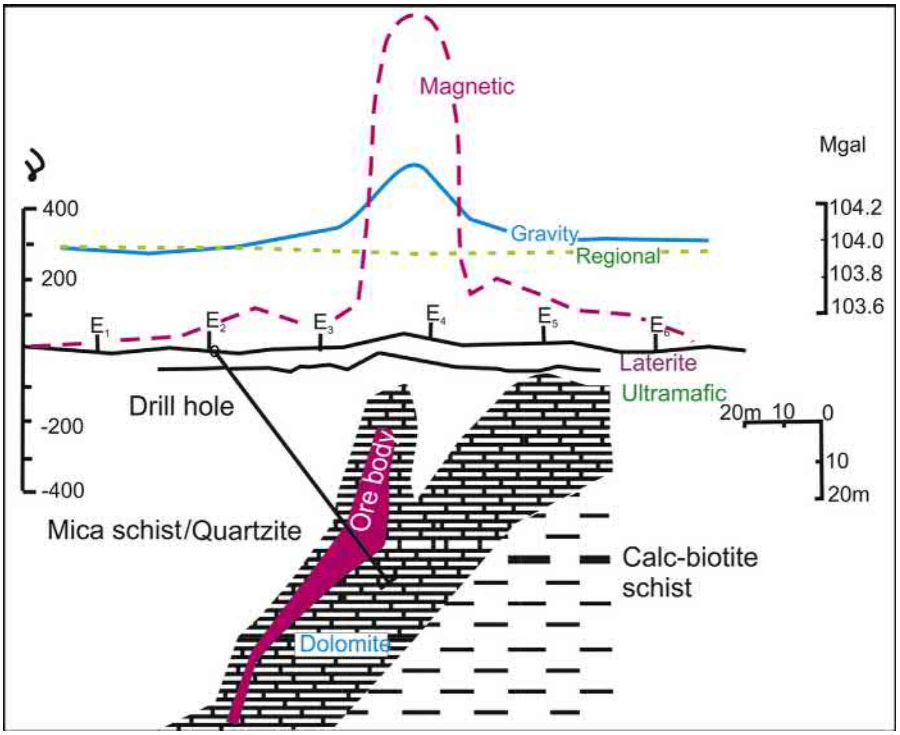

FIGURE 6.14 Geophysical interpretation of gravity and magnetic anomalies, and confirmed by drill testing of rich sulfide orebody in Rajasthan.

6.5.2 Resistivity Method

6.5.2.1 Definition

The property of electrical resistance of a material is expressed in terms of its resistivity. It is defined as the resistance between opposite faces of a unit cube. Resistivity is one of the extremely variable physical properties of rocks and minerals. Certain minerals, native metals, and graphite conduct electricity via the passage of electrons. Most rock-forming minerals are insulators. Hard compact rocks are usually bad conductors of electricity. The electric current is carried through a rock by the passage of ions in pore waters. Porosity and degree of saturation govern the resistivity of rocks. Resistivity increases as porosity decreases.

An artificially generated electric current is introduced into the ground and resulting potential differences (volts) are measured at the surface. Deviations from the background pattern of potential differences indicate inhomogeneities and the presence of anomalous objects in the subsurface.

6.5.2.2 Electrode Configuration

Various electrode configurations are designed for field practices using different linear arrays. In a Wenner array, four electrodes (current, C_1-C_2, and potential, P_1-P_2) are kept along a straight line at an equal array spacing, "a." In a Schlumberger array the distance between potential electrodes (2l) is small compared to the distance between the outer current electrodes (2L). In a dipole/dipole array configuration the potential probes, P_1-P_2, are kept outside the current electrodes, C_1-C_2, each pair having a constant mutual separation, "a." The current source is treated as an electric dipole if the distance between the two pairs, "na," is relatively large (Fig 6.15).

6.5.2.3 Field Procedure

There are two types of resistivity surveying: vertical electrical sounding and constant separation traversing.

Vertical electrical sounding or **electrical drilling** retains current and potential electrodes along a straight line at the same relative spacing around a fixed central point. It presumes that current penetrates continuously deeper with increasing separation of current electrodes. The electrical sounding infers variation of resistivity with depth from a given point on the ground for near-horizontal layers of formation below. The method is useful for determining loose horizontal overburden thickness over hard rocks in river valleys and groundwater projects.

Constant separation traversing is obtained by progressively moving an electrode spread with fixed electrode separation along a traverse line, the electrodes' configuration being aligned either in the direction of traverse (longitudinal) or at right angles to it (transverse).

6.5.2.4 Resistivity Survey Instruments

Resistivity survey instruments measure very low levels of resistance with high accuracy. Most resistivity meters

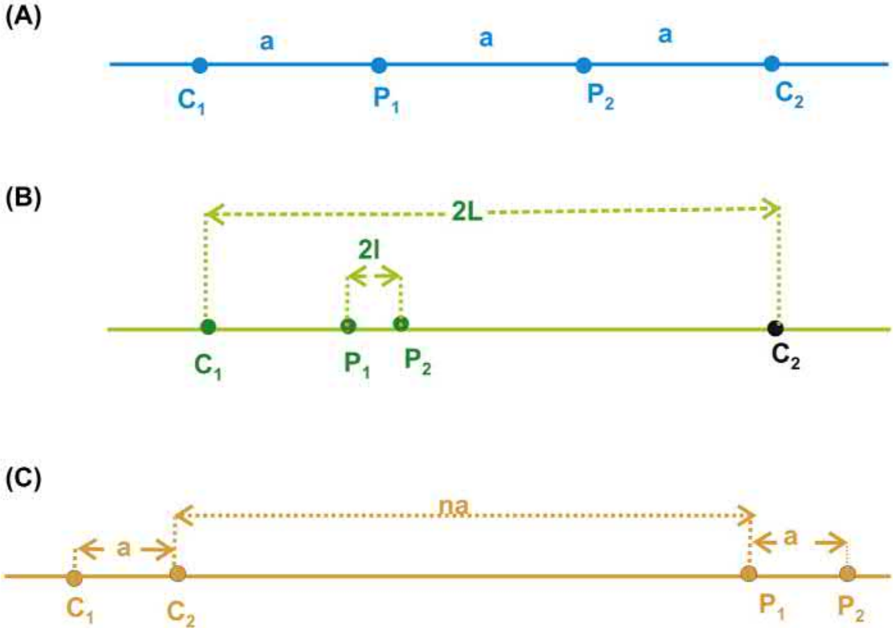

FIGURE 6.15 Schematic diagram showing common types of electrode configuration in resistivity surveying: (A) Wenner, (B) Schlumberger, and (C) dipole/dipole.

employ a microprocessor-controlled low-frequency alternating current source (between 100 Hz for shallow probes around 10 m and less than10 Hz for 100 m penetration). The direct current source along with nonpolarizing electrodes is suitable for greater depth penetration of hundreds of meters in favorable ground conditions. The unit of resistivity is the ohm-meter (ohm m or Ω m).

Electrical resistivity equipment is light, portable, inexpensive, flexible, and available at minimal fixed expense. The qualitative interpretation of the data is rapid and straightforward.

6.5.2.5 Applications

The resistivity survey was not initially favored during reconnaissance due to the slow process of manually planting electrodes before each measurement. This restriction could be complemented by increasing the availability of noncontacting conductivity measuring devices (electromagnetic survey). This is widely used in hydrogeological investigations covering subsurface structure, rock types, and water resources for drilling, engineering geological investigation sites before construction, and exploration of sulfide deposits (Fig. 6.16).

6.5.3 Induced Polarization Method

6.5.3.1 Definition

Induced polarization is an imaging technique that identifies electrical chargeability of subsurface materials (orebodies). The electrochemical voltage does not drop to zero instantly when externally applied direct current, connected through a standard four-electrode resistivity spread, is switched off abruptly (t'_0). The voltage dissipates gradually to zero at t'_3 after many seconds with a large initial decrease (Fig. 6.17). Similarly, the initial voltage jump at t_0 and a slow increment take place over a time interval ($t_1 - t_2$) before the steady-state value is reached (t_3) when the current is switched on. The ground acts as a capacitor, storing

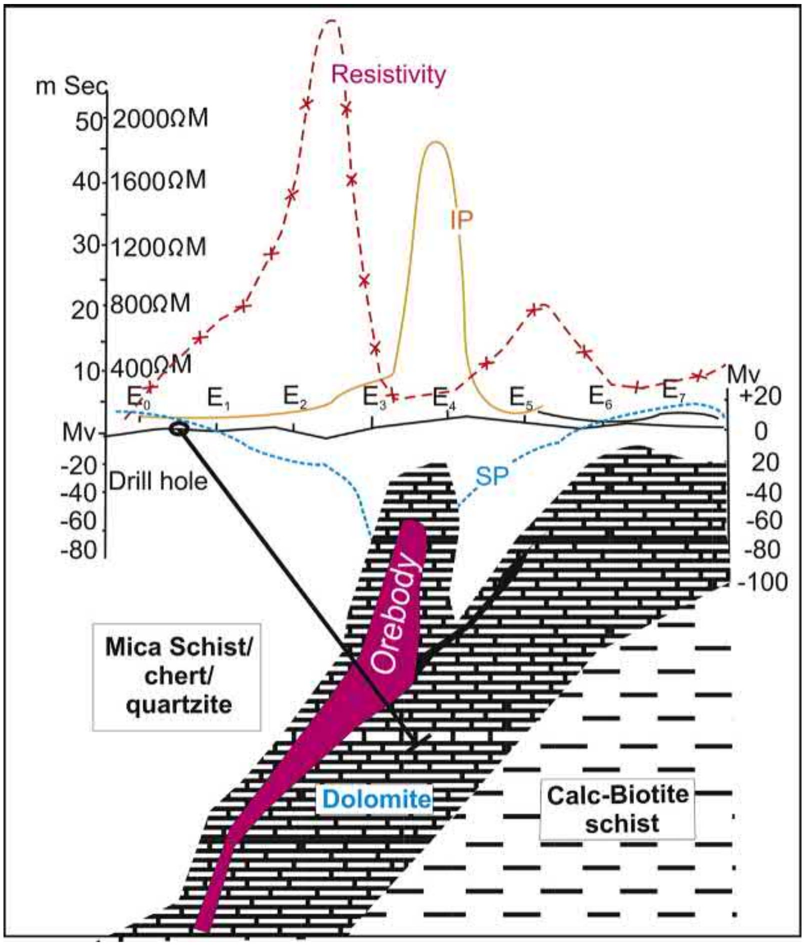

FIGURE 6.16 Geophysical interpretation of self-potential, induced potential, and resistivity survey confirmed by drill testing of rich sulfide orebody in Rajasthan.

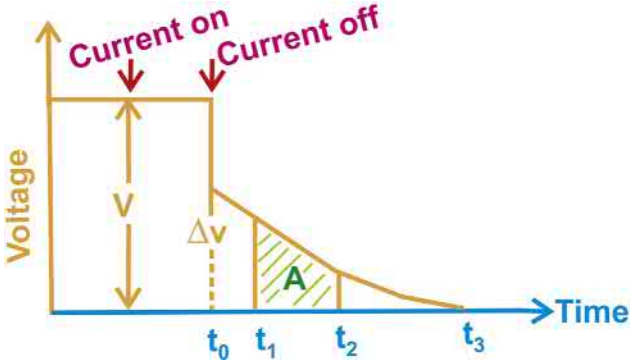

FIGURE 6.17 Schematic diagram elucidating the principles of the induced potential method of survey by means of voltage versus time curve passing through conductive mass.

electrical charge, and becomes electrically polarized (t'_1 to t'_2). The measurement of a decaying voltage over a certain time interval is known as a time-domain induced potential survey. Alternatively, if a variable low-frequency alternate current source is used for measurement of resistivity it is observed that the measured apparent resistivity of subsurface rocks decreases as the AC frequency is increased. This is known as a frequency-domain induced potential survey.

6.5.3.2 Induced Polarization Measurement

The induced polarization method works on externally imposed voltage causing electrolytic flow in the pore fluid of rocks. Thus negative and positive ions build up on either side of minerals and are charged during imposed voltage. The minerals return to their original state over a finite length of time on removal of the impressed voltage causing gradual decay of voltage. Metallic minerals, if present, become additionally charged during external current flow and the voltage gradually decays on switching off the source. This effect is known as **membrane** or **electrolytic polarization** in the case of nonmetallic minerals and **electrode polarization** or **overvoltage** in the case of metallic minerals. Metallic sulfides, oxides, and graphite are good conductors and respond better to this effect. The magnitude of electrode polarization depends on both intensity of impressed voltage and concentration of conductive minerals. The ubiquitous disseminated sulfide orebody provides a larger surface area available for maximum ionic—electronic interchange, and hence is extensively suitable for induced polarization surveys.

The measurement of decaying voltage (M), shortly after switching off the polarization current, is the area "A" of the decay curve over a specific time interval ($t'_1 - t'_2$). The area "A" is determined within the measuring instrument by analog integration. The measured parameter is **chargeability**. The unit is milliseconds (ms). Different minerals are distinguished by unique chargeability, such as pyrite (13.4 ms) and magnetite (2.2 ms).

$$M = A/V \text{ or } \Delta V/V$$

6.5.3.3 Applications

The induced polarization method is extensively and effectively used in base metal mineral exploration (Fig. 6.16) for locating low-grade ore deposits, e.g., disseminated sulfides. It has other applications in hydrogeophysical surveys, environmental investigations, and geotechnical engineering projects.

The use of induced polarization in groundwater exploration is growing in prominence. The induced polarization sounding (time-domain) method was applied near the Sauk-Soo River area in Crimea, Ukraine. The alluvial deposits in the river basin area clearly distinguished three horizons by their polarizabilities. The section consisted of a top layer of weak polarizability that represents a dry loamy layer; a second middle layer of strong polarizability representing a clayey sand layer saturated with fresh water; and a third lower layer of weak polarizability that represents impervious siltstones.

6.5.4 Self-Potential Method

6.5.4.1 Definition and Mechanism

Self-potential or **spontaneous polarization** is based on natural potential differences resulting from electrochemical reactions in the subsurface. The process is unique because it is passive, nonintrusive, and does not require the application of an electric current. The causative body has to exist partially close to the water table to form a zone of oxidation. The electrolytes in the pore fluids undergo oxidation and release electrons that move upward through the orebody. The released electrons cause reduction of electrolytes at the top of the orebody. An electronic circuit is thus created in the orebody so that the top of the body acts as a negative terminal. The self-potential anomaly is invariably centrally negative over metallic ore deposits (Fig. 6.16). The bulk of the orebody exists below the water table, endures no chemical reaction, and simply transports electrons from depth generating stable potential differences over long periods at the surface.

6.5.4.2 Equipment and Field Procedure

Standard self-potential field survey equipment utilizes a pair of nonpolarizing porous pot electrodes, connected by insulated cable via a millivoltmeter. The electrodes are composed of simple metal spikes immersed in a saturated solution of its own salt (Cu in $CuSO_4$) in a porous pot that allows slow leakage of solution into the ground. The measurements of potential differences are conducted by shifting successive electrodes or by fixing one electrode at the base station in barren ground (up to 50 mV) and by moving the second mobile field electrode in steps across the expected target area (1000 mV). The spacing between electrodes is 10, 20, and 30 m apart. Typical spontaneous polarization anomalies may have amplitudes of several hundred millivolts with respect to barren ground, and exceed several thousand millivolts over deposits of metallic sulfides, magnetite, and graphite.

6.5.4.3 Applications

The self-potential method is traditionally used:

1. As a mineral exploration tool for massive sulfide orebodies.
2. For downhole logging in the oil industry.
3. For hydrogeological investigation, and assessing the effectiveness of water-engineering remedial measures.
4. To identify seepage in dams and reservoirs.
5. For finding leaks in canal embankments.

6.6 ELECTROMAGNETIC SURVEY

Electromagnetic conductivity surveys have been well accepted by multinational specialists for mineral exploration over the years, and still enjoy the same status.

6.6.1 Definition

An electromagnetic survey is based on the response of the ground to the propagation of electromagnetic fields composed of an alternating electric intensity and magnetizing force. A primary or inducing field is generated by passing an alternating current through a coil (loop of wire called a transmitter coil) placed over the ground. The primary field spreads out in space, both above and below the ground, and can be detected with minor reduction in amplitude by a suitable receiving coil in the case of a homogeneous subsurface. However, in the presence of a conducting body the magnetic component of an electromagnetic field penetrating the ground induces alternating currents or **eddy currents** to flow within the conductor. Eddy currents generate their own secondary electromagnetic field distorting the primary field. The receiver will respond to the result of arriving primary and secondary fields so that the response differs in phase, amplitude, and direction. These differences between transmitted and received electromagnetic fields reveal the presence of a conductor and provide information on its geometry and electrical properties. The entire process of electromagnetic induction is depicted in Fig 6.18. The surface electromagnetic field, using surface loops and receiver, or a downhole tool lowered into a borehole, acts on the body of mineralization. The regional electromagnetic field uses airborne surveillance, either a fixed-wing aircraft or helicopter equipped with electromagnetic tools. Both methods can

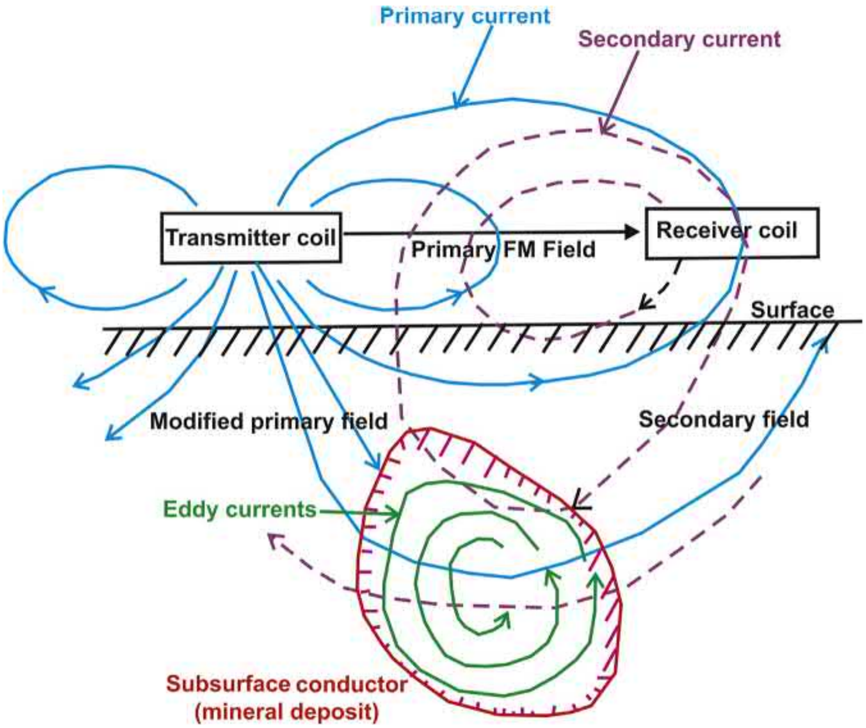

FIGURE 6.18 Conceptual diagram of electromagnetic induction processing system generating eddy currents in subsurface conductive mass.

map 3D perspectives of mineral bodies, deep in Earth, and guide further exploratory drilling for verification. The depth of penetration of the electromagnetic field depends on its frequency and the electrical conductivity of the medium through which it is propagating.

6.6.2 Detection of Electromagnetic Field

A two-frame compensator and Turam system measure the phase and amplitude relationship between primary, secondary, and resultant fields. The spacing and orientation of coils are critical. A long straight conductor is laid on the ground and supplied with alternating current. Field traverses are made by two coils at a fixed distance apart and at right angles to the conductor. Changes of phase and amplitude are measured between induced voltages in each coil.

The qualitative response of an electromagnetic field can be easily obtained by very low frequency (VLF) or audio frequency magnetic (AFMAG) methods. VLF uses powerful radio transmitters as used in long-range communication. The system needs a transmitter with a magnetic vector across the strike of the geological formation and a receiver tuned to the particular frequencies of the transmitter. Depth penetration is low. The AFMAG field method uses a natural electromagnetic field induced by thunderstorms and is known as **sferics**. This method enables deeper penetration into the ground. The high-frequency waves propagate between the ground surface and the ionosphere and act as an efficient electromagnetic waveguide.

6.6.3 Time-Domain Electromagnetic Survey

The measurement of a comparatively small secondary and resultant field is difficult in the presence of a strong primary field. The solution came with the development of the TDEM procedure. The primary field is not continuous and consists of a series of intermittent pulses separated by periods. The secondary field is only measured in the absence of the primary field. The eddy currents defuse around the boundary of a highly conductive subsurface body and decay slowly when the inducing field is removed. The rate of decay of fading eddy currents can be measured to locate anomalous conducting bodies.

6.6.4 Noncontacting Conductivity Measurement

Electrical methods require physical introduction of current into the ground through electrodes, making it labor intensive, slow, and costly. Noncontacting conductivity meters using magnetic components of an electromagnetic field have been developed to address this issue. There is no need for physical contact with the ground for either transmitter or receiver, and they can be used from aircraft at much faster speed than electrical methods.

6.6.5 Airborne Electromagnetic Survey

The airborne electromagnetic survey is widely used during reconnaissance for target detection. It is significant due to its high-speed approach to cover vast areas in the shortest time, making it cost effective. The operation is divided into two types: passive and active. In the passive system only the receiver is airborne using VLF and AFMAG methods. In the active system, both transmitter and receiver are mobile, and are frequently used because they perform in areas where ground access is difficult. Active systems are of two types: quadrature and fixed separation.

Quadrature systems use a large transmitter sling between the tail and wings, and the receiver is towed from a cable of about 150 m behind the aircraft. The receiver bird swings with the long hanging cable resulting in uncontrolled height and direction during flight movement. Only the phase difference between primary and resultant fields caused by a conductor can be measured.

In a fixed separation system the transmitter and receiver coils are mounted either on the wings of an aircraft flown at a ground clearance of 100−200 m or on a beam fixed beneath a helicopter flown at an elevation of 20 m, maintaining fixed separation and height of the flight. In single aircraft- or helicopter-bound operations an extremely small separation of the transmitter/receiver is used to generate and detect an electromagnetic field over a relatively large distance resulting in significant signal distortion. The problem can be eliminated using two planes flying in tandem, both flying at strictly regulated speed, altitude, and separation. The rear craft carries the transmitter and the forward plane tows the receiver mounted in a bird (Fig. 6.19). The airborne TDEM method INPUT (Induced Pulse Transient) is used to enhance secondary field measurement. The airborne survey is relatively expensive and requires advanced data processing facilities. However, the cost is compensated by increased depth of penetration, minimized orientation errors, and judgment of the presence of a subsurface conductor.

A typical airborne survey path is designed to fly in a regular to-and-fro grid interval (alternate E−W/W−E direction) covering the entire length of tenement area. The

FIGURE 6.19 Schematic diagram showing electromagnetic aerial survey employing two airplanes.

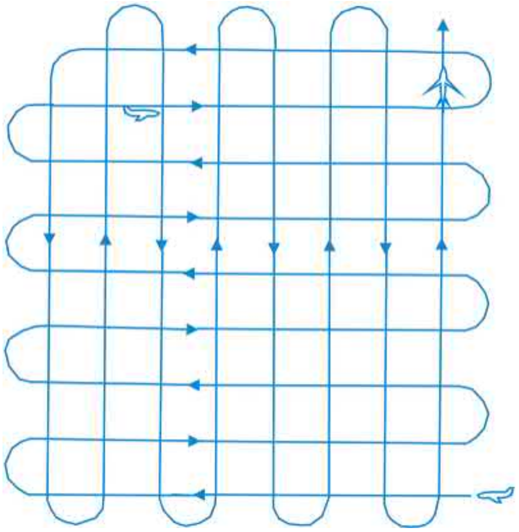

FIGURE 6.20 A typical airborne flight plan to fly E—W/W—E followed by N—S/S—N to scan the total area under investigation.

flight continues in a similar pattern (N—S/S—N direction) to cover along and across the total strike of the possible unknown mineralization (Fig. 6.20). The possibility of missing the target is minimal.

6.6.6 Applications

The following are applications of an electromagnetic survey:

1. Most suitable for detecting bodies of high electrical conductivity, such as metallic ores, particularly massive sulfides and hydrogeological studies. It is also used for delineating faults, shear zones, and thin metallic veins.
2. Electromagnetic geophysical surveys conducted in part of a large abandoned mining complex along with data derived from cores and monitoring wells inferred sources of contamination and subsurface hydrologic connections between acidic refuse deposits and adjacent undisturbed geologic materials (Brooks et al., 1991).
3. Locating abandoned mineshafts, crown pillars, and mine subsidence features.
4. Identifying bedrock and mineralization discontinuities.
5. Defining past landfill sites.
6. Mapping of soil types, land utilization, and land drainage patterns.

6.7 RADIOMETRIC SURVEY

6.7.1 Concept

The radiometric survey detects and maps natural radioactive emanations (γ-rays) from rocks and soils. Gamma radiation occurs from the natural decay of elements like U, Th, and K. The radiometric method detects these elements at the surface. The common radioactive minerals are uraninite (^{238}U), monazite (Ce, La, Nd, and Th), thorianite (^{232}Th), rubidium (^{87}Rb) in granite-pegmatite, feldspar (^{40}K), muscovite, sylvite in acid igneous rocks, and radiocarbon (^{14}C). Heat generated by radioactive disintegration controls the thermal conditions within Earth. The rate of radioactive decay of some natural elements acts as a powerful means of dating the geological time of rock formation (geochronology). Exploration for these minerals by radiometric survey became important due to the demand for nuclear fuels and detection of associated nonradioactive deposits, e.g., titanium and zircon. Isotopes are elements whose atomic nuclei contain the same number of protons, but different number of neutrons. Some isotopes are unstable and disintegrate spontaneously to generate other elements. Radioactivity means disintegration of atomic nuclei by emission of energy and particles of mass. The byproducts of radioactive disintegrations are in various combinations of α-particles of helium nuclei, β-particles of electrons emitted by splitting of neutrons, and γ-rays of pure electromagnetic radiation.

6.7.2 Instruments

Radioactivity measurement detects the number of counts of emission over a fixed period of time. The standard unit of γ radiation is the roentgen (R). The **Geiger or Geiger-Müller** counter, equipped with a meter and earphone, responds to β-particles in the proximity of a radioactive source. The Geiger counter is limited to ground surveys. The **scintillation counter** detects emissions of flashing lights using a photomultiplier at or near 100% detection of γ radiation. Airborne radiometric surveys are exclusively performed by a scintillation counter in combination with airborne magnetic and electromagnetic surveys. An advanced scintillation detector with enhanced detection sensitivity differentiates the counts due to γ radiations of different energy levels, say between uranium and thorium deposits.

6.7.3 Radiometric Dating

Disintegration, because of crystallization, of a radioactive parent isotope (uranium, thorium, rubidium, potassium, and carbon) produces a stable daughter isotope (^{206}Pb, ^{207}Pb, ^{208}Pb, ^{87}Sr, ^{40}Ar, ^{40}Ca, and ^{14}N, respectively) at a known rate of decay. Atomic proportion of a parent and daughter nuclei of a mineral or rock sample is determined by mass spectrometry. The radiometric age of events is computed mathematically from the father/daughter relationship, and experimentally determined by decay constant (λ). Precision of the result depends on collection of unaltered specimen, exact location, petrological origin, relation to surroundings, reliable chemical and isotope analyses, and expert interpretation. Radiometric methods applied in geochronology can be performed by several father/daughter isotope products, e.g., potassium—argon, rubidium—strontium, uranium—lead, fission-track, radiocarbon, and tritium methods.

6.7.4 Applications

The radiometric survey is significant for the investigation of nuclear fuel and associated minerals, determination of geochronology of rock formations to unravel many untold stories, demarcation of geological structures, and intrusives. The survey can be performed on the ground as well as in the air.

6.8 BOREHOLE LOGGING

6.8.1 Principles of Well Logging

Boreholes are drilled to study subsurface geology along the path of a hole. The information helps to interpret a 3D picture of the area. Shallow noncore holes are excavated by reverse-circulation drills in which rock fragments are blown out of the hole by air pressure. Deeper holes are sunk by rotary drills with cutting units and tungsten-carbide or diamond bits. The drill-hole provides non-coring cutting fragments flushed by drilling fluids (mud), and solid core using a core barrel and water circulation. In the case of core drilling the recovered cores are logged for lithology, mineralization, and structure. In noncore excavation and high core loss, information along the depth can be obtained by the geophysical methods of **down-the-hole** geophysical survey or **wire-line logging** using various sensors. Well logging collects information by measuring certain rock properties. The inside of boreholes is protected from wall collapse by casing and high-density fluids/cement-mixed mud to lower geophysical probes. Geophysical tools include gravity, electrical resistivity, self-potential, magnetic, electromagnetic, sonic velocity, and temperature.

The instrument is housed in a cylindrical metal tube (sonde) connected to a multicore cable fixed in a rotating drum fitted with winches and a recorder. The probe is lowered to the bottom of the hole and logging continues while hoisting the instrument up though the drilled section. The logging data are automatically recorded on a paper strip and simultaneously on magnetic tape in analog or digital form for subsequent processing. The geological properties obtained from well logging are formation thickness, lithology, porosity and permeability, proportion of water and hydrocarbon saturation, and temperature.

6.8.2 Mise-à-la-Masse

Mise-à-la-masse, meaning "excitation of the mass" in French, is a variation of an electrical resistivity survey by enhancement of sufficient resistivity contrast between the host rock and the sulfide ore compared to a conventional survey. It is a postdiscovery method with definite knowledge of existing sulfide mineralization. The interpreted equipotential maps are good indicators of continuity of mineralization in strike, dip, shape, and interconnectivity between numbers of intersections.

One of the current electrodes (C_1, the positive electrode) is planted into the conductive mass under investigation, i.e., the mineral body exposed in a pit or drill hole. The second current electrode (C_2, the negative electrode) is placed at a large distance away, 5—10 times the width of the mass on the surface or in another mineralized part of the drill hole. The current electrode (C_1) in the drill hole consists of a lead metal rod attached to an insulated flexible copper wire. One of the potential electrodes P_1 is placed on the ground close to the mass and between C_1 and C_2. The second potential electrode P_2 is placed at a large distance from C_1 and in the opposite direction to C_2 (Fig. 6.21). The surface potentials are measured with respect to the distant electrode preferably over a grid around the drill hole or pit. The potential distribution from these two current electrodes reflects the geometry of the conductive mass. Thus it can indicate the continuity of mineralization in the strike and dip direction.

6.8.3 Applications

Well logging is used for electrical imaging, mine mapping, and hydrocarbon and hydrological exploration to obtain in situ properties of possible reservoir rocks. Electric logs are considered useful for evaluating formation fluid properties. Modern well-logging techniques are used to locate deep-seated metallic ore deposits, extension of orebodies in all directions, freshwater resources, and as part of engineering test drilling. The cross-hole and up-hole tomography involves sending seismic, electrical, electromagnetic, and radar signals between a transmitter in one borehole and a receiver in another borehole. Mise-à-la-masse surveys have been conducted successfully for Mataloko geothermal field, Flores, Indonesia, lead-zinc-copper at Sawar, Ajmer, and gold-pyrite at Bhukia—Jagpura, Rajasthan, India (Bhattacharya et al., 2001).

6.9 REVIEW

Exploration geophysics is the applied science of measuring physical properties of rocks and minerals, and to detect the measurable physical contrast between them. The physical properties under reference are seismic, gravity/density, magnetic, electrical, electromagnetic, and radiometric. Exploration geophysics is capable of detecting and mapping the subsurface distribution of rock units, structures like faults, shears, folds, and intrusives, and to target the style of mineralization, including 3D perspectives,

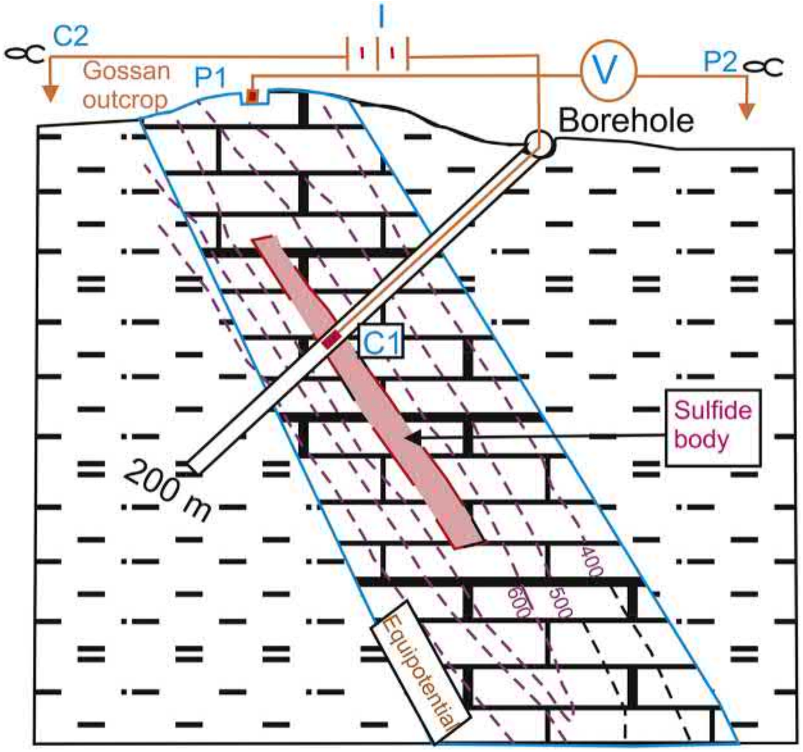

FIGURE 6.21 Electrode configurations in a mise-à-la-masse survey with one current electrode located in a borehole passing through a sulfide orebody and the other on the surface/another borehole to complete the circuit. Both the potential electrodes are located on the surface.

hydrocarbon accumulations, and groundwater reservoirs. The methods can also be used in other related areas, such as monitoring environmental impact, ancient mining voids, buried archaeological spots, subsurface salinity mapping, and civil engineering sites.

Exploration geophysics is efficient in large area reconnaissance/prospecting for rapid delineation of targets. It is comprehensive when using multidisciplinary methods to identify complex mineral environments. The application of geophysics is cost effective in reducing the vast volume of earth and to decide to initiate drilling or to abandon the area. The techniques are time tested and proven for the discovery of deep-seated mineral deposits all over the world.

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Chapter 7

Sampling Methods

Chapter Outline

> *Sampling requirements are set by the orebody, not by the engineer.*
>
> Author.

7.1 DEFINITION

Sampling is the process of taking a small portion of an object such that consistency of the part shall represent the entire property or only an adjacent portion of the object under assessment. The sampling objects in geological perspectives are granite hill, limestone deposit, alluvial soil, weathered profile, beach sand, polymetallic nodules, mineral occurrences, drill core, well water, oil, and gas. The sample interval and quantity will depend on homogeneity or complexity of minerals under search. The "unit" of sample size, i.e., millimeter (mm), centimeter (cm), meter (m), feet (f), gram (g), kilogram (kg), pound (lb), and liter (L), must be specified in particular to make it significant. The unit is needed for precise computation of the average grade conventional and statistical method.

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00007-1

7.2 SAMPLING EQUIPMENT

Samples are collected by various suitable and convenient methods and means without compromising quality and reproducibility.

7.2.1 Conventional Equipment

Conventional sampling tools are the hammer and chisel to collect rock chips. Spades, shovels, and mechanized loaders are preferred to signify large volumes of sample material. The other supporting tools are compass, Global Positioning System, handheld X-ray fluorescence (XRF) analyzer, and camera. The various drilling tools are for ultimate primary and authentic support in mineral exploration and investment decisions.

7.2.2 Drilling Techniques

The ancient Egyptians introduced a drilling principle for boring short holes during construction of the Great Pyramids of Giza during 2560 BC. The first drill machine was manufactured in 1862—63, operated by manual rotation. The need for drilling increasingly stimulated manufacture for effective design in machines and accessories to improve efficiency and cost. The search for deep-seated orebody, petroleum, and gas reservoirs was unthinkable without efficient drill machines that can collect samples at depths of +2000 m (Banerjee and Ghosh, 1997; Atlas Copco, 2014).

The drilling techniques are essentially based on three motions: percussive, rotary, and a combined effect of percussive and rotary (Bremner et al., 1996; Devereux, 1999; DMP, 2012). The various drill types are:

1. Percussion drilling.
2. Percussive cum rotary drilling.
3. Auger drilling.
4. Diamond drilling.
5. Wire-line drilling.
6. Reverse circulation drilling.
7. Air-core drilling.
8. Sonic drilling.
9. Directional drilling.
10. All hydraulic drilling.

7.2.2.1 Percussion Drilling

The **percussion** or **churn drill** digs a vertical hole using the principle of a freely falling chisel bit hanging by a cable to which percussive motion is imparted by power units. The power units work by manual lift and drop, compressed air, and electrically driven winches. A tungsten carbide bit fitted in a hammer is lifted a few meters up and allowed to drop (Fig. 7.1) to hit the bottom of the hole. The process continues in succession. The churning motion of the bit

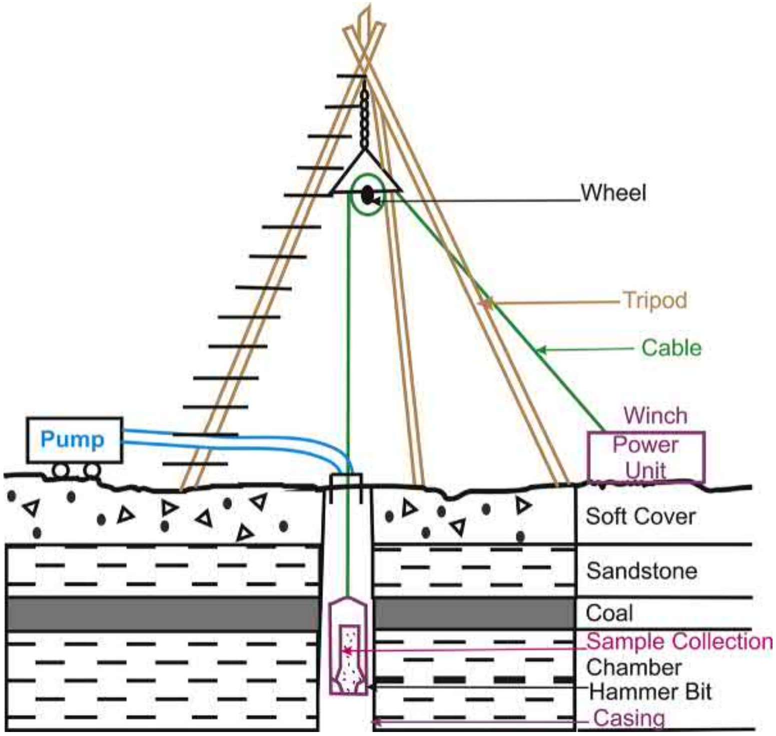

FIGURE 7.1 Schematic conceptual diagram of the percussion drilling procedure often used in engineering geology for foundation testing and occasionally in the initial stage of mineral exploration and particularly for a low-profile budget.

FIGURE 7.2 Percussion drilling in operation for rock quality and quick target test for mineral occurrences at low cost and reduced time. The hammer is detailed in the inset.

crushes and scrapes the ground to dig a hole. The rock cuttings produce mud or slurry brought about by lowering water. The crushed material is removed from the hole bottom at regular intervals to form a sample. Churn drilling is suitable for soft and medium formation. The cutting bit is required to be resharpened frequently in hard formations resulting in low progress at high labor cost. The capacity of the churn drill is limited to relatively short holes of 10−50 m.

The cost of sampling is comparatively much lower than diamond drilling under similar conditions. However, the chances of contamination between samples are high making the method inefficient to demarcate correct orebody contacts and to assess the average grade of the deposit. It provides information regarding the presence of mineralization that can be precisely explored by diamond drilling. Sample collection is modified by connecting a water pump (Fig. 7.2). The returning water brings rock cuttings to the surface to form a regular sample. A further modification is made by cutting a slit in the bit to hold cuttings (samples) at standard intervals. The method is preferred for tube wells and foundation testing.

7.2.2.2 Percussive Cum Rotary Drilling

The **percussive cum rotary drill** uses an integral or detachable tungsten carbide bit that penetrates the ground due to the resultant action of both percussive and rotary motions, e.g., jackhammer (Fig. 7.3) and wagon drills. The percussive action produces a vertical impact on the drill rod to break rock particles. The rotational motion exerts a force on the bit head to penetrate into the rocks. The drill depth is limited to 6 m. Drills are compressed air driven. Water is injected through hollow steel drill rods to cool the bit head from excessive heating. The returning water flushes out cutting material from the hole for free movement of bit and rods. The cuttings serve as samples to understand the metal content of the advancing face. These drills are used primarily for the development of tunnels, advanced mining faces, and for breaking big boulders in construction areas. They have limited use in mineral exploration. Samples are used to estimate approximate metal content of big rock exposures and mine blast quality in advance for grade control and scheduling. They provide information about the roof and floor of the coal seam, including the thickness of coal bands within.

FIGURE 7.3 Jackhammer drilling in rich sulfide mineralization for multipurpose use as underground mine face development and sample source for ore continuity and grade control.

7.2.2.3 Auger Drilling

The **auger drill** has limited use, but it plays a significant role in sampling and evaluation of soft and loose ground like soil, beach sand, mine dump, concentrate, and tailings. Auger drills can be hand operated (Fig. 7.4A) or mechanically powered. The advantages of auger drilling are mobility and speed at low cost. The hand-operated augers can penetrate up to 3 m with hole diameters between 10 and 15 cm. The mechanically driven augers with efficiently designed cutter heads (Fig. 7.4B) can drill 30 m or more depending on subsoil condition. The samples are useful to provide grade, moisture content, and other specifications quickly at low cost. However, samples may often fail to provide accurate information due to wall collapse and related contamination.

7.2.2.4 Diamond Drilling

Diamond drills, surface and underground, are most versatile tools, and extensively used in mineral exploration, at

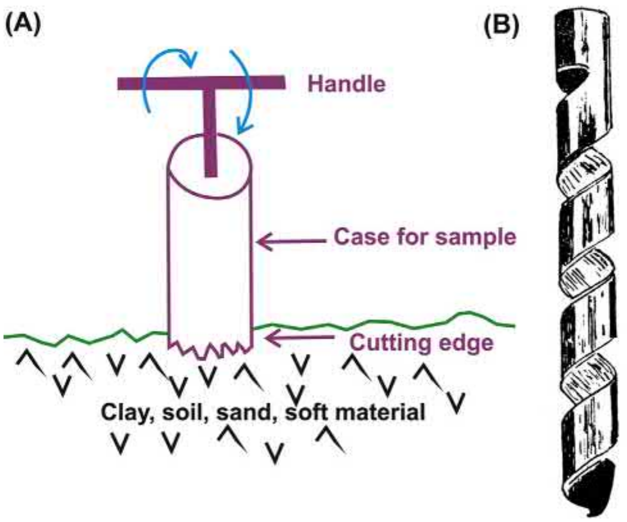

FIGURE 7.4 Sketch diagram of (A) auger drilling, a simplified, easy-to-operate, low-cost sampling unit, and (B) cutter head.

dam sites, for other foundation tests, drainage of mine workings, underground mine ventilation, oil structure investigations, and oil/gas well drilling (Heinz, 2009). The extreme hardness of diamond enables it to cut all types of rocks and minerals found in Earth's crust. The diamond drill unit (Fig. 7.5) consists of an engine (motor) attached to a drilling head and hoisting units, cutting bit with crown and reamer shell, water pump, drill rods, core barrel, core lifter, casing pipes, cutting tools, and a tripod or single stand.

The engine is powered by diesel, electricity, or compressed air. The motor, mounted on a cemented platform or truck, transmits rotating power through the transmission and clutch to a set of gears to the drilling head. There are three to four set of feed gears within the swivel head, with capacity ranging between 100 and 1000 revolutions per inch of rock cutting. The chuck equipped with jaws is placed at the bottom of the feed screw through which drill

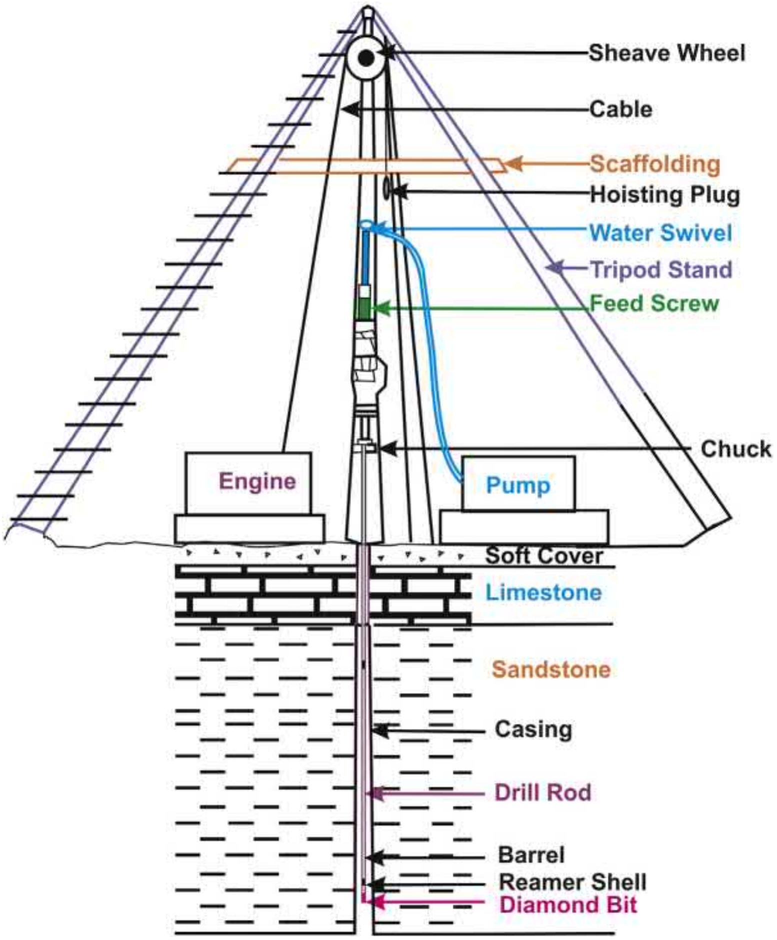

FIGURE 7.5 Schematic diagram of surface diamond drilling unit showing various components and functions to sink a borehole for recovery of core samples of all rock types passing through, including structural features and mineralization.

FIGURE 7.6 Truck-mounted diamond drill rig in operation for base metal exploration in Australia. The device is capable of drilling 50−100 m a day.

rods pass. The drill rods are attached to a core barrel and diamond bit. The total drill string is forced downward with high-speed rotation of the chuck resulting in cutting of the core and the making of a hole.

A **tripod** is commissioned by erecting three poles about 30 feet long around the drill unit. The function of the tripod is to raise and lower 10 or 20 feet rods during the drilling operation with the help of a **hoist**. **Scaffolding** is nailed and chained to the tripod where the drill crew can stand safely and operate rod hoisting/lowering. The screwing and unscrewing of rods is done efficiently by automatic mechanized means. The rods are withdrawn at intervals of 10 feet or less depending on drilling conditions. The core is removed from the barrel for geological studies (logging) and storage.

The modern truck-mounted drill rig has a single hoisting column with screwing/unscrewing ability and the capacity to sink to +2000 m depth through fully mechanized operation with two to three crews (Fig. 7.6). The drill unit can move quickly in hilly terrain, settle in a new location, and start drilling at minimum shift loss.

The drill rods are hollow steel, flush jointed or coupled, 10 feet (3.05 m) long through which water is pumped to cool the bit and flush rock cuttings. **Diamond core bit**, the main cutting tool, is a cylindrical hollow tube made of special alloys with a crown at one end (Fig. 7.7). The crown is composed of superior diamond-holding qualities of powdered metal alloys on which diamonds of different sizes, quantities, and designs are set depending on the rock types to be drilled. The fragment sizes are denoted as "spc" (stones per carat), say 80/120 spc, i.e., between 80 and 120 spc (1 carat = 200 mg).

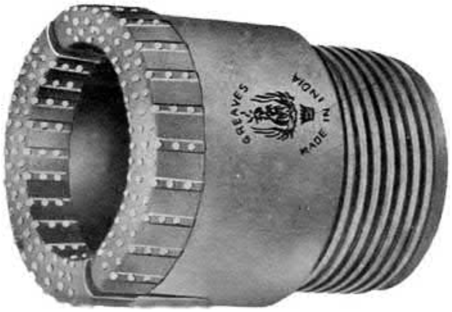

FIGURE 7.7 Standard diamond core bit studded with technically designed tiny diamonds at the crown composed of superior quality alloy grooved with channels to cool the bit head and flash the fine cuttings.

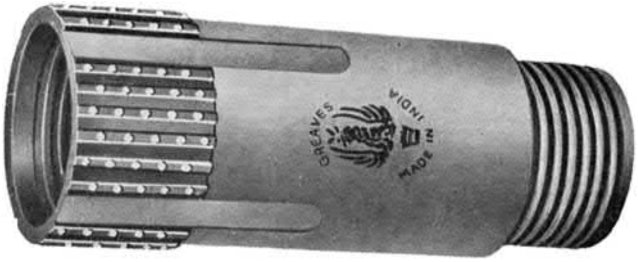

FIGURE 7.8 Standard reamer shell coupled behind the core bit embedded with diamonds at the outer surface to increase the hole diameter for easy flow of returning water and fine cuttings.

The **reaming shell** is mounted between the cutting bit and core barrel. It is an annular bit with diamonds set only on the outer surface or periphery (Fig. 7.8). The reamer shell widens the borehole diameter drilled by the diamond bit by about 0.30−0.40 mm. It maintains a uniform hole

FIGURE 7.9 Standard spring-type core lifter that protects the core from slipping into the hole and regrinding.

diameter, reduces wear and tear of the core bit and barrel, and improves the flow of returning water.

A **core barrel** is attached between the lower end of the drill rods and the reamer shell. It holds the core inside while drilling and is brought to the surface. The core barrels are **single tubes** used for drilling under the best core recovery conditions or noncoring bits in blast hole drilling. The **double tube** core barrels are suitable for better core recovery, where the inner and outer tubes are connected and rotate simultaneously. The **triple tube** core barrels are complex and expensive, and used in broken, friable, and sheared formations where samples are analyzed for estimation. A **core lifter** or core spring (Fig. 7.9) is placed at the lower end of the barrel that stops the core from dropping out of the barrel.

Core, the best and most authentic sample, is a cylindrical piece of one or multiple pieces of rock cut (Fig. 7.10) with advancement of the bit. The core represents the subsurface geology of the section passing through in general, and serves as samples for petrology and precise chemical properties for grade assessment. The core provides physical and accurate records of formations through which the drilling continues.

Water is an essential component of the drilling operation. Often, drill sites are located at remote places far away from water sources. In such conditions, water is stored in a tank dug close to the borehole collar. The water is either pumped from a nearby source or supplied periodically by tanker. Therefore utmost care is taken to recirculate water after settling of rock cuttings in the returning water tank. Any water loss in the drill hole can be prevented by **casing** the hole or by using localized cement grouting on the fractured areas. In the case of highly fractured ground conditions, water can be substituted by **drill mud** (bentonite clay, polymer). This will significantly reduce fluid loss, hole collapse, and improve drilling efficiency.

FIGURE 7.10 Standard drill core showing stratiform sphalerite and galena in calc-silicate host rock with the *red pencil line* marked for splitting into two near-identical halves at Rajpura-Dariba Mine, India.

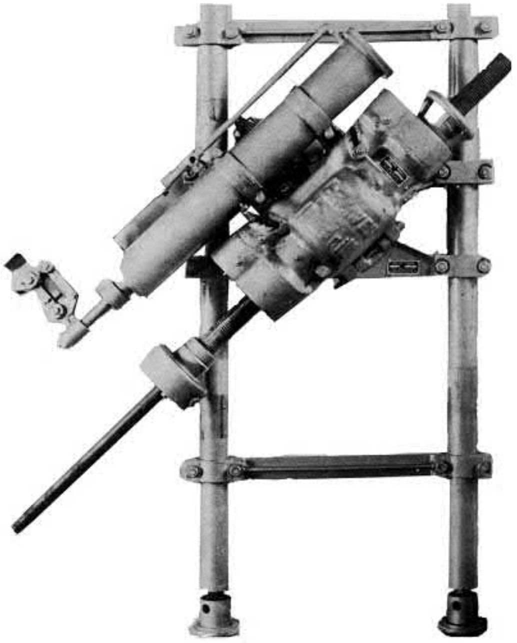

FIGURE 7.11 Typical compressed air-operated underground drill unit that can operate at 0–360 degrees rotations.

Salvaging is the recovery of the remaining diamonds from the matrix of worn-out bits and reaming shells by acid bath. The recovered stones are sorted for size and condition. They are then mixed proportionately with fresh diamond for setting new bits. The value of the recovered diamonds is credited to the purchaser.

Underground drills are lightweight compressed air or electrically driven machines mounted on a single or double drill column (Fig. 7.11). The drill rods have a 5 or 10 feet pull due to inadequate space of mine workings. The drill units can work from horizontal to 90 degrees up and down. However, the preferred drill angle is between 0 and ±45 degrees to avoid excessive load of rods and better safety of the drill crew. Capacity is +300 m.

Capacity of the drilling depth depends on power and condition of the machine, terrain, angle of the hole, and type of rocks to be penetrated. The efficiency will reduce with steep angle holes and longer depth. Drilling can be done beyond 2000 m depth. The size of the core is decided by the exploration agency based on the type of minerals under investigation and prevailing rock condition. The size

TABLE 7.1 Standard Drilling Type, Hole, and Core Diameter

Drilling Type	Hole Diameter (mm)	Core Diameter (mm)
American Sizes		
HX	99.20	76.20
NX	75.70	54.70
BX	59.90	42.00
AX	48.00	30.00
EX	37.70	21.40
Wire-Line		
HQ	96.10	63.50
NQ	75.80	47.60
BQ	60.00	36.50
AQ	48.00	27.00

of the bit, reamer shell, barrel, and drill rods is selected accordingly. Generally, drilling starts with HX size and progressively reduces to NX, BX, AX, and rarely to EX (Table 7.1). The cost of drilling will be higher with larger core diameter and more reliable sample representation, and vice versa.

The **collar** (starting point) of the surface exploration drill hole must be closed after completion with a wooden/cement plug to prevent pebbles and soil being dropped down the hole, thus making it difficult to move back in the hole again if required. It is also desirable to fill the entire hole with cement at a later date to prevent inundation of the underground mine by water gushing during heavy rains or from interconnected water channels. The top of the collar should be covered with a cemented platform marking the project and drill hole number, coordinates, angle, direction, depth, and start and end of drilling date for future reference. The collars of underground boreholes must be plugged to avoid accidents at the upper or lower levels by explosive gases during mine blasts.

7.2.2.5 *Wire-Line Drilling*

Wire-line drilling works by withdrawing the core and inner tube assembly from the hole without pulling out the hollow drill rods by a separate hoisting unit fixed on a different pulley. The inner tube assembly is lowered down inside the barrel after taking out the core and drilling continues. Therefore lowering and hoisting of drill string, barrel, and drilling head is not required after every run drilled. It also saves considerable time and energy.

Continuous core drilling works on the principle of reverse circulation. Reverse circulation refers to circulating water down to a bit head outside the drill rods and returning it up through the inside the bit, core barrel, and drill rods. The effect of reverse circulating water is to continuously float the core back to the surface. The drill rods and barrel are hollow enough to move the core upward as drilling continues. The cores are collected at the surface and placed in a core box with proper orientation and depth. The continuous core-drilling process operates for a long duration until the bit is ineffective. This saves time by not lowering and hoisting the drill string every 3 m, and avoids overgrinding of the core. Efficiency of drilling increases many times resulting in substantial cost reduction and improved core recovery.

7.2.2.6 *Reverse Circulation Drilling*

Reverse circulation drilling prefers compressed air produced by a hydraulic top drive motor under dry drilling conditions. The compressed air is introduced into the drill through a dual concentric air pipe (between the outer and inner pipe) and flows to a **down-the-hole** tungsten carbide hammer bit. The compressed air and hammering initiate breaking of chips at drill head depth, and are set in continuous motion upward by high-pressure return air through the inner sample tube. The return air is supplied by installing a high-pressure vacuum pump. The entire rock cuttings move to the surface, and are collected as an inverted sequence in a cyclone above ground level (Fig. 7.12). The samples are separated at regular intervals representing particular depths.

Reverse circulation drills (Fig. 7.13) are used for open pit excavation of iron ore, bauxite, limestone, rock phosphate, and coal seam. They drill 10−15 cm large diameter vertical blast holes at high speed and low cost. The modified reverse circulation drills can rotate the drill string from vertical to any steep angle and are popular for mineral prospecting. The reverse circulation drill sample enables quick testing of drill targets during reconnaissance and prospecting. It creates a base for further diamond drilling programs to acquire precise sample locations and high-quality core samples.

The best advantage of reverse circulation drilling is its capability of drilling in the hardest of formations with easy penetration at high speed and recovery of uncontaminated samples even in broken and fractured formations. The fast rate of drilling helps the planning of future core drilling programs and mining operations. It is cost effective and provides mobility of the rig from one location to another for both prospecting and mining.

7.2.2.7 *Air-Core Drilling*

Air-core or **rotary air blast drilling** is preferred to cut into unconsolidated weathered regolith ground mass. The drill bit has three hardened steel or tungsten carbide blades

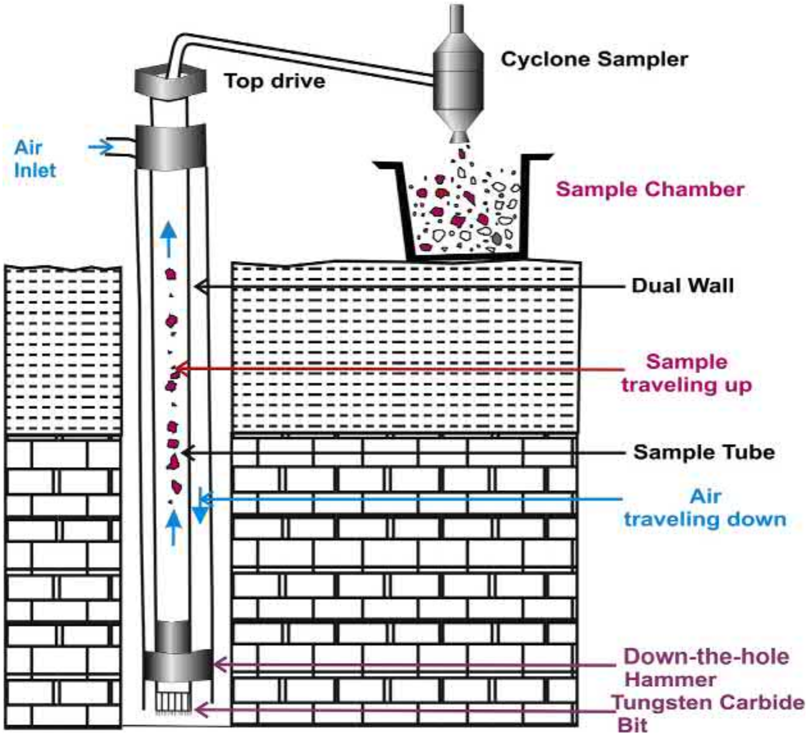

FIGURE 7.12 Conceptual framework of noncore reverse circulation drilling and sample collection, widely adopted by exploration companies all over the world due to fast sampling at low cost with reasonable reliability.

FIGURE 7.13 Reverse circulation drilling in operation and sample collection for iron ore deposits.

arranged around a bit head. The drill rod comprises a hollow inner tube placed inside a hollow outer rod barrel. A small compressor provides rotation of the cutting bit and blows air to remove rock cuttings to the surface through an inner tube, which passes through a sample separating system to form a sample. It is low cost with a faster speed up to a depth of ~125 m, and is often used in first pass exploration drill programs. Air-core drilling is efficient in the delineation of lateritic aluminum, nickel, cobalt, and platinum-group elements within saprolite and other horizons (Fig. 5.4).

7.2.2.8 Sonic Drilling

Sonic or **rotasonic drilling** is a high-speed, low-cost soil penetration technique for collecting soil/rock samples. It is suitable to identify detailed stratigraphic information of thick glacial sediments. It recovers uncontaminated continuous core and works on a variable frequency drill head to transmit vibration energy through a drill pipe and core barrel. It can penetrate overburden, fine sand, boulders, hard rock, and collect samples up to 254 mm in diameter from ~200−250 m deep vertical/inclined holes. Sonic drilling recovers 100% core in glacial till, clay, sands, gravels, and hard rock. Sonic holes are useful for the installation of groundwater monitoring devices, geotechnical instruments, and geothermal sensors (Gandhi and Sarkar, 2016).

7.2.2.9 Directional Drilling

Directional drilling under controlled deviation will result in multiple intersections from a single drill collar, follow a common path in waste formation without any physical drilling, and change drilling by using a wedge to deviate the drilling course in desired angles and directions (refer to Figs. 15.3 and 15.8). The system achieves multiple intersections at much reduced time and cost.

7.2.2.10 All Hydraulic Drilling

All hydraulic drilling is performed by single-handed, computer-controlled total automation that includes rotation, penetration, hoisting and lowering, screwing and unscrewing of rods, and lifting of accessories from rack to feed frame and back. The unit follows safety features in operations, bit efficiency, productivity, quality output, and clean work environments.

7.2.2.11 Borehole Survey

Boreholes have a tendency to deviate both in inclination (angle) and direction from original settings due to drilling through rock types of different hardness and structures, and using overspeed drilling, defective drill rods, barrel, and bits. Drill hole deviation at certain depth intervals (30−50 m), depending on the rock strength and formation structure, is suggested and measured by various ways (Devico, 2010). There are three types of borehole survey method available: the old style etch testing, low-cost Tropari, and advanced reflex multishot borehole camera with individual merits.

Etch testing is the simplest way to survey the angles of a borehole. It consists of a hollow container fitted at the lowering end of the drill rod in place of a barrel and bit. A special type of glass test tube ~13 cm long, partially filled with hydrofluoric acid and corked with a rubber stopper is placed in the container. The container is lowered to the desired depth of survey and kept stationary for ~45 min. The hydrofluoric acid reacts with the glass tube and forms a horizontal etch in the inner surface during the stationary period. The container is withdrawn from the drill hole, the tube is washed, and an etching line is marked with ink. The angle of the hole at that point is measured as shown in Fig. 7.14. The method could provide deviation of angle only, has no direction, and could be used in the case of low-budget exploration for limestone, etc.

Tropari is a single-shot, micromechanical borehole survey instrument operated by a timing device. The unit provides both inclination and direction at high precision that defines the borehole attitude at a desired survey depth. The instrument is essentially a pivoted ring-mounted compass (Fig. 7.15). It is attached with a time-clock mechanism to lock the compass needle and dip indicator within a preset delay between 5 and 90 min from lowering the unit. It is hoisted to the surface after automatic locking of the system to record inclination and azimuth direction. The device can record one set of readings at a time. It has to be lowered/hoisted repetitively to all desired depths resulting in loss of drill shifts. The time loss will be considerable in the case of a drill hole with extended depth. Regular surveys at intervals as the borehole progresses will allow a realistic plot of the borehole.

The **reflex multishot borehole camera** resolved the foregoing issues by using a digital multishot digital device ideal for nonmagnetic borehole paths. Features include capabilities like robust, reliable, and fully integrated performance on a precise electronic measuring principle, measurements in all directions, fast speed, and user friendliness. The unit comprises a multishot camera, a tiny magnetic compass, a flashlight, and an autolocking clock (Fig. 7.16). The shot and flash are synchronized with the clock. The angle and directional data are recorded on a 16 mm film/chip/data card. The string slowly moves in the

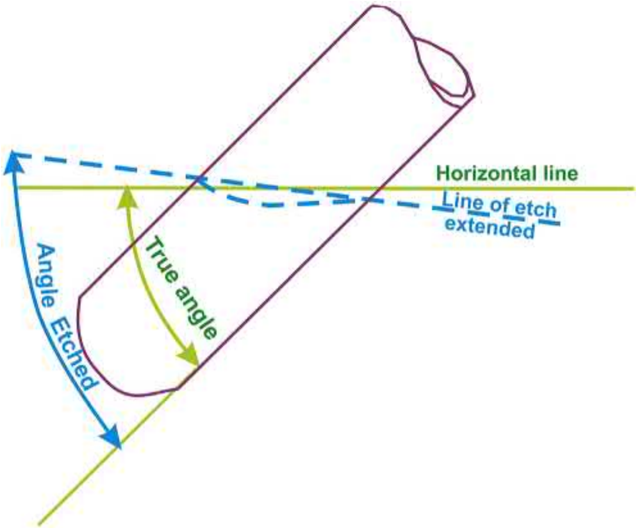

FIGURE 7.14 Borehole survey by special type of glass test tube-acid etching method at lowest cost for measuring the deviation of angle but not direction.

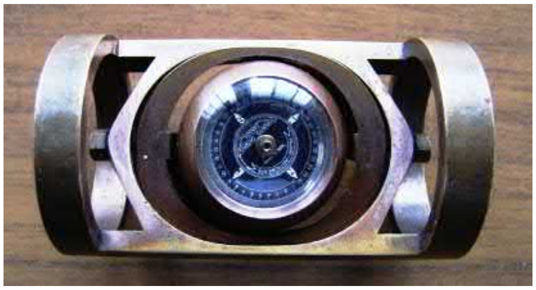

FIGURE 7.15 Borehole survey by Tropari unit capable of measuring both angle and direction for one reading at a time.

FIGURE 7.16 Borehole survey by reflex multishot camera is ideal for measuring both angle and azimuth with highest precision for holes at a number of depths at one lowering—a total borehole survey solution.

borehole and is kept stationary for 2 min at the desired depth. The process of lowering continues until the end of the hole, and the entire drill depth is surveyed in one single run. The survey data are processed for a total set of inclinations and bearings. Contemporary models conduct borehole orientation surveys and allow onsite access to survey data for incorporating corrective measures. The device is useful to geologists, drillers, tunnel borers, and ground engineers.

7.2.2.12 Core Recovery

Core recovery is a significant parameter for efficient mineral exploration programs. Good core recovery is the responsibility of drill crews. A careless crew can ruin a core by drilling too fast, overdrilling a run beyond core barrel capacity, and using an unsuitable type of barrel and defective core lifter. It can cause core drop in the drill hole and regrinding. A core recovery of 100% is hoped for, except when drilling through fractured, sheared, and caved zones. The minimum recovery through a mineralized zone must be +90%. The driller should use double or triple tube barrels in fractured mineralized formations. The driller may even change to a short run length with dry drilling. The best core recovery ensures reliability and precision of estimation. The existing hole should be rejected in the worst core recovery conditions and a fresh hole drilled with extreme care.

7.2.2.13 Core Preservation

A drill hole costs millions of dollars. The valuable cores are collected carefully from barrel, and kept in wooden or aluminum core boxes marking the direction of drill depth with an →. Each run length is separated by a peg mark indicating depth of drilling. The core boxes are generally 1.5 m long and can hold about 8 m of core in channels separated by thin separation plates (Fig. 7.17). The box may have a hinged or nailed cover to protect the core while shifting. The drill core is a valuable resource that needs to be accessed easily and kept in good condition. Many exploration companies create core library facilities to store for 15−30 years. The core boxes are stacked in order in uniquely designed shacks. Each box in the library can be identified by project name, box and borehole number, drill run, and date of drilling. The complete core boxes from standard sections are preserved for future study, and the rest can be destroyed during mining stages. Special lighting is provided to view the core. The online core library data repository is an emerging technology for exploration and mining companies.

7.2.2.14 Core Logging

Diamond drilling and drill core play key roles in mineral exploration. The quality of drilling is judged by best possible core recovery, proper core placement in preservation box with correct arrow marking, and shifting to the core shade from drill-site. Each activity needs extreme care before core logging study, and finally sampling. Any slip of the core in between will add the uncertainty of accurate ore boundaries in space. The reason may be due to misplacing or missing cores during drilling, collection, placement in core box, and shifting to core library. Apparently, it may look insignificant in comparison to shifting of contacts by

FIGURE 7.17 Standard wooden, plastic, and metallic (aluminum) core boxes essential for drill core preservation.

FIGURE 7.18 The resident geologist checks the placement of each core piece to be in perfect order, carry thorough wash before logging, and sample demarcation to the best of his sincerity. His work efficiency indorse the reliability of data collection norm in mineral exploration (at Lennard Shelf camp, Australia). Any discrepancy may reject the expensive diamond drill hole.

fractions of a meter, change of reserve by a few thousand tonnes, and metal grade in the second decimal. However, maintaining importance at each insignificant and major issue is important. Therefore the core is spread initially on extra-long conical plastic trays in the core laboratory. The arrow direction on each piece is checked and the edges of two successive core pieces are perfectly matched. Any discrepancy in identical matching must be sorted out without any compromise, and recorded. The core is washed thoroughly by water spray (Fig. 7.18) and is then ready for geological studies and sampling. The author experienced and appreciates the unique sincerity of geologists at Lennard Shelf exploration camp of Meridian Minerals Limited, Australia.

Core logging is the geological study and recording of drill cores. Records are made on printed sheets (Table 7.2). This covers a general description of the core, i.e., from and to, core size (NX, BX, AX, BQ), run and core length, % recovery, color, grain size, textures, structures, foliation with core axis, fractures, shears, folds, faults, mineral composition, alterations, visual estimates of metal values, sample number, and finally rock name. The lines are marked on mineralized core for splitting into two halves of identical mirror images. The visual estimates are made before sample preparation and assaying. Each visual estimate is compared with the assay value; the core is rechecked in case of major differences; and a duplicate is sent for reanalysis. **Tough-book core logger** (Fig. 7.19), a portable rugged laptop, is extensively used for recording at site. It is designed with multiple Excel sheets for a database comprising collar, survey, rocks, and assay files. It can be interfaced to a process computer by both wireless and hardware transmission for 3D modeling and reserve estimate. Many exploration companies conduct continuous color photography of the entire length of a borehole by a high-tech scanner as permanent records.

7.3 SAMPLING METHODS

A variety of sampling methods exist as appropriate for the mineralization environment. Sampling aims to generate the

TABLE 7.2 A Sample Borehole Core Log Sheet

Project Name:				BH No.		Date of Logging							
Logged by													
From (m)	To (m)	Core Size	Run Length (m)	Core Length (m)	% Core Recovery	Color	Grain Size	Structure	RQD	RFM	OFM	VE	Remarks

BH, Borehole; *OFM*, ore-forming minerals; *RFM*, rock-forming minerals; *RQD*, rock quality designation; *VE*, visual estimate.

FIGURE 7.19 Tough book—a high-tech internet interfaced data-sharing drill core logger used at Lennard Shelf zinc deposit, Australia.

best representative of the object under search (Moon et al., 2006; Dowing, 2014). Soil and rock chipping, pitting, trenching, stack, and placer sampling are practiced for surface features. Channel and chip sampling, both surface and underground, is of limited application today, but has its own merits. The diamond drill core, reverse circulation drill cuttings, and sludge collection are suitable for both surface and underground mineral exploration, and constitute +95% of the samples for the most reliable estimation of reserves and resources. Grab, muck, car, and bulk sampling are suitable for quick estimation of run-of-mine grade and are useful in both grade monitoring and control for blending.

7.3.1 Soil Sampling

Soil samples from residual or transported material are collected (Fig. 7.20) at a specified grid pattern designed during orientation survey. The sieve analysis of samples indicates that −80 mesh fraction of soil represents sufficient material for further processing and provides maximum contrast between background and threshold value. The standard practice is to obtain (−) 80 mesh fraction for analysis of various elements.

7.3.2 Pitting

Pitting is practiced during the initial stage of surface geochemical exploration. Sampling is carried out by excavating $\sim 1 \times 1\ \text{m}^2$ pits in a rectangular or square grid pattern covering the entire target area. Pit depth varies depending on extent of weathering and nature of rocks. The material from each meter of the vertical depth is kept in separate low-height rectangular flat stacks to determine the variation in grade and other distinctive features. Each stack represents a sample. The pits showing the presence of mineralization can be contoured (Fig. 5.2) to identify the strike and depth continuity of the orebody for drill testing.

7.3.3 Trenching

Trenches are cut across the orebody (Fig. 7.21) after the probable configuration of mineralization is outlined either by pitting or by rock/soil sampling. The sample recovered from each meter of trench is stacked separately as a sample for analysis to identify variations across mineralization. The walls of trenches can be sampled by channel cut or chipping for comparing with results of stack samples.

7.3.4 Stack Sampling

Stack sampling is the collection of representative broken material generated by pitting, trenching, or any mine production. The samples are collected by inserting a

FIGURE 7.20 Collection of soil sample during reconnaissance for Pt−Pd target search around Tagadur chromite-magnesite open pit mine at Nuggihalli schist belt, Karnataka, India.

FIGURE 7.21 Trench sampling for platinum-group elements and chromite during reconnaissance survey at Sitampundi layered igneous complex, Tamil Nadu, India.

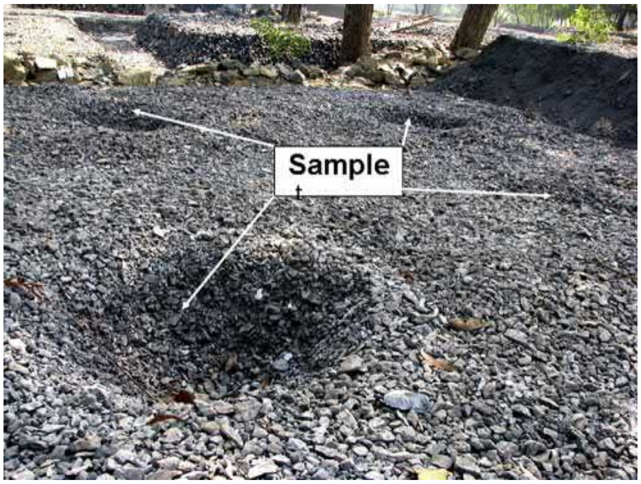

FIGURE 7.22 Stack sampling of chromite mine production ore at Sukinda belt, India.

10–40 cm diameter cylinder down to the base of the stack. It is also done by collecting buckets full of sample. A number of collection points from a stack are selected. A composite sample is prepared by a combination of one from the central part and four more from halfway between the center and corners (Fig. 7.22). Alternatively, particularly in the case of small pits and narrow trenches, the total recovered material can be reduced by successive crushing, coning, and quartering, and treated for chemical analysis.

7.3.5 Alluvial Placer Sampling

Alluvial placer deposits are formed by weathering, transportation, and deposition of valuable minerals. The large alluvial placer platinum deposit at the Ural Mountains in Russia is an example of such deposits discovered way back in 1823. In general these deposits are less consolidated, loose, and soft materials. Scooping by hand spade or the use of auger drills is employed to collect wet or dry loose sandy samples at regular grid intervals up to certain depths. A casing is driven into the deposit to protect wall collapse and avoid contamination during sample collection.

7.3.6 Channel Sampling

Channel sampling is suitable for uniformly distributed mineralization in the form of veins, stringers, and disseminations. Sampling is performed by the cutting of channels across a mineralized body in fresh surface exposures or underground mine workings, such as the mine face, walls, and roof. The area is cleaned to remove dust, dirt, slime, and soluble salts by any of three processes. These are washing with a hose pipe (air/water) or scrubbing with a stiff brush or by chipping of the outer part of rocks to smoothen the sampling face. A linear horizontal channel is cut between two marked lines at a uniform width and depth (Fig. 7.23). The width is between 5 and 10 cm at a depth of 1–2 mm. Sample length varies depending on variation in mineralization. The length is preferred at a uniform unit between 1 and 2 m within mineralization to promote statistical applications.

The standard tools are hammer and a sharp pointed end chisel made of drill steel, or pneumatic hammer with a pointed/chisel bit (Fig. 7.24). While the sampler cuts the channel, a second person collects chips, fragments, and fines in a clean box, sack, or on a canvas sheet spread on the floor. A sample of 1 m length will weigh ~1–2 kg.

7.3.7 Chip Sampling

Channel sampling may not be representative in the case of mineralization that is irregularly distributed or disseminated, and is not easily recognized by eye. **Chipping fragments** of ~1–2 cm by 1–2 cm size covering the entire surface exposure, underground mine face, walls, and roof in a regular grid interval of 25 cm× 25 cm (Fig. 7.25) will be a better alternative. The area is cleaned before sample cutting. The sampler chips off fragments by

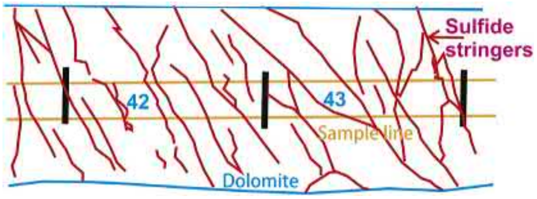

FIGURE 7.23 Schematic presentation of channel sampling of mineral exposure at surface and underground mine cross-cut wall at 1 m intervals.

FIGURE 7.24 Channel sample cut by pneumatic drill machine for exploration of platinum-group elements at open pit bench face, Boula-Nausahi chromite mine, Orissa, India.

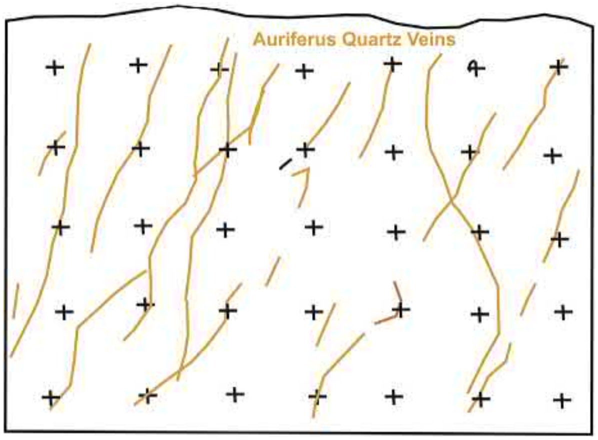

FIGURE 7.25 Chip sampling (+) of wall/face in irregular vein-type deposits such as auriferous quartz veins.

hammer and a pointed chisel. The chips are collected in a clean box or satchel or on a canvas sheet spread on the floor. The weight of samples from a 3 m × 3 m area is between 1 and 2 kg. Channel sampling is laborious, tedious, time consuming, and expensive compared to chip sampling. Chip sampling is preferred due to low cost, faster identification of mineralized contacts, and quick evaluation of grade of the area.

7.3.8 Diamond Drill Core Sampling

Diamond drill core sampling cuts/splits the core along its length into two identical halves or mirror images with respect to mineral distribution as observed during logging. One half is grinded, reduced, and sent to the laboratory for chemical analysis. The other half is preserved in the core boxes as a primary record for future check studies. The second half can also be used as a composite sample for metallurgical test works during the initial stage of exploration to develop a laboratory-scale beneficiation process flow diagram. Metallurgical test work will indicate amenability, optimum grinding, liberation, and recovery leading to producing clean marketable concentrates.

A simple type of core splitter operates manually by framing a splitting unit comprising a short piece of rail foundation, with a matching chisel fitted on top and a hammer as illustrated in Fig. 7.26. The core is placed tightly between the rail and chisel, and hammered from the top to split the core into two identical halves. Hammering can be powered by compressed air. The unit is handy and low cost, and can be used in remote camp locations.

The modified form works by electric power. The cutting head is either a diamond cutting unit or a blade made of hard metal alloy (Fig. 7.27) that cuts the core into two smooth identical halves (Fig. 7.28).

FIGURE 7.26 Semimechanical core splitter used at Khetri copper mine during the 1970s.

FIGURE 7.27 Fully mechanized electric core cutter used at Lennard Shelf zinc deposit, Australia.

FIGURE 7.28 Stratiform sulfide drill core split into two identical halves by electric core cutter.

7.3.9 Sludge Sampling

Sludge is the finer coproduct particles of diamond drilling generated by cuttings of rocks between core and outer hole diameter. **Sludge sampling** forms an integral alternative in case of poor core recovery due to drilling through fractured mineralized zones. It is pertinent to recover the maximum portion of sludge in such circumstances.

Sludge collection is done in various ways as suits the operator. The simplest way is to use a plastic or metallic tub and allow the returning water to pass. The cuttings settle and can form a sample corresponding to the drilling interval. The method can be modified by using a large sludge box with three to four longitudinal partitions. The returning water can flow in a zigzag pattern between successive partitions so that settling of materials is improved. Commercially designed sludge cutters with mechanical operation are available. The sludge samples are not incredibly authentic due to contamination between drill runs. However, they show the existence and to some extent the quality of mineralization in the absence of good core recovery.

7.3.10 Reverse Circulation Drill Sampling

Reverse circulation drill sampling is the collection of rock cuttings with respect to drill depth. The entire rock cuttings are raised to the surface by return air pressure and collected in glass chambers in an inverted sequence of depth (refer to Figs. 7.12 and 7.13), forming a sample. Reverse circulation drill samples are not an exclusive and ultimate solution to mineral deposit evaluation. These samples are supported, complemented, and balanced by a certain amount of diamond drilling from a global perspective. Reverse circulation drill samples are extensively used in grade control of mine production in advance, and particularly for large open pit mines.

7.3.11 Grab Sampling

Grab sampling is performed at any stage of exploration, and more so during mine production for a quick approximation of run-of-mine grade. The samples are randomly picked up from loose broken material from outcrops, pits, trenches, mine workings, stope drawpoints, mine cars, load shipments, and all types of stockpiles. Good care should be taken to avoid inclusion of any foreign objects like wood, iron pieces, nails, masonry, and plastics.

7.3.12 Muck Sampling

Muck sample is composed of a few handheld spades or mechanized shovels full of mineralized fragments and fines collected from the mine face or stope drawpoints (Fig. 7.29). These samples collected from mine production are useful to compare with drill estimates, as well as cuttings/sludge sample values of jackhammer and long hole drills. The grades rarely match on a day-to-day basis. However, the average production grade over a period of a week, fortnight, month, quarter, or year can be comparable depending on heterogeneity of the deposit. It also helps to indicate the intrinsic external mining dilution.

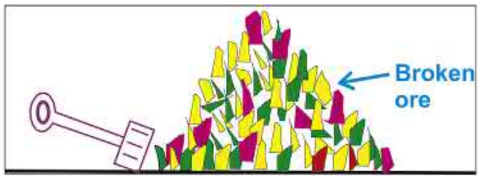

FIGURE 7.29 Muck sampling collected from all sides using a handheld spade or mechanized shovel depending on the volume of the sample.

7.3.13 Car Sampling

A **car sample** comprises a handful of broken pieces picked up randomly from every 5th/10th/15th moving mine car from an underground mine (Fig. 7.30), or dumpers/trucks from a surface mine, or aerial ropeway tubs that transport ore to integrated or third-party beneficiation plants and smelters. The sample values are compared between run-of-mine and mill head grade for valuation, grade control, and reconciliation. The method is suitable for valuation of metal grade, penalty components, and moisture content of ore/concentrate being shipped for integrated or third-party smelters.

7.3.14 Bulk Sampling

A **bulk sample** comprises a large volume of material (100−1000 tonnes) representing all metal grades and

FIGURE 7.30 Car sample in underground mine by collecting a handful of ore randomly from mine cars.

mineral distributions of an entire orebody. Samples are collected from different parts of stockpiles generated from surface trial pits, underground cross-cuts, and run-of-mine ore of regular production. The best collection equipment is shovels to handle huge volumes. Total material is mixed thoroughly to reduce heterogeneity. Samples are used for developing beneficiation flowsheets for optimum reagent consumption and maximizing recovery efficiency.

7.3.15 Ocean Bed Sampling

Deep ocean floor mineral resources include polymetallic nodules, manganese crusts, active/extinct hydrothermal sulfide vents, and diamonds. They cover large areas between 4000 and 6000 m below the ocean's surface. The polymetallic nodules contain mainly nickel, copper, cobalt, and manganese. The manganese crusts include primarily manganese, copper, vanadium, molybdenum, and platinum. The sulfide vents contribute largely copper, zinc, lead, gold, and silver. These raw materials are found in various forms on the ocean floor, usually in higher concentrations than in land-based mines.

Sample collection from prospective areas of the sea bottom is conducted by progressive reduction of sample grids through $100 \times 100, 50 \times 50, 25 \times 25$, and $12.5 \times 12.5\ \text{km}^2$. The collection unit is designed as a bucket-in-pipe nodule-lifting system (Fig. 7.31), and tested successively. The quantity of materials collected in a trip is ~10 tonnes and reduces to 200−500 kg.

7.4 SAMPLE REDUCTION FOR CHEMICAL ANALYSIS

Analytical laboratories require a few grams (~5 g) of homogeneous fines at ~100 mesh size for chemical analysis. Therefore samples collected by different methods are reduced without sacrificing the property of mass being sampled. **Sample reduction** is done by progressive grinding of fragment size and gradual reduction of quantity at stages. Samples can be prepared manually by mortar and pestle. Manual processing is slow and precision is low due to uncontrolled bias. Therefore the size is reduced successively by using a succession of mini-crusher (jaw crusher) (Fig. 7.32), grinding roll crusher, (Fig. 7.33), and pulverizing disc/ball/rod pulverizer/mill, (Fig. 7.34).

The final samples change to relatively homogeneous after each stage of crushing, grinding, and pulverizing. The sample quantity is further reduced by coning and quartering as shown in Fig. 7.35 for procedural concept and Fig. 7.36 for technical application. A Jones refill splitter (Fig. 7.37) is a mechanical device for sample reduction. The laboratory crusher/grinder/pulverizer is small in size and low cost. The units can be easily moved to other exploration camps and installed as and when necessary.

Two identical samples of 50 g each are prepared: one part is sent to an analytical laboratory and the duplicate is preserved at the exploration department for future reference. Laboratory chemists/technicians further grind the material, mix thoroughly, and reduce to ~5 g for analysis and to preserve the remainder for reference.

FIGURE 7.31 Bucket-in-pipe polymetallic nodule sample lifting system collected from the deep ocean floor.

FIGURE 7.32 Sample size reductions by a small, portable, laboratory jaw crusher.

FIGURE 7.33 Sample grinding by a laboratory-scale small roll crusher.

7.5 ANALYTICAL METHODS

Analytical methods must satisfy optimum cost, best accuracy, and precision to create an unbiased database for resource estimation acceptable by international major investment stakeholders. The standard methods in order of applicability, affordability, and precision are as follows.

7.5.1 Atomic Absorption Spectrometry

Atomic absorption spectrometry (AAS) is a widely accepted, rapid, precise, and commonly used method for quantitative determination of a large number of samples for multielemental analysis. About 5 mg of sample is treated with 5 mL of aqua regia and digested over a hot plate. The solution is aspirated into an air-acetylene or N_2O-acetylene flame for complete atomization of test metals. Absorbance of a characteristic radiation of desired metal is measured for computation of elemental concentration. Approximately 30 elements can be determined from one solution, one after another, by AAS using specific hollow cathode lamps with background correction.

FIGURE 7.34 Sample size reductions by a laboratory-scale disc, ball, or rod pulverizer.

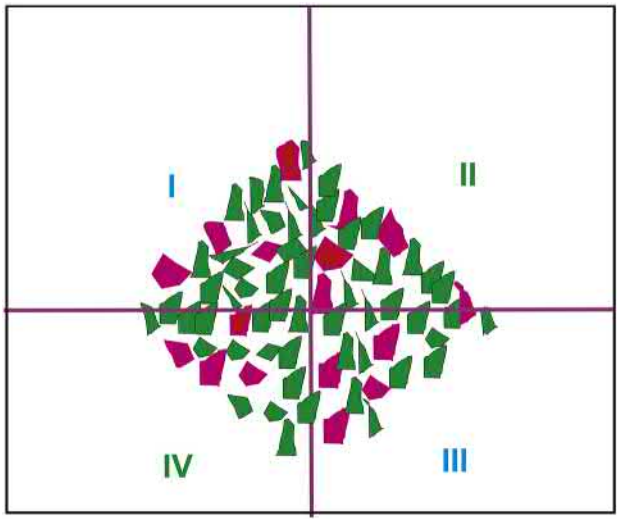

FIGURE 7.35 Sample quantity reductions by coning-and-quartering principles.

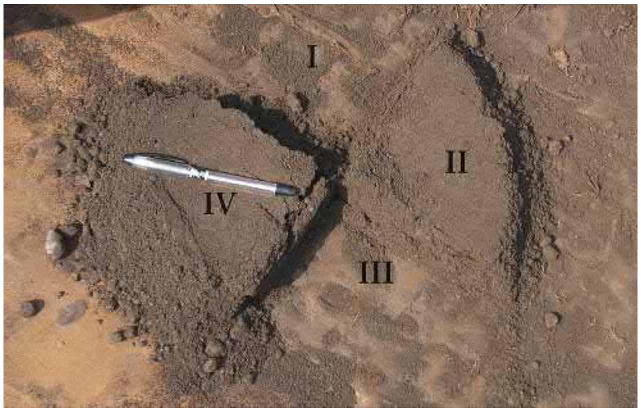

FIGURE 7.36 Sample quantity reductions for chromite production grade at the mine head by coning-and-quartering practices. Quarters II and IV will be mixed for further reduction.

FIGURE 7.37 Sample quantity reductions by a Jones refill splitter.

7.5.2 X-ray Fluorescence—Portable XRF

The **XRF** technique uses high-energy X-ray photons from an X-ray generation analyzer to excite secondary fluorescence characteristic X-rays from samples. The characteristic line spectra emitted by the different elements of sample are detected in an analyzer. The intensity of each line is proportional to the concentration of individual elements.

The **portable XRF** or handheld XRF is a lightweight rapid analytical instrument (Fig. 7.38). It is used as a nondestructive test to detect elemental/chemical analysis ranging between Mg and U. Typical applications are detection of minerals, including precious metals in exploration and mining projects, alloy in industrial locations and scrap markets, environmental remediation, and lead paint identification. The portable XRF unit has revolutionized the sampling of soil and stream sediment. The instrument/method is handy as part of core and rock chip logging, and with an additional bonus of mineral identification.

FIGURE 7.38 Handheld portable XRF analyzer. *From Gandhi, S.M., Sarkar, B.C., 2016, Essentials of Mineral Exploration and Evaluation, Elsevier Publication, 422 p.*

7.5.3 Inductively Coupled Plasma-Atomic Emission Spectrometry

Inductively coupled plasma-atomic emission spectrometry (ICP-AES) works on an optical emission method excited by inductively coupled plasma. It is a promising emission technique that has been successfully used as a powerful tool for fast multielemental analysis since 1975. The flame for this technique consists of incandescent plasma of argon heated inductively by radiofrequency energy at 4–50 MHz and 2–5 kW. The energy is transferred to a stream of argon through an induction coil, whereby temperatures up to 100 K are attained.

Sample solutions are forced through a capillary tube, nebulizer system, and spray chamber to a relatively cool central hole of the plasma torus. The spray chamber reduces the particle size of the aerosol to an ideal 10 μm. The sample atomizes and ionizes. The radiation from plasma enters through a single slit, and is then dispersed by a concave reflection grating. The light from each exit slit is directed to fall on the cathode of a photomultiplier tube, one for each spectral line isolated. The light falling on the photomultiplier gives an output that is integrated on a capacitor; the resulting voltages are proportional to the concentration of the elements in the sample. Multichannel instruments are capable of measuring the intensities of emission lines of up to 60 elements simultaneously.

7.5.4 Instrumental Neutron Activation Analysis

The **instrumental neutron activation analysis** technique utilizes high-energy neutrons for irradiation of a sample to produce gamma radiation that can be analyzed for the detection of elements. The method is suitable for the detection of trace elements and rare earth elements with a high level of accuracy.

7.5.5 Scanning/Transmission Electron Microscope

Detailed knowledge of the physical nature of the surfaces of solids is significant in geology, chemistry, and material science. Finer surface information at considerably higher resolution is obtained by scanning electron microprobe. The surface of a solid sample is swept in a raster pattern with a finely focused beam of electrons in the **scanning electron microscope** technique to obtain a precision image. The beam is swept across a surface in a straight line (the X-direction), then returns to its starting position and shifts downward (the Y-direction) by standard increments. The process is repeated until a desired area of the surface has been scanned. A signal is received above the surface (the Z-direction) during the scanning process and stored in a computer for conversion to the final image.

A **transmission electron microscope** is used either in biological applications for ultrahigh-resolution transmission electron photomicroscope studies of thin slices of cell and tissue material, or in metallurgical studies, including investigation of defect structures in alloy material. Subject to some limitations, equivalent studies are carried out on geological samples. However, samples must be prepared as thin foils. The quantitative measurements of photomicrograph data can be derived in two ways: (1) crystal structure data from the pattern resulting from electron diffraction within the sample, and (2) compositional data from characteristic X-ray emissions excited by the electron beam as it is transmitted through the foil.

7.5.6 Electron Microprobe and Secondary Ion Mass Spectrometer

The **electron microprobe** provides a wealth of information about the physical and chemical nature of surfaces. With the electron microprobe method, X-ray emission is stimulated on the surface of the sample by a narrow focused beam of electrons; the resulting X-ray emission is detected and analyzed with either a wavelength or energy dispersive spectrometer.

The **secondary ion mass spectrometer** (SIMS) has proven useful for determining both the atomic and molecular composition of solid surfaces. SIMS is based upon bombarding the surface of the sample with a beam of 5–20 KeV ions, such as Ar^+, CS^+, ${N_2}^+$, and ${O_2}^+$. The ion beam is formed in an ion gun in which gaseous atoms or molecules are ionized by an electron impact source. The positive ions are then accelerated by applying a high DC potential. The impact of these primary ions causes the surface layer of atoms of the sample to be tripped off, largely as neutral atoms. A small fraction, however, forms as positive (or negative) secondary ions that are drawn into a spectrometer for mass analysis.

7.5.7 Fire Assaying

Fire assaying is quantitative determination in which a metal or metals are separated from impurities by fusion processes and weighed to determine the amount present in the original sample. The fire assay method is most accurate, but totally destructive for determination of precious metals. It is a critical cupellation step by refining in metallurgy, where ore/precious metals/alloys are treated in fire under extremely high temperatures, and have controlled operations to separate noble metals like gold, silver, platinum, and palladium from base metals like copper, lead, zinc, arsenic, antimony, and bismuth present in ore. If performed on ore materials using fusion followed by cupellation separation, detection may be in parts per billion/million.

Fire assaying can be applied for proving the existence of precious metals, especially as a prerequisite concentrating step prior to neutron activation analysis or ICP-MS analysis.

7.5.8 Carbon Dating

Carbon dating is a standard method for determining the age of an object containing organic material (plant or animal) by using properties of radiocarbon (^{14}C—a radioisotope of carbon). ^{14}C is continuously being created in the atmosphere by the interaction between cosmic rays and atmospheric nitrogen. The resulting ^{14}C combines with atmospheric oxygen to form radioactive CO_2. ^{14}C integrates into plants by photosynthesis and subsequently imparts to animals through nourishment. The process stops exchanging carbon in its environment after demise of the organism, and the contained ^{14}C endures radioactive decay. Amounts of ^{14}C decay can be measured to predict when the organism died with a range of accuracy. The best samples for ^{14}C age dating include wood used as wall supports, baskets, ladders, platforms, water channels (Figs. 4.3, 4.5−4.7), and animal bones from ancient mining/smelting sites.

Examples can be cited from ancient mining history at Kolar (1290 ± 90 to 1500 ± 115) and Hutti (1945 ± 70) gold mine (Agarwal and Margabandu, 1975−1976) and Zawar (2410 ± 100) and Rajpura-Dariba (3040 ± 150) zinc-lead mines, (Willies, 1987), India.

7.5.9 Choice of Analysis

The primary objective is to identify techniques that are widely used for the unbiased reporting of elements, and examine the analytical potential of individual techniques.

1. AAS, XRF, and portable XRF are most widely used, and acceptable for determination of major elements.
2. Since 1984, ICP-AES has become better established for trace and rare earths, but is costly. SEM, TEM, and electron microprobes are excellent, efficient, and accurate for surface- and structure-related compositional analysis. Instruments are expensive, research oriented, and may not be within the reach of everyone.
3. Fire assaying is a link between (2) and (3). ^{14}C age dating is used to establish exploration/mining/smelting heritage.

7.6 ACCURACY AND DUE DILIGENCE IN SAMPLING

Sampling due diligence, which makes an authentic geological resource assessment, needs the validation of six principal components:

1. Sample representation, integrity, and security.
2. Accuracy of laboratory assays.
3. Insertion of blank and standard samples at industry-accepted intervals in the sample string within mineralization.
4. Adequacy of sample.
5. Quality assurance and quality control (QA/QC) protocols.
6. Mineral resource continuity.

Sampling errors generally occur due to the following reasons:

1. Improper choice of sampling method.
2. Bias and selective collection of heterogeneous mineralization, including salting.
3. Bias and selective collection from host rocks with variable hardness.
4. Mirror image of drill core splitting.
5. Errors in chemical analyses.

7.7 QUALITY ASSURANCE AND QUALITY CONTROL

The critical issue in sampling is to identify bias expected to be associated with any activity of collection, preparation, and analysis. QA/QC measures are essential in current exploration programs for creating a reliable database free of any bias/error (McDonald and Leclair, 2004; Mitchell, 2006). QA/QC pass database assures a trustworthy quantity (tonnes) and quality (% grade) within an acceptable confidence of reserve and resource base of the deposit under feasibility study and mining investment. Sample audit eliminates the risk factors. This is more relevant when the investigation data and reports in standard stock exchanges for commercial trading in a competitive manner are uploaded. Some of the control measures are as follows:

1. The reserve and resource estimation of mineral deposits is based on several sampling methods conducted during exploration, such as drill core, channel, and chip. A multiple sampling campaign should be piloted during the feasibility/mine development stage by creating a comparable sample database of several sampling methods over the fixed designed location and length of mineralization, as conducted at Rampura-Agucha exploration program, India.

   An incline was developed along a controlled drill section up to a limited depth from the surface to access the orebody (Fig. 7.39). An underground borehole was drilled along the dip direction and kept unsampled. A cross was developed following the borehole. The face chip and grab/muck sample from each mine blast was collected. The borehole, cross-cut wall channel, and chip samples were prepared following the exact length of mine face advancement, and analyzed. A set of five types of samples of the same location and length comprising borehole, channel, chip, grab/muck, and face chip were available. The results were compared and statistically tested before accepting the best suitable sampling technique for estimation of reserves and resources.
2. In the case of drill core sampling, usually one half of the core is processed for analysis and used for reserves/resources estimation without confirming the grade representation of the other half (mirror image) in the system. The second half of the core should be processed, analyzed for a certain length of mineralization, statistically verified, and accepted/modified/rejected (Fig. 7.40).
3. There can be an inherent human and process error in a laboratory while analyzing a sample. The duplicate samples of known value are inserted at an industry-accepted protocol of 10th or 20th positions in the sample run and analyzed throughout the exploration phase

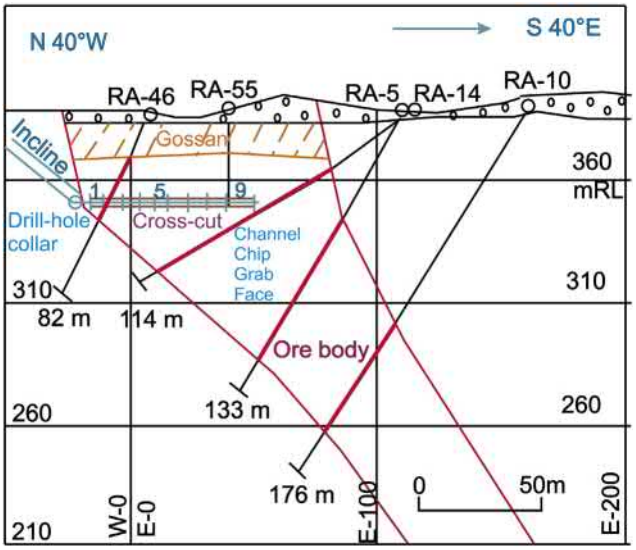

FIGURE 7.39 Comparative sampling study is necessary for a new exploration project before accepting/rejecting any sampling method. Various types of samples are compared using statistical tests before estimation of reserves and resources, Rampura-Agucha exploration program, India.

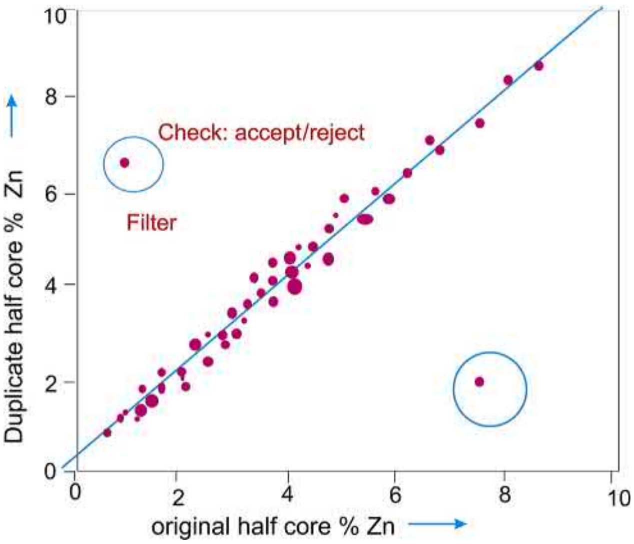

FIGURE 7.40 Scatter plot of original and duplicate half core sample values confirms significant statistical reproduction.

at the same laboratory without disclosing the identity of the sample. The results of two sets can be tested statistically for mean, variance, scatter plot, correlation coefficient, "f," paired "t," and pool "t" before final acceptance/modification/rejection.

4. Standard (certified reference material of known value) and blank (certified reference material of zero value) samples are inserted within the routine samples at industry-accepted intervals and dispatched to laboratories for quality control purposes. These standard and blank samples can be inserted at the start, end, and every 10th or 20th position in the sample string. It is desirable to change the sequence of insertion of blanks and standards from time to time for quality assurance (similar to Fig. 7.40) in case of major differences. Samples are sent for repeat reanalysis. The QA/QC can be repeated in batches.
5. If the samples are analyzed at different laboratories there is likely to be some bias due to different laboratory personnel (analysts), analytical procedures (AAS, volumetric, XRD, etc.), and location-based laboratory environment (water used for analysis, contamination, cleanliness, and work culture). A set of the same sample should be analyzed at all the concerned laboratories, as well as in a referee laboratory of international repute. Results are statistically tested for equality.

   Surface exploration at the newly rediscovered zinc, lead, and silver deposit, India, was conducted with great urgency to complete ~24,000 m of surface drilling in 18 months between 1978 and 1980. This resulted in 12,000 samples for chemical analysis. None of the Hindustan zinc chemical laboratories were equipped to analyze large amounts of zinc, lead, silver, and iron. Therefore the samples were sent in batches to five company laboratories at Zawar group of mines, Rajpira-Dariba Mine, Agnigundal lead mine, Debari zinc smelter, and Central Research and Development Laboratory.

   A lot of 46 samples from the Rampura-Agucha project were selected, divided into seven identical sets, and sent to five company laboratories in India, one to SNC Laboratory in Canada for authentication and reference, and one as a reserve. The results of all the six laboratories are statistically analyzed, compared, and accepted for reserve estimation. Reserve estimation is accepted as a bankable document for investment by all related stakeholders.
6. The **data error** between paired sets can be analyzed by various statistical tests. The simplest one is a scatter plot of paired data. The scatter diagram will easily identify the presence of extreme, erratic, high, or low values in the system. The erratic sample pair must be sorted, identified, and isolated, and their authenticities investigated along with probable source of errors. The samples can be verified and rejected if they do not satisfy and fit into geological conditions. The filtered dataset will be suitable for QA/QC analysis.
7. The plot must show a remarkable degree of correlation at high confidence (r^2) level. If the check assay results are lying in the acceptable range of standard deviation or within less than 5% variation from the mean value at 95% level of significance, then assay results are captured in a main assay database. The file turns into a **stable database**. It is a continuous process with incoming additional assay input until the exploration ends. In the process, some of the results are

unacceptable and the rejected values are not included in the database. A complete set of sample data base, technically accepted by QA/QC protocol, can only be used for the estimation of reserve and grade of a deposit.

8. The confirmation of correlation between two complementary assay data strings can be performed by:
   - **a.** A percentile/percentile plot.
   - **b.** A quartile/quartile plot.
   - **c.** A cumulative frequency plot.

7.8 OPTIMIZATION OF SAMPLES

Sampling is a continuous process during exploration and grade control. Diamond drilling is the most authentic and accepted process, but is costly. The hardest question often raised in an exploration program is: "When does drilling start?" Even harder is: "When does it stop?"

The first issue is guided by evidence from surface signature, supported by airborne and ground geophysical and geochemical anomalies indicating subsurface continuity of mineralization during reconnaissance/prospecting. The decision for drilling is based on above evidences, with a view to establish and delineate the deposit for continuity in strike and depth.

Drilling continues in sequence to achieve defined objectives. Drill interval depends on complexity and value of commodity as in the case of the platinum group of precious metals. Drilling quantity should be adequate to establish 60% of the total resources in the demonstrated reserve (measured + indicated) category for investment decision. Drilling can be stopped for the time being until additional reserve is required.

Precision for width (tonnage) and grade (% or g/t metal) with increasing number of boreholes in an ongoing exploration can be determined by applying statistical/geostatistical tools, and exploration can be optimized. The tools include frequency, probability, and geostatistical models. The curves become steady and flat after drilling at optimum interval with adequate confidence, and suggest for investment decision without further drilling, other than specific requirements, such as, weathering profile, and grade control.

Drill sampling can be optimized, and exploration stops at that point. Mine development is initiated and regular production continues. Exploration drilling will begin again in the future for the enhancement of ore reserves along dip and strike. The cycle of exploration repeats and finally closes when the deposit is fully exhausted in all respects.

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Chapter 8

Mineral Resource and Ore Reserve Estimation

Chapter Outline

> *Any due diligence investigation of a reserve/resource requires a geologist to do the audit and to prepare the data to be audited.*
>
> L.A. Wrigglesworth.

8.1 DEFINITION

Mineral resources and ore reserves are defined by the quantity (tonnage) and quality (grade of elements) of in situ concentrations of material in or on Earth's crust. Resources and reserves exist within well-defined 3D mineralized envelopes. Estimation is based on the information generated during various stages of exploration from inception onward. All types of sampling data are collected, validated with due diligence, and captured in a main database. The boundaries are interpreted between ore and waste. The in situ geological resources are generally higher than minable ore reserves due to the fixing of firm economic mining boundaries, rejection of uneconomic mineralization around irregular shapes, and tail ends of orebodies. The availability of detailed and accurate sampling input provides higher confidence in the estimation of reserves and resources. A firm knowledge of reserves and resources is needed for investment decisions of any property.

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00008-3

8.1.1 Estimation of Resource and Reserve

The mineral resources and ore reserves of a mineral deposit are estimated principally by one straightforward formula with minor variations as and when they arise. The unit of measurement is the tonne (t):

$$\mathrm{t} = \mathrm{V} \times \mathrm{Sp.\ Gr.}$$

$$\mathrm{V} = \mathrm{A} \times \text{Influence of a third dimension}$$

$$\text{Total T} = \sum_{i=1}^{n} (\mathrm{t}_1 + \mathrm{t}_2 + \mathrm{t}_3 \ldots \mathrm{t}_n)$$

where t or T = measured quantity in tonnes, V = volume in cubic meters (m^3), A = area in square meters (m^2) and is derived by measurement from plans or sections of a geologically defined mineralized area.

The influence of a third dimension is the thickness of the horizontal or layer type of deposit, like coal seam, lignite, bauxite, placer deposits, or the interval between drill sections; more technically, the halfway influence on either side of individual sections for large deposits. The influence on the extreme end sections of the deposit is the addition of half distance in the inner side, and between one-third and three-quarters on the outer side guided by geological knowledge of the area.

Specific gravity (Sp. Gr.), bulk density, and tonnage factor are used in the computation of tonnes by including likely volume of voids and pore spaces in the host rock within the defined boundary under computation. The measurement of average Sp. Gr. is measured from the number of random mineralized drill cores or bulk samples as a reliable means to establish tonnage factor. Sp. Gr. can also be measured selectively for high-, medium-, and low-grade mineralization for obtaining précised tonnage of the deposit.

8.1.2 Mineral Resource

Mineral resource is the in situ natural concentration of minerals within a geologically defined envelope. The geological characteristics (quantity, grade, and continuity) are partly known, estimated, or interpreted from broad-based evidence and regional knowledge. The presence of mineralization is inferred without comprehensive verification and cut-off concept. The main emphasis is the estimation of resource inventory at low confidence made during the early stages of exploration or around the outer periphery of known economic concentration. The evidence is based on wide space sampling. Economic viability is premature and intends to establish after advanced stages of exploration. The shape, quantity, and grade indicate intrinsic future interest and reasonable prospects for eventual profitable extraction.

8.1.3 Ore Reserve

The mineral reserve or precise ore reserve is the well-explored and defined part of the deposit at a specific cut-off after completion of detailed exploration. The reserve is estimated with a high level of confidence based on detailed and reliable information. The sample locations are spaced closely enough to confirm geological and/or grade continuity. This reserve must be technoeconomically viable. The geological characteristics must be so well established to support production planning. The deposit can be mined and marketed at a profit. The metallurgical tests show optimum recovery. A prefeasibility or feasibility report is prepared to make an investment decision. It includes mine planning, financial analysis, including losses associated with mine dilution, and metallurgical processing.

8.1.4 Minable Reserve

Minable reserve is the very précised accounting of the quantity and grade present within the stope boundary, and finally the sum total of all stopes. The minable reserve includes all three types of planned and unplanned dilution associated with large-scale mining (Fig. 8.1). **Internal dilution** is comprised of narrow low-grade or barren rocks that exist within the mineral body or between rich mineral bodies (Fig. 8.3). **External or planned dilution** is the intended addition of extraneous barren rocks outside the ore contacts for uniform designing of blast holes. **Unplanned** and **wall dilutions** are caused by overdrilling and blasting beyond the planned boundary, deviation of blast holes, and weak and sheared formation at ore contacts. Wall dilution can be anticipated based on past experience with similar mining methods, the type and structure of wall rock, and rock mechanical studies. It is pragmatic to consider all

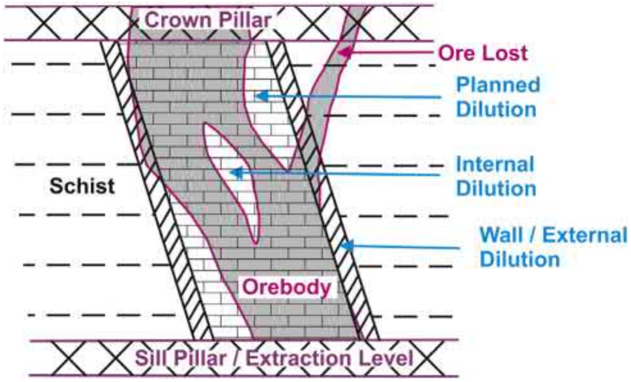


FIGURE 8.1 A schematic cross-section showing designed stope boundaries and expected planned, internal, and wall/external dilution during mine planning. The actual will vary to certain extent depending on many factors, like, rock quality, stope drilling accuracy, explosive selection, and blasting.

dilution waste at “0” grade to produce a conservative estimate. A margin of 5%—10% mining loss of ore is expected at the contacts depending on mining methods. Total waste dilution can be expressed as:

% Waste dilution = Total waste/Ore

Some part of the ore reserve is blocked in vertical pillars around the shafts/inclines and as horizontal crown/sill pillars between upper and lower mining blocks. These pillars act as mine support systems. It is not considered an ore reserve until and unless it becomes recoverable at a later phase of mine life. The category of pillar reserve is then upgraded and merged with minable reserve.

8.2 ESTIMATION OF GRADE

The grade/grades of resources and reserves is/are the relative concentration of minerals and metals. The unit of measurement is % and grams per metric tonne (g/t) (10% Zn, 10 g/t Au). The various features associated with grade estimation are the following.

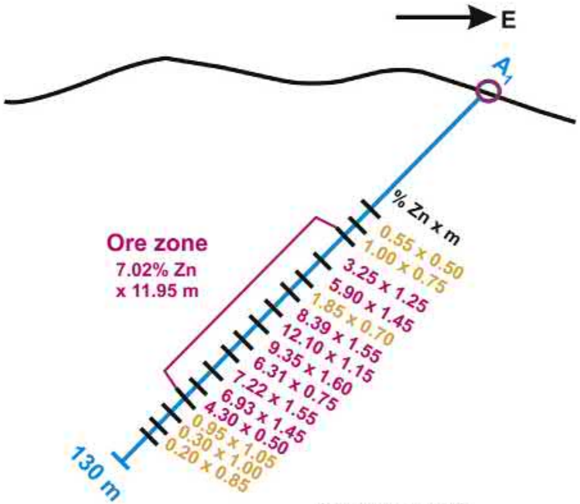


FIGURE 8.2 The average grade computation of a mineralized zone from borehole samples leaving low values on either side of ore boundaries at 3% Zn cut-off and 2 m minimum mining width.

8.2.1 Cut-off Grade

Cut-off is the most significant relative economic factor for computation of resource and reserve from exploration data. It is an artificial boundary demarcating between low-grade mineralization and technoeconomically viable ore (Fig. 8.2) that can be exploited at a profit. The cut-off boundaries change with the complexity of mineral distribution, method of mining, rate of production, metallurgical recovery, cost of production, royalty, taxes, and the commodity price in the international market (LME or London Metal Exchange). A change of any one criterion or of a combination of criteria gives rise to different cut-offs and average grades of the deposit. The cut-off never changes on a short-term basis. The market trend is continuously monitored over a long-term perspective and situations may compel the cut-off to change or the mining operation to close. The concept works well in the case of deposits with disseminated grade, gradually changing from outer limits to the core of the mineralization.

In heterogeneous vein-type deposits with rich minerals/metals at the contacts, the cut-off has little application in defining the ore limits. In large-scale mechanized mining operations the internal waste partings are unavoidable. The minimum acceptable average grade, defined by combination of alternate layers of ore and waste, is the basic criterion of decision-making. In this situation an even run-of-mine grade is obtained by scheduling ore from a number of operating stopes with variable grades. The combination of ore veins and waste partings with marginal cost analysis will define the shape of the orebody. The ore veins at the margins along with the internal waste must satisfy the cost of production, otherwise the marginal vein should be excluded while mine planning. This is known as the **variable** or **dynamic** cut-off concept (Fig. 8.3).

The cut-off grade perceptibly denotes a simple issue, but it is probably the most misunderstood or misused factor in resource estimation. The selection of cut-off must be critically reviewed before acceptance. The cut-off grades are expressed in percentages (%) of major metals (Cu, Pb, Zn, Fe, Al, Cr) and in g/t, or parts per million (ppm), or ounces per dry short ton (oz → sh tn) for precious metals

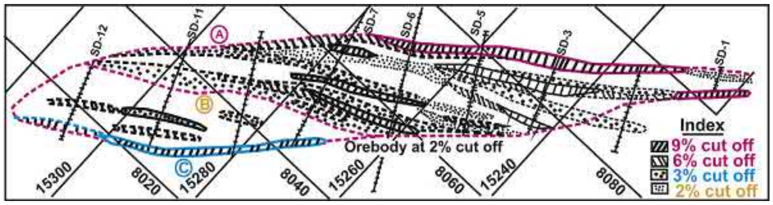


FIGURE 8.3 The concept of dynamic or variable cut-off for a vein-type deposit at Balaria zinc-lead mine, Rajasthan, India. The material between “B” and “C” has been excluded for mining. The area is not economically payable by itself.

(Au, Ag, Pt, Pd). It can be given as a percentage equivalent of predominant mineral commodity for multimetal deposits.

$\%$ Eq. Cu $= \%$ Cu $+ \{(\text{Ni price} \times \%\ \text{Ni})/\text{Cu price}\} + \{(\text{Au price} \times \%\ \text{Au})/\text{Cu price}\} + \ldots$

$\%$ Eq. Zn $= \%$ Zn $+ \{(\text{Pb price} \times \%\ \text{Pb})/\text{Zn price}\} + \{(\text{Ag price} \times \%\ \text{Ag})/\text{Zn price}\} + \ldots$

8.2.2 Minimum Width

The ultimate use of reserves and grades is related to mining the economically. The mining of ore, by open pit and underground methods, requires a minimum width of the orebody for technical reasons. A narrow width of orebody restricts the vertical limit of open pit mining due to the increase in ore-to-waste ratio with depth. A minimum of 3 m is suitable for semimechanized ore extraction in underground mining. However, the greater the width of the orebody, the larger will be the volume of ore production, the higher the mechanization and ore man shift leading to low cost production. Therefore cut-off-based mineralized zone computation is performed keeping in view the minimum width.

8.2.3 Cutting Factors

Many base metal (Cu, Zn, Pb) and the majority of precious metal (Au, Ag, Pt, Pd) deposits show occasional or frequent high sample values. These values are considered to be erratic and are designated as nugget value. Some of the estimators of exploration and mining companies prefer to introduce a cutting factor, i.e., an arbitrary upper limit marker value in the ore reserve estimation. Any individual assay value greater than the cutting factor is reduced to the latter before computation of average grade. Some groups of estimators practice logarithmic transformation of all sample values for average grade estimation to reduce the nugget effect. This rule of thumb application can significantly understate or overstate the average grades of resources and reserves. Equal-length samples should be statistically analyzed. If the higher values together represent 10%−20% of the population it should be considered as a natural phenomenon, which coexists with lower values. This phenomenon can be further supported by a volume−variance relationship. It means that the bigger the volumes of sample (say 1 day mine production), the smaller the grade variation will be. Therefore application of a cutting factor is not desirable without conducting statistical studies of the distribution pattern based on adequate number of samples. The understatement of average grade by applying a cutting factor may turn an economic deposit into an unviable proposition.

8.2.4 Average Grade

The average grade of an intersection along a trench, borehole, underground workings, cross- and long section, level plan, individual orebody, total deposit, and national and global resources and reserves is computed by the following formula.

1. Composite grade of channel, borehole intersection:

$$\text{Grade(g)} = \sum(\mathrm{l}_1 \times \mathrm{g}_1 + \mathrm{l}_2 \times \mathrm{g}_2 \cdots + \mathrm{l}_n \times \mathrm{g}_n) \Big/ \sum_{i=1}^{n}(\mathrm{l}_1 + \mathrm{l}_2 \cdots + \mathrm{l}_n)$$

where l = length of sample, g = grade of sample.
Exercise: A diamond drill hole has been sampled (Fig. 8.2 and Table 8.1). Calculate the average grade of intersection at 3% Zn cut-off grade.
The mineralized zone has been marked between 31.35 and 43.30 m along the borehole at 3% zinc cut-off.

$$\sum(\mathrm{l}_1 + \mathrm{l}_2 \cdots + \mathrm{l}_n) = 11.95\text{m},$$

$$\sum(\mathrm{l}_1 \times \mathrm{g}_1 + \mathrm{l}_2 \times \mathrm{g}_2 \cdots + \mathrm{l}_n \times \mathrm{g}_n) = 83.914$$

Average grade (g) = 83.914/11.95 = 7.02% Zn for 11.95 m.

TABLE 8.1 Sample Assay Values of Borehole A1 for Estimation of Average Grade Along the Borehole at 3% Zn Cut-off

Sample No.	From (m)	To (m)	Sample Length (m)	% Zn
A1/1	30.10	30.60	0.50	0.55
A1/2	30.60	31.35	0.75	1.00
A1/3	31.35	32.60	**1.25**	**3.25**
A1/4	32.60	34.05	**1.45**	**5.90**
A1/5	34.05	34.75	**0.70**	**1.85**
A1/6	34.75	36.30	**1.55**	**8.39**
A1/7	36.30	37.45	**1.15**	**12.10**
A1/8	37.45	39.05	**1.60**	**9.35**
A1/9	39.05	39.80	**0.75**	**6.31**
A1/10	39.80	41.35	**1.55**	**7.22**
A1/11	41.35	42.80	**1.45**	**6.93**
A1/12	42.80	43.30	0.50	**4.30**
A1/13	43.30	44.35	1.05	0.95
A1/14	44.35	45.35	1.00	0.30
A1/15	45.35	46.20	0.85	0.20

2. Average grade of section, plan, orebody and deposit, national and global:

$$\text{Average grade}(g) = \sum(t_1 \times g_1 + t_2 \times g_2 \cdots + t_n \times g_n) \Big/ \sum(t_1 + t_2 \cdots + t_n)$$

where t = tonnes of subblock, g = grade of subblock.

3. Average grade by statistical and geostatistical method. The average grade of a drill hole intersection is the arithmetic mean grade of all samples having equal sample length, and is expressed as:

$$\text{Sample mean grade} = (\overline{X}) = (1/n) * \left\{ \sum_{i=1}^{n} X_i \right\}$$

where X_i = value of ith sample, n = number of samples in the borehole intersection, $(\overline{X})$ = statistical average or mean grade.

The statistical method can quantify the confidence limit (±) of the average grade.

The average grade computation by the geostatistical method needs knowledge of a 3D semivariogram, which can estimate the best linear unbiased estimation.

8.2.5 Minable Grade

The minable grade is the average grade of the stope/mine considering internal and external waste inclusion and loss of ore at irregular mineralized boundaries during stope planning (Section 8.1.4). This is different from average grade of deposit.

8.2.6 Run-of-Mine Grade

The run-of-mine grade is the final quality of ore coming out of the mine. The mine production grade is expected to be lowered by 5%–10% for estimation and forecast plan. This is on account of inherent internal and unavoidable external dilution and mining losses due to changes in blast hole orientation and length, improper blasting, extra dilution along sheared contacts, and incomplete recovery from the stoping area.

8.2.7 Mill Feed and Tailing Grade

All samples discussed so far are composed of heterogeneous fragment sizes, and do not represent to be accurate. The mill feed ore is sampled after a continuous process of systematic mixing, crushing, grinding, and pulverizing in the beneficiation plant. The fragment sizes have attained a best possible interlining homogeneity and uniformity at (−) 100 mesh size, and are collected by automatic sampler at 15/30 min intervals after ball/rod mills. Modern-day plants are equipped with advanced microprocessor-based sampling probes in the conditioner. The multiple assay values are displayed and monitored at 2–5 min intervals in the centralized computer control room. The reagents in the flotation cells are adjusted accordingly by an autocontrol system. The online grade trend of mill feed, shift, and daily average is available. The total scheme of microprobe metal analysis, screen display, data capture, and reagent control is a centralized integrated system. The mill feed sample grades are considered as final values of ore production to reconcile the grade of mine for the hour/shift/day/month/quarter/year/life of the mine.

Similarly, the tailing outflow is continuously sampled by electronic probe at 15/30 min intervals, and displayed and captured on a centralized circuit panel. The mill feed and tailing grades facilitate computation of metal balance in the plant with respect to recovery parameters and overall performance.

8.3 CONVENTIONAL RESOURCE/RESERVE ESTIMATION

The selection of conventional estimation methods depends on the shape, dimension, complexity, and sample type. The procedures become complex with complexity of deposit, having a large volume of sample information. The simple deposits are seam, horizontal layers, and placer type, e.g., coal, oil, and gas, limestone, iron ore, and bauxite explored mostly by short vertical holes. The complex types include copper, zinc, lead, and noble metals. Sampling is primarily carried out by a large number of fan-shaped diamond and reverse circulation drill holes in close intervals. The number of samples is extremely large. The area of influence assumes continuity of mineralization between sample intervals. It must be judged critically to minimize the error in estimation of tonnage and grade of the deposit. The various times of tested traditional estimation procedures are (Popoff, 1966; Annels, 1991; Sinclair and Blackwell, 2002):

1. Old style.
2. Triangular.
3. Square and rectangle.
4. Polygonal.
5. Isograde/isopach.
6. Cross-section.
7. Longitudinal vertical section.
8. Level plan.
9. Inverse power of distance.
10. Oil and gas estimation.

The triangular, square, rectangle, and polygonal methods are point estimates by declustering of cells around the samples. The declustering methods divide the entire plan and section area into a representative polygon around samples, which is called a cell. It is always safe to follow two to three complementary methods of estimation for any deposit. The outcome of each procedure must be close to each other with respect to tonnage and grade to accept the final result. The estimated outcomes by cross-section, long section, level plan, and statistical methods have to be complementary to each other.

8.3.1 Old Style

The old style of estimation was in practice for gold mines in South Africa and auriferous smoky quartz veins of Kolar and Hutti gold mines, India. The structure control linear system of auriferous veins is either exposed on or close to the surface, and acts as an excellent surface guide for mineral exploration. Geological and geochemical exploration is supported by a few surface drill holes to establish existence and continuity of auriferous mineralization at depth. Entry to subsurface mining is by adit, inclines, and shafts. The mine levels are developed at short vertical intervals of ~30 feet and connected by raises and winzes passing through mineralization. The channel and chip samples are cut at short intervals of 3–6 feet all along the drives, raises, and winzes (Fig. 8.4), making square and rectangular stope blocks.

The reserve is estimated by multiplication of the block area, average thickness of mineral-bearing vein, and average Sp. Gr. The grade is computed by averaging all sample values generated within the block/stope. Stope sizes are at bare minimum dimensions, exposed and sampled from all sides, and extraction methods are adopted by the lowest mechanized manual underground open shrinkage stoping. Rock condition is good to prevent any wall dilution and the filling in of open stopes.

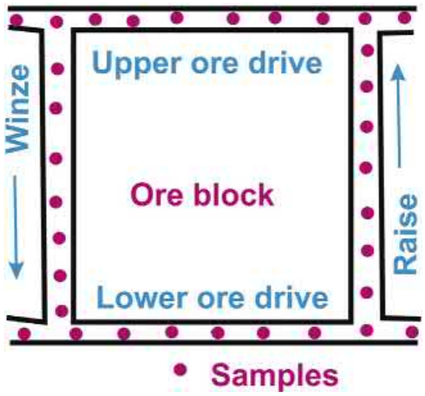


FIGURE 8.4 The old-style estimation method for vein-type deposits by averaging the channel and chip sample values around the ore block.

8.3.2 Triangular

The simplest and yet near-accurate reserves and resources estimation method widely uses the three points triangular technique. The triangles ($T_1 \ldots T_n$) are formed by joining three adjacent positive drill hole intersection points defining a block (Fig. 8.5). Volume and tonnage of the deposit is determined using simple geometrical equations. The plan area of each block is measured. The volume is obtained by multiplication of area (A) and the average thickness of mineralization (width). Tonnage is computed by multiplying volume (V) and the average Sp. Gr. of the ore. The average grade is computed by either simple averaging of three corner values of the triangle, or thickness (length) weighted average of the corner points. The total deposit reserve is the summation of block tonnages and weighted average grade. The triangular estimation method is suitable for flat and near-surface deposits having good continuity, such as laterite, bauxite, and placer deposits.

$$\text{Area} = \text{area of resulting triangle.}$$

$$\text{Volume} = \text{Area} \times \text{Average mineralized thickness of the drill} - \text{holes.}$$

$$\text{Tonnage} = \text{Volume} \times \text{Tonnage factor or average Sp. Gr.}$$

$$\text{Deposit tonnage} = \sum(\text{tonnage}_{1-n}).$$

$$\text{Deposit grade} = \text{arithmetic or weighted average grade of total blocks.}$$

8.3.3 Square and Rectangle

Sampling for flat-type deposits can also be planned by drill location at the center of square or rectangular cells (Fig. 8.6). The reserve and grade of individual blocks and for the deposit will be estimated in the same way as described for the triangular method.

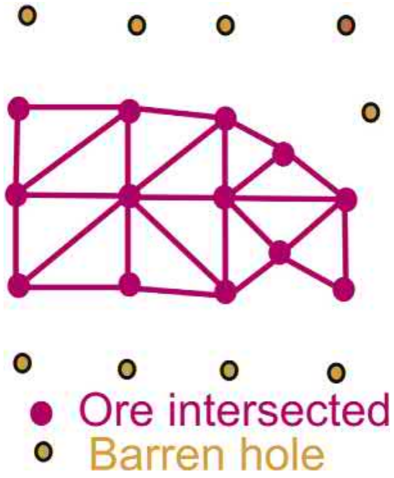


FIGURE 8.5 Reserve estimations by the triangular method for flat-type deposits considering the area of the triangle for tonnage and average grade of the holes located at the three corners.

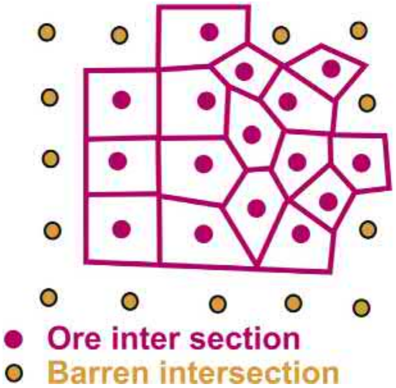


FIGURE 8.6 Reserve estimations by square, rectangle, and polygonal methods keeping samples at the center of the square or polygon.

8.3.4 Polygonal

Polygons are drawn around each drill sampling point to establish the surface coverage that extends half the distance (d/2) of the sampling distance between two sampling points (d) and in an equidistant measure. The surface area of the individual polygon (Fig. 8.6) is measured by geometric procedure, planimeter, or using reserve estimation software. A planimeter, also known as a platometer, is a measuring device used to determine the area of an irregular 2D shape. The block, total reserves, and grade are estimated as described for triangular, square, and rectangular methods.

8.3.5 Isograde/Isopach

The isograde method is based on the concept of isolines constructed by interpolation between points of known values assuming a gradual change between points. Isograde and isopach contour maps represent grade and thickness (Fig. 8.7) of the mineral body, respectively. The areas lying between successive pairs of contours are measured by planimeter on both maps. The total tonnage is the summation of volumes derived from thickness contours greater than a specified minimum mining height, and multiplied by average bulk Sp. Gr. The average grade is the thickness weighted grade of values above cut-off. The method is suitable for flat and low-dipping disseminated deposits showing gradual change.

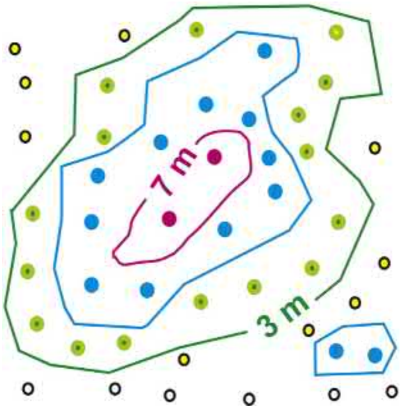


FIGURE 8.7 Reserve estimations by isoline contours of identical grade and thickness of mineralization.

8.3.6 Cross-Section

The geological cross-section is a vertical image across geological continuity of the area. The extent of the section is planned around mineralization supported by available surface and drill hole information. The surface features include rock contacts, structures, mineralized signatures, weathering profile, and gossans. The cross-section is drawn with local coordinates along the surface profile at scales of 1:2000, 1:1000, and 1:500. The surface profile is drawn based on the contours and indicates elevation of the section line. All boreholes falling on and around the section are plotted based on its collar coordinate (x or y and z), drill hole direction →, angle of drilling, deviation, and length of the hole. Information on core recovery, rock contacts, structures, analytical results (individual or composite value), and rock quality designation (RQD) from log-sheets is plotted along the trace of the borehole (Box 8.1). The orebody is interpreted and can be extended up to the surface with direct exposure or by indirect signature of oxidation/gossan, pit, and trench samples. Otherwise it

BOX 8.1 Rock Quality Designation

Rock quality designation (RQD) is a standard technique in the mining industry for the qualitative and quantitative assessment of rock quality and degree of jointing, fracturing, and shearing in a rock mass. RQD is defined as the percentage of intact drill core pieces longer than 10 cm recovered during a single core run (Abzalov, 2016), and the general equation is expressed as:

$$\text{RQD index (\%)} = 100 \times \Sigma\ (\text{Length of core pieces} \geq 0.10\ \text{m})/(\text{Total length of core run})$$

RQD Rock Mass Classification	
Excellent	≥90%–100%
Good	≥75%–90%
Fair	≥50%–75%
Poor	≥25%–50%
Worse	≤25%

Rock quality designation is a science of geoengineering that helps in mine design for all activities, including footwall and hanging wall design and stability, safe entry systems to underground mines, stope design, stability, forecast/protection of essential unground mine pillars, and void filling of underground stopes.

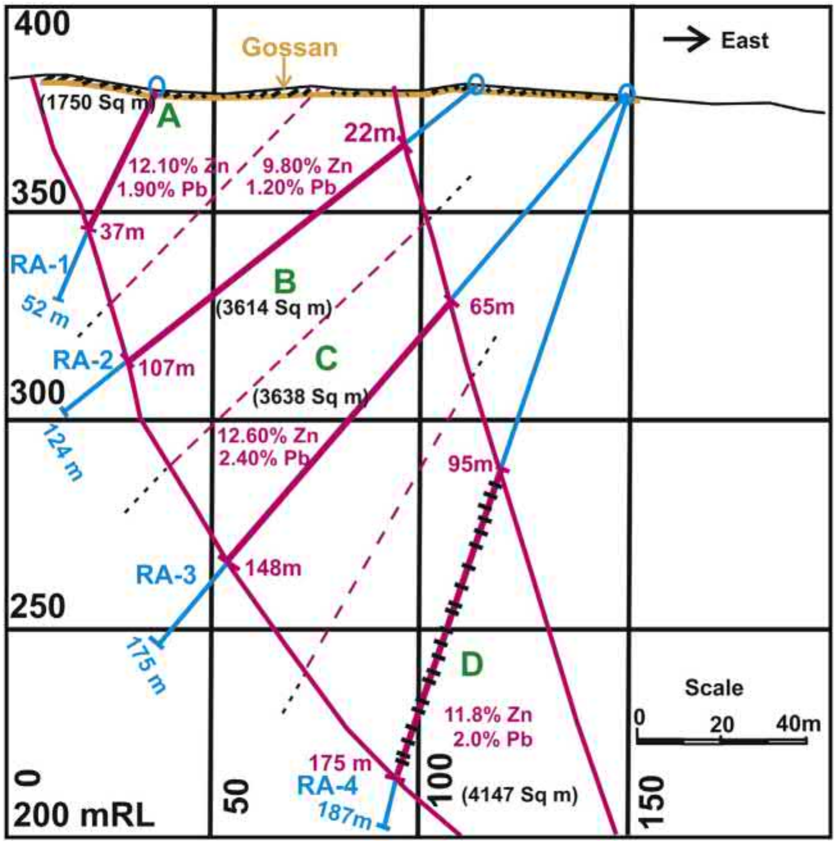


FIGURE 8.8 Reserve estimations by the cross-section method—most popularly and widely adopted by all levels of professionals for many decades.

will be considered as a concealed type and the shape will be drawn from drill information. Orebody configuration can be simple or multiple veins and complex type by splitting and coalescing with each other.

The total mineralized area is interpreted on cross-section and divided into subblocks around each borehole intersection by halfway influence marked by joining mid-points of hanging wall and footwall mineralization contacts between two adjacent boreholes (Fig. 8.8). The area of each subblock is measured by geometrical formulae for rectangular, square, and triangular orebodies. A planimeter or an overlay of transparent graph sheet or AutoCAD software can be used for measuring the area of an irregular orebody. A planimeter is a drafting instrument used to measure the area of a graphically represented planar region by tracing the perimeter of the block/subblock. The volume of the subblock is computed by multiplying the third dimension, i.e., half of the drilling interval on either side. The extremities of the orebody at both end sections can logically be extended any distance less than or equal to half of the drill interval. Halfway influence on either side for volume computation may introduce significant errors in tonnage and grade if a similar configuration does not exist in the adjacent sections. It is recommended to draw a longitudinal vertical section and level plan simultaneously to depict a reasonable 3D perspective. The tonnage and average grade of the section is computed by the formulae at Sections 8.1.1 and 8.2.4.

Exercise: A zinc-lead-silver deposit in Rajasthan, India, was identified by a gossan outcrop extending over 1500 m in a NE—SW direction. Surface exploration was conducted by diamond drilling at 50 m section intervals. Four boreholes were drilled at section A—A (Fig. 8.8). The section subblock area around each borehole was marked by halfway influence. The estimation of reserve and grade with bulk Sp. Gr. of 3.00 was (Table 8.2):

$$\text{Average grade} = \text{Grade (g)}$$

$$= \sum(\mathrm{t}_1 \times \mathrm{g}_1 + \mathrm{t}_2 \times \mathrm{g}_2 \cdots + \mathrm{t}_\mathrm{n} \times \mathrm{g}_\mathrm{n}) \Big/ \sum_{i=1}^{n}(\mathrm{t}_1 + \mathrm{t}_2 \cdots + \mathrm{t}_\mathrm{n})$$

where Area is measured by planimeter or superimposed graph sheet, Volume = Area × Halfway influence (50 m), Block tonnage (t) = Volume × Bulk Sp. Gr. (3.00),

TABLE 8.2 Details of Drill Hole Information Along Section A—A and Estimation of Reserve and Grade Using the Cross-Section Method

Borehole	Block	Area (m^2)	Volume (m^3)	Tonnage (t)	% Zn	% Pb
A-1	A	1,750	87,500	262,500	12.10	1.90
A-2	B	3,614	180,700	542,100	9.80	1.20
A-3	C	3,638	181,900	545,700	12.60	2.40
A-4	D	4,147	207,350	622,050	11.80	2.00
Total		13,149	657,450	1,972,350 1.97 Mt	11.51	1.88

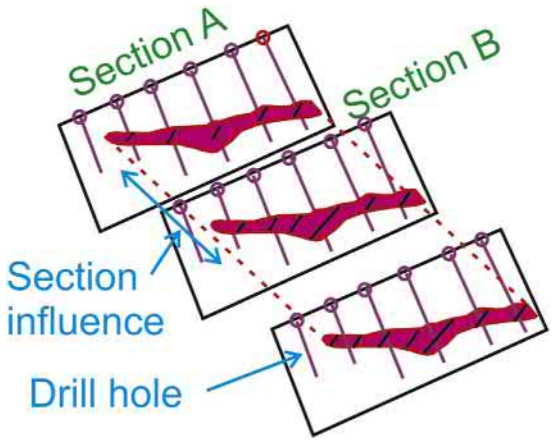


FIGURE 8.9 The concept of the cross-section method for section and deposit reserve and grade estimation.

Total section tonnage (T) = sum of all block tonnes $\Sigma(t_1 + t_2 \ldots + t_n)$.

The reserves and grades of total orebody are the cumulative tonnage and weighted average grades of all sections (Fig. 8.9).

8.3.7 Longitudinal Vertical Section

The longitudinal vertical section (projection) is the creation of a vertical image of features like lithology, ore geometry, categorization, and ore reserve along an elongated direction. Traces of surface profile, subsurface mineralized intersection in drill holes, and underground workings are plotted in a vertical plane. The negative drill hole information will delimit the mineralization boundary.

The total mineralized envelope on the longitudinal vertical section is divided into subblocks around positive mineralized intersections with halfway influence (Fig. 8.10 and Table 8.3). The tonnage and average grade of individual subblocks and the total ore reserves are computed.

Exercise: A concealed silver-rich Zn—Pb deposit in India was identified at a depth of 120 m from the surface. Surface drilling was conducted at 100 m intervals. All mineralized intersections were projected on longitudinal vertical sections. The subblocks around each intersection were marked by halfway influence and individually measured. The estimation of reserve and grades with Sp. Gr. of 3.00 was:

$$\text{Average grade} = \text{Grade (g)}$$

$$= \sum(t_1 \times g_1 + t_2 \times g_2 \cdots + t_n \times g_n) \Big/ \sum_{i=1}^{n}(t_1 + t_2 \cdots + t_n)$$

where Area is measured by planimeter or superimposed graph sheet, Volume = Area × Mineralization plan width (m), Block tonnage (t) = Volume × Bulk Sp. Gr. (3.00), Total long section tonnage (T) = sum of all block tonnes $\Sigma(t_1 + t_2 \ldots t_n)$.

8.3.8 Level Plan

The level plan is the horizontal image of any subsurface datum plane similar to a surface geological map. A plan view of a specific level is created taking measurements from cross-sections and underground drill and development sampling information. The reserve is computed in the same way as discussed in Sections 8.3.6 and 8.3.7 (Fig. 8.11 and Table 8.4).

Exercise: A concealed silver-rich Zn—Pb deposit in India was identified by routine drilling along a structural lineament at a depth of 120 m from the surface. Surface drilling at 100 m intervals was followed by entry to the subsurface by incline and development of a footwall drive for closely spaced underground drilling at 50 m intervals and a delineation of orebody. The reserve and grade were estimated by the level plan area method as:

$$\text{Average grade} = \text{Grade (g)}$$

$$= \sum(t_1 \times g_1 + t_2 \times g_2 \cdots + t_n \times g_n) \Big/ \sum_{i=1}^{n}(t_1 + t_2 \cdots + t_n)$$

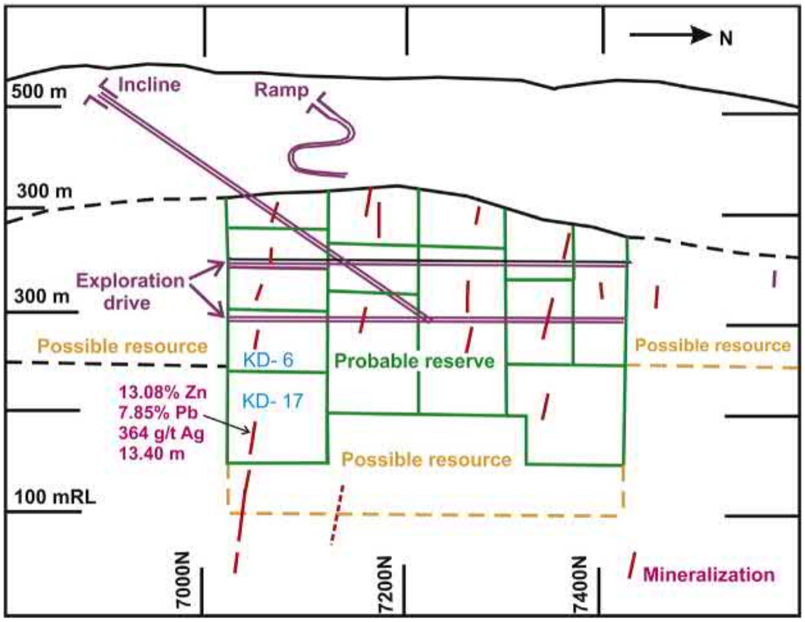


FIGURE 8.10 The estimation of reserve and grade by longitudinal vertical section (LVS)—an alternative process to validate the estimate by other techniques.

TABLE 8.3 Details of Borehole Information Along a Longitudinal Vertical Section and Estimation of Reserve and Grades

Borehole	Area (m^2)	Volume (m^3)	Tonnage (t)	% Zn	% Pb	g/t Ag
KD-17	8,000	96,000	282,000	13.08	7.85	364
KG-06	5,525	112,157	336,472	5.15	7.75	266
Total	13,525	208,157	624,472	9.27	7.80	311

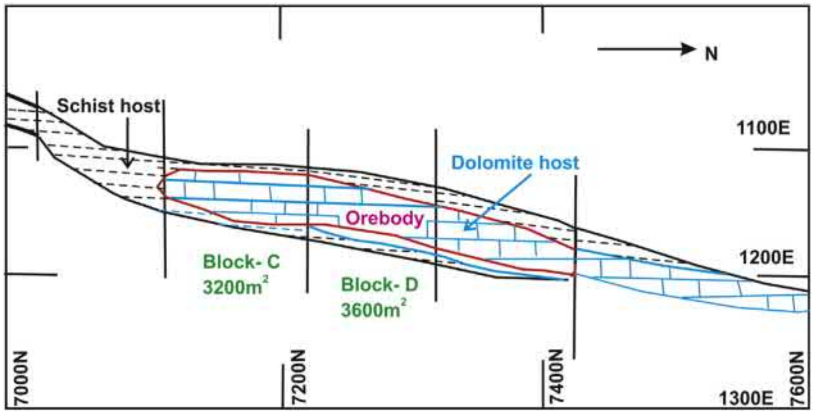


FIGURE 8.11 The estimation of reserve and grade by the level plan method—an alternative technique to cross-check estimates by other procedures.

where Area is measured by planimeter or superimposed graph sheet, Volume = Area × Halfway influence (50 m), Block tonnage (t) = Volume × Bulk Sp. Gr. (3.00), Total section tonnage (T) = sum of all subblock tonnes $\Sigma(t_1 + t_2 \ldots t_n)$.

8.3.9 Inverse Power of Distance

The mining industry applies software-based computerized extension functions for estimation of acceptable mine production block/subblock grades based on the principle of

TABLE 8.4 Details of Subblock Area for Estimation by the Level Plan Method

Block	Area (m^2)	Volume (m^3)	Tonnage (t)	% Zn	% Pb	g/t Ag
C	3,200	160,000	480,000	5.01	0.93	89
D	3,600	180,000	540,000	7.89	1.88	86
Total	6,800	340,000	1,020,000 1.02 Mt	6.53	1.43	87

gradual change. **Inverse power of distance** or ($1/D^n$) interpolation is the preferred method. The technique uses straightforward mathematics for weighting the influence of samples around the block being estimated (Fig. 8.12). It selects only those samples falling within the influence zone relevant to mineralogical affinity (continuity function) of the population. It also reflects the anisotropic character within the deposit, and varies the distance weighting function directionally with the help of a semivariogram function in various directions (refer to Chapter 9).

The mining block is divided into a series of regular 2D or 3D slices within the planned boundary equivalent to a blast hole of mine production. A 2D cross-section model or rock matrix is illustrated in Fig. 8.13. The block dimensions and approach for an open pit mine are 12.5 m along the strike (infill drill interval), 10 m vertically (bench height), and 5 m across the dip (face movement). Each cell is designated by a code number (say −200, 17, 19) controlled by identification of section, bench, and cell; e.g., −200 is south 200 section, 17 is the bench between 330 and 340 m level, and 19 is the cell position between 40 and 45 east.

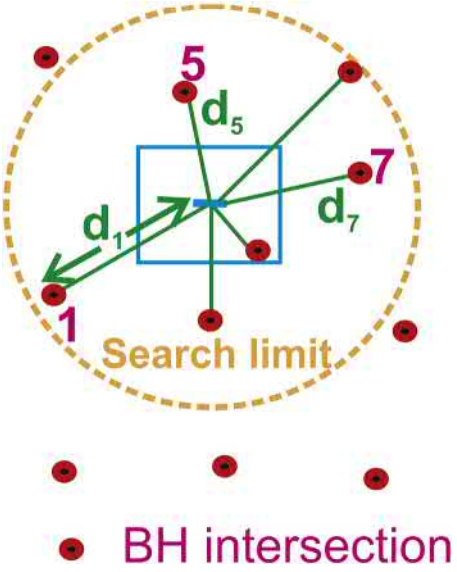


FIGURE 8.12 Principle of inverse power of distance method considering samples falling within an optimum search circle or ellipse in two dimensions.

The samples along the boreholes are converted to uniform composite length (5 m). The selection of samples for computation of a panel is controlled by a search ellipse oriented with its major axis along the down-dip of the orebody (range = 90 m) and minor axis across (range = 30 m). The intermediate axis is oriented along the strike direction (range = 115 m) in the case of 3D computation. The ranges in various directions are obtained from the semivariogram function (Chapter 9). The search ellipse moves on the plane of the cross-section, centering the next computational panel while performing interpolation. The strong anisotropic nature, if observed in the semivariogram, is further smoothened by differential weighting factors on samples selected through search ellipse screening. The samples located down-dip are assigned a greater weighting factor than across the orebody. These factors are tested in various options near controlled cells. In this method the near sample points receive greater weighting than points further away. The power factor is often employed as d^2.

The tonnage of each panel is estimated by block dimension and bulk Sp. Gr. The cell values (tonnage and grade) can be displayed as a series of bench plans for production scheduling. The inverse power of distance computation is performed by in-house or commercial software following:

$$G_B = \sum_{i=1}^{n} \left\{ \left(g_i/(d_i)^k + \cdots + g_n/(d_n)^k \right) \right\} \Big/ \sum_{i=1}^{n} \left(1/d_i^{\,k} + \cdots + 1/d_n^{\,k} + C \right)$$

where G_B = estimated block grade, g_i = grade of the ith sample, d_i = distance between block center and ith sample, k = 1, 2, 3 (power and often = 2), C = arbitrary constant.

8.3.10 Oil and Gas Estimation

Estimation methods for heterogeneous oil and gas reserves include analogy, volumetric, decline analysis, material balance calculations, and reservoir simulation. The commonly used volumetric method involves defining areal extent of the reservoir, rock pore volume, and fluid content

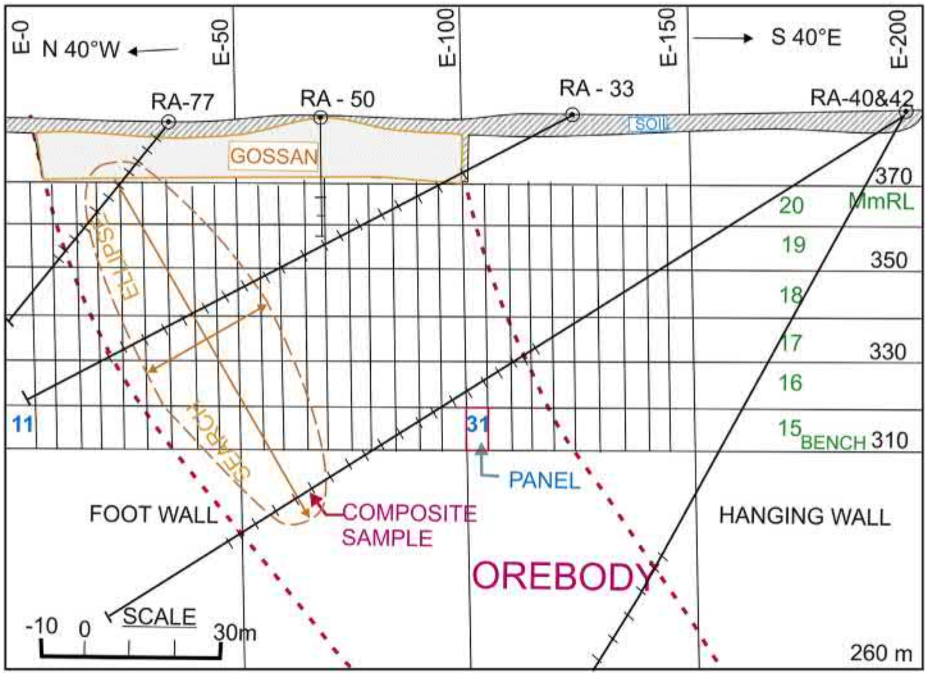


FIGURE 8.13 Computation of small block reserve on cross-section employing the inverse squared distance method—very significant information for production scheduling and grade control.

within the pore volume with applications of geophysics and well drilling (Chapter 4, Fig. 4.16). This provides an estimate of the amount of hydrocarbons-in-place. Ultimate recovery can be estimated by using an appropriate recovery factor. Each of the factors used in the foregoing calculation has inherent combined uncertainties causing significant reservations in the reserves and resource estimate. The problem has been improved by geostatistics (kriging theory), which has the advantage of providing the best linear, unbiased estimator of the unknown reservoir parameters (Fernando and Ley, 1992).

8.4 MINERAL RESOURCE AND ORE RESERVE CLASSIFICATION

Mineral resources and ore reserves are estimations of tonnage and grade of the deposit as outlined three dimensionally with variation in density of sampling and even with limited mine openings. The estimate stands on certain interpretations and assumptions of continuity, shape, and grade. Therefore it is always approximate and not certain until the entire ore is taken out by mining. The different types of sampling techniques are adopted at different densities or intervals with associated uncertainties during exploration. One part of the deposit may have been so thoroughly sampled that we can be fairly accurate of the orebody interpretation with respect to tonnages and grades. In another part of the same deposit, sampling may not be intensely detailed, but we have enough geologic information to be reasonably secure in making a statement of the estimate of tonnage and grade. The knowledge may be based on a very few scattered samples on the fringes of the orebody. However, we have enough information from other parts of the orebody supported by geologic evidence and our understanding of similar deposits elsewhere to say that a certain amount of ore with a certain grade may exist. The increase in sampling in the lower category region will certainly enhance the status as mining proceeds.

The mineral resource and ore reserves classification system and reporting code have evolved over the years by different countries exclusively based on geological confidence, convenience to use, and investment need in the mineral sector. The conventional or traditional classification system was in use during the 20th century. The new development took place from the third and fourth quarters of the same century, satisfying statutes, regulations, economic functions, industry best practices, competitiveness, and international acceptability. There are several classification schemes and reporting codes worldwide: US Geological Survey (USGS)/US Bureau of Mines (USBM) reserve classification scheme, USA, United Nations Framework Classification (UNFC) system, Joint Ore Reserve Committee (JORC) Code, Australia and New Zealand, Canadian Institute of Mining classification, South African Code for the Reporting of Mineral Resources and Mineral Reserves (SAMREC), The Reporting Code, UK, and global hydrocarbon classifications.

BOX 8.2 Qualified Person

A qualified person (QP) is a reputed professional with a graduate or postgraduate degree in geosciences or mining engineering. The QP must possess sufficient experience (more than 5 years) in mineral exploration, mineral project assessment, mine development, mine operation, or any combination of these. The QP should preferably be in good standing or affiliated with national and international professional associations or institutions. The QP is well informed with technical reports, including exploration, sampling adequacy, quality assurance, quality control and analytical verification, discrepancy and limitations, estimation procedure, quantity, grade, level of confidence, categorization, and economic status (order of magnitude, prefeasibility, feasibility study) of the deposit concerned. The QP is in a position to make the statements and vouches for the accuracy and completeness of the contained technical report, including information and the manner in which it is presented, even if he/she is not the author of the report. This is a matter of professional integrity and carries legal risk. Misleading statements can result in legal sanctions in the country and other jurisdictions.

The basic material and information for mineral resources and ore reserves classification schemes and reporting codes must be prepared by or under the supervision of a **qualified person** (QP) (refer to Box 8.2).

8.4.1 Conventional Classification

The degree of assurance in estimates of tonnage and grade can subjectively be classified by using convenient terminology. Increasing geological exploration creates high confidence levels and technoeconomic viability. Categorization has broadly been grouped as **economic reserves** and **subeconomic conditional resources**. The economic ore reserves and subeconomic resources are further subdivided as Developed, Proved, Probable, and Possible (Fig. 8.14). The classification system helps the investor in decision-making for project formulation and activities required at different stages. These terms are supported by experience, and have been time tested and well accepted over the years. The terminology is comparable with equivalent international jargon that is used by USGS or Russian systems such as Measured, Indicated, and Inferred. The conventional or traditional reserve/resource classification scheme includes five components based on decreasing geological/exploration information: Developed, Proved, Probable, Other ore, and Possible.

8.4.1.1 Developed

Developed or **Positive** or **Blocked** reserves attain the highest category and are parts of the orebody that have been exposed from all four directions, i.e., top, bottom, and both sides. Top surface exposure can be unearthed by trenches or trial pits on the surface for open pit mines or bounded on all sides by levels above and below, and raises and winzes on the sides of the block for underground mines. With definition or delineation drilling between 30 and 15 m intervals completed, all sides are sampled. The block is ready for stope preparation, blast hole drilling, blasting, and ore draw. Draw point sampling is initiated to assign stope production grade, blending ratio for the stock pile, reconciliation with respect to additional dilution, and estimation of errors. The risk of error in tonnage and grade is minimum with confidence of estimate at around 90%.

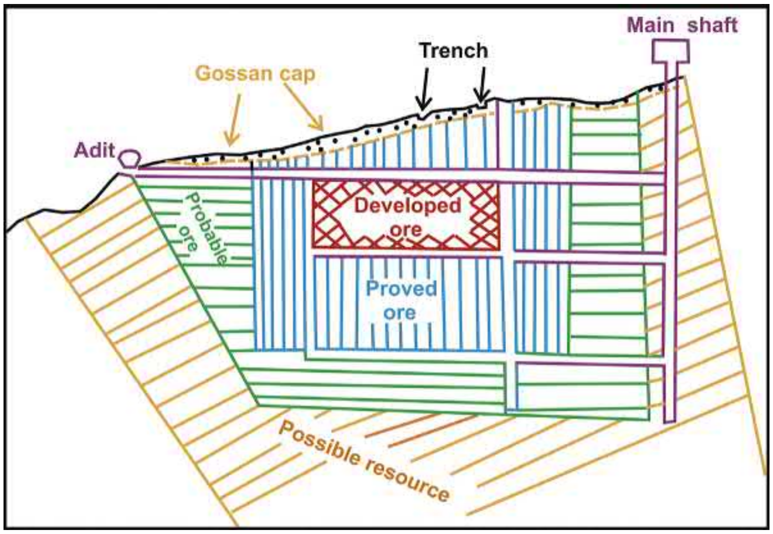


FIGURE 8.14 Conventional reserve classification systems showing various categories of reserve and resources based on enriched geological experience—a good option for small players in the mining industry.

8.4.1.2 Proved

Proved or **Measured** reserves are estimated based on samples from outcrops, trenches, development levels, and diamond drilling. The drilling interval is 200 m or even 400 m for simple sedimentary bedded deposits (coal seam, lignite, bauxite, and iron ore) with expected continuity along the strike and dip, other than structural dislocation. The sample interval is 50 m by 50 m for base metal deposits. The deposit is either exposed by trenches or trial pit for open pit mines, and by development of one or two levels for underground drilling. Stope delineation drilling and sampling will continue to upgrade the category to developed reserves. The confidence of estimate is about 80%.

8.4.1.3 Probable

The **Probable** or **Indicated** ore reserve estimate is essentially based on wide-spaced sampling and surface and underground drilling between 100 and 400 m intervals depending on the complexity of the mineralization. The opening of the deposits by trial pit or underground levels is not mandatory to arrive at this category. The confidence of estimate is about 70%.

The sum total of Developed, Proved, and Probable ore reserves is termed the **Demonstrated** category. The reserve of a project under investment decision should contain about 60% in the Demonstrated category.

8.4.1.4 Other Ore

A part of the ore reserve is blocked in sill, crown, and rib pillars for stability of the ground during mining operation and related impacts (Fig. 8.1). This blocked reserve is designated as **other ore**, and monitored as the Proved category. The reserve is elevated to Developed category as and when the other ore is likely to be recovered after completion of the nearby stoping blocks.

8.4.1.5 Possible

Possible or **Inferred** mineral resources are based on a few scattered samples of information in the strike and dip extension of the mineral deposit. There is sufficient evidence of mineralized environment within a broad geological framework having a confidence of about 50%. The possible resource will act as a sustainable replacement of mined-out ore reserves.

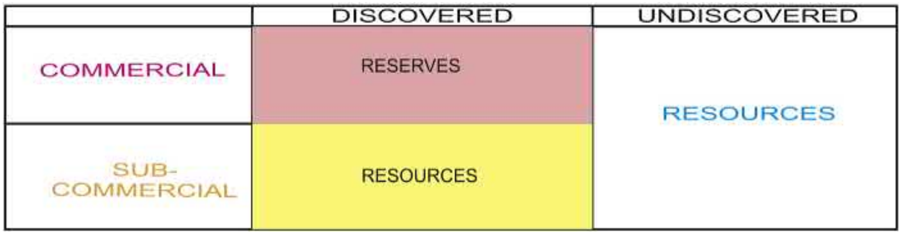
8.4.2 USGS/USBM Resource Classification

USGS collects and updates nationwide information about mineral resources and reserves over the years. Dr. V.E. McKelvey, a former director of USGS, first conceptualized a set of resource classification systems in 1972 (Fig. 8.15) to make a standard classification system.

USGS and USBM developed a common classification system in 1976 (USGS, 1976). Additional modifications were incorporated to make it more workable in practice and more useful in long-term public and commercial planning. The success of the future plan/program will rely entirely on: (1) precise knowledge of available reserves and resources for fixing priorities, (2) developing existing unworkable deposits to economic proposition by cost cutting and technological breakthrough, and (3) the probability of new discoveries on a regular basis. The resource base must be continuously reassessed in the light of new exploration input, advancement in mining and process technology, and change in commodity price. The collaboration continued to revise Bulletin 1450-A. The final document was published in 1980 (USGS, 1980) as USGS Circular No. 831—"Principles of a Resource/Reserve Classification for Minerals."

The concept of classification and block diagram was developed as a 2D representation (Fig. 8.16). The X- and Y-axis represent the geological degree of assurance and increasing economic feasibility. The geological axis is divided into two broad divisions of Identified and Undiscovered resources, and further subdivisions based on increasing exploration support. The economic feasibility axis is divided into two major divisions of Economic and Subeconomic, and further subdivisions based on the technoeconomic viability of the present market price.

The definition and specification of various identified resources have been described. The classification scheme elasticities give emphasis to Identified Subeconomic resources for future new exploration targets. It also initiates the concept of probability of existence of undiscovered resources simply on hypothetical and speculative grounds.



	DISCOVERED	UNDISCOVERED
COMMERCIAL	RESERVES	RESOURCES
SUB-COMMERCIAL	RESOURCES	

FIGURE 8.15 The initial concept of the resource classification system conceived as the McKelvey Box in 1972.

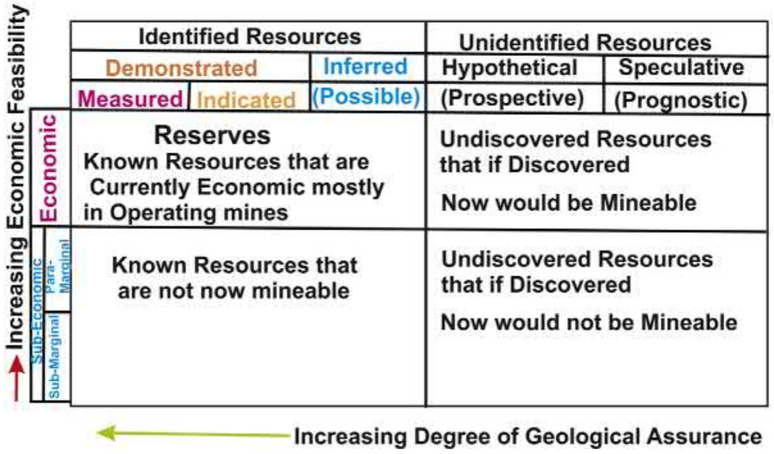


FIGURE 8.16 United States Geological Survey (USGS) resource classification scheme. *Adapted from McKelvey (1972).*

8.4.2.1 Paramarginal

Paramarginal is the portion of Sub-economic resources that exists at the margin of the economic/uneconomic commercial border, being a nonrenewable asset, and can be exploited at marginal profit with innovative mining and metallurgical techniques. The other type of Paramarginal resource is not commercially available solely because of safety, legal, or political circumstances. Examples are from Gorubathan multimetal deposit, West Bengal, India, having high-grade metals of >10% Zn + Pb on account of misbalancing the Himalayan ecosystem, and extension of orebody below the railway line at Balaria Zn—Pb metal mine of Zawar Group, India.

8.4.2.2 Submarginal

Submarginal represents the portion of Subeconomic resources that would require a much higher price at the time of mining or a major cost reduction by advanced research and development technology toward low-cost mining and higher metallurgical recovery. An example is Sindesar-Kalan near-surface base metal deposit with 100 million-tonnes of resources of low grade 2.5% Zn + Pb in graphite mica schist. The deposit is situated at the fringe of deep-seated Sindesar-Khurd producing mine with 61 million-tonnes of reserves at 9.6% Zn + Pb and 215 g/t Ag, and 6 km north of Rajpura-Dariba mining project, having 42 Mt of 8.0% Zn + Pb and 82 g/t Ag calc-silicate host rocks.

The Sindesar-Kalan deposit with large tonnage and low grade in graphite mica schist host rock is exposed to a flat surface. The open pit mining cost will be low with the support of major common infrastructure at Rajpura-Dariba and Sindesar-Khurd mining complex. The metallurgical breakthrough in recovery of low-grade ore from graphite mica schist and increase in metal price will convert it to the economic category.

8.4.2.3 Hypothetical

Hypothetical or **Prospective** resources are undiscovered academic mineral bodies in nature that may logically be expected to exist in known mining districts or regions under favorable geological conditions. Their existence, if confirmed by exploration and revealed by quantity and quality assessment, would be reclassified as Reserves or Identified Subeconomic resources.

The Neves Corvo polymetallic deposit, Portugal, located ~250 km in the southeast extension of the Iberian pyrite belt in Spain, and the Sindesar-Khurd zinc-lead-silver deposit, located 6 km in the northeast extension of Rajpura-Dariba mine, India, were discovered at a depth of +330 and 120 m, respectively, under similar geological conditions below barren surface cover during routine exploration in the known belt.

8.4.2.4 Speculative

Speculative or **Prognostic** resources are tentative mineral bodies in nature that are yet to be discovered and may occur either in known favorable geological settings where no discoveries have yet been made, or are unknown types of deposit that remain to be recognized. This is useful for the long-term allocation of an exploration budget. Their existence, if confirmed by exploration and revealed by quantity and quality assessment, would be reclassified as Reserves or Identified Subeconomic resources.

Uranium deposits worldwide are hosted by one of the following geological settings: unconformity-related conglomerate, sandstone, quartz pebble, vein type, breccia complex, collapse breccia pipe, intrusive, phosphorite, volcanic, surficial, metasomatite, metamorphic, lignite, and black shale. The search for uranium can be speculated for these favorable environments and tested.

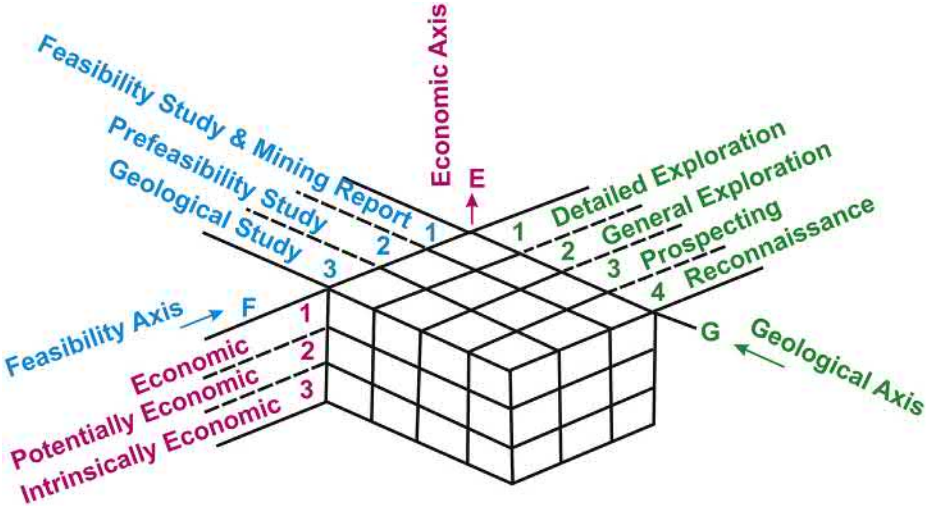


FIGURE 8.17 Resource and reserve scheme by United Nations Framework Classification (UNFC) system adopted by many countries, including the government of India.

8.4.3 United Nations Framework Classification

The UNFC system is a recent development in reserve categorization (E/2004/37-E/ECE/1416, February 2004) (UNFC, 2004). The scheme is formulated giving equal emphasis to all three criteria of exploration, investment, and profitability of mineral deposits. The format provides: (1) stage of geological exploration and assessment, (2) stage of feasibility appraisal, and (3) degree of economic viability. The model is represented by multiple cubes (4 × 3 × 3 blocks) with geological (G) axis, feasibility (F) axis, and economic (E) axis. The three decision-making measures for resource estimation are further specified in descending order:

Geological axis (G) →

1. Detailed exploration
2. General exploration
3. Prospecting
4. Reconnaissance

Feasibility axis (F) →

1. Feasibility study and mining report
2. Prefeasibility study
3. Geological study

Economic axis (E) →

1. Economic
2. Potentially economic
3. Intrinsically economic

The scheme is presented in a 3D perspective (Fig. 8.17) with simplified numerical codification facilitating digital processing of information. Each codified class (Table 8.5) displays a specific set of assessment stages with associated economic viability. The scheme is internationally understandable, communicable, and acceptable across national boundaries under economic globalization, which makes it

TABLE 8.5 Example of United Nation Framework Classification (UNFC) Codification System

Economic Axis	Feasibility Axis	Geological Axis	Code
Economic	Feasibility study and mining report	Detailed exploration	**111**
Economic	Prefeasibility study	Detailed exploration	121
Economic	Prefeasibility study	General exploration	122
Potentially economic	Feasibility study and mining report	Detailed exploration	211
Potentially economic	Prefeasibility study	Detailed exploration	221
Potentially economic	Prefeasibility study	General exploration	222
Intrinsically economic	Geological study	Detailed exploration	331
Intrinsically economic	Geological study	General exploration	332
Intrinsically economic	Geological study	Prospecting	333
Intrinsically economic	Geological study	Reconnaissance	334

easy for the investor to take the right decision. The government of India has accepted and adopted the UNFC classification reporting code for submission of annual mineral reserves and resources updates for all official purposes. The Indian Bureau of Mines process and publish the annual mineral reserves and resources in the *Minerals Yearbook*.

8.4.4 Joint Ore Reserve Committee Classification Code

The Minerals Council of Australia, the Australian Institute of Mining and Metallurgy, and the Australian Institute of Geoscientists established the Australian JORC (JORC, 2004) for public reporting of exploration results, mineral resources, and ore reserves. The scheme was formulated on the basic principles of transparency, materiality, and competency. The other organizations represent in JORC are the Australian Stock Exchange (ASX), the Securities Institute of Australia, and incorporated into the New Zealand Stock Exchange (NZX) listing rules. All exploration and mining companies listed in Australian and New Zealand stock exchanges are required to comply with the JORC Code, which regulates the publication of mineral exploration reports on the ASX. Since 1971 the Code has been effectively updated for comparable reporting standards introduced internationally. The JORC Code applies essentially to all solid mineral commodities, including diamond and other gemstones, energy resources, industrial minerals, and coal. The general relation between exploration results, mineral resources, and ore reserves classifies tonnage and grade estimates. The format reflects the increasing levels of geological knowledge and rising confidence. It takes due consideration of mining, metallurgical, technical, economic, marketing, legal, social, environmental, and governmental factors. The scheme imparts a checklist for authenticity at each level.

Mineral resources are concentrations or occurrences of mineral prospects that eventually may become sources for economic extraction. They are placed in the Inferred category. Mineral reserves on the other hand are the economically minable parts of Measured and/or Indicated ore. They include the dilution and allowance on account of ore losses likely to occur during mining. The relationship between mineral resources and reserves is presented in Fig. 8.18.

The reporting of exploration results includes total database, sufficient information, and clear, unambiguous, and understandable nonmisleading reports generated by exploration programs that may be useful to investors. The report comprises statements of regional and deposit geology, sampling and drilling techniques, location, orientation and spacing, core recovery, logging, assaying, including reliability and cross-verification, 3D size and shape diagrams, estimation methods used, mineral tenements, and land tenure status. It should also include exploration done by other agencies, baseline environmental reports, and the nature and scale of planned further work.

The reporting of mineral resources and ore reserves is comprised of database integrity, location, geological characteristics, continuity, dimension, cut-off parameters, bulk density, modeling techniques, quantity, grades, estimated or interpreted specific geological evidence and knowledge, accuracy, confidence and reviews, mining and metallurgical factors and assumptions, cost and revenue factors, and market assessment.

The Code applies to the reporting of all potentially economic mineralized material in the future. This includes mineralized fill, remnants, pillars, low-grade mineralization, stockpiles, and dumps and tailings where there are reasonable prospects for eventual economic extraction in the case of mineral resources, and where extraction is reasonably justifiable in the case of ore reserves.

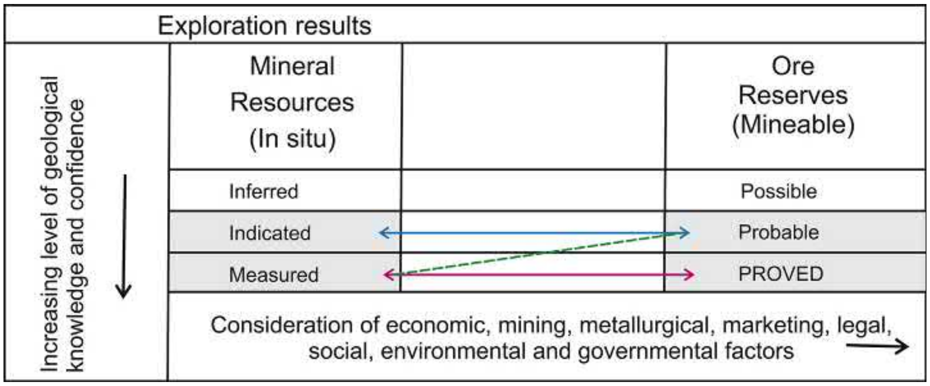


FIGURE 8.18 Joint Ore Reserve Committee (JORC) Code developed by professionals of the Australian Institute of Mining and Metallurgy (AusIMM) showing the relationship between mineral resources and mineral reserves. JORC compliance organizations are registered with the Australian Stock Exchange (ASX).

The JORC Code is now well accepted in Australia and New Zealand. In recent years it has been used both as an international reporting standard by a number of major international exploration and mining companies, and as a template for countries in the process of developing or revising their own reporting documents, including the United States, Canada, South Africa, United Kingdom/Europe, and South America, including Mexico, Argentina, Chile, and Peru.

8.4.5 Canadian Resource Classification

The mineral resource classification scheme in Canada (Fig. 8.19) is known as National Instrument 43-101 (NI 43-101) used for standards of disclosure of scientific and technical information about mineral projects within the country. NI covers metallic minerals, solid energy products, bulk minerals, dimension and precious stone, and mineral sands commodities. The NI is a codified set of rules and guidelines for reporting mineral properties owned or explored by national or foreign exploration and mining companies listed on the stock exchanges of the TSX Venture Exchange, Toronto Stock Exchange, Canadian Securities Administrators, ASX, Johannesburg Stock Exchange, and London Stock Exchange. The NI is broadly comparable and interchangeable with JORC and SAMREC codes. NI 43-101 ensures that misleading, erroneous, or fake information relating to mineral properties is not published and promoted to investors on the stock exchanges within the country overseen by the Canadian Securities Authority. The reporting format includes scientific or technical information on mineral resources or mineral reserves of the property.

8.4.6 Oil and Gas Resources Classification

The hydrocarbon (crude oil and gas) resource classification is based on the same concept as metallic/nonmetallic minerals established by McKelvey (1972). The model has undergone changes (Fig. 8.20). The total resource base is the sum total of estimated contained hydrocarbon in the subsurface, including quantities already produced. The resource is the volume estimates derived from an-accumulation, and reserves are only quoted for a known accumulation. The reserves are a subset of the resource base.

Reserves are those quantities of hydrocarbon that are anticipated to be commercially recovered from known accumulations from a given date forward. They must satisfy four criteria: discovered, recoverable, commercially viable, and remaining. The reserves are classified under three categories of Proved (1P), Probable (2P), and Possible (3P) with increasing range of geological uncertainties and decreasing range of commerciality (Fig. 8.20). The project status is subdivided into three categories:

1. Currently on production and marketing.
2. Under development and all essential approvals obtained.
3. Planned for development as it satisfies all criteria for reserves, and there is a firm intent to develop, but detailed development planning and/or necessary approvals/contracts have yet to be finalized.

Contingent Resources are those discovered and potentially recoverable quantities that are currently not considered to satisfy the criteria for commerciality. Contingent Resources are those quantities of hydrocarbon

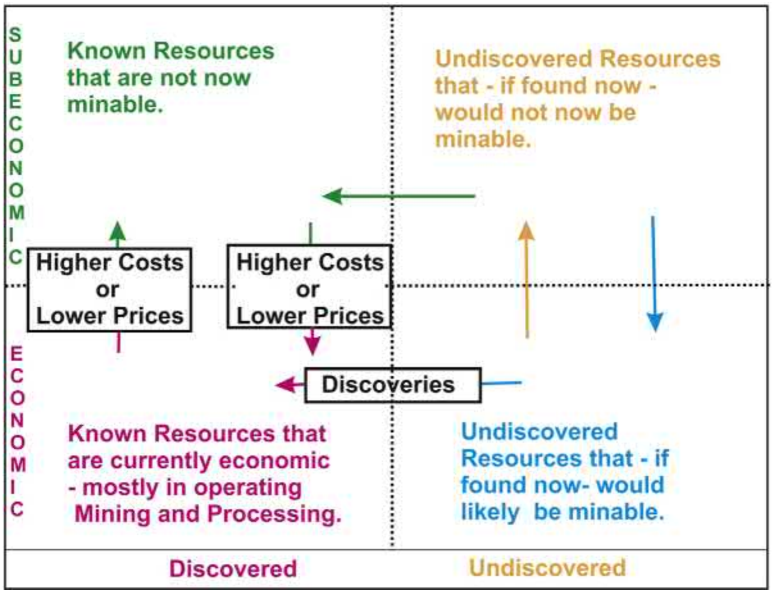


FIGURE 8.19 A schematic view of the Canadian mineral resources classification scheme.

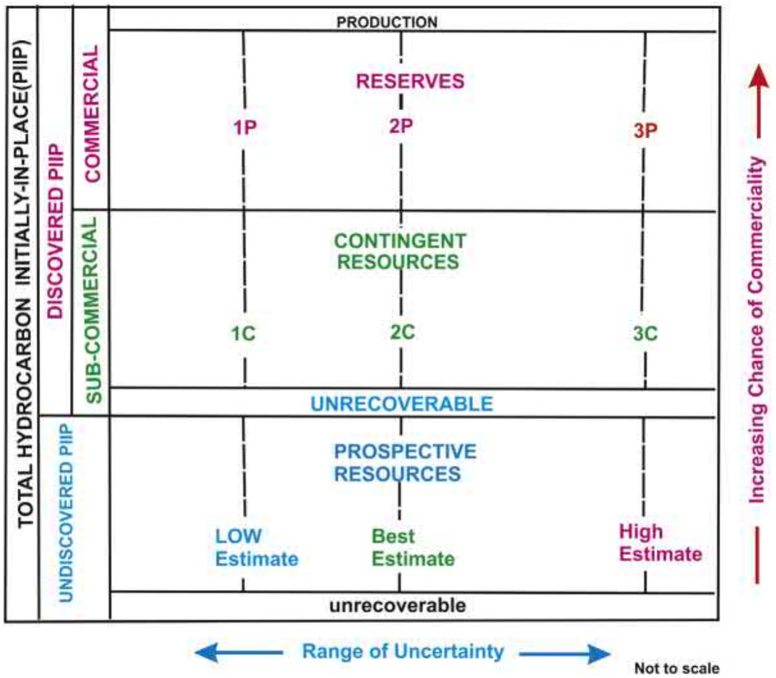


FIGURE 8.20 Schematic presentation of resources classification adopted internally for petroleum and gas. The system defines major recoverable reserves at successive phases of production, development, and planning. It distinguishes Contingent and Prospective Resources, and Unrecoverable Resources.

(crude oil and gas) that are estimated, on a given date, to be potentially recoverable from known accumulations, but which are not currently considered to be commercially recoverable and fall under subcommercial status. The project status is subdivided into three groups:

1. Development pending: as it requires further data acquisition and/or evaluation to confirm reserve criteria and commerciality.
2. Development on hold: the reservoir describes significant size, but is awaiting development of a market or removal of other constraints to development that may be technical, environmental, or political.
3. Development not viable: no current plans to develop or acquire additional data due to limited production potential.

Prospective Resources are those potentially recoverable quantities in accumulations yet to be discovered. Prospective Resources are those quantities of hydrocarbon (crude oil and gas) that are estimated, on a given date, to be potentially recoverable from undiscovered accumulations. This category stands as undiscovered and uneconomic as on date.

8.4.7 Comparison of Reserve Classification

The conventional or traditional reserve classification system is a plain and simple representation of the status of mining and other categories of reserves and resources. It is more a qualitative depiction of reserves concept based on past experience, and easily understandable by small mine owners dealing with minerals like soapstone, kaolin, marble, garnet, and quartz, and common users that have no advanced knowledge of the trade. The classification system is not internationally exchangeable with geologists, mining engineers, and others operating in the global mineral field under open investment opportunity. The ore reserves and resources classification needs a common definition, language, understanding, and scale of exploration inputs.

The USGS/USBM mineral resource classification system conveys a common classification and nomenclature, more workable in practice and more useful in long-term public and commercial planning. The objectives are based on the probability of discovering new deposits, developing economic extraction processes for currently unworkable deposits, and knowing immediate available resources. It believes in continuous resources reassessment with new geologic knowledge, progress in science and technology and research and development, and changes in economic and political conditions. The departments monitor the need, understanding, and classification of mineral resources all over the world and expect it to be a universally accepted system. The classification of mineral and energy resources is necessarily arbitrary, because the definitional criteria do not always coincide with natural mineralization boundaries. The system can be used to report the status of mineral and energy-fuel resources for the nation or for specific areas.

UNFC is a flexible system that is capable of meeting the requirements for application at national, industrial, and institutional levels, as well as being successfully used for international communication and global assessments. It meets the basic needs of an international standard required to support rational use of resources, improve efficiency in management, and enhance the security of both energy supplies and associated financial resources. The classification will assist countries with transition economies in reassessing their mineral resources according to the criteria used in market economies. UNFC has given maximum importance to commercial aspects suitable for planners, bankers, and other financial institutions.

The strengths of the JORC classification and reporting code are recognized for their clarity, transparency, materiality, and competency. The reporting system for exploration results, mineral resources, and ore reserves is exhaustive with a check-list at each level. The database format includes increasing levels of geological knowledge acquired during the successive exploration phase, attaining higher confidence. It takes into account rational reflection of mining, metallurgy, technical, economic, marketing, legal, social, environment, and governmental issues. The reporting domain is a complete documentation of exploration input, minability, extraction recovery, and economic viability supported by the essence of a prefeasibility/feasibility study. It provides a clear vision and mission of projects under consideration for investment decisions. All global exploration and mining companies listed in standard stock exchanges, particularly in Australia (ASX) and New Zealand (NZX), are required to comply with resource/reserve reporting of the JORC Code. The current project status with ongoing exploration and other test works is regularly communicated online through stock exchanges. Investors and financial hubs can initiate and expedite mutual commercial transactions accordingly. The JORC reporting code is fully accepted in Australia and New Zealand, and is being used as an international reporting standard by major exploration, mining, and financial companies from United States, Canada, South Africa, Europe, and South America, including Mexico, Argentina, Chile, and Peru.

The Canadian NI 43-101 code of reporting requires significantly more technical disclosure to the stock exchange by code originated from Canadian Securities Authorities. The equivalent JORC is primarily a code for reporting the status of a mineral resource derived by an independent mineral industry body formed from industry professional associations.

The resources and reserves classification for crude oil and gas follows an internationally accepted common assessment and reporting format.

Finally, constant efforts are being made to simplify, harmonize, and unify the USGS, UNFC, JORC, Canadian National Instrument (CNI), Council of Mining and Metallurgical Institutes (CMMI), and other classification systems for an acceptable reporting standard code for all.

8.5 ORE MONITORING

The status of ore reserves and resources is revised at the end of each calendar or financial year as practiced in different countries. The revision is made due to changes on account of annual depletion, status resources and reserves upgradation, and addition of reserve with exploration activity during the year. Mine production at the end of each year is taken out of Developed ore. Similarly, part of Proved ore is elevated to the Developed category due to mine development. Part of Probable ore is added to the Proved reserve-based routine exploration input. Part of Possible resource is enhanced to Probable reserve based on ongoing exploration programs in the mine block in depth and along the strike direction within the mining lease. The new Possible resources are also generated on account of exploration activities in prospecting lease areas.

The revised resource/reserve table provides realistic status of minable ore to the management and managerial staff at all levels. This enables short- and long-term strategies to be drawn for mining operations toward planned production and exploration programs for enhancing the resources to various categories for sustainable mine life.

8.5.1 Mine Status

The status of a producing mine can be depicted on a longitudinal vertical projection showing activities by blocks and status of individual stope (development, production, and exhaust)/production center (Fig. 8.21). This type of update acts as a management tool to review the scheduling of production and monitoring.

8.5.2 Forecast, Grade Control, and Monitoring

In any producing mine, advanced ore production scheduling is used as an information base to achieve the targets of tonnage and grade for durations such as 5 years/annual/quarterly/monthly/fortnightly/weekly/daily. The aim is to produce average mill feed grade and optimized supply of metals over the life of the mine. The scheduling practices evolve by simple mathematical calculation to complex linear programming tools using dynamic systems.

The mine production grade is anticipated by sampling blast holes of open pit benches and sludge of underground

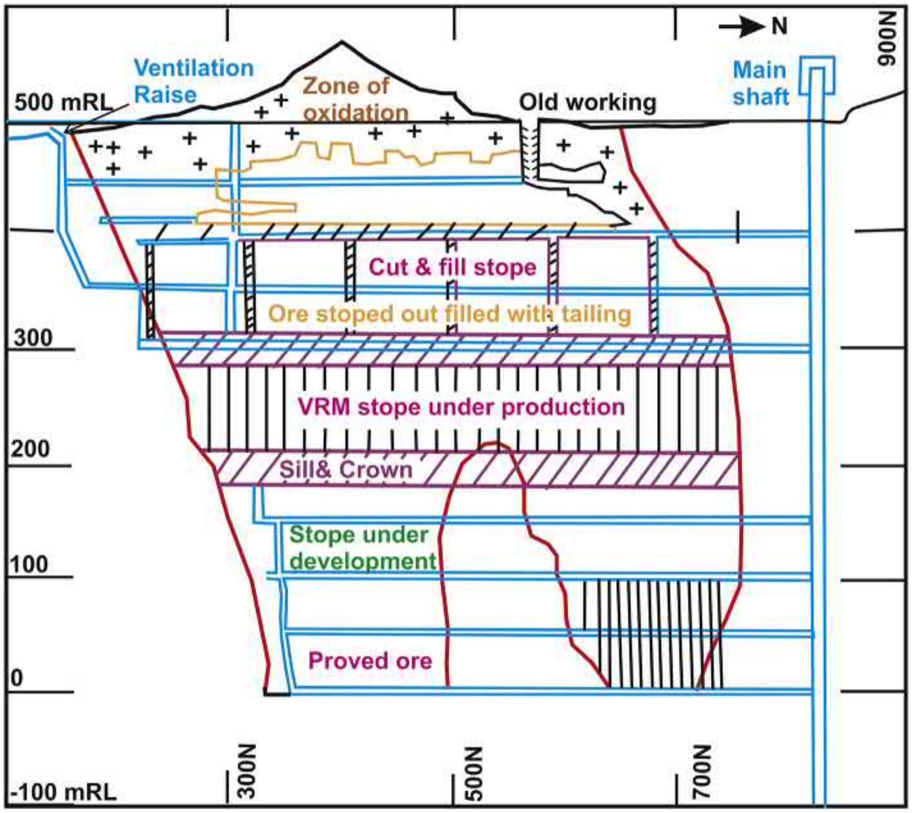


FIGURE 8.21 Schematic views of ore reserve monitoring and mining status of a producing mine. *VRM*, vertical retreat mining.

mine drill hole cuttings. The grade can be further corroborated by stope draw point samples to schedule grade control operation. The final mine production grade over a stipulated period is achieved by run-of-mine sampling at the mine head before it is diverted to various stockpiles.

The sources of all mine samples comprise coarse fragment sizes. Therefore the final grade of the deposit, or more precisely minable grade of the deposit, is reconciled by computation of mill feed and tailing tonnage and grade for metal balancing at −100 mesh sizes after considering beneficiation recovery.

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Chapter 9

Statistical and Geostatistical Applications in Geology

Chapter Outline

> *Statistical and geostatistical study enhances the analytical and interpretive skill of the operator to visualize the inside characteristics of the orebody.*
>
> Author.

9.1 WHY GEOSTATISTICS?

Geologists and mining engineers advocate that the grade of a mineral deposit depends on the location of a subblock within the orebody and sample value of a small block. Thus conventional methods of resource and reserve estimation (refer to Chapter 8) are based on spatial position and value of the surrounding ground. There is no objective way to measure the reliability of the estimation. Professional **experience factors** are applied to compromise as and when the estimate goes wrong, often resulting in write-off payable deposits or overvalued uneconomic deposits that never deliver the predicted grades.

Workers in the field of mineral resource and ore reserve estimation (Davis, 1971) corrected this shortcoming by borrowing techniques from formal statistical theory. These include analysis of sample population, range, frequency distribution, histogram plot, mean, variance, standard deviation, correlation coefficients, analysis of variances, t-test, F-test, trend analysis, and inverse distance for univariate and multivariate elements. The statistical techniques compute the global reserves with an overall confidence limit of estimation (tonnage and grade). The classical

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00009-5

statistical methods assume that sample values are randomly distributed and are independent of each other. They do not include the inherent geological variance within the deposit, and ignore spatial relationships between samples.

Krige (1951) and Matheron (1971) developed the theory of regionalized variables to resolve this problem. Regionalized variances are random quantities that assume different values depending on their position within a region. In ore reserve estimation, the orebody is the region and grade, thickness, etc. are the regionalized variables. This technique offers the **best linear unbiased estimate** (BLUE) of the reserves in the context of both local and global bases. It also provides a direct quantitative measure of reliability. The procedure involves the creation of a semivariogram, sample cross-validation, and an estimation technique known as **point and block kriging**.

9.2 STATISTICAL APPLICATIONS

Statistics is a branch of applied mathematics. It deals with the development and applications of procedures to collect, organize, analyze, interpret, present, and summarize quantitative data for understanding and drawing conclusions. It uses probability theory to estimate the population parameters present, including future prediction. **Univariate** statistics describes the distribution of individual variables (Koch and Link, 1986; Davis, 2002; Sahu; 2005). The data in earth science often demonstrate inherent relationships and interdependencies between variables, and are called **bivariate** or **multivariate** statistics. The important parameters are the mean $(\overline{X})$, median, mode, variance ($\boldsymbol{\sigma}^2$ or S^2), standard deviation ($\boldsymbol{\sigma}$ or $\mathbf{s}$), and coefficient of variation (CV). Statistical application prefers at least 30 samples for drawing any inference.

Statistical procedures, tests of hypotheses, and applications involve different assumptions, and accordingly are assembled in two groups: **parametric**, and **nonparametric** (Henley, 1981). Parametric statistics fundamentally relies on the assumption that the parent populations are normally distributed, and preserve homogeneity of variance within groups. Nonparametric statistics does not require normal distribution or variance assumptions about the populations from which the samples are drawn.

9.2.1 Universe

Universe is the total mass of interest and total source of all possible data. Universe is characterized by one or more attributes and can be single or multidimensional. An example of a geological universe is the area of our interest—a stratigraphic province, a mineral deposit with a defined boundary. The characteristics of universe change with changing boundary limits.

9.2.2 Population, Sample, and Sampling Unit

Population consists of a well-defined set of elements—finite or infinite. **Sample** is a subset of elements taken from a population. Geological sample collection, preparation, and chemical analysis are the most critical issues for the correct representation of the extremely variable nature of mineral occurrences. The **sampling unit** is part of the universe on which the measurement is made. It is 5 kg of rock or an ore sample, a truckload of bulk sample, or a 3 m piece of drill core. One must specify the sampling unit to recognize different populations, and treat them separately. The population of 1 m drill core, channel, or chip samples is likely to be statistically very different from the population of 10 × 10 × 10 m^3 blocks of ore. The size of the sampling unit is significant. One should never make a statement about the population of a grade without specifying what grade it is—say 2% Cu.

9.2.3 Probability Distribution

Probability is the determination of the probable from the possible. The possible outcome of a random selection is described by the probability distribution of its parameter. When a coin is tossed the possible outcomes are either heads or tails, each with an independent equal probability of ½. Similarly, when a perfect dice is thrown, the possible outcomes are either 1, 2, 3, 4, 5, or 6, each with an equal probability of 1/6. This is the case of a discrete variable that assumes only integer values; the distribution will associate with each possible value x of probability $P(x)$. The value will be nonnegative, and summation of all possible $P(x)$ will be equal to one. Probability, in an applied sense, is a measure of the likeliness that a random event will occur.

Geological events are typically not discrete, having infinite and continuous numbers of possible outcomes. The range of possible outcomes is finite. The exact result that may appear cannot be predicted within the range. Such events are called continuous random variables. For example, one may wish to know the chance of obtaining a grade in the interval of 2%—4% or 6%—8% in a mineral deposit. In practice, such a distribution will never be known. All that can be done is to compute an experimental probability distribution and then try to infer which theoretical distribution may have produced such an experimental sampling distribution, e.g., normal curve.

9.2.4 Frequency Distribution

The measurements of some attributes, say the analytical value of samples of a mineral deposit, can be classified into grade groups of 0%—1%, 1%—2%, 2%—3%, and so forth. The frequency of occurrences (number of assays per grade

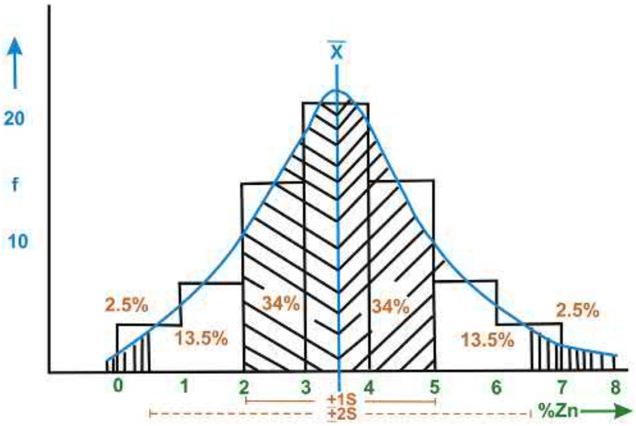

FIGURE 9.1 Relative frequency plot showing the % area covered by 1 and 2 standard deviations on either side of a central value or mean grade of 1 m sample population in Table 9.2, which represents a standard normal probability distribution.

interval) in the different groups is tabulated. This information would constitute a grouping or **frequency** or **relative frequency** distribution. The grouped information is plotted with class intervals on the abscissa (x-axis) and frequency is plotted on the ordinate (y-axis). This allows a proportionate area for occurrence of each frequency against the grade interval, and provides a visual picture, known as a **histogram** (Fig. 9.1). Distribution is a function of sample numbers. The sampling unit should be mentioned while defining the histogram. The population may be symmetric, asymmetric, normal, log-normal, or bimodal. If there are n number of samples (Table 9.1), each with a value of $\mathbf{x_i}$, where i = 1, 2, 3, …, n, then the samples can be grouped into a number of classes such as in Table 9.2.

TABLE 9.1 % Zinc Content of Exploration Drill Hole Samples at 1 m Uniform Length

% Zn	% Zn	% Zn	% Zn	% Zn	% Zn
5.70	3.90	4.50	3.30	3.60	4.60
1.50	2.60	5.50	3.40	4.50	2.20
4.20	4.40	2.40	2.60	7.50	4.70
4.40	3.50	1.40	3.70	3.60	1.20
2.50	0.50	5.50	4.70	0.70	2.40
0.50	5.60	2.60	3.30	1.80	4.30
3.70	2.70	3.40	4.30	1.60	3.60
3.30	5.10	4.60	3.50	2.70	4.50
5.90	3.10	4.80	1.50	2.80	3.50
2.30	1.30	3.60	2.40	5.30	5.40
2.90	4.90	2.10	4.10	3.70	6.50
0.30	3.40	3.20	3.40	3.80	2.30

9.2.5 Normal or Gaussian Distribution

Normal or **Gaussian** distribution is a continuous probability distribution that has a bell-shaped probability density function (Gaussian function), or informally a bell curve. The frequency distribution plot of Table 9.2 and Fig. 9.1 depicts the bell-shaped curve and stands for the normal or Gaussian distribution of attributes with a definite function of spread from the mean (μ). In the case of a theoretical normal distribution curve the rule of thumb is that 68% of the population or sample assays will be plus or minus one standard deviation (δ or S) from the population or sample mean (μ or $\overline{X}$). Similarly, 95% of the population or sample values will stretch out between plus and minus two standard deviations (precisely 1.96) on either side of the mean. Theoretical normal distributions show a single mode, but in natural conditions, mineral distribution can be bimodal and multimodal in character. The normal distribution is an approximation that describes the real-valued random distribution that clusters around a single mean value.

A **cumulative** frequency is a process that understands whether collective information in a data set is less than or equal to a particular value. The plot will display graphically the observations by number (n) or percentage (%) or proportion (1). The cumulative frequency curve provides the continuity of information instead of discrete number of a particular group. A cumulative frequency distribution obtained from n number of samples can be transformed into a continuous probability distribution (percentage or proportion) by dividing each frequency by n, the total number of observations (Table 9.2, Fig. 9.2). The total area of the cumulative frequency distribution curve is transformed into continuous probability (Isaak and Srivastava, 1989). This approach to probability is intuitively appealing to geologists, as the concept is closely akin to unification.

9.2.6 Minimum, Maximum, Range, Median, Mode, and Mean

Minimum and **maximum** are the smallest (X_{min}) and largest (X_{max}) values in the data set, respectively. The smallest and largest numbers in Table 9.1 are 0.30% Zn and 7.50% Zn.

Range is the difference between the largest and the smallest values. It can be expressed that % Zn varies between 0.30 and 7.50 with a range of 7.20% Zn. The **mid-range** is half of the range $(x_{max}-x_{min})/2$.

Median is the middle value of a group of numbers (say assay values) that have been arranged by size in ascending order. The median splits the data set in two equal halves. The median is the middle entry in the series when the total number of observations is odd. In an odd series of 1, 2, 3, 4, **5**, 6, 7, 8, 9 →, 5 is the median. Similarly, the median is equal to the sum of the two middle numbers divided by two

TABLE 9.2 Frequency Table of 1 m Borehole Assay Data of Table 9.1

Sample Class of % Zn			Number of Samples	Cumulative Frequency	Cumulative Frequency (%)
Lower Limit	Upper Limit	Midpoint			
0	1	0.5	4	4	5.6
1	2	1.5	7	11	15.3
2	3	2.5	15	26	36.1
3	4	3.5	21	47	65.3
4	5	4.5	15	62	86.1
5	6	5.5	8	70	97.2
6	7	6.5	1	71	98.6
7	8	7.5	1	72	100.0

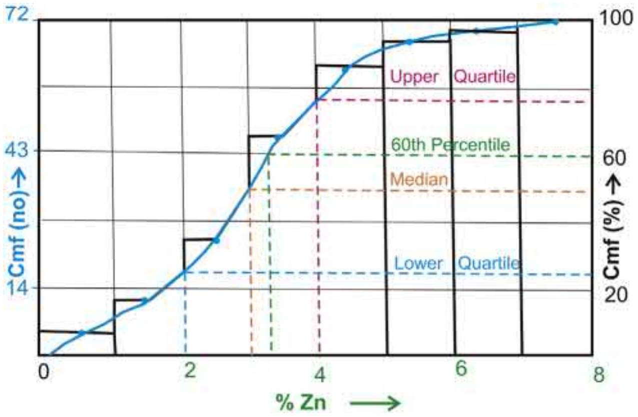

FIGURE 9.2 Cumulative plots by number, percent, proportion, quartile, deciles, and percentiles of 1 m sample grades in Table 9.2.

when the numbers of the series are even. In an even number series of 1, 2, 3, **4**, **6**, 7, 8, 9 →, (4 + 6)/2 = **5** is the median. The odd and even rule is important. In an order data string, half of the population is below the median value.

Mode is the value that occurs most frequently in a set of numbers or the highest frequency in grouped data or in a sample population. In a series of 1, 2, 3, **4**, **4**, **4**, 5, 5, 6 →, **4** is the most frequently occurring number. There may be more than one mode when two or more numbers have an equal or relatively high number of instances (bimode or multimode). A mode does not exist if no number has more than one instance.

Quartiles split ascending or descending order data sets into quarters. A quarter ($\leq$25%) of the data falls below the lower or first quartile (Q_1). Similarly, a quarter ($\geq$75%) of the data lies above the upper or third quartile (Q_3). **Deciles** split the order data set into 10 divisions. One-tenth of the data falls below the lower or the first decile, and 1/50th is the fifth decile and is equal to the median. **Percentiles** split the data set into 100th divisions and the 50th percentile is equal to the median. The 25th and 75th percentiles are equal as first and third quartiles, respectively. The order data set is plotted in the x-axis in normal scale and cumulative frequency percent is plotted in the y-axis in normal (Fig. 9.2) or logarithmic scale. **Quantiles** are generalizations of the data-splitting concept. They represent the points taken at regular intervals from the cumulative distribution function of a random variable. A **quantile-quantile** or q-q plot is a graphical presentation on which the quantiles from two distributions are plotted versus one another. A q-q plot compares two distributions, and is particularly useful when there are sufficient reasons to expect that the two distributions are similar.

Sample **mean**, arithmetic mean, or average value $(\overline{X})$ conceptualizes the central tendency of distribution parameters around which it disperses on either side. It is computed by the sum of the values of all observations within the population divided by the number of samples:

$$\text{Sample mean grade}\left(\overline{X}\right) = (1/\text{n}) \times \left\{\sum_{i=1}^{n} X_i\right\}$$

The % zinc contents of an exploration drill hole sampled at 1 m uniform length have been tabulated in Table 9.1 for the computation of mean grade:

$$\sum_{i=1}^{n} \text{x}_\text{i} = 248.80$$

$$\text{n} = 72$$

$$\text{Mean}\left(\overline{X}\right) = 248.80/72 = 3.45\ \%\ \text{Zn}$$

The computation of arithmetic mean assumes that all observed values are composed of the same size of

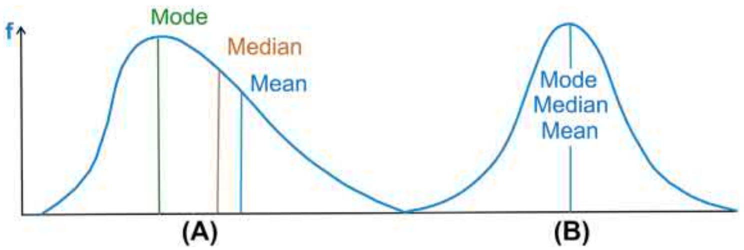

FIGURE 9.3 Schematic diagram showing (A) asymmetric and (B) symmetric probability distribution.

sample length. Therefore unequal sampling units cannot be utilized together to calculate valid statistical parameters. Transformation of raw data to equal length of the sample unit is a prerequisite in statistical applications.

The three measures of central tendency, i.e., mode, median, and mean, will be different in an asymmetric distribution curve (Fig. 9.3A). The normal distribution curve is symmetric, and the three statistical measures of central tendency will coincide (Fig. 9.3B).

9.2.7 Sample Variance and Standard Deviation

A reasonable way to measure sample variation about the mean value is to subtract the mean from the observed value and sum as follows:

$$\sum_{i=1}^{n}\{X_i-(\overline{X})\}$$

As the algebraic sum of the deviation of a set of numbers from its mean is always zero, the foregoing formula becomes meaningless as a measure of **variance**. The average variance is thus expressed as the sum of the squared deviation of the mean from each observed value (Table 9.1) divided by the number of observations −1, representing the **degree of freedom**. The population sample variance estimator is expressed as:

$$\text{Sample variance}(\mathbf{S^2}) = \sum_{i=1}^{n}\{X_i-(\overline{X})\}^2\big/(\text{n}-1)$$

$$\text{or,} = \left\{\sum_{i=1}^{n}X_i^2-\left(\sum_{i=1}^{n}X_i\right)^2\right\}\Big/(\text{n}-1)$$

$$\therefore \text{S}^2 \text{ for Zn distribution} = 154.638/71 = 2.178$$

The square root of sample variance is the sample **standard deviation** estimator:

Sample standard deviation (**S**) $= \sqrt{S^2} = \sqrt{2.178} = 1.476$
Variance of the mean $= \text{S}^2/\sqrt{\text{n}} = 2.178/\sqrt{72} = 0.256$
Standard error of the mean $= \text{S}/\sqrt{\text{n}} = 1.476/\sqrt{72} = 0.174$
Or confidence limit at 68% probability level $= \text{S}/\sqrt{\text{n}} = 1.476/\sqrt{72} = 0.174$
Confidence limit at 95% probability level $= \text{S}/\sqrt{\text{n}}\times 1.96 = \pm 0.34$ % Zn

CV or relative standard deviation is the ratio between standard deviation and mean. CV represents the alternative to skewness to describe shape of the distribution. The CV will be ≤1 for normal distribution. A CV of ≥1 indicates the presence of some erratic high sample values that have a significant impact on estimated mean grade. The erratic high values may be due to sampling error. These samples are sorted, located, and rejected if they do not fit in the geological system:

$$\text{CV} = \text{S}/(\overline{X}) = 1.476/3.455 = 0.427$$

The computation of mean from grouped data (Table 9.2) is:

$$\text{Mean}(\overline{X}) = \sum(\text{F}\times\text{mp})\Big/\sum\text{F} = (249/72)$$
$$= 3.458 \ \%\ \text{Zn}$$

where F = frequency and mp = midpoint:

$$\text{Sample variance}(\text{S}^2) = \left\{\sum(\text{F}\times\text{mp}^2)\Big/\text{N}\right\} - (\overline{X})^2$$
$$= (1012/72)-(3.458)^2$$
$$= 14.05-11.95 = 2.10$$

9.2.8 Probability Plot

Mean and standard deviation can be obtained from the plot of the upper class value limit (grade) versus the cumulative frequency percentages on linear probability paper (Fig. 9.4). A normal distribution will create a straight line on normal probability paper. The grade corresponding to the 50% probability line gives the mean. The difference in grade between 84% and 50% probability gives an estimation of standard deviation.

9.2.9 Log-Normal or Pareto Distribution

The **log-normal** or **Pareto** distribution plot exhibits exponentially and is skewed to the right or left. The

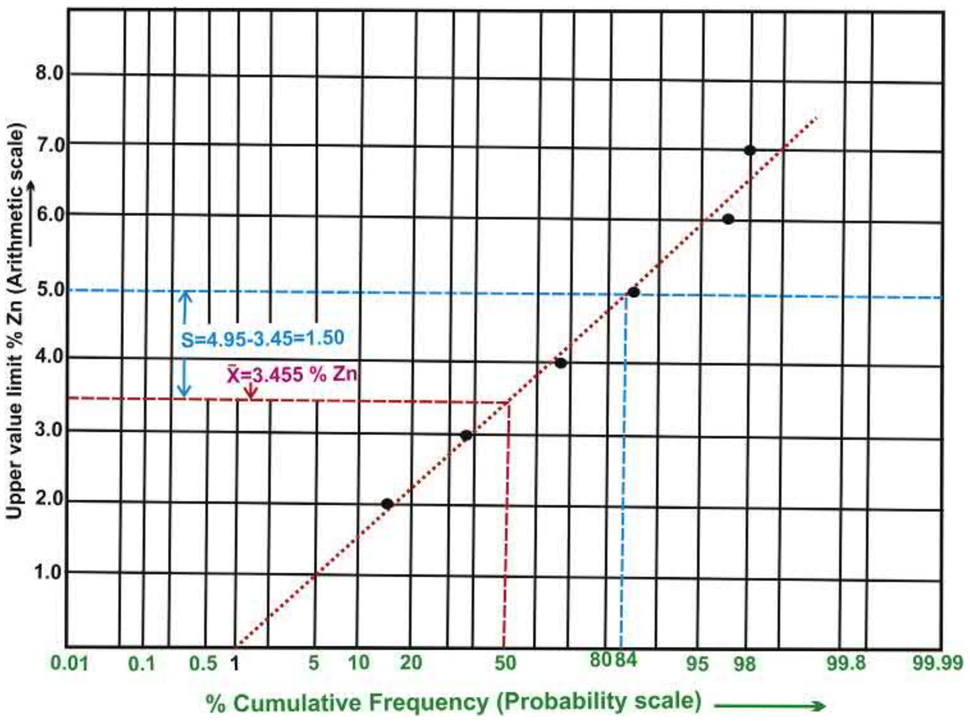

FIGURE 9.4 Probability plot of Table 9.2 for computation of sample mean and standard deviation of Zn grade.

skewed log-normal distribution corresponds to spotty or low-grade mineral deposits. High values are occasionally encountered, while the majority of samples are of lower grade. The log-normal distribution generally corresponds to the normal distribution by logarithmic transformation of these values. The plot of group values often depicts a straight line on log probability paper. Alternatively, a three-parameter log-normal paper is used to obtain a straight line. A constant can be added to each class for better results. The mean value for a logarithmic distribution is estimated by the following relationship from Table 9.3, Figs. 9.5 and 9.6:

$$\text{Mean} = e^{\alpha} + \beta^2/2 = \mathbf{e}^{\text{geometric mean}} \times e^{\beta^2/2}$$

$$\text{Standard deviation(S)} = e^{\alpha} + \beta^2/2 \times \sqrt{\left(e^{\beta^2} - 1\right)}$$

$$= \text{Mean} \times \sqrt{\left(e^{\beta^2} - 1\right)}$$

$$\text{Confidence Limit(CL)} = (\text{S} \times 1.96)\Big/\sqrt{\text{n at 95\% probability}}.$$

Geometric mean (α) is the logarithm (Ln) of mean grade at 50% point frequency. Geometric standard deviation of the log value (β) is the difference between the natural logarithm of the grade at the 50% and 84% cumulative frequency ordinates. It corresponds to one standard deviation.

9.2.9.1 Log-Normal Computation

A total of 2229 samples from a surface borehole at 0.50 m uniform length from Baroi lead-zinc deposit, Rajasthan, India, have been tabulated in Table 9.3.

The frequency diagram and three-cycle logarithmic plot have been depicted in Figs. 9.5 and 9.6, respectively.

N = 2229
Ln at 50% = Ln (5.00) = 1.6094
Ln at 84% = Ln (11.05) = 2.4024
β = Ln 84% − Ln 50% = 0.79299
β^2 = 0.6288
$\beta^2/2$ = 0.3144
Mean = $e^{(1.6094+0.3144)}$
= $e^{(1.9238)}$
= 6.848 − 3.0 (constant added)
= 3.85% Pb
Standard deviation = 3.85 × 0.932
= 3.58%
Confidence limit = $(3.58 \times 1.96)/\sqrt{2229}$
= ± 0.149% Pb

TABLE 9.3 Grouped Borehole Sample Data of Baroi Lead-Zinc Mine, India

Class Interval (% Pb)	f	Cumulative Frequency	Cumulative Frequency (%)	Class Interval (% Pb)	f	Cumulative Frequency	Cumulative Frequency (%)
0–1	811	811	36.38	15–16	54	2183	97.94
1–2	296	1107	49.66	16–17	2	2185	98.03
2–3	229	1336	59.94	17–18	5	2190	98.25
3–4	202	1538	69.00	18–19	3	2193	98.38
4–5	135	1673	75.06	19–20	4	2197	98.56
5–6	102	1775	79.63	20–21	4	2201	98.74
6–7	82	1857	83.31	21–22	–	22.01	98.74
7–8	59	1916	85.96	22–23	5	2206	98.97
8–9	49	1965	88.16	23–24	–	2206	98.97
9–10	44	2009	90.13	24–25	1	2207	99.01
10–11	38	2047	91.83	25–26	2	2209	99.10
11–12	31	2078	93.23	26–27	–	2209	99.10
12–13	20	2098	94.12	27–28	2	2211	99.19
13–14	21	2119	95.07	28–29	2	2213	99.28
14–15	10	2129	95.51	29–30	2	2215	99.37
				>30	14	2229	100

9.2.9.2 Sichel's t-Estimate

Sichel formulated tables to simplify the estimation procedure, especially in the case when only a few samples are available such as:

$$
\begin{aligned}
N &= 2229 \\
\alpha &= \text{Ln at } 50\% = \text{Ln } (5.00) = 1.6094 \\
& \text{Ln at } 84\% = \text{Ln } (11.05) = 2.4024 \\
\beta &= \text{Ln } 84\% - \text{Ln } 50\% = 2.4024 - 1.6094 = 0.7929
\end{aligned}
$$

Log variance $= \beta^2 = 0.6288$

Read the variance (β^2) for corresponding t-value from mean of lognormal population available at standard Sichel's Table-B for stated number of samples (n). If the variance is in between the table value interpolated value can be computed between higher and lower table values:

$$
\begin{aligned}
\text{Mean} &= \text{Log value at } 50\% \times \text{t—constant(if any)} \\
&= 5 \times 1.3638 - 3 \\
&= 6.82 - 3 \\
&= 3.82\% \text{ Pb}
\end{aligned}
$$

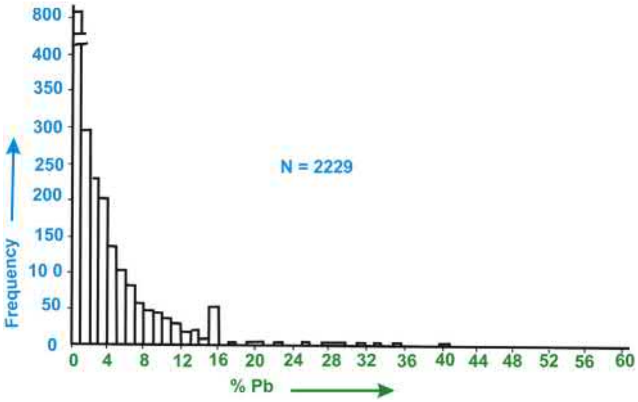

FIGURE 9.5 Frequency plot of % lead grade at 0.50 m uniform sample length showing log-normal probability with positively skewed distribution.

9.2.9.3 Confidence Limits

Read the lower and upper limits of **t-**value of log variance corresponding to stated number of samples (n) from standard Sichel's t-Table

$$\text{Lower limit} = \text{Mean} \times \text{t lower value} = 3.82 \times 0.554 = 3.649$$

$$\text{Upper limit} = \text{Mean} \times \text{t upper value} = 3.82 \times 1.048 = 4.00$$

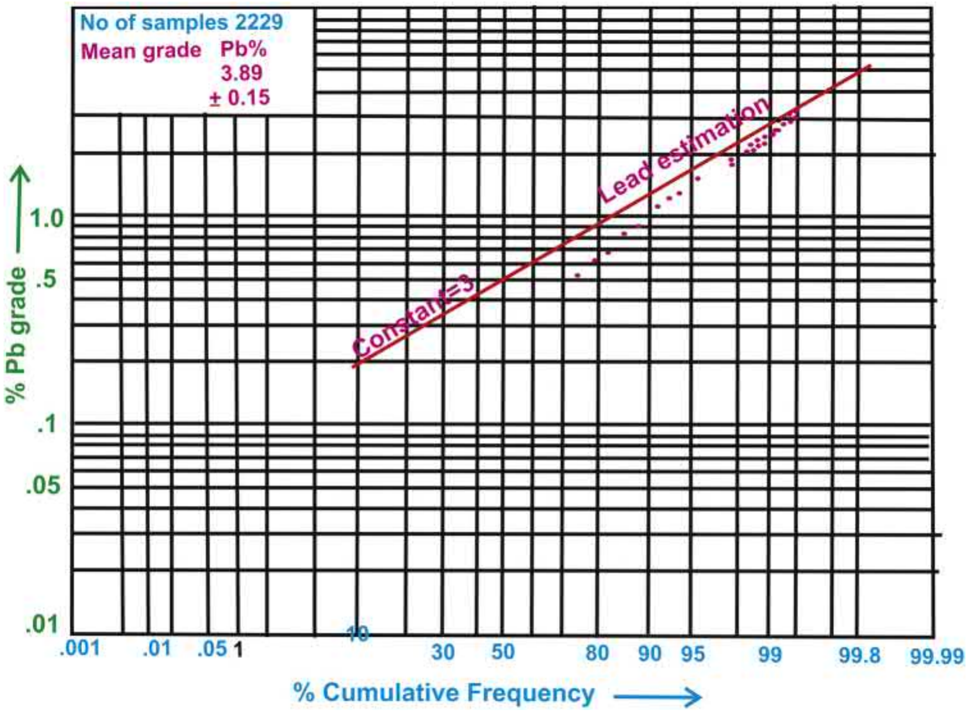

FIGURE 9.6 Plot and computation of $\overline{X}$, S^2, and confidence limit of lead sample values by double logarithmic paper.

9.2.9.4 *Coefficient of Skewness*

The quantity of symmetry of the sample distribution is the **coefficient of skewness** or **skewness**. The statistics are plotted as a histogram and defined as:

$$\text{Coefficient of skewness} = \left[1/\text{n}\sum_{i=1}^{n}(x_i-\overline{x})^3\Big/\delta^3\right]$$

9.2.10 Covariance

In typical geological situations, more than one variable is measured on each observational point, e.g., % Pb, % Zn, % Fe, g/t Ag, and g/t Cd content of mill feed. The data can be arranged in an n × m array, where n is the number of observations (months) and m is the number of variables (% or g/t metals). The statistical parameters of each variable such as $\overline{X}$, S^2, S, CL, and CV can be computed. However, different variables measured on the same object usually tend to change together in some manner. The variables, which have no relation to each other, are said to be mutually independent, i.e., an increase or decrease in one variable is not affected by a predictable change in another variable. Some measure of their mutual interface or relationship is expected in the case of variables not being totally or always independent of each other. The procedure employed to compute the variance of a single parameter can be extended to calculate the measure of mutual variability for a pair of parameters. **Covariance** (COV) is the joint variation of two variables about their common mean:

$$\text{COV(X, Y)} = \left\{\sum_{i=1}^{n}(x_i-\overline{x})\times\left(y_i-\overline{y}\right)\right\}\Big/(\text{n}-1)$$

$$= \left\{\sum_{i=1}^{n}x_iy_i-\left(\sum_{i=1}^{n}x_i\times\sum_{i=1}^{n}y_i\right)\Big/\text{n}\right\}\Big/(\text{n}-1)$$

Annual mill feed data by month of a process plant is tabulated in Table 9.4 for computation of covariance between lead and silver content.

9.2.10.1 *Computation of Covariance*

	Pb	Ag
$\sum X$	16.32	470
$\sum X^2$	23.749	19,000
$\overline{X}$	1.36	39
S	0.3758	7.334

$$\sum_{i=1}^{n}\text{Pb}_i\times\text{Ag}_i = 663.92$$

$$\text{COV(Pb, Ag)} = \{663.92-(16.32\times470)/12\}/11$$

$$= 2.247$$

TABLE 9.4 Monthly Average Mill Feed Grade of a Zinc-Lead-Silver Beneficiation Plant During 2010–11

Month	% Zn	% Pb	% Fe	g/t Ag
April	3.67	1.67	5.50	49
May	3.34	1.12	4.60	38
June	3.30	0.86	4.30	33
July	3.55	1.28	4.40	41
August	3.76	1.40	3.60	43
September	3.50	2.25	4.30	52
October	3.80	1.40	4.30	45
November	4.12	1.50	4.50	41
December	3.97	1.60	3.70	36
January	3.32	1.12	3.20	33
February	2.92	0.93	3.60	30
March	3.37	1.19	3.80	29

9.2.11 Correlation Coefficient

The **correlation coefficient** (r) is the measure of degree of interrelationship between variables. The computation is not influenced by the unit of measurement of variables. Correlation is the ratio between the covariance of two variables and the product of their standard deviation:

$$\mathrm{r(j,\ k)} = \mathrm{COV_{JK}/S_J S_K}$$

The correlation coefficient is a ratio and is expressed as a unitless number. Covariance can be equal but cannot exceed the product of the standard deviations of its variables. The correlation coefficient will range between +1 (perfect direct relationship) and −1 (perfect inverse relationship). The spectrum of the r exists between these two extremities of perfect positive or negative relationships passing through zero (no relation) in a linear function. The correlation between Pb and Ag from the data of Table 9.4 will be:

$$\mathrm{r(Pb,\ Ag)} = \{\mathrm{COV_{Pb,\ Ag}/(S_{Pb} \times S_{Ag})}\}$$

$$= 2.247/(0.3758 \times 7.334) = 0.815$$

$$\text{Goodness of fit} = \mathrm{r}^2 = 0.66 \text{ or } 66\%$$

9.2.12 Scatter Diagram

The interrelation between two variables can be visualized by plotting an independent variable along the x-axis and its corresponding dependent variable along the y-axis. The plot is known as a scatter diagram, which provides an instant sense of the expected relationship (Fig. 9.7).

9.2.13 Regression

The linear mathematical relationship between two variables based on the interdependability function is formulated as: Y is a function of X, i.e., Y = f(X):

$$\widetilde{\mathbf{Y}}_i = \mathrm{b}_0 + \mathrm{b}_1 X_i$$

where $\widetilde{\mathbf{Y}}_i$ is an estimated value of Y_i at a specified value of X_i, Y_i is a dependent or regressed variable, and X_i is an independent or repressor variable

The fitted line will intercept the y-axis at a point b_0 and a slope of b_1. The equation must satisfy the condition that the deviation of Y_i from the line is minimal such as:

$$\sum_{i=1}^{n} \left(\widetilde{\mathbf{Y}}_i - Y_i\right)^2 = \text{Minimum.}$$

$$\mathrm{b}_1 = \left\{ \sum_{i=1}^{n} X_i Y_i - \left(\sum_{i=1}^{n} X_i \times \sum_{i=1}^{n} Y_i \right) \Big/ \mathrm{n} \right\} \Bigg/ \left\{ \sum_{i=1}^{n} X_\mathrm{i}^2 - \left(\sum_{i=1}^{n} X_i \right)^2 \Big/ \mathrm{n} \right\}$$

$$= \mathrm{SP_{xy}/SS_x}$$

$$= (\text{Sum of products for covariance}) \Big/ (\text{Sum of squares for variance})$$

$$\mathrm{b}_0 = \overline{Y} - \mathrm{b}_1 \overline{X}$$

The silver (dependent) and lead (independent) contents from Table 9.4 are plotted in a scatter diagram (Fig. 9.8). The regression equation is computed as:

$$\mathrm{b}_1 = (663.92 - (16.32 \times 470)/\mathrm{n}) / \{23.749 - (16.32)^2/\mathrm{n}\}$$

$$= 24.720/1.554 = 15.907$$

$$\mathrm{b}_0 = 39.167 - (15.907 \times 1.36) = 17.533$$

$$\therefore \text{The equation is: Ag(g/t)} = 17.533 + (15.907 \times \%\ \mathrm{Pb})$$

9.2.14 The Null Hypothesis

The null hypothesis is a characteristic arithmetic theory suggesting that no statistical relationship and significance exists in a set of given, single, observed variables between two sets of observed data and measured phenomena. The hypotheses play an important role in testing the significance

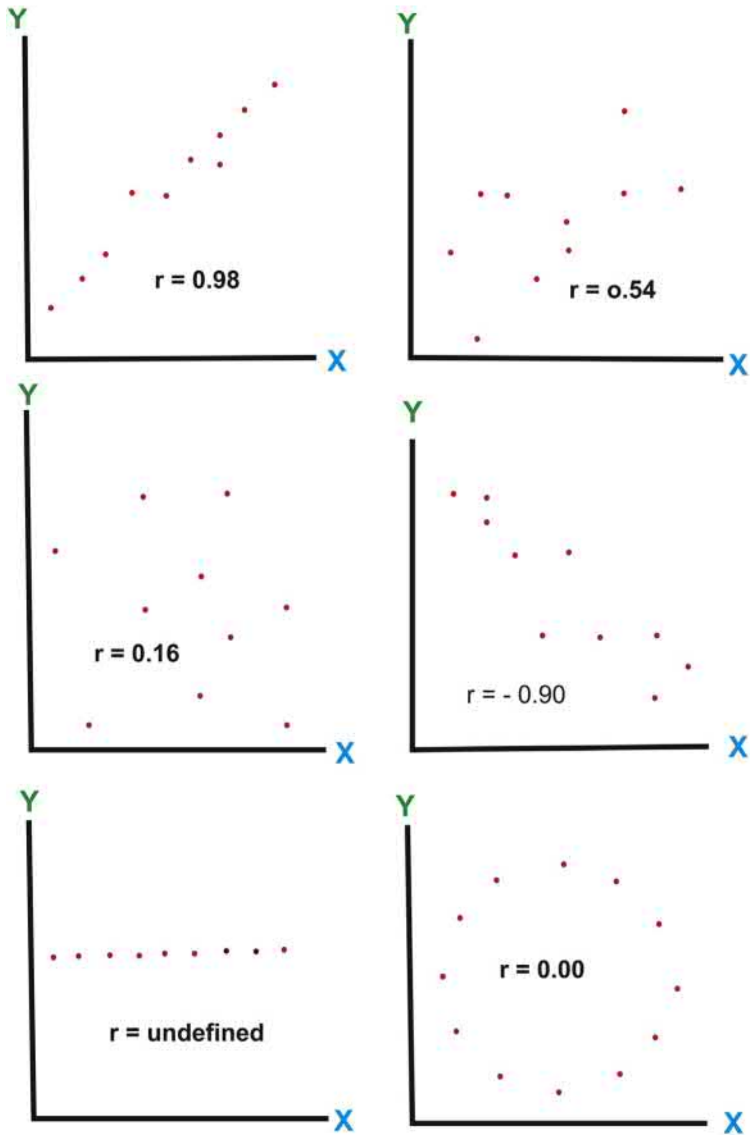

FIGURE 9.7 Plot of scatter diagrams of two variables showing different types of correlations between them depending on mutual interdependability.

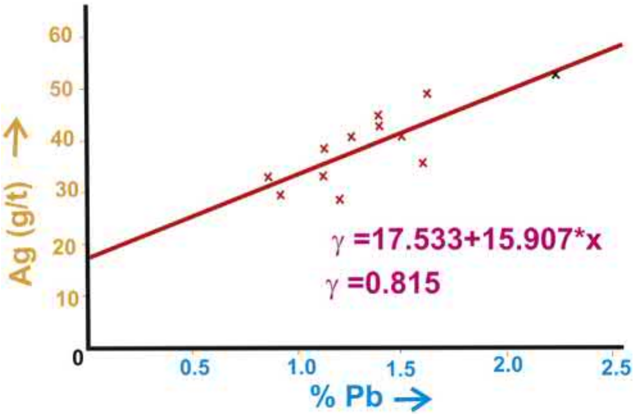

FIGURE 9.8 Plot of scatter diagram showing the regression line of Pb versus Ag from Table 9.4.

of differences in experiments and between observations. H_0 symbolizes the null hypothesis of no difference. It presumes to be true until evidence indicates otherwise. Let us take two sets of mill feed silver samples from Table 9.5 and compare the mean grade between set and population and between two sets. The null hypothesis presumes and states that:

$$H_0 : \mu_1 = \mu_0$$

where $H_0 =$ null hypothesis of no difference, $\mu_1 =$ mean of population 1, and $\mu_0 =$ mean of population 2.

The null hypothesis states that the mean μ_1 of the parent population from which the samples are drawn is equal to or not different from the mean of the other population μ_0. The samples are drawn from the same population such that the

TABLE 9.5 Average Monthly Mill Feed Silver Grade (g/t) of a Zinc-Lead-Silver Mine

Sample	Set I	Set II	Difference (d) Set (I–II)	$(\text{Difference})^2$
April 2010	49	51	−2	4
May	38	31	7	49
June	33	33	0	0
July	41	41	0	0
August	43	40	3	9
September	52	43	9	81
October	45	51	−6	36
November	41	32	9	81
December	36	35	1	1
January 2011	33	30	3	9
N	10	10	10	10
SUM (Σ)	411	387	24	270
AVG $(\overline{X})$	41.1	38.7	2.4	27.0
VAR (S^2)	40.77	61.57	23.60	1078.67
STD (S)	6.38	7.85	4.86	32.84

variance and shape of the distributions are also equal. Alternative statistical applications such as t, F, and chi-square can only reject a null hypothesis or fail to reject it. The evidence can state that the mean of the population from which the samples are drawn does not equal the specified population mean and is expressed as:

$$H_0: \mu_1 \neq \mu_0$$

9.2.15 The t-Test

The t-test follows parametric statistics assuming certain conditions of normal probability distribution and equality of variance between groups and parent populations. The t-test or Student's t-test is based on t-probability distribution, similar to normal distribution with widespread, and dependent upon the size of the samples. This is powerful for testing the hypothesis and useful for establishing the likelihood that a given sample could be a member of a population with specified characteristics (mean), or for testing a hypothesis about the equivalency of two samples. The t-statistic is computed by:

$$t = \left(\overline{X} - \mu_0\right) / \left(S/\sqrt{n}\right)$$

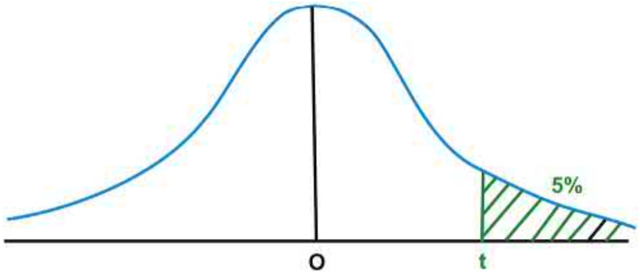

FIGURE 9.9 Schematic diagram showing analysis of the t-test.

where $\overline{X}$ = mean of the sample, μ_0 = hypothetical mean of the population, n = number of observations, and S = standard deviation of observations.

If the computed value exceeds the table value of t at a specific degree of freedom, level of significance, or lies in the critical region (Fig. 9.9) or region of rejection, the null hypothesis ($\mu_1 \leq \mu_0$) is rejected, leaving the alternative that $\mu_1 > \mu_0$. If the computed value of t is less than the table value, it can only be stated that there is nothing in the sample to suggest that $\mu_1 > \mu_0$, but it cannot specify that $\mu_1 < \mu_0$. This indecisiveness is a consequence of the manner in which statistical tests are formulated. They can demonstrate, with specified probabilities, what things are not. They cannot stipulate what they are.

The average monthly mill feed silver grade (g/t) of a zinc-lead mine over 10 months is given in Table 9.5. There are two sets of samples collected at different time intervals. The hypothetical mean grade (μ_0) of the deposit is 40 g/t Ag. The t-value of samples at Set I is computed to test the hypothesis of likelihood of the means of samples $\left(\overline{X}\right)$ and population (μ_0):

$$\begin{aligned} t &= \left(\overline{X} - \mu_0\right) / \left(S/\sqrt{n}\right) \\ &= (41.10 - 40.00) \Big/ \left(6.38 \Big/ \sqrt{10}\right) = (1.10/2.02) \\ &= 0.54 \end{aligned}$$

The calculated value of 0.54 is much less than the table value of t (1.83) for 9 degrees of freedom and 5% ($\alpha = 0.05$ for a one-tail test) level of significance (Box 9.1). The t-computed value lies away from the region of rejection. The test is indecisive to suggest that the population mean is greater than 40 g/t Ag.

The two sets of samples (I and II) collected at different time intervals are unpaired and independent. The **pooled**

BOX 9.1 CRITICAL VALUE OF T

Critical Values of **t** for Various Degrees of Freedom and Selected Levels of Significance from Table 21, Penguin-Honeywell Book of Tables (Kellaway, 1968).

t-estimate tests the null hypothesis and the equality of the mean of two normally distributed populations. The test statistical form is stated as:

$$t = \left(\overline{X}_1 - \overline{X}_2\right) \Big/ \left\{ \mathrm{Sp} \times \sqrt{(1/n_1 + 1/n_2)} \right\}$$

where Sp is the pooled estimate of the population standard deviation based on both sample sets:

$$\mathrm{Sp}^2 = \left\{(n_1 - 1) \times S_1{}^2 + (n_2 - 1) \times S_2{}^2\right\} / (n_1 + n_2 - 2)$$

$$\text{Pooled t} = (41.10 - 38.70) \Big/ \left[\left\{\sqrt{(9 \times 40.77) + (9 \times 61.57)/18}\right\} \times \sqrt{0.2}\right)\right]$$

$$= 2.40 \Big/ \sqrt{\{(366.93 + 544.13)/18\}} \times \sqrt{0.20}$$

$$= 2.40 \Big/ \left(\sqrt{51.17} \times \sqrt{0.20}\right)$$

$$= 2.40/(7.15 \times 0.44) = 2.40/3.146 = 0.76$$

The table value of t for a two-tailed test with 18 or 9 degrees of freedom and the 10% (5% in each tail) level of significance are −1.73 and +1.73. The calculated t-value of 0.76 does not fall into either critical region. The null hypothesis cannot be rejected. There is no evidence to suggest that the two samples came from populations having different means.

The **paired t-test** provides a hypothesis test of the differences between population means for a pair of random samples whose differences are approximately normally distributed. Let us assume that the two sets of samples in Table 9.5 are a repeat analysis of silver at two different laboratories. The paired t-value can be computed for testing equivalency of the means:

$$\text{Paired t} = \overline{d} \Big/ \overline{Sd}$$

where d_i = difference of each paired sample and $\overline{d}$ = mean difference:

$$\overline{Sd}^2 = \left\{ n \times \sum_{i=1}^{n} d_i^2 - \left(\sum_{i=1}^{n} d_i \right)^2 \right\} / n(n-1)$$

$$\overline{Sd} = \sqrt{(Sd^2/n)}$$

From Table 9.5:

$$\overline{d} = 2.4 \quad \Sigma d = 24 \quad \Sigma d^2 = 270$$

$$Sd^2 = \{(10 \times 270) - 576\}/(10 \times 9) = 23.60$$

$$\overline{Sd} = \sqrt{(23.60/10)} = \sqrt{2.36} = 1.536$$

$$\text{Paired t} = 2.40/1.536 = 1.56$$

The estimated t-value of 1.56 is less than the table value of 1.83 for 9 degrees of freedom and the 5% ($\alpha = 0.05$ for the one-tail test) level of significance. It does not fall into the critical region and it will be concluded that there is no evidence to suggest that the two samples came from populations having different means. Three assumptions are necessary to perform this test:

1. Both samples are selected at random.
2. Populations from which the samples were drawn are normally distributed.
3. Variances of the two populations are equal.

9.2.16 The F-Test

The F-test pertains to parametric statistics and follows the assumptions and conditions of normal probability distribution of populations from which the samples are drawn. The equality of variances of two data sets can be found and tested based on a probability distribution known as the F-distribution under the null hypothesis. The F-test is sensitive to nonnormality. F is the ratio between the variances of two populations. The F-distribution is dependent upon two values: each associated with each variance in the ratio. The samples are expected to be randomly collected from a normal distribution to satisfy the condition of F-distribution.

The F-hypothesis test is defined as:

$$H_0: \delta_1{}^2 = \delta_2{}^2$$

$$\delta_1{}^2 < \delta_2{}^2 \quad \text{for a lower one} - \text{tailed test}$$

$$\delta_1{}^2 > \delta_2{}^2 \quad \text{for a lower one} - \text{tailed test}$$

$$\delta_1{}^2 \neq \delta_1{}^2 \quad \text{for a two} - \text{tailed test}$$

$$F = \text{Explained variance/Unexplained variance}$$

$$F = \left(S_1{}^2/S_2{}^2\right)$$

where $S_1{}^2$ and $S_2{}^2$ are the sample variances of the population.

It is concluded that the greater this ratio deviates from 1, the stronger the evidence for unequal population variances. In other words, the variance in the populations is not same in the two groups if the computed F-value exceeds the table value. If the calculated value is less than the table value we would have no evidence that the variances are different. The two-sample data sets will represent the same population in the case of $S_1{}^2 = S_2{}^2$.

9.2.17 The Chi-Square Test

The chi-square (χ^2) test relates to nonparametric statistics, is typically easy to compute, and is capable of processing data measured on a nominal scale (categorical variables). χ^2 is a statistical test frequently used to compare observed data with data expected to be obtained according to a specific hypothesis. If a sample of size n is taken from a population having a normal distribution with mean μ and standard deviation α, it may allow a test to be made of whether the variance of the population has a predetermined value. Each observation can be standardized to the standard normal form with 0 mean and unit variance following $Z_i = \left(X_i - \overline{X}\right)/S)$ for samples or $Z = (X_i - \mu)/\alpha$ for population parameters. The values of Z are squared to eliminate the sign and summed to formed a new statistic: $\sum Z^2 = \sum_{i=1}^{n} \{(X_i - \mu)/\alpha\}^2$.

Data processing, interpretation, and testing of the hypothesis are similar to parametric t- and F-tests. The chi-square test computes a value from the data using the χ^2 procedure. The value is compared to a critical value from a χ^2 table with a degree of freedom equivalent to that of the data (Box 9.2). If the calculated value is greater than or equal to the table value the null hypothesis is rejected. If the value is less than the critical value the null hypothesis is accepted. χ^2 is an important test in nonparametric statistics. It is used to test the difference between an actual sample and another hypothetical or previously established population, which is expected due to chance or probability:

$$\chi^2 = \sum_{i=1}^{n} (O_i - E_i)^2 / E_i$$

where O_i = observed frequency of the ith class and E_i = expected frequency of the ith class.

Example: A balanced coin is tossed 20 times and yields 12 times heads and 8 times tails against expected probability values of 10 and 10 (Table 9.6).

The calculated value of χ^2 is 0.80 (without any correction factor) and is much less than the table value of 3.84 at 1 degree of freedom, which is not statistically significant at the 0.05 level. It can be concluded that the deviation between observed and expected frequency is due to sampling error or to chance alone.

BOX 9.2 CRITICAL VALUES OF χ^2

Critical Values of χ^2 for Various Degrees of Freedom and Selected Levels of Significance from Table 24, Penguin-Honeywell Book of Tables (Kellaway, 1968).

TABLE 9.6 Results of Coin Toss and χ^2 Calculation

	Observed (O_i)	Excepted (E_i)	$(O_i - E_i)^2$	$(O_i - E_i)^2/E_i$
Head	12	10	2	0.40
Tail	8	10	−2	0.40
Total	20	20		0.80

9.2.18 Analysis of Variance

The analysis of statistical variance (ANOVA) compares groups of samples. The observed variance in a particular variable is partitioned into components attributable to different sources of variation. There are several models and procedures to perform analysis of variances due to the effects of categorical factors. The models are one-way ANOVA, multifactor ANOVA, variance component analysis, and the general linear model. One-way ANOVA deals with single categorical factors equivalent to comparing multiple groups of data sets. Multifactor ANOVA uses more than one categorical factor arranged in a crossed pattern. The variance component analysis model utilizes multiple factors arranged in a hierarchical manner. The linear model is a complex type and uses categorical and quantitative, fixed and random factors arranged in crossed and nested patterns. The general format of the one-way model is presented in Table 9.7.

Five ore samples are collected from a zinc-lead deposit. The samples are analyzed for % Pb content at six standard laboratories (Table 9.8). Each assay value of one sample analyzed at different laboratories is called a replicate. In one-way analysis, total variance of the data set is broken into two parts: variance within each set of replicates and variance among the samples.

The total variance of all observations (all replicates of all samples) can be computed as:

$$SS_T = \left(\sum_{j=1}^{m} \sum_{i=1}^{n} Xij^2 - \left(\sum_{j=1}^{m} \sum_{i=1}^{n} Xij \right)^2 \right. \Big/ N$$

$$= 96.66 - (52.77)^2/30 = 3.84$$

The variance among the samples and within replicates is:

$$SS_A = \left\{ \sum_{j=1}^{m} \sum_{i=1}^{n} Xij^2/n \right\} - \left(\sum_{j=1}^{m} \sum_{i=1}^{n} Xij \right)^2 \Big/ N$$

$$= 95.20 - (52.77)^2/30 = 2.37$$

$$SS_W = SS_T - SS_A = 3.84 - 2.37 = 1.47$$

TABLE 9.7 Model of One-Way Analysis of Variance of Grouped Data

Source of Variation	Sum of Squares	Degree of Freedom	F-Test
Among samples	SS_A	m − 1	MS_A/MS_W
Within replicates	SS_W	N − m	
Total variation	SS_T	N − 1	

m, number of samples; *n*, number of replicates and N = m × n.

TABLE 9.8 % Pb Assay Value of Five Samples Analyzed at Six Standard Laboratories

	m = 5						
n = 6	Replicate (Lab)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	N = 5 × 6 = 30
	1	1.92	1.87	1.25	2.03	1.99	
	2	1.87	1.43	1.43	2.25	2.43	
	3	2.13	2.02	0.87	1.76	1.76	
	4	1.65	1.76	1.14	1.84	2.02	
	5	1.73	1.93	0.95	1.59	1.84	
	6	2.24	1.61	1.65	1.90	1.91	
	$\sum x$	11.54	10.62	7.29	11.37	11.95	= 52.77
	$\sum x^2$	22.45	19.03	9.29	21.80	24.07	= 96.66

TABLE 9.9 Results of Analysis of Variance

Source of Variation	Sum of Squares	Degree of Freedom	Mean Squares	F-Test
Among samples	2.37	4	0.59	10.17
Within replicates	1.47	25	0.058	
Total variation	3.84	29		

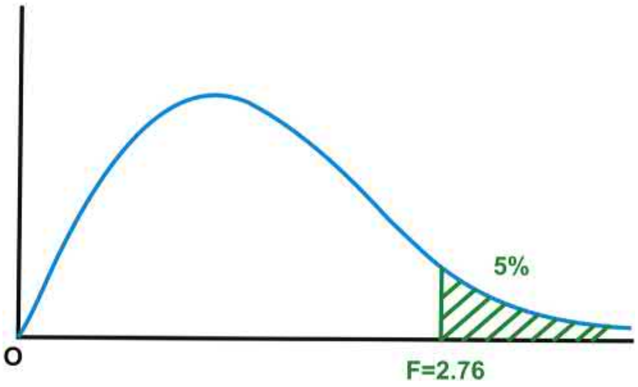

FIGURE 9.10 Analysis of the F-test from the table value at a 5% level of confidence.

The results of the analysis of variances as derived from data set in Table 9.8 are given in Table 9.9.

The computed F-value of 10.17 is greater than the table value of 2.76 at a 5% level of confidence (Fig. 9.10). Therefore it can be concluded that the variation is not the same in the two groups.

9.2.19 Trend Surface Analysis

Trend surface mapping is a mathematical technique for computing an empirical 2D plane or 3D curves, contours, and wire meshes derived by the regression method. It provides the overall structure of spatial variation present in the data set. It is a linear function of geographic coordinates of total scattered observations; it constructs global functional relations and estimates new values on regular grid points. The estimated values must minimize the deviations from the trend functioning as a wide range operator. It is a global pattern recognition technique in mineral exploration. The mathematical equation expressing the functional relationship is stated as:

$$Zn = a_0 + a_1x + a_2y + e \quad (\text{first} - \text{degree equation})$$

$$Zn = a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2 + e \quad (\text{second} - \text{degree equation})$$

and by similar types of equations, where:

Zn = dependent variable (sample value)

X, Y and Z (elevation) = independent variables (location of sample coordinates)

e = random error component,

$a_0 \ldots a_n$ = unknown coefficients.

The number of coefficients is dependent on the degree (NDEG) of the polynomial used, and is computed as $\{(\text{NDEG} + 1) \times (\text{NDEG} + 2)\}/2$. The higher degree of polynomial attempts to reduce the noise level in data minimizes the sum of squares of residuals, and allows definition of the trend in a unique manner. However, it is observed that after reaching a certain degree, the linear fit becomes static due to error propagation and the noisy nature of the large matrices.

In a first-degree equation we need three normal equations to find the three coefficients:

$$\sum Zn = a_0 n + a_1 \sum x + a_2 \sum y$$

$$\sum xZn = a_0 \sum x + a_1 \sum x^2 + a_2 \sum xy$$

$$\sum yZn = a_0 \sum y + a_1 \sum xy + a_2 \sum y^2$$

The equation in matrix form is:

$$\begin{bmatrix} n & \sum x & \sum y \\ \sum x & \sum x^2 & \sum xy \\ \sum y & \sum xy & \sum y^2 \end{bmatrix} \times \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \sum Zn \\ \sum xZn \\ \sum yZn \end{bmatrix}$$

The coefficients for the best-fitting linear trend surface are obtained by solving this set of simultaneous equations.

The trend surface technique is illustrated by a 2D case study. A zinc-lead orebody extends along N42°W−S42°E over a strike length of 90 m. It is lens shaped and widest at the center. The width varies between 2 and 16 m with an average of 7 m. It pinches at both ends. Mineralization dips to the west and plunges 55°NW. The orebody has been drilled from underground at four levels at 15 m intervals. The mineralized intersections are predominantly zinc rich with moderate iron and subordinate amounts of lead. The grades vary between 3.96 and 11.18 with an average of 6.87% Zn, 0.00 and 5.98 with an average of 0.40% Pb, and 2.44 and 15.25 with an average of 6.05% Fe. The drill intersection values are plotted along a longitudinal section. The dependent variables, e.g., Pb, Zn, Fe, and width, are assumed as a numerical functional relation of criteria variables of x (strike) and y (level) coordinates. The trend surface maps of lead and zinc at the fourth degree are generated on a longitudinal vertical section (Figs. 9.11 and 9.12, respectively) considering local coordinates of x and y.

The zinc value has been computed at every observed drill intersection point of the orebody using the fourth-degree trend surface equation. The comparison between actual sample and computed values is given in Table 9.10.

The analysis and observations from actual samples and the trend surface equation (Table 9.10) are:

$$\text{Total variance (TV)} = 71.80$$

$$\text{Unexplained variance (UV)} = 12.10$$

$$\text{Explained variance (EV)} = (\text{TV} - \text{UV}) = 59.70$$

$$\text{Goodness of fit (GF)} = (\text{EV/TV}) \times 100 = 83.15\%$$

GF is a measure of efficiency of the trend equation applied, and depends on input data and inherent structure. The extreme values will lower the GF even with a large database. GF is a useful measure for a homogeneous population, but is not appropriate for skewed or mixed types. Hence lack of significance or high significance needs to be supported by geological interpretation. It determines the functional relationship between predictor and criteria variates.

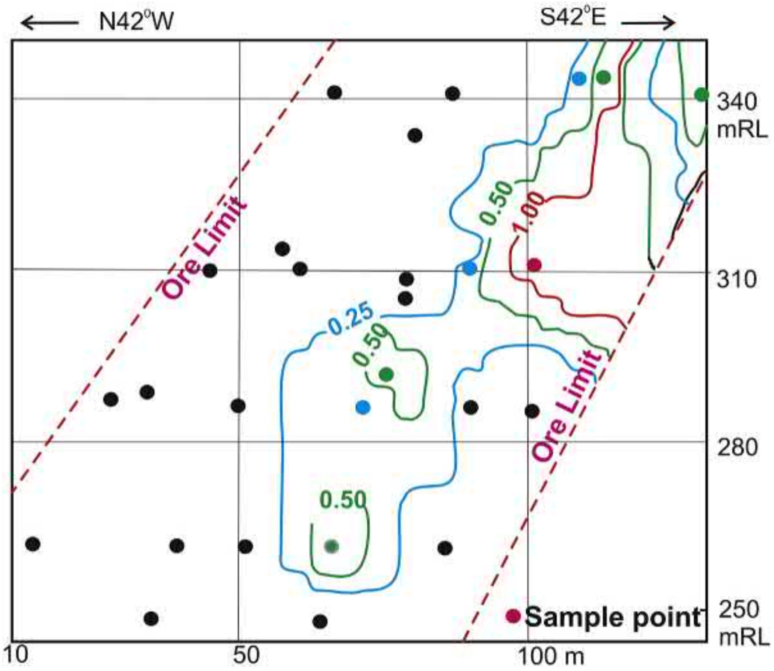

FIGURE 9.11 Fourth-degree trend surface map of lead content of orebody 7W, Balaria deposit, Rajasthan, India.

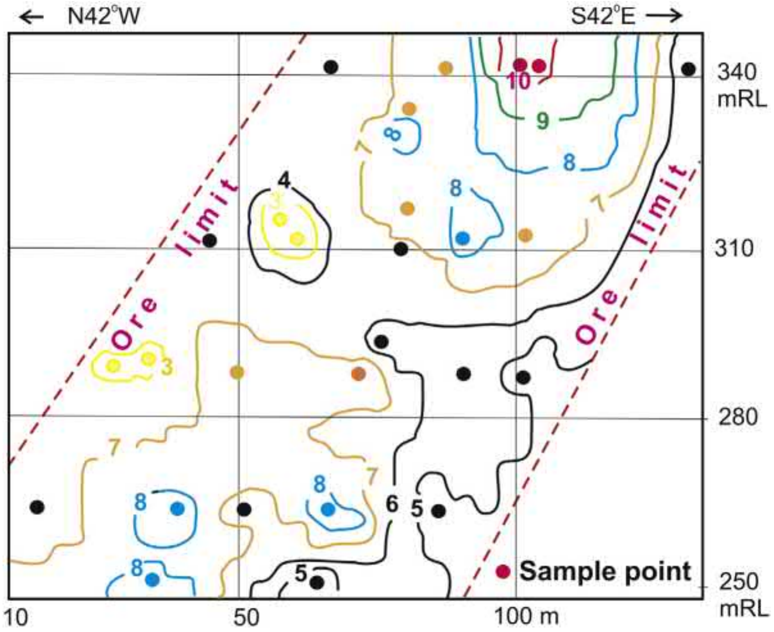

FIGURE 9.12 Fourth-degree trend surface map of zinc content of orebody 7W, Balaria deposit, Rajasthan, India.

TABLE 9.10 Computed Value of Zinc Content of Orebody 7W, Balaria Deposit, Rajasthan, India

Level	Latitude	% Zn (Sampled)	% Zn (Computed)	Level	Latitude	% Zn (Sampled)	% Zn (Computed)
343	68	6.11	6.05	288	102	4.85	4.27
343	86	7.17	7.46	263	15	6.44	6.67
343	102	11.18	10.24	263	38	8.28	8.26
343	105	10.01	10.62	263	54	6.81	7.92
343	134	4.41	4.49	263	67	8.54	7.04
314	46	6.63	6.75	263	84	4.51	4.81
314	60	6.37	6.21	250	5	7.30	7.15
314	82	7.70	7.55	250	35	8.22	8.23
314	91	8.73	7.88	250	64	4.13	4.27
314	101	7.44	7.17	317	59	6.34	6.17
288	28	6.20	6.19	286	34	6.29	6.41
288	49	7.58	6.98	330	81	6.88	7.18
288	74	8.74	7.92	309	80	6.11	7.56
288	90	5.34	6.96				

Unpublished Ph.D. Thesis, Haldar, 1982.

The accuracy of map generation is centered on the midpoint of the 2D grid. The computed trend value and actual values may show a strong divergence away from the midpoint. The margins are the most inaccurate zones. Extrapolation of the trend equation beyond the control point will result in erroneous values.

The trend surface map can indicate (1) possible continuity of mineralization in depth and strike directions, (2) inherent pattern of mineralization like metal zoning and association, and (3) the grain of longer and shorter axes of variations. It may often generate false anomalies since the separation of noise into positive and negative sets is closely linked and together they sum to zero. Smoothing of higher values and enhancement of lower values are an inbuilt part of the procedure. Subset trend maps show no relation to composite trend maps. In spite of those constraints, these are utilized for a generalized pattern of global variation.

9.2.20 Moving Average

Moving average is a technique of smoothing data that occur infrequently at high and low values. It is an estimator operating within a pattern of adjacent values by designing appropriate weighting criteria. The pattern may be linear combinations, circular, rectangular, or square window.

9.2.20.1 Moving Weighted Average of Block Mean

A sizable block of ore is removed during a mining operation. The minimum size depends on the orebody configuration and extraction method. It varies from deposit to deposit and mine to mine. Large blocks are less subjective to extreme grade fluctuation due to the volume/variance relations.

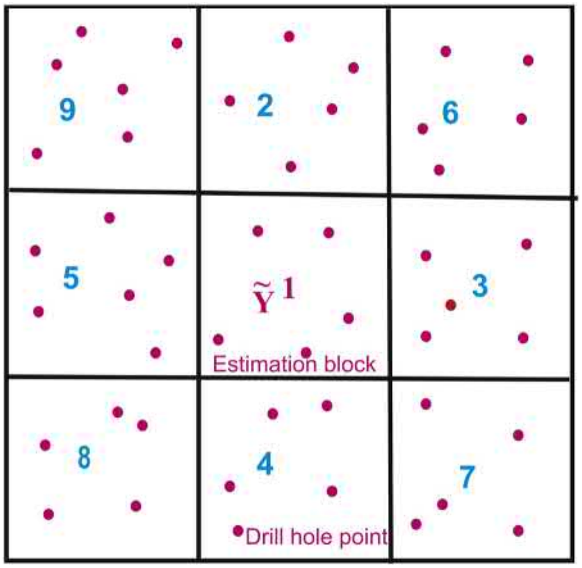

FIGURE 9.13 Diagram showing concept of "block" estimation by the moving average method.

The weight factor (W) of a block is to be determined to establish a moving average based on block mean value $(\overline{Y})$. A block moving average design is shown in Fig. 9.13. $\tilde{\mathbf{Y}}$ is the estimated grade of block 1 from the averages of the exploration sample in blocks 1–9. $\tilde{\mathbf{Y}}$ is the estimated grade of ore to be produced from the center block and $\overline{Y}_1$ is the mean assay value of the drill core in the same block. The sample design will move to a new region once the equation is obtained:

$$\tilde{\mathbf{Y}}_{\mathrm{ij}} = \sum_{k=1}^{n} \mathrm{W_k Y_k}$$

$$\mathrm{Y} = \mathrm{b_o} + \sum_{i=1}^{n} \mathrm{b_i}\overline{Y}_{\mathrm{i}}$$

Y = Actual from past record

$\overline{Y}$ = Mean of exploration data

b = Coefficients

The estimated $\tilde{\mathbf{Y}}$ is based on the weighted sum of adjacent observation Y:

$$\tilde{\mathbf{Y}}_{\mathrm{ij}} = \sum_{k=1}^{n} \mathrm{W_k Y_k}$$

$\tilde{\mathbf{Y}}$ = estimated value

W = weight

Y = adjacent block value

The sum of total weight must be equal to 1:

$$\sum_{k=1}^{n} \mathrm{W_k} = 1$$

9.2.20.2 Moving Arithmetic Average

The arithmetic average of adjacent samples on either side controlled by a window can give an estimation of near-homogeneous ore distribution as in the case of underground working or grid samples (Fig. 9.14A and B).

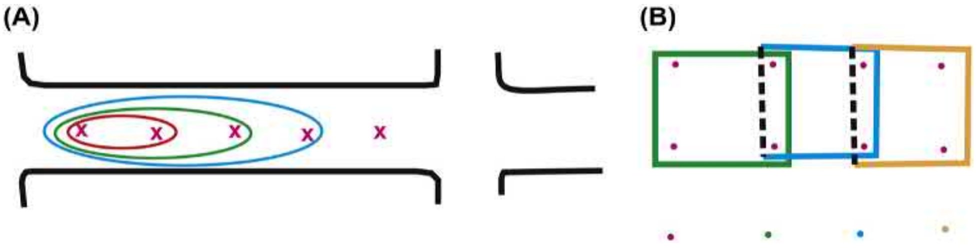

FIGURE 9.14 Concept of moving arithmetic average grade computation of (A) underground workings and (B) geochemical grid samples on the surface.

9.2.20.3 Other Mathematical Techniques

The occurrence of erratic high values in the spatial distribution, as in the case of gold, silver, platinum, and similar precious metals, can be smoothed by log transformation (Fig. 9.15A and B).

9.3 MISCLASSIFIED TONNAGE

Krige (1951) observed that blocks of ore estimated as high grade using long-standing traditional methods repetitively indicate lower true grade after mill feed-grade reconciliation. Similarly, estimated low-grade blocks signify a constant higher true grade. The true versus estimated grades of all blocks is plotted in Fig. 9.16. An elliptical envelope is observed with a major axis (least square fit) not parallel to the 45 degree line from the origin.

All the estimated versus actual points would fall on or close to the 45 degree line if the blocks had been estimated correctly. The estimation technique is expected to provide close proximity between estimated and actual production sample grade. In reality, a number of blocks would have a similar estimated grade with wide variation from true grade. This indicates that any estimated value has a bias (error) when compared with the true block values except where the line of best fit intersects the 45 degree line. The average of all the blocks' estimates would not necessarily be much different than the true average grade. If we apply a desired cutoff grade, four regions, namely, I, II, III and IV, will be formed on the estimated true grade distribution:

1. Region I is comprised of all those blocks that have both an estimated and true grade above the cutoff grade, which would be and should be mined.
2. Region II includes all those blocks that have an estimated and true grade below the cutoff grade, which would not and should not be mined.
3. Region III includes blocks estimated to be above the cutoff grade but have a true grade below the cutoff grade. These blocks would be mined when they should not and would thus reduce the mine head grade.

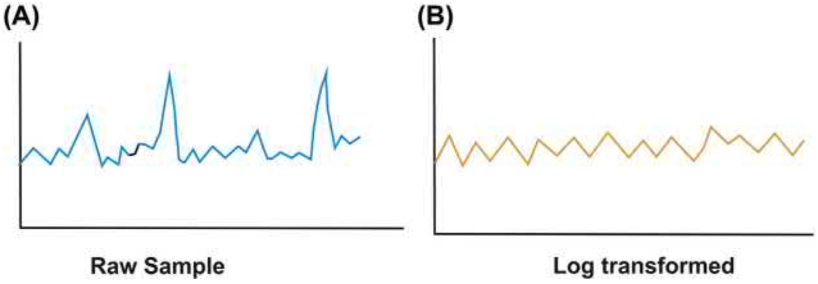

FIGURE 9.15 Transformation of (A) fluctuating raw samples to (B) smooth values.

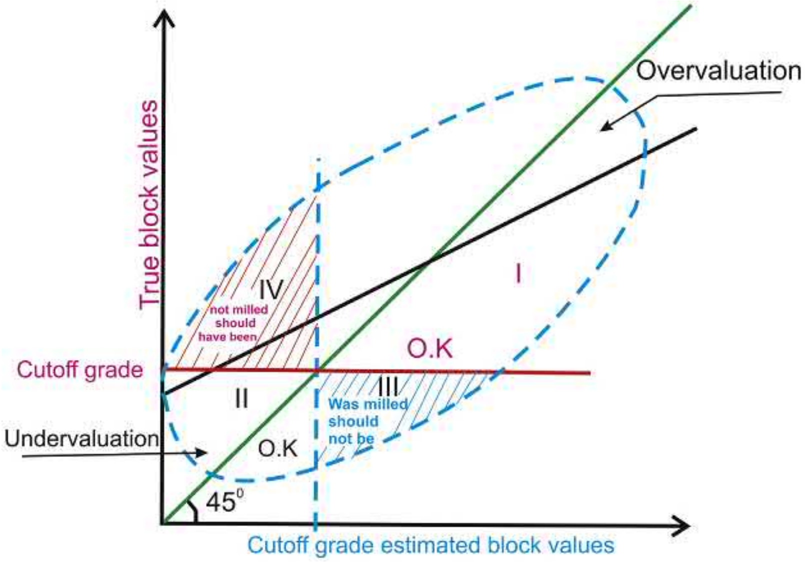

FIGURE 9.16 Misclassified tonnages as conceived by Krige (1951) portray that the "estimated" and "true production" grades vary considerably due to inadequate sampling, estimation flaw, and complexity of mineralization.

4. Region IV is comprised of blocks estimated to be below the cutoff grade, but have a true grade above the cutoff grade. These blocks would not be mined when they should have been and thus will reduce the mine head grade.

The misclassified-tonnage curve represents an envelope of dispersion or variance of block grades. The difference between the expected or planned mine-head grade and true grade can be identified after the application of cutoff grade criteria. It is therefore necessary to employ that technique, which decreases the variance in block estimates, i.e., decreases the spread of block estimates so that the regression line moves to 45 degrees. In addition, it is necessary to employ an estimating technique that will reduce variance of the error of estimation or estimation variance so that the envelope narrows and ideally becomes the 45 degree line.

9.4 GEOSTATISTICAL APPLICATIONS

These problems of grade/tonnage mismatch and wider grade variances of estimated blocks have been resolved by developing regionalized stationarity and variability of metal distribution within the deposit (Matheron, 1971, Hans, 2013).

9.4.1 Block Variance

Let us assume that we have a large number of evenly spaced sample points distributed within the orebody. The body is divided into a number of blocks of equal size. An average grade can be computed for each block by taking the arithmetic or weighted average of all the sample points falling in that block. The simplest case would be an equal number of blocks with one sample in each block. The other extreme case would be only one block representing the whole deposit that contains all sample points. If the variances of the block grades are plotted against size of the block, the block variance relationship is obtained (Fig. 9.17).

Obviously, the variance of block grades decreases with increase in block size. As each block value is an average of all sample points in the block and the mean of the ore deposit is the mean of all block values, the mean of the deposit remains constant. The variance of the errors between the true grade of a block and that estimated from a center sample point generally decreases with increase in block size.

The estimation of block size will depend on mine planning and it is necessary to select an estimation technique that will take into account all surrounding samples to reduce the variance of the estimation error. An orebody model has to be developed based on geological and statistical information. Some geological concepts that need to be considered are:

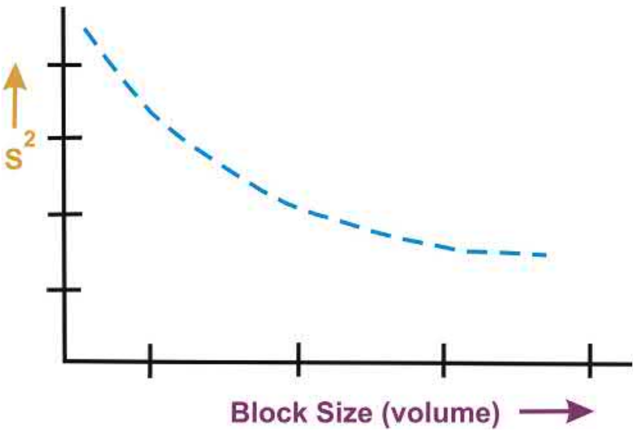

FIGURE 9.17 Concept of mutual relationship between sample volume size and variances.

1. The better the orebody continuity, the smaller the error associated with extrapolating a given grade over a larger area.
2. Influence of a sample over an area may be related to a geological zone of influence that may vary in different directions (anisotropy).
3. Some ore deposits, such as gold, silver, and platinum, may exhibit a nugget effect (large variation in grade over a small distance) and therefore larger samples may be required since a sample is a volume (support) and not a point.
4. Demarcate geologically distinct areas within a deposit so that different estimation procedures may be required (nonstationarity).

9.4.2 Semivariogram

The most natural way to compare two values is to consider their differences. Let us assume that two samples Z(x) and Z(x + h) are located at two points, x and x + h, with two different % metal grades. The second sample is h meters away from the first. This value expressing the dissimilarity of grade between two particular points is insignificant. The average difference for all possible pairs of samples at h meters apart throughout the deposit will be geologically significant. The difference between any pair of samples will be either positive or negative, and the sum of all pairs will be misleading. It is therefore logical to square the differences, sum them, and divide by the number of pairs to understand the average variance of paired samples at certain distances apart. This dissimilarity function is expressed by the model equation:

$$2\gamma\rightarrow(h) = \text{Average } \Sigma\{Z(x) - Z(x+h)\}^2$$

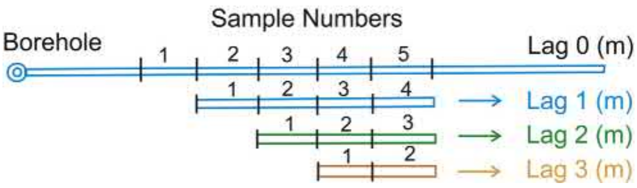

FIGURE 9.18 Concept of semivariogram by sliding sample data string at certain space intervals.

where $2\gamma\rightarrow(\mathrm{h})$ is the **semivariogram** or simply **variogram** function. It is the function of a vector; in other words, a distance and the orientation of that distance. It articulates how the grades differ on average according to the distance in that direction (Fig. 9.18).

The semivariogram is thus stated as:

$$\gamma(\mathbf{h}) = \mathbf{1/2N}\sum_{i-1}^{N}\{Z(x)-Z(x+h)\}^{2'}$$

where $\gamma(\mathbf{h})$ = semivariogram function value, N = number of sample pairs, Z(x) = value at point (x), may be grade, width, accumulation, etc., and Z (x + h) = value at point (x + h), i.e., h distance away from point (x).

The simplest semivariogram computation can be by sliding mineralization in one direction along a borehole (Fig. 9.18). Let there be a set of five samples of 1 m length each along a borehole as 2%, 6%, 3%, 9%, and 12% Zn. The sample string slides by one step (1 lag), i.e., at 1, 2, 3 m lag, to compute the average variance and continue.

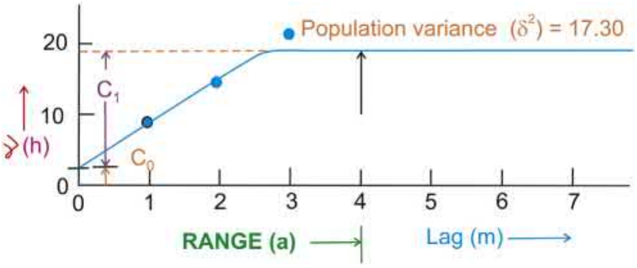

FIGURE 9.19 Drawing of standard semivariogram along the drill hole samples.

This can be represented in a semivariogram plot of lag against γ(h) function along the x- and y-axes, respectively (Fig. 9.19). The freehand or fitted curve is extended downward to intersect the variance axis. If it touches above the origin, this part is known as the **nugget effect (C_0)**. The curve then rises up to the maximum variance (population variance δ^2) at a particular lag equivalent distance and levels out or flattens. This distance is known as **range (a)**. Each sample value has an influence up to about 2/3 of the range. The extension variance C_1 is the difference between population variance and nugget effect.

In the case of 2D grid sample data the variogram is computed in different directions. Sample points on either side of the variogram line, within acceptable limits, are projected on it. The variance between points is computed and grouped under a similar lag range. This process is repeated on all samples and arranged in serial order as per lag. The number of participating pairs contributing to the

Sample	Lag	Difference	Difference^2	
2	**1 m**			
6	2	4	16	Σ difference = 70^2
3	6	−3	9	No. of pairs = 4
9	3	6	36	Average variance = 70/(2 × 4)
12	9	3	9	Semivariance = 8.75
2	**2 m**			
6				
3	2	1	1	Σ difference^2 = 91
9	6	3	9	No. of pairs = 3
12	3	9	81	Average variance = 15.16
2	**3 m**			
6				Σ difference^2 = 85
3				No. of pairs = 2
9	2	7	49	Average variance = 21.25
12	6	6	36	

sum of differences square is known, and a variogram is computed. Similarly, variograms in other directions within the study area are computed and compared.

In practice, a theoretical semivariogram is never realized. The gamma function $\gamma(h)$ is estimated from limited points and is called the experimental variogram (Fig. 9.20).

Fig. 9.20 displays a number of sample points at equal distances apart with their sample values, say thickness next to each point. We wish to compute $\gamma(1)$, i.e., the semivariogram value of all samples points at 1 unit distance (lag) apart, irrespective of direction. There are 17 sample pairs at 1 unit apart:

$$\begin{aligned}\gamma(1) = {} & 1/2N(1-2)^2 + (2-2)^2 + (2-3)^2 + (2-1)^2 + \\ & (1-4)^2 + (4-3)^2 + (2-1)^2 + (1-1)^2 + \\ & (1-2)^2 + (1-2)^2 + (2-2)^2 + (2-1)^2 + \\ & (1-1)^2 + (2-4)^2 + (4-1)^2 + \\ & (3-3)^2 + (3-2)^2 \\ = {} & 31/34 = 0.91\end{aligned}$$

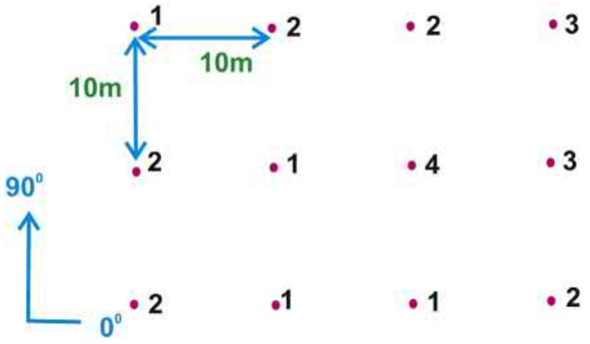

FIGURE 9.20 Computation of experimental semivariogram of grid sample data along various directions such as 0 and 90 degrees.

The next shortest sample distance is $\sqrt{2}$ unit distance apart with total sample pairs of 12:

$$\therefore \gamma\left(\sqrt{2}\right) = 26/24 \text{ or } \gamma\left(\sqrt{1.4}\right) = 1.08$$

The gamma functions for all the possible lags are computed and plotted as $\gamma(\mathbf{h})$ against lag. The semivariogram is shown in Fig. 9.21.

9.4.2.1 *Properties of a Semivariogram*

9.4.2.1.1 Continuity

Continuity is reflected by the growth rate of $\gamma(h)$ for a small value of h. The growth curve exhibits the regionalized element of samples. The steady and smooth increase is indicative of the high degree of continuity of mineralization until it plateaus off at some distance. This is known as the structured variance or explained variance (C or C_1) read on a $\gamma(h)$ scale. A typical semivariogram of a coal deposit showing good continuity is given in Fig. 9.22.

9.4.2.1.2 Nugget Effect (C_0)

The semivariogram value at zero separation distance (lag = 0) is theoretically 0. However, a semivariogram often exhibits a nugget effect (>0) at an infinitely small distance apart. The complex mineral deposits, like base and noble metals, may occur as nuggets, blobs, and are often concentrated as alternate veinlets resulting rapid changes over short distances. The gamma functions are extrapolated back to intersect the y-axis (Fig. 9.23). The nugget effect (C_0) is the positive measure of $\gamma(\mathbf{0})$ representing random or unexplained elements of samples. Noble and precious metals like gold, silver, and platinum-group elements often exhibit very high nugget effects even up to total unexplained variance. This creates a lot of uncertainty in the continuity of mineralization and grade estimation leading to extensive sampling.

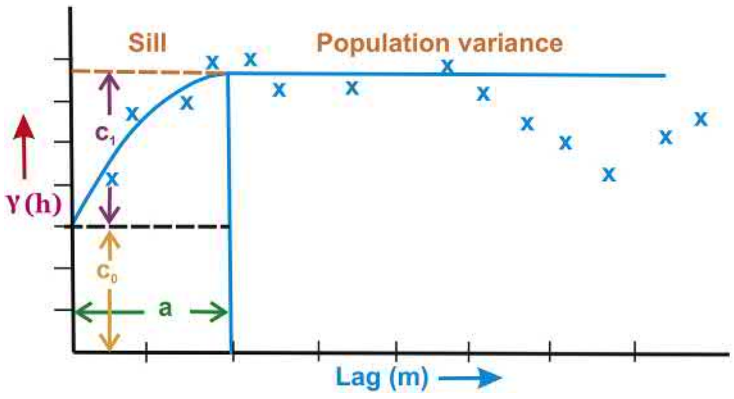

FIGURE 9.21 Typical semivariogram plot with curve fitting following the population variance after reaching the zone of influence.

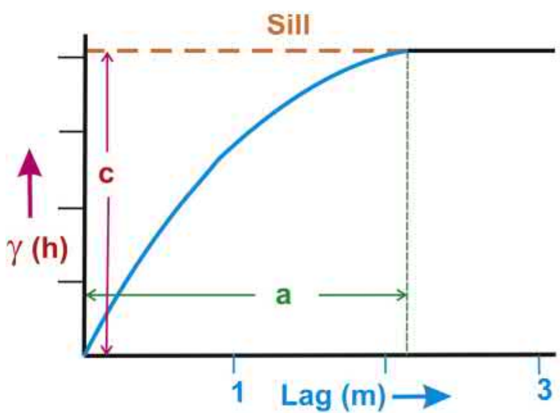

FIGURE 9.22 Typical spherical semivariogram from coal deposits without any nugget effect.

There are three possible reasons for the nugget effect of various magnitudes:

1. Sampling and assaying errors.
2. Smaller microstructures or nested variograms at shorter distances where no borehole data exist.
3. Combination of both.

9.4.2.2 Semivariogram Model

The computed experimental points of a semivariogram can be tailored to a standard type to fit a model. There are many semivariogram models that fulfill certain mathematical constraints (Rendu, 1981; Clark, 1982). The models can be broadly divided into two groups: (1) those with a sill and (2) those without sill. A sill implies that, once a certain distance h is reached, the values of $\gamma(h)$ do not increase, although they may oscillate around the population variance. Models without a sill have growing values of $\gamma(h)$ with increasing values of h.

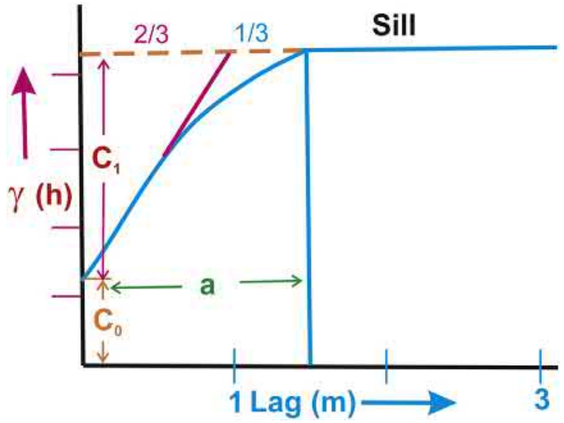

FIGURE 9.23 Typical semivariogram from massive base metal deposits with moderate unexplained variance (C_0).

9.4.2.2.1 Features of a Semivariogram

The sill $(C_1 + C_0)$.

The growing semivariogram curve normally reaches a plateau after a certain lag, and equals the population variance. This is known as the sill. In practice the gamma function may fluctuate on the sill line because of metal zoning, layering, and the hole effect:

$$\text{Sill}(C) = C_1 + C_0$$

9.4.2.2.2 The Zone of Influence (a)

The zone of influence is that neighborhood beyond which the influence of a sample disappears and samples become independent of each other. The zone of influence in a given direction is characterized by the distance at which the semivariogram eventually reaches a plateau and levels out. The first few points of $\gamma(\mathbf{h})$ are joined by freehand or polynomial regression, and extended to the sill. The intersection with the sill is ~2/3 of the zone of influence or range (a).

9.4.2.2.3 The Isotropic Anisotropies

The isotropic anisotropies are defined by computing semivariograms in different directions. The semivariogram that points in the east—west orientation of Fig. 9.20 will be:

$$\gamma(1) = 15/18$$

$$\gamma(2) = 12/12$$

$$\gamma(3) = 5/6$$

Semivariograms in the north—south or any other direction can be computed and compared. The semivariogram is **isotropic** if the underlying structure exhibits the same features irrespective of the directions. The semivariograms is **anisotropic** if the structure displays different features in various directions. An average semivariogram can be considered in such a condition.

The types of semivariogram with and without sills are given in Figs. 9.24 and 9.25 and as follows:

1. Spherical model

   $$\gamma(h) = C_0 + C_1\left(1.5h/a—0.5\left(h^3/a^3\right)\right),\ \text{for } h < a,\ \text{and}$$

   $$\gamma(h) = C_0 + C_1,\ \text{for}\ \ h \geq a$$

   where C_0 = nugget value, C_1 = explained variance, $C_0 + C_1$ = sill, h = distance between points, and a = zone of influence or range.
2. Random model

   $$\gamma(h) = C_0 + C_1, \quad \text{for all h}$$

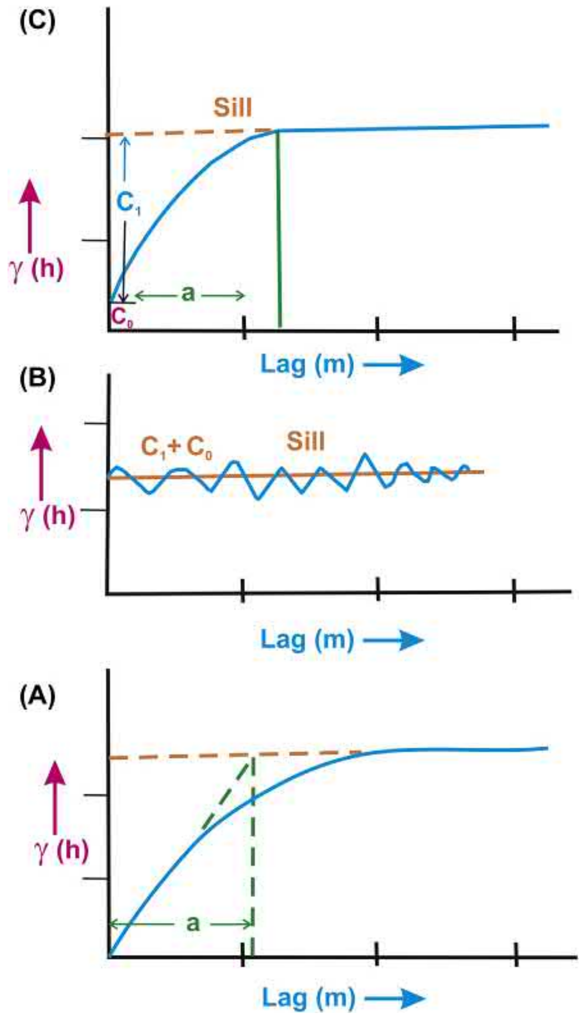

FIGURE 9.24 Semivariogram models with sill: (A) spherical, (B) random, and (C) exponential.

3. Exponential model

$$\gamma(h) = (C_0 + C_1)\left(1 - e^{-h/a}\right), \quad \text{for } h < a$$

The types of variogram without sills are (Fig. 9.25):

1. Linear model

$$\gamma(h) = \left(\alpha^2 h/2\right)$$

where α^2 is a constant.

2. Logarithmic model

$$\gamma(h) = 3\alpha \log^h$$

3. Parabolic model

$$\gamma(h) = 1/2\alpha^2 h^2$$

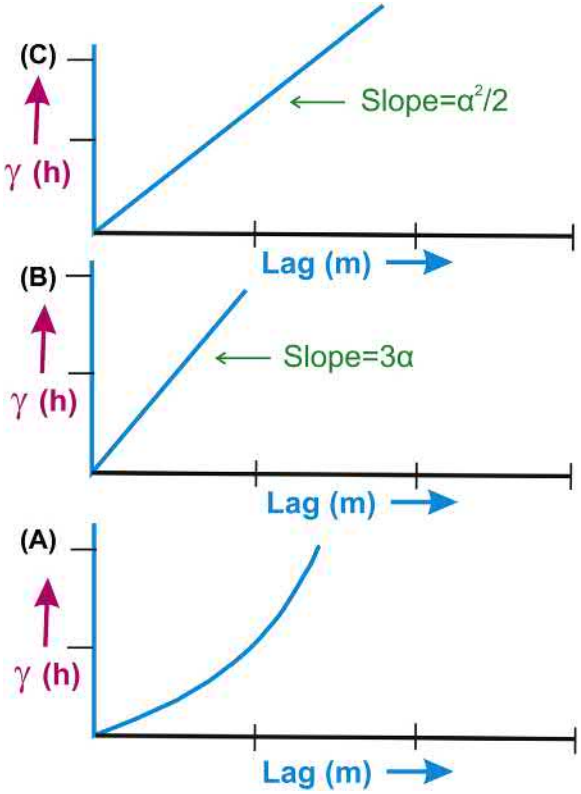

FIGURE 9.25 Semivariogram models without sill: (A) parabolic, (B) logarithmic, and (C) linear.

The following points are to be observed when constructing an experimental semivariogram:

1. Most semivariograms (>95%) in mineral applications are spherical models. The sill is considered equal to δ^2 to fit the variogram. A straight line through the initial few points should intersect the line of the sill at ~2/3 of the slope.
2. A minimum of 50 pairs of samples is used for the computation of experimental points. Approximately 100 sample values are required to achieve this, although satisfactory models can be fitted with fewer data.
3. As distance h increases, the number of sample pairs decreases, indicating less reliability of γ(h) for larger distances. The initial 5–10 experimental points are enough to fit a model.

9.4.2.3 Smoothing a Semivariogram

The sample data in Fig. 9.20 are equally spaced. However, the coordinates of borehole collars are irregular to some odd meters away from the gridlines, even in a regular drilling pattern. If a semi-variogram is to compute at a specific distance h, it may not find a sample pair at exactly h distance apart. The γ(h) computation for calculated values of h will be incomplete due to inadequate sample pairs. This will result in a random pattern of experimental semivariograms and no model can be fitted to a statistically valid experimental prototype.

The effect of data at irregular intervals can be preserved as a **noise**, and the data need to be smoothed to find the underlying semivariogram structures. Optimal smoothing can be done by (1) step interval and (2) angular tolerance.

9.4.2.3.1 Step Interval

The simple procedure is to select experimental points for a range of distances Δh. If the samples are irregularly spaced at an average distance of ~100 m, a step interval of 110 m can be opted to select all sample pairs from 0 to 100 m, 100 to 200 m, 200 to 300 m, etc. Semivariograms are computed at different step intervals of +5, 10, and 20 m with most variables occurring at short intervals. As the step value increases, the filtering effect reduces the noise, and a smoother and more statistically viable model is obtained. Oversmoothing will mislay the underlying structure, and a straight line of experimental points at population variance will appear incorrectly, suggesting a random model with no special correlation.

Referring to sample data from Fig. 9.20 the γ(h) in an east—west direction is:

$$\gamma(0-2) = 27/30$$

$$\gamma(2-4) = 5/6$$

The average of the distance is used for the single value of γ(h):

$$\gamma(1.4) = 27/30$$

$$\gamma(3) = 5/6$$

9.4.2.3.2 Angular Regularization

Angular regularization is based on the fact that irregular samples may not fall along specific directions when anisotropic behavior is apprehended. No pair of samples may lie along the east—west axis (0—180 degrees). This method of smoothing is not to calculate the semivariogram for a single discrete direction, but for a direction and range Δα to either side of it (Fig. 9.26). Therefore with a direction of 0 degrees, angular regularization of ±45 degrees, and a step interval of 1 unit distance in Fig. 9.20, the values of γ(h) are for the exclusive/inclusive range:

$$\begin{aligned}
\gamma(0-1) &= \gamma(1) &&= 15/18\\
\gamma(1-2) &= \gamma(1.7) &&= 28/36\\
\gamma(2-3) &= \gamma(2.3) &&= 33/30\\
\gamma(3-4) &= \gamma(3.3) &&= 6/12
\end{aligned}$$

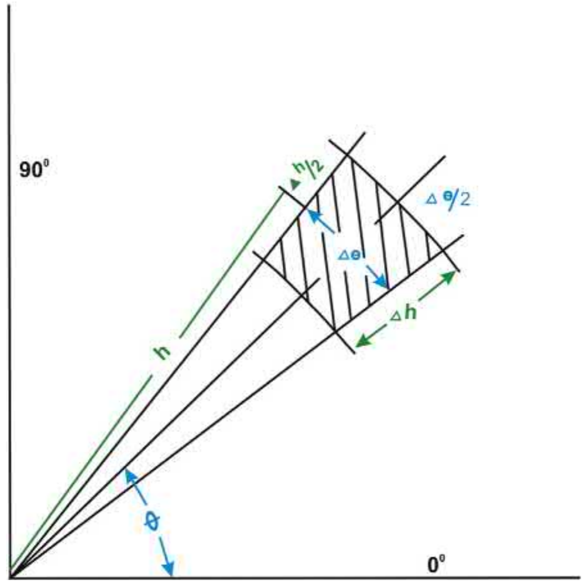

FIGURE 9.26 Angular regularization-sample falling in sketch area are accepted by tolerance in distance (David, 1988).

The greater the distance for each step and the wider the angle around a specific direction, the greater is the smoothing. Insufficient smoothing could be difficult to fit a model. Oversmoothing will destroy the actual character.

9.4.3 Estimation Variance

Estimation variance is the variance of error made in estimating the grade of a panel or block of ore by assigning the sample values lying in and around it within the zone of influence. It is apparent from the semivariogram that the relative location of samples to block will have an influence upon the weighting coefficients that can be assigned to each sample value.

$Z(V_i)$ are true unknown grades of blocks V_i, and $Z^*(V_i)$ are the linear combinations, where $Z^*(V_i) = \sum_{j=1}^{n} a_j Z(X_j)$ of the sample grades at locations X_j ($j = 1 \ldots n$). Then $Z^*(V_i) - Z(V_i)$ will be the error made in assuming that the value Z_i^* extends over V when the true value is V_i, and $VAR(Z_i - Z_i^*)$ is the variance of this error.

$$VAR(\text{Error}) = VAR\left(Z_i - Z_i^*\right)$$

If a block value is estimated by a sample or a number of samples each given an equal weight, then the variance of the error δ_e^2 associated with the estimated mean is:

$$\delta_e^2(W_s \text{ to } W) = +2\bar{y}(W_2;\ W) - \bar{y}(W_s;\ W_s) - (W;\ W)$$

where W_s = sample support and W = block.

Or, in the presence of the nugget effect, C_0/n is to be added, where n = number of samples.

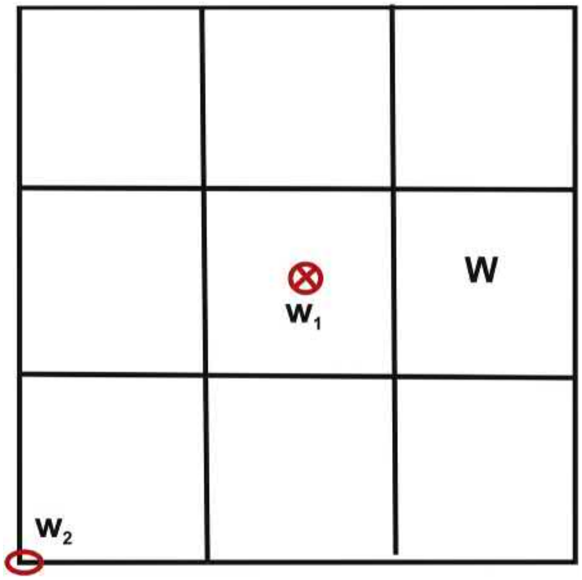

FIGURE 9.27 Block (W) estimation representing nine subblocks with one sample in the center (w_1) and one sample at the corner (w_2).

In the general case where the weights are different for each sample that is used to estimate the block value, the weights still add up to 1.0 so that the estimation is not biased, and the formula for the estimation variance is:

$$\delta_e^2 = 2\sum_{i=1}^{n} b_i\bar{y}(w_i;\ W) - \sum_{i=1}^{n}\sum_{j=1}^{n} b_i b_j \bar{y}\left(w_i;\ w_j\right) - \bar{y}(W;\ W)$$

where b_i or b_j = the weights for each sample and n = 1, I, or j.

Therefore

Block value = $\sum_{i=1}^{n} b_i Z(\mathbf{w_i})$

where $Z(w_i)$ = sample value and $\sum_{i=1}^{n} b_i = 1$.

It is possible to vary the two weights applied to $\mathbf{w_1}$ and $\mathbf{w_2}$ in an infinite number of combinations (Fig. 9.27). A new δ_e^2 can be estimated for each combination, but only one combination will minimize δ_e^2. **Kriging** is the method of determining b_1 and b_2 to minimize δ_e^2. The optimal weights are derived from Krige's equation dependent on a semi-variogram or spatial correlation of distance function and direction.

9.4.4 Kriging

Prof. D.G. Krige initiated and developed the application of geostatistics in the valuation and optimization of ore in South African gold mines in the early 1970s (Krige, 1951, 1962, 1978; David, 1977, 1988; Journel and Huijbregts, 1978; Sinclair and Blackwell, 2002). Prof. Matheron called the estimator kriging. The principles of the estimation procedure are:

1. It should be a linear function of the sample value x_i (Armstrong, 1998). The block value of:

$$W = \sum_{i=1}^{n} b_1x_1 + b_2x_2 + \cdots b_nx_n$$

   where b_i is the weight given to sample w_i.
2. It should be unbiased. The expected value (μk) should be equal to the true block value (μW):

$$E\{(\mu k - \mu W)\} = 0$$

3. The mean squared error of estimation of μW should be a minimum:

$$E\left\{(\mu k - \mu W)^2\right\} = \text{a minimum}$$

The kriging estimator (μk) satisfies these conditions of linear function, unbiased estimation, and minimum variance. The corresponding error of estimation from sample (w_s) to block (W) is the kriging error $\left(\delta_e^2\right)$. The kriging estimator is also known as BLUE.

A block W of 3 × 3 is estimated using two samples: w_1 in the center and w_2 in the corner (Fig. 9.27). A set of simultaneous equations is used to resolve for the optimum set of weights assuming the population mean is unknown:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} b_i b_j \bar{y}\left(w_i;\ w_j\right) + \lambda = \sum_{i=1}^{n} b_i \bar{y}(w_i;\ W)$$

where λ = the lag range multiplier.

The error of variance δ_e^2 can be estimated from the kriged weights by:

$$\sum_{e}^{2}\sum_{k}^{2} = -\bar{y}(w;\ W) + \sum_{i=1}^{n} b_i\bar{y}(w_i;\ W) + \lambda$$

For example, and ignoring λ for the moment:

$$b_1\bar{y}_{11} + b_2\bar{y}_{12} = \bar{y}_1W$$
$$b_1\bar{y}_{21} + b_2\bar{y}_{22} = \bar{y}_2W$$

The simultaneous equations when written in matrix form are:

$$\begin{bmatrix} \bar{y}(w_1w_1) & \bar{y}(w_1w_2) \\ \bar{y}(w_2w_1) & \bar{y}(w_2w_2) \end{bmatrix} \times \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} \bar{y}(w_1;W) \\ \bar{y}(w_2;W) \end{bmatrix}$$

or:

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \times \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 0.536 \\ 0.882 \end{bmatrix}$$

Therefore $b_2 = 0.536$ and $b_1 = 0.882$.

However, $b_1 + b_2$ must be equal to 1, but in this case $(0.536 + 0.882) = 1.1418$. Therefore the lag range multiplier is to be introduced to ensure $b_1 + b_2 = 1$. The new matrix is:

$$\begin{bmatrix} \bar{y}(w_1 w_1) & \bar{y}(w_1 w_2) & 1 \\ \bar{y}(w_2 w_1) & \bar{y}(w_2 w_2) & 11 \\ 1 & 1 & 0 \end{bmatrix} \times \begin{bmatrix} b_1 \\ b_2 \\ \lambda \end{bmatrix} = \begin{bmatrix} \bar{y}(w_1; W) \\ \bar{y}(w_2; W) \\ 1 \end{bmatrix}$$

or:

$$\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \times \begin{bmatrix} b_1 \\ b_2 \\ \lambda \end{bmatrix} = \begin{bmatrix} 0.536 \\ 0.882 \\ 1 \end{bmatrix}$$

$$\therefore b_2 + \lambda = 0.536$$

$$b_1 + \lambda = 0.882$$

$$b_1 + b_2 = 1$$

Solving b_1, b_2, and λ:

$$b_1 = 0.673$$

$$b_2 = 0.327$$

$$\lambda = 0.209$$

$$b_1 + b_2 = 1 \text{ as required}$$

The mean estimate for the block is:

$$0.673Z(w_1) + 0.327Z(w_2)$$

And the error of estimation is:

$$\begin{aligned} \delta_e^2 &= -0.683 + 0.673 \times 0.536 + 0.327 \times 0.882 + 0.209 \\ &= 0.175 \end{aligned}$$

where $\delta_e = 0.418\%$, the confidence limit, which is independent of grade.

In summary, we observe that if we estimated the block value by different sample configurations the following errors were made:

In the block estimated from the corner sample, $\delta_e^2 = 1.081$.

In the block estimated from the center sample, $\delta_e^2 = 0.389$.

In the block estimated from the corner and center samples with equal weights, $\delta_e^2 = 0.235$.

In the block estimated from the corner and center samples using kriged weights, $\delta_e^2 = 0.175$.

The kriging method is best with minimum error variance, unbiased as weights sum to 1.0 denoting expected block value equal to true block value, and a linear estimator in its application.

9.4.5 Kriging Estimation: An Example

Point and block kriging estimates the value at a point or block, exclusively supported by a semivariogram. The accuracy of kriging estimation, to a large extent, is proportional to the precision factor of the variogram. Point kriging has been suggested as a test for a semivariogram model. Each sample point is kriged by a selected semivariogram model without actual sample values being used in the matrix. The kriged point values are compared with actual sample values and the model is adjusted until the errors are minimized. This is known as the **jackknife test**.

The stepwise kriging computation for part of an orebody (sublevel stope) is demonstrated by seven sample points. The sample details, semivariogram for kriging at a central point "Q" of block ABCD (25 m × 25 m), are given in Table 9.11, Figs. 9.28 and 9.29.

The semivariogram of the total population provides $C_0 = 0.8$, $C_1 = 2.5$, and $a = 50$ m. Five samples, namely,

TABLE 9.11 Sample Coordinates and Grade From a Sublevel Stope

	Coordinate (m)		
Sample No.	Easting	Level	% Zn
1	314	83	2.40
2	314	93	2.76
3	314	107	4.84
4	288	74	5.98
5	288	90	6.38
6	288	105	7.04
7	298	76	3.63

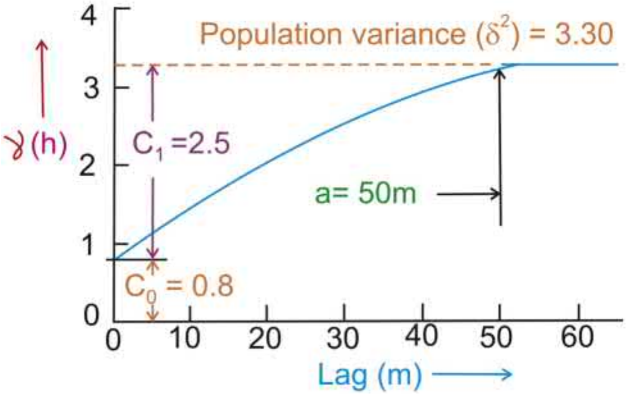

FIGURE 9.28 Semivariogram parameters of samples from Table 9.9.

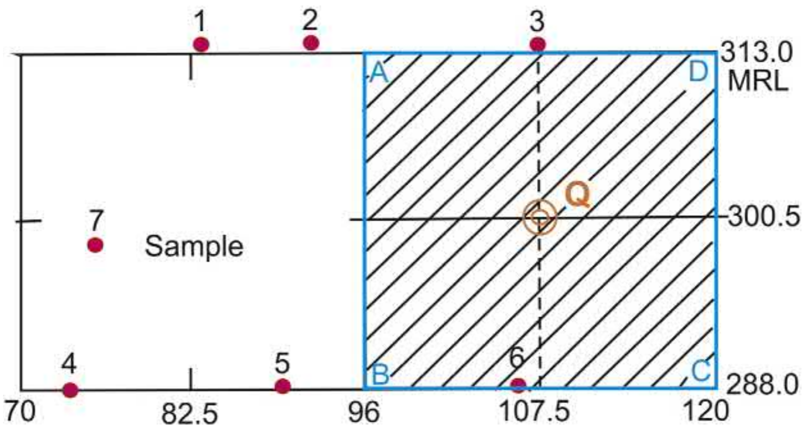

FIGURE 9.29 Conceptual block kriging from surrounding samples.

1, 2, 3, 5, and 6, are selected that fall within the radius of influence of 30 m from computation point Q. The distances d_1 (1 to Q), d_2 (2 to Q), d_3 (3 to Q), d_5 (5 to Q), and d_6 (6 to Q) are necessary for interpolation. The kriging technique computes distances and semivariances between 1 and 1, 1 and 2, 1 and 3, 1 and 5, 1 and 6, 2 and 1, 2 and 2, 2 and 3, 2 and 5, 2 and 6, 3 and 1, 3 and 2, 3 and 3, 3 and 5, 3 and 6, 5 and 1, 5 and 2, 5 and 3, 5 and 5, 5 and 6, 6 and 1, 6 and 2, 6 and 3, 6 and 5, and 6 and 6, i.e., with five samples an additional 5 × 5 intersample distances are computed. Intersample variances eliminate the shadowing effect present in sample distribution within the zone of influence.

The equations are formulated in matrix form to compute a semivariogram for expressing the relation between distances and variances:

$$\begin{bmatrix} V_{11} & V_{12} & V_{13} & V_{15} & V_{16} \\ V_{21} & V_{22} & V_{23} & V_{25} & V_{26} \\ V_{31} & V_{32} & V_{33} & V_{35} & V_{36} \\ V_{51} & V_{52} & V_{53} & V_{55} & V_{56} \\ V_{61} & V_{62} & V_{63} & V_{65} & V_{66} \\ a_1 & a_2 & a_3 & a_4 & a_5 \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ \lambda \end{bmatrix} = \begin{bmatrix} V_1Q \\ V_2Q \\ V_3Q \\ V_5Q \\ V_6Q \\ 1 \end{bmatrix}$$

where $a_1 + a_2 + a_3 + a_4 + a_5 = 1$ (weights for coefficients) and $V_{11} \ldots V_{nn}$ represent the variances instead of the distances, which were measured earlier. In the present data set the following equation is obtained:

$$a_1 0.0 + a_2 1.8 + a_3 2.5 + a_4 2.7 + a_5 1.9 = 2.2$$

$$a_1 1.8 + a_2 0.0 + a_3 2.8 + a_4 2.5 + a_5 2.1 = 1.9$$

$$a_1 2.5 + a_2 2.8 + a_3 0.0 + a_4 1.9 + a_5 1.6 = 2.3$$

$$a_1 2.7 + a_2 2.5 + a_3 1.9 + a_4 0.0 + a_5 1.8 = 1.8$$

$$a_1 1.9 + a_2 2.1 + a_3 1.6 + a_4 1.8 + a_5 0.0 = 1.8$$

$$a_1 + a_2 + a_3 + a_4 + a_5 = 1.0$$

This relates interassay variance to variance contribution to point Q. The solution to the foregoing equations will provide five weighting coefficients for five sample assays, and another coefficient λ for the kriging estimator. The coefficients are computed as:

$$a_1 = 0.10,\ a_2 = 0.31,\ a_3 = 0.07,\ a_4 = 0.31,\ a_5 = 0.21 \text{ and } \lambda = 0.27$$

Therefore the estimated value at Q will be:

$$\begin{aligned} & a_1 \times 2.4 + a_2 \times 2.76 + a_3 \times 4.84 + a_4 \times 6.38 + a_5 \times 7.04 \\ &= 0.1 \times 2.4 + 0.31 \times 2.76 + 0.07 \times 4.84 + 0.31 \times 6.38 + 0.21 \times 7.04 \\ &= 4.82\ \%\ \text{Zn} \end{aligned}$$

The estimated value of 4.82% Zn has an associated variance. The process of computation provides extension variance of 2.2 from Q to 1 (block–point covariance), while we utilized only 0.10 (a_1) of this variance to get an estimate of Q. Similarly, 0.31 has been used for the second sample out of 1.9 and so on. Summation of the variances utilized for estimation at Q will be:

$$a_1 \times 2.2 + a_2 \times 1.9 + a_3 \times 2.3 + a_4 \times 1.8 + a_5 \times 1.8 = 1.94$$

The total covariance utilized for the estimation, i.e., block–point covariance (1.94) and point–point kriging covariance λ (0.27), is 2.21. The semivariogram of the orebody can explain 1.72 in terms of variance for a block size of 25 m × 25 m (an average distance of 12.5 m from any point to another point within the block). The residual variance of the estimate is $2.21 - 1.72 = 0.49$, which is not explained by the estimate at Q and will be equivalent to 0.7 in terms of standard deviation. The mean grade (4.82% Zn) has a possible variability of 0.7 over the mean. The confidence interval at 95% probability will be $(0.7/\sqrt{5}) \times 1.96$ or $\pm$ 0.61. The error of the mean is 4.82% Zn $\pm$0.61. Keeping other conditions constant, if we change the block size to 15 m × 15 m the explained variance equivalent to 7.5 m is 1.5 and the error of the mean by computation will be $\pm$0.74. It can be concluded that as the block size decreases, the confidence limit value (range) will increase.

Kriging methodology relies largely on the precision of the variogram, which in reality is not smooth and indicative of disturbances inherent within the samples. Since the semivariogram used is a generalized average, the estimate may differ from the true value. Local trends existing in the data set should be removed before kriging.

9.4.6 Benefits of Statistics and Geostatistics

1. Statistical techniques (mean, variance, standard deviation, confidence limit, correlation coefficient, and various tests) will provide sequential analysis of an exploration sample database with broad parameters at any stage of exploration. It will focus on the adequacy of the exploration input and the power of decision-making toward investing in mining, continuing exploration, or keeping the project in abeyance and waiting for the next opportune time.
2. The semivariogram parameters ($\gamma(h)$) in geostatistics quantify the range of influence of the samples in all directions, indicating the isotropic/anisotropic nature of the deposit and selection of sample for estimation.
3. The semivariogram also extracts the explained (C_1) and unexplained nugget (C_0) variances of the orebody that control the estimation of block grades.
4. Point, area, and block estimation by kriging techniques represent BLUE, which minimizes error variance.
5. Statistical and geostatistical applications compute associated estimation errors that are risk factors for investment decision.
6. The advance estimation methods estimate reserves and resources (tonnage), and average grade of individual blocks for planning of selective mining and grade control.
7. The techniques can optimize sampling design and density (refer to Chapter 15, Section 15.10).
8. The techniques are capable of analyzing the estimated and actual performances.
9. Finally, a good knowledge of statistics, geostatistics, and the application of geology and mining software will not be enough to estimate the reserves and resources of a deposit with full confidence. An inherent and in-depth understanding of mineralization by extensive fieldwork, an unbiased and unique sample database, and visualization of physical and chemical variations of grade in various directions have to be blended with the mathematical formula supported by statistical and geostatistical tests and case studies (Haldar et al., 1990).

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Chapter 10

Exploration Modeling

Chapter Outline

> *Boundless imagination may conceive an idea* → *An idea may give birth to a concept* → *A concept may perceive a model and* → *finally a geoscientist shall discover a mineral deposit.*
>
> Author.

10.1 DEFINITION

Modeling is an applied analytical technique of existing facts and figures in all branches of science, including mineral exploration. It uses physical, chemical, and/or mathematical representations of a system or theory that accounts for all or some of its parameters. Process building is the conceptualization of a logical illustration of all activities (the model) related to the phenomenon under investigation. Geological modeling or geomodeling is the creation of representations or the numerical equivalent of portions of Earth's crust made on and below its surface. Exploration modeling covers interrelationships ranging between geology, geochemistry, geophysics, sedimentology, stratigraphy, structure, host rock affinity, genesis, and exploration input in the context of water, petroleum, gas, coal, and mineral/ore deposits. The models are developed based on observations of the past, data input of the present, and interpretation to make an experimental and empirical prototype for future search. It visualizes the "unknown" to reach the expected goal. Thus the individualistic approach makes the model quite distinct and different for the same object (deposit). The poorly constructed model can be misleading, counterproductive, and at times end up in a confused state. A model can be modified and corrected with the incoming information. A model follows the same principle anywhere under similar geological conditions with allowance for local effects.

Mineral deposits are available in most local areas for reliable identification of important geoscientific variables or for robust estimation of undiscovered deposits with the help of mineral deposit models. Globally based deposit models allow recognition of important features and geologic environments hosting possible mineral deposit types and resources that might exist in a region. Mineral deposit models play the central role in transforming geoscientific information into a form useful to policymakers (Singer et al., 2008).

Comprehensive objectives and strategies are to be defined in clear terms so that the orientation can be streamlined accordingly. The purposes of exploration modeling are

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00010-1

target selection, future investment, resource augmentation, exploration optimization, economic evaluation, and midterm corrections under multidisciplinary activities. The objectives are defined and depend on technological support, financial capacity, and market strategy of the exploring/exploiting agencies. Geoscientists have to follow a dynamic routine, disciplined planning, integration, and interpretation of multidimensional functions, and make a determined effort to attain success in mineral discovery.

10.2 TYPES OF MODEL

The models themselves can be classified according to their essential attributes such as:

1. Descriptive model.
2. Conceptual model.
3. Genetic model.
4. Mineral deposit/belt model.
5. Predictive model.
6. Statistical and geostatistical model.
7. Orebody model.
8. Mineral inventory model.
9. Grade/tonnage model.
10. Empirical model.
11. Exploration model.

10.2.1 Descriptive Model

This is the first step in the modeling approach and includes the collection, study, analysis, and reinterpretation of existing information available as published literature, maps on various scales, and ground geochemical and airborne geophysical data. It includes a description of all measurable physical and chemical properties of occurrences and deposits. Geological parameters include depositional features, tectonic setting, and age of formation. The microlevel features of the deposit itself comprise location, discovery history, surface signatures, rock types, mineralogy, structure, deformation, metamorphic grade, ore control, geochemical and geophysical responses, weather profiles, presence of geochemical halos, evaporites, tonnage, and metal content. This information is accessible either free or at a cost depending on a country's mineral policy. This forms the base for applying for a reconnaissance permit.

10.2.2 Conceptual Model

The conceptual model represents interrelated ideas. A mental image of mineralized environments or processes describing general functional relationships, present or predicted, between major components in a system is conceptualized. These mental images can be, and are, often translated into simplified schematic written descriptions and abstract visual representations. The purpose is to formulate activity plans and flow diagrams. A working model would be under continuous development and modification. It is based on experience to visualize similar geological processes likely to exist elsewhere. It includes assumptions on stratigraphy, mineral properties, dimensionality, and governing processes.

10.2.3 Genetic Model

The genetic model is the perception of ore genetic processes based on direct and indirect evidence and knowledge of host environments. It includes overall insight into geological forces that influence the formation of ore deposits. These descriptive and interpretive features classify the process of formation as igneous, sedimentary, hydrothermal, sedimentary exhalative (SEDEX), volcanogenic massive sulfides (VMS) or volcanic-hosted massive sulfides (VHMS), and layered mafic/ultramafic intrusives. Most deposits are deformed, metamorphosed, and remobilized, and this may obscure the primary structure. Much corroborating evidence is collected for specific types of deposit before advocating a particular genetic process. The model plays an important role, e.g., a layered mafic/ultramafic intrusive is significantly indicative for hosting platinum-group elements closely associated with chromium-nickel-copper-gold-silver-cobalt mineralization, e.g., Bushveld, Sudbury, Stillwater, and Sukinda-Nausahi layered igneous complex. The distinguished type of deposits known for a genetic model include Broken Hill base metals, NSW, Australia (SEDEX), Kidd Creek copper-zinc, Timmins, Canada (VMS), and New Brunswick zinc-gold, Bathurst, Canada (VHMS).

10.2.4 Mineral Deposit/Belt Model

Mineral deposit models are "an organized arrangement of information describing the essential characteristics or properties of a class of mineral deposits" (Stoeser and Heran, 2000). The mineral deposit/belt model contains systematically arranged information describing some or all important characteristics, variations within a group, and type of known deposits. It uses results of previous investigations to foresee the geological nature of wider areas or belts. Belt is divided into a number of blocks (cells/subcells) of equal size. The block sizes are based on the dimension of the existing deposits and complexity of data being processed (Fig. 10.1). The **control** block must have at least one deposit in it.

The possibility of mineralization in the unknown cells can be predicted using the interrelationship of key geological attributes of the control cells. The mathematical techniques applicable are cluster, multiple regression, and characteristic analysis. The derived equation can be extended under similar geological environments (Fig. 10.2) for anticipating new exploration targets.

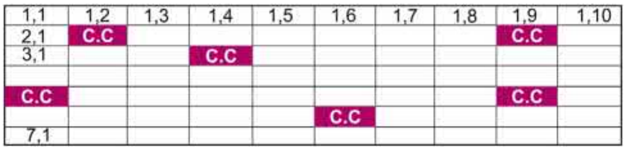

FIGURE 10.1 Creation of cells (4 × 4, 5 × 5, 10 × 10, km × km) for mineral deposit/belt model. C.C stands for "Control Cell" with geological characteristics including definite presence of mineralization (*red*).

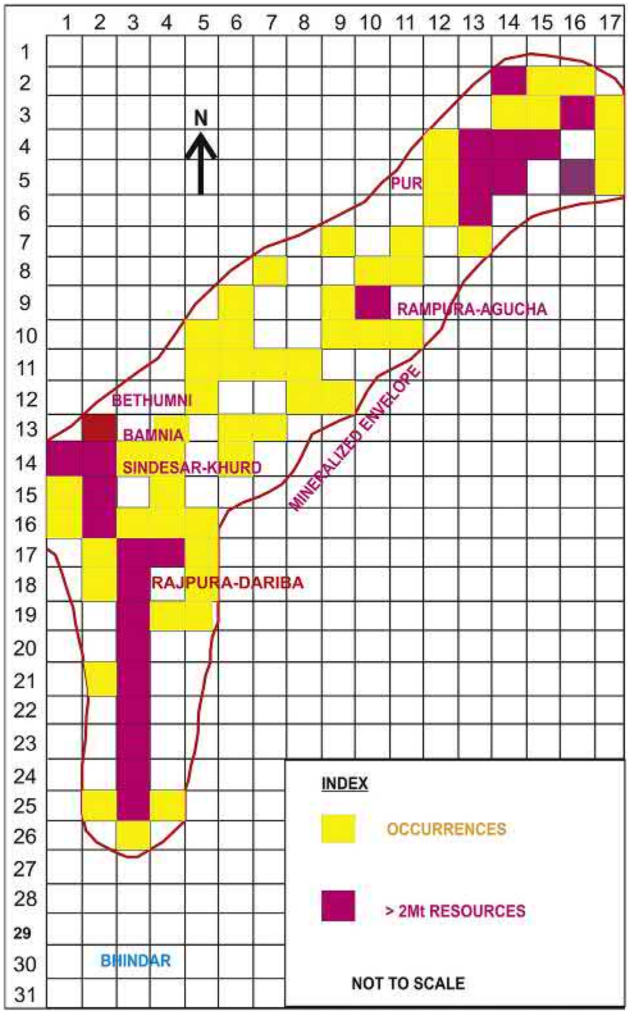

FIGURE 10.2 Expected exploration targets through deposit modeling showing established mineral resources (*red*), prospective target area (*yellow*), and barren subblocks (*blank*) at Rajpura-Dariba-Bhendar Belt, Rajasthan, India.

10.2.5 Predictive Model

The predictive model is a mathematical technique used to forecast the prognostic mineral deposits and probability of mineral occurrences, metal resources, and expected areas likely to host mineralization. The model thereby assigns priorities for initial reconnaissance activity and looks for prospective areas. The model has many phases: (1) area selection, (2) target generation, (3) resource evaluation, (4) reserve definition, and (5) economic viability. The predictive models of either geological, geochemical, or geophysical anomalies, or prospective areas are generally empirical models, which depict locations where mineral deposits of the type sought plausibly exist. Such pieces of spatial geoinformation are important for decision-making in mineral exploration programs (Carranza, 2009).

Future mineral resource prediction is made generally by collecting all existing information, analyses, and appraisals by probability mapping and applying a mathematical model. Expectation is based on extrapolation of estimated data or a "guesstimate" of geological analogy for which no precision can be assigned that often requires enormous data input and thorough knowledge of geological environments. There are many mathematical equations available, and the widely convincing one is the application of Zipf's law. This model has effectively been applied for exploration target appraisal for oil field resources of Western Canada, gold deposits of Western Cordilleras, copper deposits of Zambia, gold, uranium, copper-lead, and tin deposits of Australia (Rudenno, 1981), and zinc-lead, copper, and iron ore deposits in India. The degree of exploration maturity could have consistently been estimated with a high degree of accuracy such as 17% of predicted gold endowment discovered in 1973, 33% in 1989, 62.5% in 2003, and 75% in 2008. The application of Zipf's law would have represented an effective motivator to embark on a well-resourced gold exploration campaign in the Yilgarn craton, Western Australia (Guj et al., 2011).

Professor G.P. Zipf stated in his book *Human Behavior and the Principle of Least Efforts* that "the biggest is twice as big as number two, three times as big as number three, and so on" (Zipf, 1949). This concept applies where a free and natural competition mechanism exists, e.g., free migration of people between lesser and better developed cities. The size of populations between big cities shows similar distribution patterns when ranked. In the case of ore deposits though, such an assumption is difficult to make: perhaps the so-called free competition mechanism may be controlled by favorable geological conditions such as lithology and structures for migration of elements.

The law is the limiting case of the Pareto distribution in statics. The series is expressed as:

$$X, X/2, X/3 \ldots X/n$$

The law is expressed mathematically as $S_m/S_n = (n/m)^k$, where S_m is the size of the item of rank m, S_n is the size of the item of rank n, and k is a proper fraction. Zipf gave many distributions with $0.5 \le k \le 2.0$.

10.2.5.1 *Limiting Conditions*

The following limiting conditions are imperative with Zipf's equation:

1. The series under study usually belongs to a lognormal series (Rudenno, 1981).
2. The current geological condition is assumed to achieve a stable equilibrium at $K = 1$ (Zipf function).
3. The law applies where a free competition mechanism exists, e.g., free migration of people between lesser- and better-developed cities. In the case of ore deposits though, such an assumption is difficult to make; perhaps the so-called free competition mechanism may be controlled by favorable geological conditions, such as lithology, structure, etc., for migration of elements.
4. Even if genetically dissimilar types of deposits are grouped together, this law proved to be valid (Rudenno, 1981).
5. In the case of multimetal deposits the variables are many, such as multiple metals with grade variation and total resource of individual existing participating deposits under study. The deposits with high resource quantity (tonnage) having very low or very high quality (grades), and vice versa, cannot be compared for economic significance. Therefore the total metal content of deposits is considered as a single variable for application of the predictive model.
6. All existing deposits under study should be economically viable. A very large deposit with extremely low grade or a tiny mineral occurrence having extremely high grade will not be of any use. The acceptable existing deposits must pass through the economic cutoff limit.
7. The variables (metal contents) of all existing deposits are ranked in descending order and plotted on double logarithmic paper. If the plot does not satisfy a line fitting at the first instance, rank 1 should be shifted to the second position to generate a new series following Zipf's equation, plotted again, and continued until the best fit is achieved. The new numbers within the original series are the missing link and treated as the new discovery target.

10.2.5.2 *Statement of the Model*

The 24 existing Proterozoic zinc-lead deposits with cumulative resources of 21.346 million tonnes (Mt) of metals in India are ranked on total metal content (Zn + Pb) in descending order (Table 10.1) and plotted on double logarithmic paper. The plot of existing series shows an irregular curve. The existing largest deposit of Rampura-Agucha at number 1 is shifted to the second rank position and fitted to the foregoing equation of Zipf's law. The number 1 deposit in the new series is considered to be double the size of Rampura-Agucha. The new series generates 38 additional missing deposits with total metal accumulation of 87.321 Mt (Table 10.2). The plot of the new series (Fig. 10.3) demonstrates an ideal straight line. The new series is comprised of 62 deposits, with 24 existing and 38 deposits of prognostic category.

TABLE 10.1 **Total Metal (Zn + Pb) Accumulation of 24 Known Zinc-Lead Deposits in India in Descending Order (1986)**

Number	Deposit	Metal (Zn + Pb) in Tonnes × 10^6
1	Agucha	9.265
2	Mokhampura	2.000
3	Rajpura-Dariba	1.991
4	Sindesar-Kalan (East)	1.848
5	Zawar Mala	1.031
6	Balaria	0.846
7	Central Mochia	0.684
8	Ambamata	0.623
9	West Mochia	0.538
10	Baroi	0.358
11	Dariba (East)	0.357
12	East Mochia	0.285
13	Dewas	0.238
14	Rajpura-Dariba (B + C)	0.226
15	Sargipali	0.177
16	Gorubathan	0.162
17	Devpura	0.123
18	Bandalamottu	0.122
19	Samodhi	0.119
20	Baroi (N + S)	0.115
21	Zangamarajupalli	0.091
22	Tikhi	0.065
23	Deri	0.058
24	Rangpo	0.024
Total		

Close analysis of the model indicates that about 75% of zinc and lead metal has yet to be discovered (Paliwal et al., 1986) (Fig. 10.4). The prospective areas for new investigation are suggested to continue in a Proterozoic SEDEX-type of environment of the Middle Aravalli System of rocks. Continued exploration established additional reserves totaling 157 Mt reserves of high grade until 2017 in existing deposits (Rampura-Agucha) and new discoveries

TABLE 10.2 Known and Predicted Zinc + Lead Deposits in India (Ranked and Fitted in Zipf's Equation) (1986)

Deposit	Metal (Zn + Pb) in Tonnes × 10^6	Rank	Deposit	Metal (Zn + Pb) in Tonnes × 10^6	Rank
A	18.53	1	a	0.54	34
Agucha	9.26	2	West Mochia	0.53	35
B	6.18	3	b	0.51	36
C	4.63	4	c	0.50	37
D	3.70	5	c	0.49	38
E	3.09	6	d	0.47	39
F	2.65	7	e	0.46	40
G	2.32	8	f	0.45	41
{Rajpura-Dariba Mokhampura}	2.00	9	g	0.44	42
Sindesar-Kalan (E)	1.85	10	i	0.43	43
H	1.68	11	j	0.42	44
I	1.54	12	k	0.41	45
J	1.43	13	l	0.40	46
K	1.32	14	m	0.39	47
L	1.23	15	n	0.38	48
M	1.16	16	o	0.37	49
N	1.09	17	p	0.36	50
Zawar Mala	1.03	18	q	0.36	51
O	0.98	19	{Baroi Dariba (E)}	0.36	52
P	0.93	20			
Q	0.88	21	r	0.35	53
Balaria	0.84	22	s	0.34	54
R	0.81	23	t	0.34	55
S	0.77	24	u	0.33	56
T	0.74	25	v	0.32	57
U	0.71	26	w	0.32	58
Central Mochia	0.69	27	x	0.31	59
V	0.66	28	y	0.31	60
W	0.64	29	z	0.30	61
Ambamata	0.62	30		0.30	62
X	0.60	31			
Y	0.58	32			
Z	0.56	33			
			Total	87.321 tonnes × 10^6	

(Bamnia-Kalan, 5 Mt, Sindesar-Khurd, 110 Mt, and Kayar, 11 Mt) of high-grade ore.

The predictive modeling approach is an optimistic tool for an investment decision for a high-risk mineral exploration program. Modeling has never been a blind methodology, but always supported by a knowledge base and thought processes. In India, the Zawar group of deposits with about 15 Mt of reserves at 6% Zn + Pb was

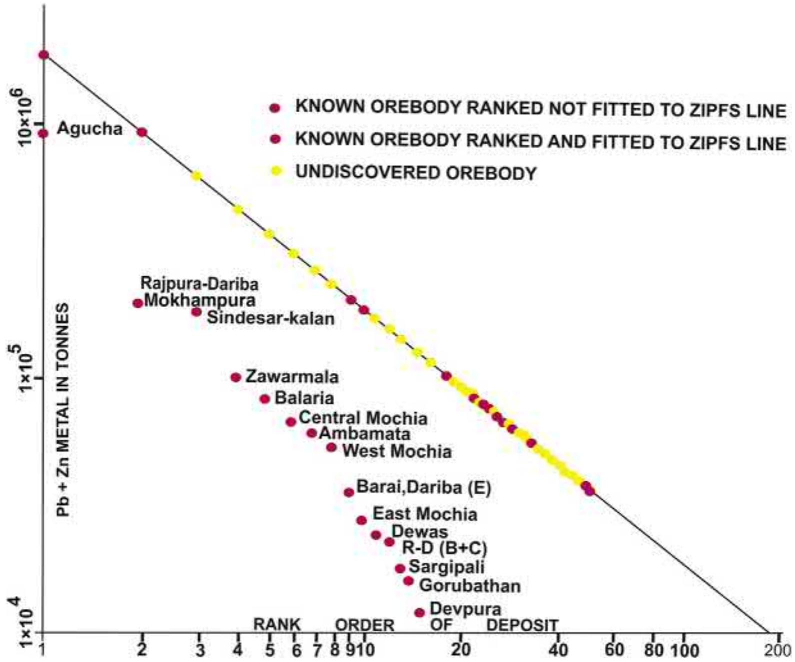

FIGURE 10.3 Twenty-four zinc-lead deposits in India, ranked and fitted to Zipf's law in 1985. The irregular series fitted well at one step shifting in Zip's equation. Over100 Mt reserves added, including discovery of two hidden deposits by 2011.

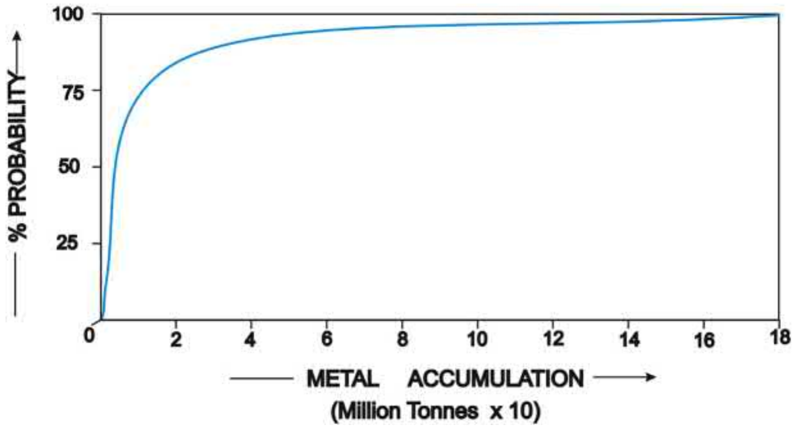

FIGURE 10.4 Probability of a deposit less than or equal to a given metal accumulation.

believed to be the best deposits until the late 1960s. The discovery of Rajpura-Dariba in the early 1970s with +20 Mt of reserves at 9.5% Zn + Pb and 82 g/t Ag was interpreted then to be the largest and richest ore deposit in the country. However, the discovery of Rampura-Agucha with +60 Mt at 15.5% Zn + Pb has changed again the perceived potential in the 1980s. This history of progressive discovery of larger and richer ore deposits led to optimism that has supported resource prediction and the search for future discoveries. The Rampura-Agucha deposit has doubled its size since 2010, and is the largest zinc deposit in India and a world-class type. Continued exploration discovered silver-rich zinc-lead of Sindesar-Khurd deposit with 60.8 Mt at 5.8% Zn, 3.8% Pb, and 215 g/t Ag at a depth of 120 m from the surface.

10.2.6 Statistical and Geostatistical Model

The statistical and geostatistical model is part of the resource and reserve appraisal system. Traditional methods of ore reserve estimation are developed based on characteristics and metal contents of the surrounding ground. The procedures do not consider any valid way to measure the reliability or uncertainty of the tonnage and grade. "Experience" factors are applied to make necessary corrections when things go wrong. This results in a write-off of payable deposits and overvalue of low-grade deposits. Conventional procedures occasionally deliver ore of estimated grades to the mill, particularly for short-term and midterm periods.

Techniques based on classical statistical theory provide solutions to the problem. The techniques include sample mean, range, standard deviation, variance, frequency distribution, histogram, correlation coefficient, analysis of variance, and t-test, f-test, and chi-square test for single variable and multivariate elements. Statistical methods provide deposit tonnage and grade with overall confidence limits. The techniques safeguard the quality control and quality assurance of all-purpose sampling, including optimization of exploration input (Geoffroy and Wignall, 2011), (refer to Chapter 15, Section 15.10.14). The classical statistical method is based on the assumption that sample values are randomly distributed and are independent of each other. It does not include the inherent geological variance within the deposit and ignores spatial relationship.

D.G. Krige in the 1960s and subsequently Matheron in the 1970s developed the theory of regionalized variables. It is a random quantity that assumes different values based on its position in space within a particular region. This technique produces the best linear unbiased estimate of reserve and yields a direct quantitative measure of reliability.

Statistical and geostatistical applications are capable of recognizing the distribution pattern, identifying characteristics of elements, and establishing correlation between variables and estimation of tonnage/grade with associated level of confidence. The techniques are competent to optimize sampling interval by sequential analysis during ongoing exploration and midterm corrections. Statistical and geostatistical procedures can assist in the optimization of exploration drilling for specific objectives (Fig. 15.26).

10.2.7 Orebody Model

The 2D and 3D orebody model conceptualizes the 2D and 3D perspective of the orebody. This can be done by creating a series of drill hole sections for delineation of the orebody. The 2D outlook is a simple plan or section view of the orebody. The geological interpretation is logically controlled by preparation of cross-sections, longitudinal sections, and level plans so that a 3D view can be accomplished. One can experience an orebody model of clay or plaster of Paris for 3D perspective. The 3D modeling technique has become a favorite tool to observe and analyze the world, and is used widely in various trades. The geological body is enriched with mineral resources, and the spatial shape and petrophysical distributions of the geological body are controlled by geological conditions. The 3D geological modeling of petroleum exploration and development of Yulou oil formation, Jin-16 block, Liaohe oil field, is realized by visualization of the geological body (Shao et al., 2011). The 3D orebody view with digitized geological maps, drill hole data, and mine working layout can easily be achieved by using geology/mining software using total samples information. This is done by orebody interpretation in all cross-sections and joining a number of points from top to bottom of the footwall and hanging wall boundaries of the orebody between two adjacent sections on either side, and is known as wireframing (Fig. 10.5). The 3D wireframe model can be viewed from all directions and used for mine planning, blast hole design, and production scheduling.

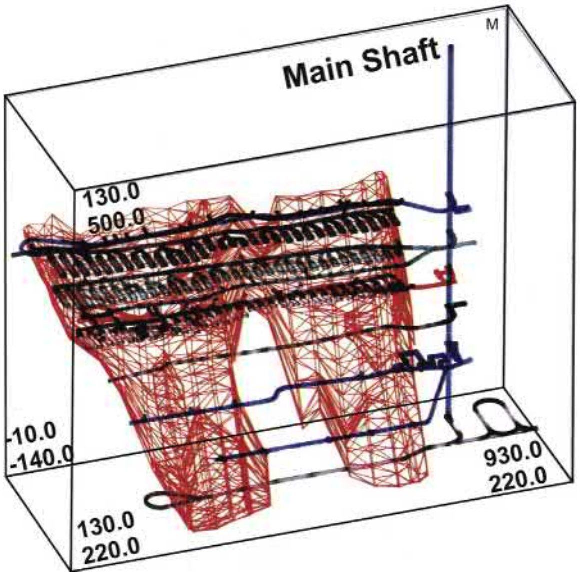

FIGURE 10.5 3D orebody wireframe model based on 50 m × 50 m drill interval of main lode (south) at Rajpura—Dariba mine, India, processed by DATAMINE software in 1991.

The 3D wireframe model can generate small subblocks for estimation of tonnes and grades. Block size is controlled by mining method and is equivalent to daily/weekly/quarterly/annual production. It is created at an advanced stage of exploration having sufficient physical and chemical properties of the orebody with a high level of confidence. The information forecasts grade and other parameters, and is used for mine design, planning, scheduling, blending, and quality control. The bench and block plans are prepared with graphic facilities of user friendly commercial software (Fig. 10.6). The models enable planners to select effectively the most promising means of extracting ore both physically and economically.

10.2.8 Mineral Inventory Model

The preparation and maintenance of mineral reserves and resources inventories are important functions for respective stakeholders with a clear objective, purpose, and scale. The United States Geological Survey (USGS)/United State

FIGURE 10.6 Zinc distribution on longitudinal section of Rampura-Agucha zinc-lead-silver deposit, India, at 25 m × 25 m × 10 m block size showing the zinc metal grade useful for forecasting, scheduling, and monitoring the Mineral Inventory File.

Bureau of Mines collects and compiles up-to-date reserves and resources of minerals, annual production, export/import, and all related statistics covering all mineral commodities and all countries. The *Minerals Yearbook* is published regularly in the public domain and is available free/at little cost. The Canadian *Minerals Yearbook* and Indian *Minerals Yearbook* are published annually and available in the public domain.

Exploration and mining companies create and update the status of their mineral inventory on short- and long-term bases to achieve committed current production tonnes and grades, as well as planning for a smooth future. The mineral reserves and resources inventories are computed and maintained in great detail with respect to unit size and accuracy. The mineral inventories are maintained by the company as a whole at corporate level, as well as the individual deposits, orebodies, blocks, levels, and stopes in particular, with high accuracy of tonnages and precessions in grade at production level. Any major deviation at the mine production stage will interrupt the metallurgical performance and recoveries affecting the profit and loss of the organizations.

3D orebody wireframe models for mine planning and production scheduling are composed of a series of small blocks and subblocks of equal size to estimate the total mineral reserves inventory. The block models can be developed for both open pit, underground, and a combination of both in case surface deposits continue to a greater depth. The block dimensions for a large-sized open pit zinc-lead-silver mine (Rampura-Agucha, India) are designed at 25 m along the strike equaling the infill drill distance, 5 m vertical equaling bench height, and 5 m across the dip to minimize dilution at the contact. All drill sections are uniform grids with 5 m × 5 m cell size for estimation of block tonnage and grade. The Mineral Inventory File at 25 m × 5 m × 5 m mining blocks in a digital array has been estimated by inverse square distance, as well as the kriging method using composite sample assay values within the block neighborhood. The cells outside the footwall and hanging wall boundaries are controlled by the ore boundary. A 3D search ellipsoid oriented with major, intermediate, and minor axes along the strike and dip, and across the orebody, respectively, controls the selection of samples. The ellipsoid moves horizontally or vertically centering the computational cell while performing interpolation. The strong anisotropic nature is further incorporated by differential weighting coefficient to reflect the effect of metal zoning. Samples located down-dip are given more weight than across following strike, dip, and depth directions. These parameters were tested (jackknife test, Box 10.1) by various options on controlled cells having actual sample values. Thirty-six blocks had been estimated

BOX 10.1 The Jackknife Test

The jackknife test is one of the useful resampling techniques in statistics for variance and bias estimation accrued with predicted values. A block having an actual drill hole sample point is reestimated by surrounding known samples falling within the 3D influence window and eliminating the original sample value being reestimated. The jackknife estimator of a parameter is found by systematically leaving out each observation from a dataset and calculating the estimate and then finding the average of these calculations. The jackknife test is the linear approximation of the bootstrap technique.

TABLE 10.3 Block Grade and Tonnage Estimate at 365 m Bench at Rampura-Agucha Exploration Block Based on Surface Diamond Drill Holes

	Block/Cell	% Zn									
		% Pb									
		% Fe									
Section	Section total tonnage and % Zn, % Pb, % Fe										
S-00	0.02	11.4	10.5	13.1	11.6	7.0	5.3	10.9	12.1	10.9	% Zn
	0.03	0.7	1.0	2.2	2.1	1.2	0.9	2.4	2.8	2.3	% Pb
	8.0	7.3	5.9	5.8	6.2	6.1	6.2	6.6	6.7	6.6	% Fe
	SEC = 39,375 tonnes, 9.38% Zn, 1.35% Pb, 7.08% Fe										
N-25	0.0	14.0	18.1	18.9	16.7	13.6	10.9	8.5	6.1	7.4	% Zn
	0.0	1.9	3.9	4	3.6	2.9	2.3	1.9	0.9	0.8	% Pb
	3.0	7.1	5.8	6.6	6.5	6.3	6.3	6.1	6.3	7.4	% Fe
	SEC = 35,625 tonnes, 13.08% Zn, 1.98% Pb, 6.65% Fe										
SEC	7	8	9	10	11	12	13	14	15	16	Grade
S-25	11.7	13.0	13.3	13.3	13.5	13.9	11.2	12.4	10.8	8.6	% Zn
	0.2	0.3	1.2	2.1	2.5	2.6	2.2	2.6	2.3	1.6	% Pb
	6.5	6.0	5.8	5.9	6.4	6.4	6.1	5.7	5.4	5.2	% Fe
	SEC = 43,125 tonnes, 10.88% Zn, 1.49% Pb, 6.02% Fe										

by 3D linear kriging. The estimated block values based on 25 m × 25 m drilling inputs are displayed at 5 m bench (Table 10.3) for long-term production planning and grade forecast.

10.2.8.1 Model Testing

A surface pit (Fig. 10.7) was opened at the end of exploration, global, and mine block estimation for creating a large volume of representative ore samples for pilot plant-scale metallurgical test work during a project formulation period. This was an opportunity to initiate a sampling program for cross-validation of the estimated blocks covering a number of blocks in the trial pit. The blast hole chip samples represent individual estimated blocks/cells (Fig. 10.8), constitute pilot plant feed, and are analyzed to modify/firm up block matrix estimation parameters. The estimated block grades are compared with blast hole sample grades using a scatter diagram and mean, variance, and correlation coefficient. The estimated and blast hole grades (referee) show appreciable differences and are spread widely at individual block level (Fig. 10.9). The average grade over large tonnage for continuous three (quarter), six (half-yearly), and 12 (annual) months' production gradually converge. This estimate will serve the purpose of long-term planning.

FIGURE 10.7 A surface pit was opened at the end of exploration, estimation, and project formulation to generate large volumes of representative samples for pilot plant metallurgical tests, and bench blast-hole sampling to compare with estimated block grades.

The blast hole cuttings are used as cluster samples. The semivariograms of blast samples are drawn along and across the orebody. Variography at individual blast hole and block composite level depicts high variability across collection, monitoring, and updating of the Mineral Inventory File on at least a weekly basis (Fig. 10.10). This

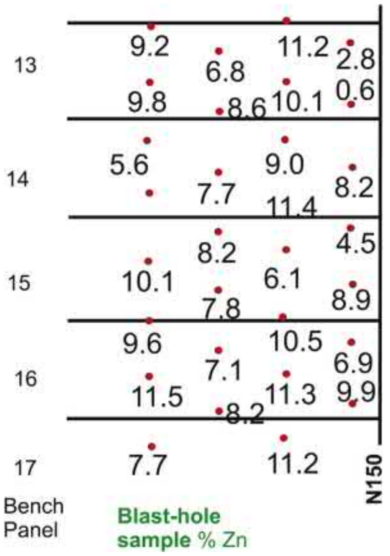

FIGURE 10.8 The blast-hole locations on trial pit bench are planned by over-laying the estimation-blocks, and compared. The study suggests infill drilling for short term grade forecast.

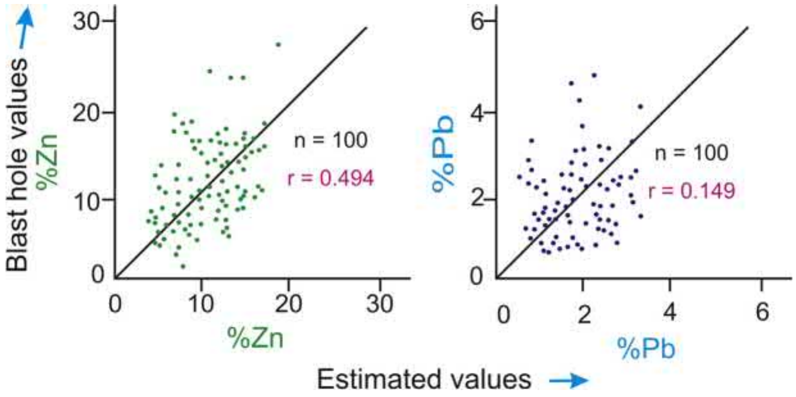

FIGURE 10.9 Scatter plot to compare between estimated and blast hole grade that shows poor global correlation indicating that the average grade forecast will tally on a long-term/annual basis.

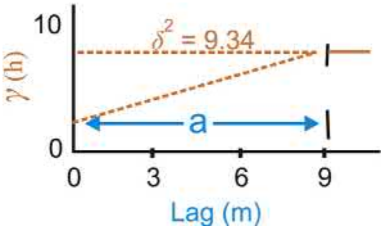

FIGURE 10.10 The semivariogram of blast hole samples confirms variation between directions of strike, dip, and depth of the orebody.

introduces infill in-pit length noncore drilling at an interval of 25 m × 12.5 m. The estimated block grade based on infill drilling will be the base for medium-term planning, i.e., quarterly/monthly. The blast hole cutting samples will serve run-of-mine feed scheduling and grade control. This model can be used as "Role on Plan" with every additional set of blast-hole drilling.

10.2.9 Grade/Tonnage Model

The grade and tonnage models can organize a comparative status of mineral deposits from a regional and global perspective that will help to identify a potential exploration environment (Haldar, 2004). A number of existing worldwide zinc-lead deposits are grouped with respect to their

TABLE 10.4 Premining Tonnage and Grade of Important Zinc-Lead-Silver Deposits in America, Australia, and India

Deposit	Reserve (Mt)	% Zn	% Pb	% TMC	Metal (Mt)	g/t Ag	Age (~Ma)
A. North America							
Red Dog	150	16.2	4.4	20.6	30.9	110	300
Sullivan	170	5.5	5.8	11.3	19.21	59	1468
B. Australia							
Broken Hill	158	8.9	6.0	14.9	23.5	55	1650
HYC	227	9.2	4.1	13.3	30.2	60	1640
Century	118	10.2	1.5	11.7	13.8	36	1595
Lady Loretta	8.3	18.4	8.5	26.9	2.2	125	1647
Mt. Isa	150	7.0	6.0	13.0	19.5	150	1652
Hilton	120	10.2	5.5	15.7	18.8	100	1652
Lennard Shelf	17	5.5	4.0	9.5	1.6	10–75	380
C. India							
Rampura-Agucha	157	13.5	2.0	15.5	24	54	1804
Rajpura-Dariba	25	8.0	2.2	10.2	2.6	100	1799
Sindesar-Khurd	110	6.7	3.2	9.8	10.8	154	1800
Bamnia	5	5.7	2.5	8.2	0.4	100	1800
Sindesar (E)	94	2.1	0.6	2.7	2.5	20	1800
Mokhampura	63	2.2	0.7	2.9	1.8	10	1800
Kayar	11	10.4	1.6	12.0	1.3	10	1745
Mochia	17	4.3	1.8	6.1	1.0	40	1710
Balaria	16	5.9	1.2	7.1	1.1	36	1702
Zawar Mala	7	5.0	2.2	7.2	0.5	40	1708
Baroi	6	0.0	4.6	4.6	0.3	50	1700
Deri	1	10.2	8.0	18.2	0.2	15	990
Ambaji	7	5.3	3.3	8.6	0.6	15	990

TMC, total metal content (%ZN + % Pb).

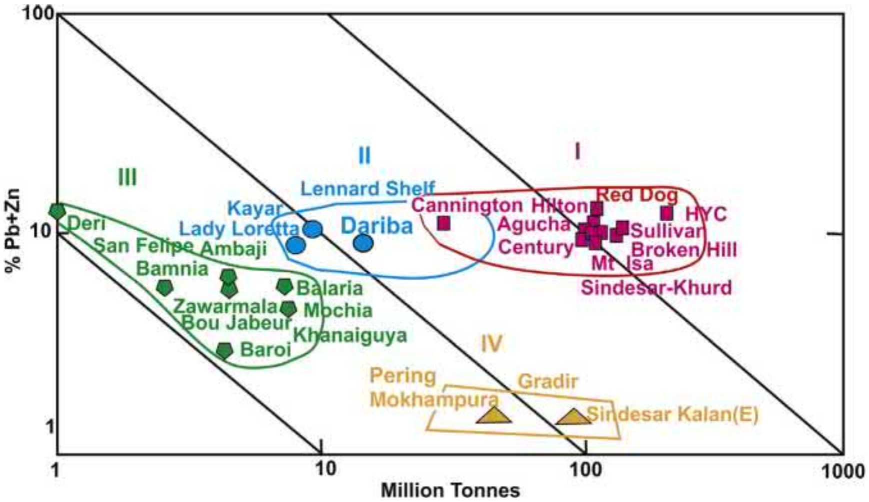

FIGURE 10.11 Grade/tonnage diagram for explored zinc-lead-silver deposits in the world showing four clusters of very high and very low grade with various sizes of resources.

premining size and grade (Table 10.4) to develop a grade/tonnage model. Tonnage versus total grade of the deposits is plotted in a logarithmic scale (Fig. 10.11). The graphical presentation can be compared and provides a clear picture of deposit type and is mined accordingly. The model provides information to speculate likely tonnage and grade of undiscovered deposits in the region. It also helps to assess the economic analysis of these prognostic resources.

The present grade/tonnage model outlines four distinct types of clusters existing in the world:

1. Group I is represented by world-class high-grade/high-tonnage zinc-lead-silver deposits, namely, Red Dog, Sullivan in North America, Here is Your Chance (HYC), Broken Hill, Mt. Isa, Century, Hilton in Australia, and Rampura-Agucha and Sindesar-Khurd in India. The reserves (+100 Mt), Zn + Pb grade (+10%), and silver content (+50 g/t) rank these deposits economically and exceptionally attractive for easy investment decisions. These types of deposits qualify for large production capacity, quick payback period, and long mine life.
2. Group II includes medium-tonnage and medium-grade deposits, like Lady Loretta, Cannington, Lennard Shelf in Australia and Rajpura-Dariba and Kayar in India. These deposits are economically significant for reserves (+10 Mt), grade (8%−10% Zn + Pb), and rich silver content.
3. Group III deposits are comprised of medium tonnage (−10 Mt), low grade (6%−7% Zn + Pb), and low silver. The deposits like San Felipe in Mexico, Bou-Jabeur in Tunisia, Khanai-Guiya in Saudi Arabia, and Mochia, Balaria, Zawarmala, Baroi, Deri, Bamnia, and Ambaji in India are marginally breakeven. The deposits continue mining because of the existing infrastructure and periodical increase in metal price.
4. Group IV consists of Pering in South Africa, Gradir in Montenegro, and Sindesar-Kalan and Mokhampura in India with high resources (30−100 Mt), very low grade (<2% Zn + Pb), and negligible silver content. These big deposits are favorable for large low-cost mining, application of density media separation for pre-concentrate generation, innovative technological breakthrough in metallurgy, and rise in metal price.

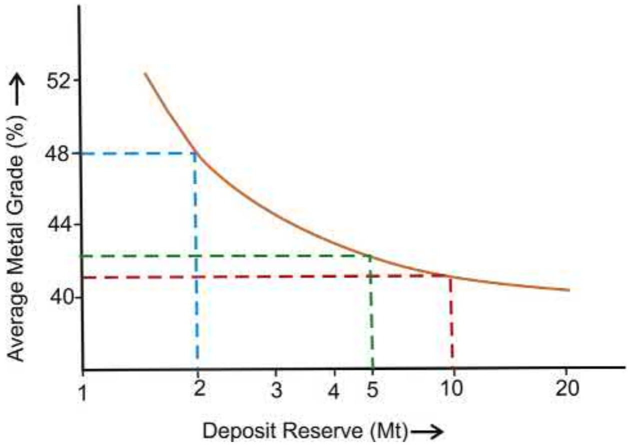

FIGURE 10.12 Conceptual presentation of grade/tonnage curve for broad valuation of chromite or bauxite properties aiming at investment for mine development.

The grade/tonnage relationship of a deposit can be visualized by plotting the reserve on the X-axis in logarithmic scale and total average metal grade on the Y-axis in normal scale (Fig. 10.12). The deposits cluster as a group and provide a quick evaluation of a deposit for its mining viability between tonnage and required grade. The variation in grade within a deposit is resolved by production scheduling to maintain an optimum even grade to the metallurgical plant.

10.2.10 Empirical Model

The empirical model is a simplified representation of a system or phenomenon that is based on experience or experimentation. The modeling revolves around the need for future projection of possible availability of commodity under similar geological conditions to satisfy the ever-growing demand of society. The system can be developed by grouping or categorization of deposits on the basis of past experience in exploration. It can be used for future mineral search under a similar favorable host environment. The key parameters are identified from known deposits to conceptualize the module and targets. The target is to be defined in clear terms such as type of resources and reserves, category of mineral grades, structurally controlled high-grade deposits, location of orebody (near surface or deep seated), and metal-to-metal ratio such as Zn to (Zn + Pb) ratio. It can be demonstrated that the Paleoproterozoic zinc-lead deposits of Australia and India have many common features like surface signature, host rock assemblage, linear alignment, metamorphic grade, presence of geochemical halos, metal zoning, and age of formation. The key geological features between Australia and India are:

1. Surface signature: Surface oxidation/weathering as gossan is a common key indicator of a sulfide deposit below. Size, shape, and attitude of gossan can be an important tool for drawing an exploration program after initial geochemical sampling. However, a deep-seated body will be devoid of any such remnant. Most Proterozoic deposits like Broken Hill, Mt. Isa in Australia, and Rajpura-Dariba, Rampura-Agucha, Saladipura, Khetri, and Jagpura in India show excellent preservation of gossan.
2. Mineralization: Essentially strata-bound and often stratiform, disseminated to massive, and layered to fracture filled. The common ore minerals are sphalerite, galena, pyrite, pyrrhotite, chalcopyrite, and sulphosalts with recoverable value added metals like, Ag, Au, Cd, and Ni.

3. Host rock: Essentially a single/multiple unit of sedimentary origin having tuffaceous components representing greywacke, black shale, siltstone, dolostone, calc-silicate, phyllite, and schist with or without graphitic material. Primary sedimentary structures are obscured by subsequent various grades of deformation and metamorphism.
4. Metamorphism/deformation/shearing: Deposits are metamorphosed, deformed, and intensely sheared and vary between lower green schist and upper amphibole-granulite facies and strong penetrative deformation. HYC mineralization in Australia is unmetamorphosed.
5. Carbonaceous matter: Most Proterozoic deposits are associated with carbonaceous matter with varying proportions.
6. Evaporites (gypsum/barite): The presence of gypsum and barite indicates shallowing and deepening of fluctuating sedimentary basin evolution in which metal formation events happen through exhalative metal-bearing fluids and addition of metal from country rocks to form a mineral occurrence. Many of the SEDEX deposits contain barite and gypsum.
7. Halos: The presence of pyrite, siderite, Mn, and carbonaceous material is a common feature enveloping mineral body. The geochemical halo can be a good guide for regional exploration if identified correctly.
8. Time of mineralization: All Australian deposits in Broken Hill, McArthur-Mt. Isa basin belong to the Paleoproterozoic age, ranging between +1600 and 1700 Ma. Major Indian deposits in the Aravalli supergroup of NW Indian shield belong to the same age group ranging between 1700 and 1800 Ma. Sullivan deposit, Canada, is dated as Middle Proterozoic age at 1470 Ma.

10.2.11 Exploration Model

Exploration models promote the idea of generating prospects using a series of decision loops following successive inputs from different sources (Haldar, 2007). Each input contains new data to aid in the decision-making process. The model starts with the study of existing literature and regional maps followed by various stages of reconnaissance → large area prospecting → prospecting → exploration → phase I, II, III → estimation/classification → feasibility study. A dynamic model follows a logical flow diagram implying objectives, time, and cost along with decision-making criteria to continue, modify, and temporarily discard (stack in shelf) at any stage of activity. Exploration activity can be summarized in the following stages.

10.2.11.1 Regional Geological Activity: Reconnaissance Permit

Mineral exploration starts with a study of the demand/supply scenario, existing literature, and satellite maps and imageries to support new investment, and is supported by application of a mathematical/forecasting model. A regional field check is required to identify the presence of surface signatures, suitable stratigraphic formation, and favorable host rock, structures such as shear, lineament, pathfinder elements, and halo from geochemical traverses, and response from airborne geophysics. The final goal would be identification of a mineral province or belt.

10.2.11.2 District Geological Criteria: Large Area Prospecting or Prospecting License

Activities involve detailed geological mapping, geochemical, and ground geophysical survey, prioritization of targets, and diamond/reverse circulation drilling. The result would be estimation of reserve and resources, and classification.

10.2.11.3 Local Geological Activity: Mining Lease

This is the final stage of exploration comprising detailed close-space drilling to derive reserves and grades with highest confidence within well-defined boundaries. The reserve/resource base is classified under the USGS/UNFC/JORC system and certified by a **Qualified Person**. Metallurgical testing at laboratory/bench/pilot plant level are completed. The deposit is thoroughly understood covering mineralization features, stratigraphic control, host rock assemblage, structure, lineament, and tectonic setting. Grade distribution within the total envelope of the orebody (Fig. 10.4) is clearly estimated and depicted (Fig. 10.5) in blocks/subblocks to ensure scoping study and feasibility reports, mine planning, production scheduling, and grade control until mine closure. The exploration continues.

10.3 EXPLORATION MODELING: A HOLISTIC DYNAMIC APPROACH

The mineral exploration flow diagram is a step-by-step sequential synthesis of all activities. It evaluates the property at the end of each stage for economic significance and opens two alternative paths suggesting either to "level pass" or continue successive exploration activities, or to store conditionally for the future with emerging technology and changing economic environment (Fig. 10.13). The objectives of search and associated activities are defined at the beginning. It is proposed to analyze the demand/supply scenario of the mineral or group of minerals at national and global perspectives for prioritizing the long-term national investment policy. Once the mineral(s) is/are identified, the existing literature on occurrences, geological packages, exploration history, preferred host environment in space, and characterization of deposits in the country and elsewhere are compiled. The common key parameters are discussed with linkage if it exists. An understanding of the stratigraphic horizon is essential to define a broad target area.

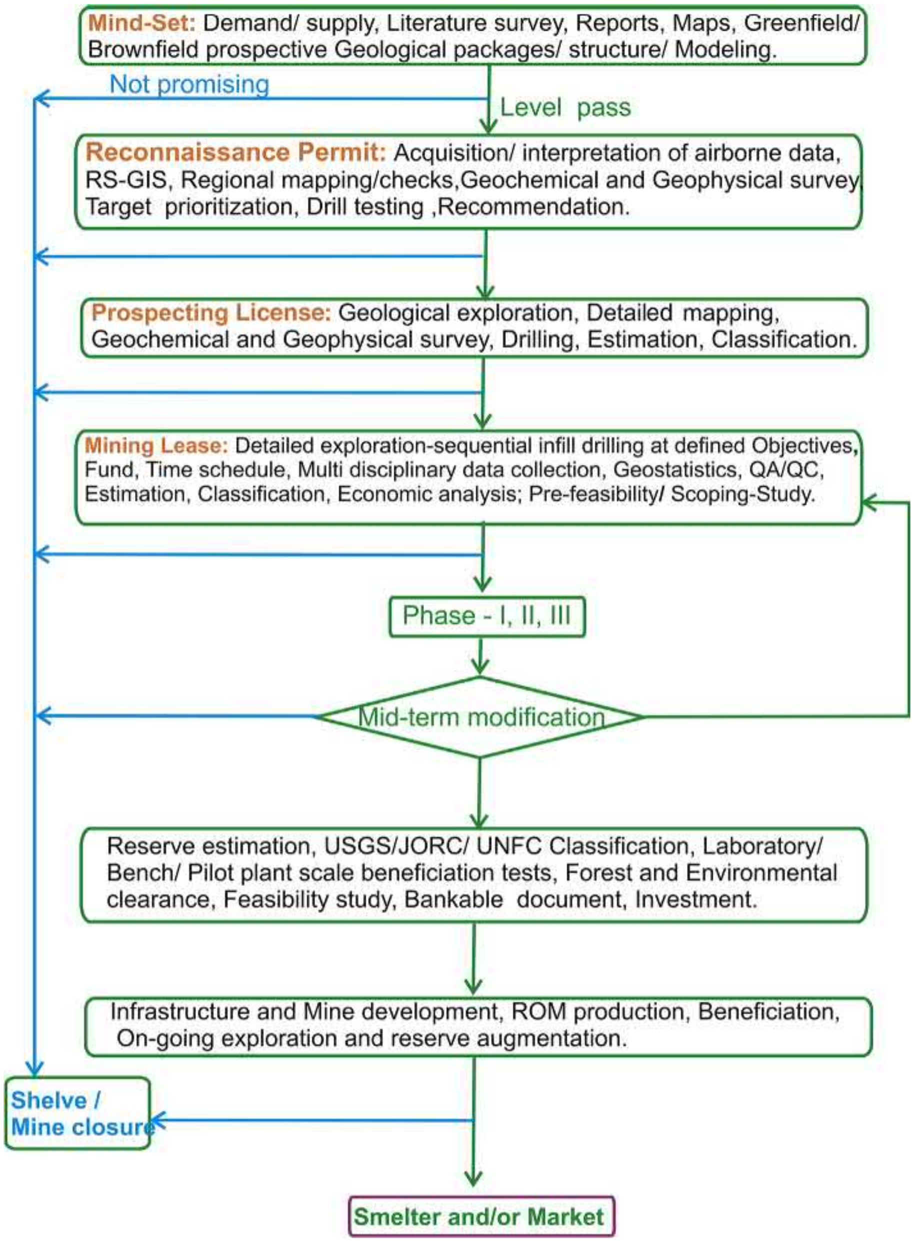

FIGURE 10.13 Holistic concept and flow diagram of mineral exploration system can be achieved by breaking the first lucky rock exposed in the field to transport the metals to the market. *QA/QC*, quality assurance/quality control; *ROM*, run-of-mine; *RS-GIS*, remote sensing-geospatial information system; *USGS/JORC/UNFC*, US Geological Survey/Joint Ore Reserve Committee/United Nations Framework Classification.

The model concept looks for a favorable host environment. A preliminary field check along with a few geochemical samples from probable rocks will indicate the significance of the area for submission of a reconnaissance permit. The works envisaged are acquisition and interpretation of existing airborne data, if any, stream sediment sampling, and airborne electromagnetic survey with advanced configuration system. The survey is carried out in both frequency and time domain with higher penetration capacity to identify deep-seated metallic bodies. Regional mapping, checking of existing maps, ground geophysics, and test drilling will identify anomalies and set the priority of targets with future exploration strategies. A statement on reserve and resource status is premature.

If the result passes the first level, a large area prospecting or prospecting license is applied to conduct a general exploration comprising detailed mapping of the target area along with geochemical and ground geophysical survey, broad-based drilling, and estimation of reserves/resources. The status of reserves and resources is expressed under USGS/UNFC/JORC Standard Codes of Reporting following increasing knowledge of geological confidence and economic feasibility.

Positive outcome allows submission of a mining lease. Detailed exploration by close-space/infill drilling with defined objectives, fund and time schedule, infrastructure, mine planning and development, metallurgical tests, forest and environment clearance from respective authorities, detailed project report, and financial sources are completed before the start of regular mine production and beneficiation. The ore reserves signify highest confidence of tonnage and grade. The adequate reserves keep sustained production over the projected mine life. The routine mine production is substituted by reserve augmentation aiming at "2 tonnes" of ore replacement for "1 tonne" of mine production.

10.4 LIMITATIONS

Geological processes are events that occur on a geological timescale ranging between millions of centuries, hundreds of meters, and thousands of kilometers. Compare this to the everyday models from physics and engineering operated at laboratory units and the scale of human lifetime. Geological concepts represent an abstraction of nature, and the numerical model represents a tremendous simplification of a geological concept. Geological models are conceptualized with the physical, chemical, and biological processes observed from stratigraphic sequences and syn-depositional and postdepositional phenomena introduced by external and internal tectonic forces. Uncertainties are present at various levels, and these limitations are to be appreciated. The results need to be compared with observations. A geologic model can be considered predictive only when the applied parameters are within a reasonable range of values, supported either by measurements or by some type of geological reasoning, and only when the differences between the model outcome and observations are within an acceptable range of uncertainty. There is no guarantee with respect to the uniqueness of a result in a particular situation, and hence these should be expressed in a probabilistic rather than in a single-value manner.

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Chapter 11

Mineral Economics

Chapter Outline

> *Mines are not found but made, usually at great cost and often with significant risk.*
>
> Author.

11.1 DEFINITION

The mineral industry forms the backbone of a nation's economy and growth of its people. It is an opportunity-based investment venture under the shadow of a high degree of risk associated at each stage of activity. The risks revolve around geological uncertainties, technical competency, needs of society, commercial feasibility, economic viability, political stability, and the will of federal and regional governments. Risks can be minimized by generating adequate information during the various phases of exploration and critical economic analysis to safeguard the investment. Therefore clear in-depth knowledge and professional experience in the field of mineral economics and its use in understanding the behavior of mineral commodity markets and in assessing public, corporate, and government policies is essential in this important economic sector (Tilton and Guzmán, 2016). The strategy should be equally focused on metallic and nonmetallic commodities, including oil, coal, and other energy commodities.

Economic minerals are minerals of commercial value that earn revenue for the return on investment. A comprehensive knowledge of **ore geology** (reserves and resources), **economic minerals** (metallic, nonmetallic, solid, liquid, and gas), as well as **mineral economics** (cost and revenue analysis) (Tiwari, 2010, 2014) is vital. All the activities are largely scientific and technical in nature. Procedures on various exploration techniques, estimation with appropriate level of accuracy through **quality control and quality assurance**, mining, beneficiation, smelting, and refining resulting in finished goods for society were discussed in previous chapters and continue in the following chapters. Political stability, the will of the governments, and regional attitudes are socioeconomic attributes that involve federal/state governments and private entrepreneurs for overall economic and social sustainable development of the area in particular, and the country/globe as a whole.

Commercial and economic aspects are not in the hands of the investor and mainly rely on the global market scenario. Feasibility analysis can indicate the conversion of mineral resources to marketable commodities with adequate returns on investment. Mineral resources are made ready for end users by four well-defined processes, namely, exploration, development, production, and extraction

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00011-3

(Johnson, 1988; Campbell, 1999). The investment decision for each stage centers around the interrelated components of **resource**, **risk**, and **revenue**.

11.2 INVESTMENT PHILOSOPHY

A mineral exploration program and subsequent development to a producing mine need investment of different magnitudes without earning any revenue during the initial exploration stages. The returns, revenues, or benefits of different magnitudes on investment are realized in the last phase. Investment in the early phase of exploration, i.e., **reconnaissance**, may fail to discover any mineral deposit and total expenditure ends in loss. The second phase, i.e., **large area prospecting** or **prospecting**, may delineate a mineral body with certain resource and metal contents. The deposit may or may not be viable at this stage without further investment. The right answer is endorsed at the end of **detailed exploration**, which provides an economic deposit with assurance. The project may still fail to deliver the benefits due to unknown factors indicating high risk in the mineral industry. However, success in one deposit out of 100 attempts will compensate the earlier losses, and make the investment profitable.

The demand for minerals in national economies promotes the basic stimulus for investment. But who are the prospective investors under such speculative investment in the mineral industry? Investors are either from federal/state governments and government enterprises for socioeconomic developments or private sectors for business opportunities. Investors may operate as individual entities or as joint venture partners in big and small, organized and unorganized structures. Each one works with its own philosophy on investment.

Small unorganized investors cannot absorb the shocks of failure and do not capitalize large sums on exploration and development. Their targets are small mineral properties like silica sand, garnet, soapstone, marble, and limestone at both low investment and revenue.

Private organized sectors invest in exploration and subsequent programs mainly on financial criteria, strive to maximize profits, and urge to attain quick returns on investment. The primary and long-term objectives of maximizing profit are achieved by increasing production size and ore-man-shift, cost reduction by mechanization, dilution control, higher recovery efficiency in the mine, ore dressing and smelting plant, and market share. These companies are specialized for particular types of minerals, namely, iron ore, bauxite, zinc, lead, copper, manganese, chromite, nickel, platinum-palladium, coal, lignite, phosphate, etc.

Government-backed companies work on optimum profit with long-term objectives of economic growth, development of strategic minerals like uranium, tungsten, oil and gas, self-sufficiency of the country as a whole, and socioeconomic development of the region in particular. Federal and regional governments conduct regional exploration programs covering all minerals, outline mineral-based regions, and generate mineral inventories. The objectives are many-fold, such as overall socioeconomic growth, generation of employment, reduction of demand/supply goals, and enhancement of foreign exchange reserve.

11.3 STAGES OF INVESTMENT

Three well-defined stages of activities cum investment are exploration, development, and production. The unified practices convert once unknown mineral resources into profitable products. The sequential approach of reconnaissance, prospecting, and detailed exploration establish an economic deposit. The development phase creates infrastructure facilities, including mine entry systems, and designs mineral processing roots. The exploration and development phase witnesses net cash outflow or **negative cash flow**. The expenditures are capitalized. The operating costs in the production stage are compensated for through revenue generation, and end with **positive cash flow** or cash inflow of different magnitudes into the project.

Cash flow is the difference between all cash inflows (revenue) and all of their cash outflows (costs/expenses). Two types of cash flow are associated with any investment:

1. Cash flow before tax
   Cash flow before tax of an investment is the actual flow of money into and out of the business without any tax deduction. The method ensures incentive by the government to promote sustainable development of remote areas for the welfare of local inhabitants.
2. Cash flow after tax
   Cash flow after tax accounts for tax liability and essentially profit/loss after tax.

The net cash flow of one iron ore deposit with 8 years of mine life is computed in Table 11.1. The net present value (NPV) is positive before tax deduction and negative after tax deduction over the life of the mine. The deposit can only be viable if tax is exempted by the authorities as an incentive to promote local development. NPV computation is discussed at Section 11.4.2.1.

11.4 INVESTMENT ANALYSIS

The investment opportunity of a mineral project can be evaluated and compared with the cost at different stages of exploration, development, and production vis-à-vis the expected revenue to be earned during the first 10–15 years of mine production. The opportunity is worth considering if the benefits are higher than the associated costs. The investment analysis begins with estimation of the resource

TABLE 11.1 Simplified Presentation of Net Cash Flow Computation Before and After Tax for the Iron Ore Deposit Under Investment Showing (+) and (−) Loss/Revenue, Respectively

Year	Net Cash Flow Before Tax (Million $)	Net Cash Flow After 20% Tax (Million $)	Activity
0	−2	−2	Prospecting
1	−2	−2	Exploration
2	−50	−50	Development
3	5	4	Initial production
4	10	8	Production buildup
5	20	16	At full production
6	20	16	At full production
7	20	16	At full production
8	20	16	At full production
9	10	8	Reduced production
10	5	4	Mine closure starts
NPV at 12%	10.14	−1.10	Mine closed

NPV, net present value.

to be spent on exploration, development, production, royalties, taxes, and other activities versus the revenue expected to be received from the sale of end products. The phasing of activities, investment, cash flow, and chances of failures over the years is conceptualized in Fig. 11.1A–C. Fig. 11.1B indicates that cash flow during exploration and development is negative and becomes positive with the commencement of production.

There are a number of financial analyses available for project investment decisions that include undiscounted and discounted methods. Investors work on either of the two principles depending on the business philosophy:

1. The **bigger-the-better** (bigger benefits are preferred to smaller benefits).
2. The **bird-in-the-hand** (early benefits are preferred to late benefits).

11.4.1 Undiscounted Method

Undiscounted future cash flows are cash flows expected to be generated or incurred by a project, which have not been reduced to their present value. This condition may arise when interest rates are so near zero or expected cash flows cover such a short period of time that the use of discounting would not result in a materially different outcome. The undiscounted method is simple and quick to apply in getting an essence of investment climate to get back the original investment rapidly. The computation is the **payback period** of the original investment. It is the number of years required for the cash income from the project equal to the initial investment incurred (Table 11.2).

At face value, Project-A with a 3-year payback period would be preferred over Project-B with 4.25 years. However, Project-B will be more profitable at a higher internal rate of return (IRR, see Section 11.4.2.2) of 20% on long-term bigger benefits.

Average accounting rate of return (AARR) is another simple way of computing the return on investment by dividing the average annual net profit by the initial investment (Table 11.3).

$$\text{Average net profit} = 70/4 = 17.5$$

$$\text{Investment} = 100$$

$$\text{AARR} = 17.5/100 = 17.5\%$$

11.4.2 Discounted Method

Discounted cash flow (DCF) is a valuation method used to estimate the attractiveness of an investment opportunity. DCF analyses use future free cash flow projections and discount them, using a required annual rate, to arrive at present value estimates. The investment made during the early phase of the project (−ve cash flow) and the revenue received later (+ve cash flow) are not directly comparable (Fig. 11.1) as discussed for the undiscounted method. It must be adjudged for the time value of money. The time value concept of money states that “a dollar received today is worth more than a dollar received tomorrow.” Investors can simply deposit their capital (fund) preferably in the nationalized banks or other reputed financial institutions, and earn a risk-free income without sweating their toil. However, why should investors invest their resources, knowledge, skill, and time in risky mineral-based proposals without being compensated by enough benefits for receiving payment tomorrow rather than ensured regular earnings? Therefore the value of future cash inflow (revenue—cost) must be discounted before comparing with the capital to be invested today to develop a project tomorrow.

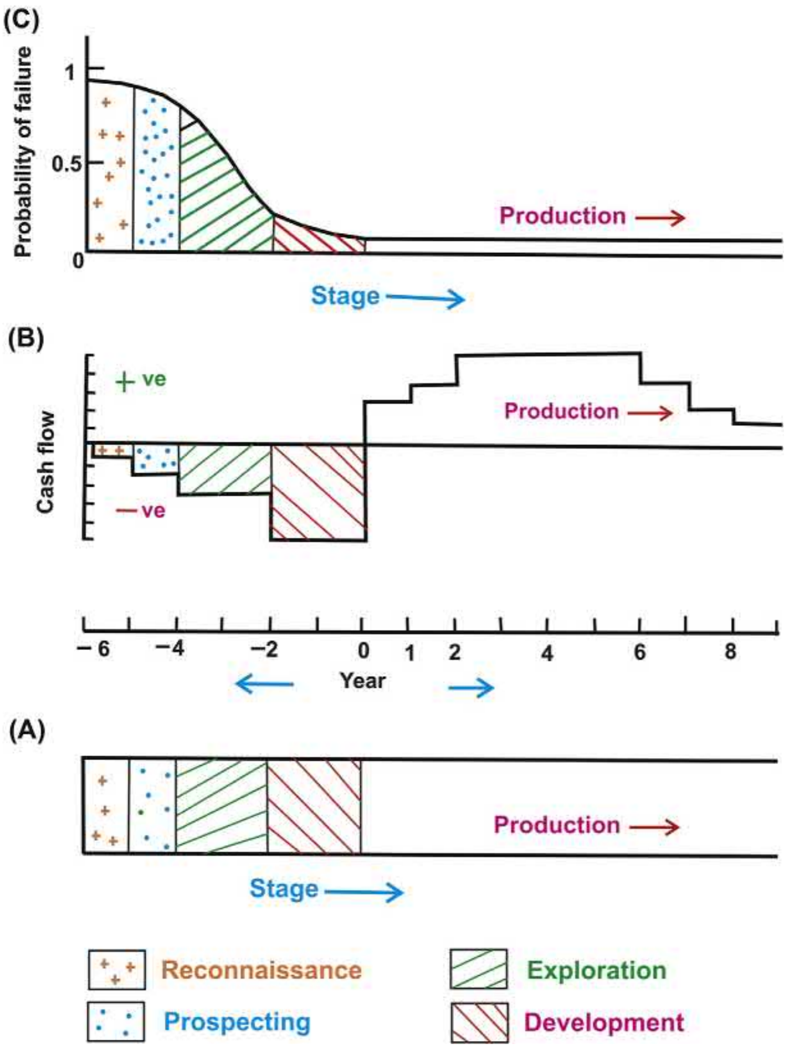

FIGURE 11.1 Schematic phasing of investment and cash flow distribution in mineral deposit: (A) stages of exploration and development, (B) cash flow, and (C) probability of failure.

The time value of money concept is expressed by the following formula and is elaborated in Table 11.4.

$$A = P(1 + i)^n$$

where A = accumulated value of an investment (P) annually computed over (n) years at a variable interest rate (i).

The investor can invest US\$100 today and will receive US\$152 at the end of year 3. This is the key concept in computing the present value of money to be received at different future years. Money received annually at the end of different years is not equal in value to today's money, and therefore must be discounted to its present value of today. The present value is estimated by the following formula and elaborated in Table 11.5. The present value of US\$100 after 10 years at a discounted rate of 12% is worth US\$32.20.

$$PV = 1/(1 + i)^n$$

11.4.2.1 Net Present Value Method

NPV is the difference between the present values of future cash flows from an investment. NPV is the sum of differences between a series of discounted revenues and the relative cost. It is computed by the formula:

$$NPV = (R_0 - C_0) + \frac{(R_1 - C_1)}{(1 + r)} + \frac{(R_2 - C_2)}{(1 + r)^2} + \cdots \frac{(R_n - C_n)}{(1 + r)^n}$$

where NPV in year 0 is the sum of revenues (R) minus cost (C) in year 0 through n, adjusted back to the present using a

TABLE 11.2 Payback Period Method (Cash Flow in Million US$)

Year	Project-A	Project-B	Activity
0	(−) 60	(−) 70	Exploration and development
1	20	10	Mine production
2	20	10	Mine production
3	20	20	Mine production
4	10	20	Mine production
5	10	40	Mine production
6	10	50	Mine production
Payback period	3 years	4.25 years	
IRR	15.5%	20.0%	

IRR, internal rate of return.

TABLE 11.3 Average Accounting Rate of Return (Cash Flow in Million US$)

Year	1	2	3	4	Total
Net profit	10	15	20	25	70

TABLE 11.4 Simplified Presentation of "Time Value of Money" Concept—Compound Interest Rate Computation at 15% Over 3 Years

No. of Years	Original Investment ($)	15% Compounded Interest	Accumulated Value (US$)
1	100	(1.15)[a]	115
2		(1.15) (1.15)[a]	132
3		(1.15) (1.15) (1.15)[a]	152

[a] *Multiplication with principal investment.*

TABLE 11.5 Simple Way to Compute Present Value up to 10 Years

No. of Years From Present	Original Amount Received (US$)	Discount Factor at 12%	Present Value (US$)
0	100	100/1[a]	100
1		100/(1.12)[a]	89.28
2		100/(1.12) (1.12)[a]	79.72
3		100/(1.12) (1.12) (1.12)[a]	71.18
4		100/(1.12) (1.12) (1.12) (1.12)[a]	63.55
5			56.74
6			50.66
7			45.23
8			40.39
9			36.06
10			32.20

[a] *Multiplication with principal investment.*

discount rate, r. A positive NPV indicates that the total expected revenues exceed total expected costs, and suggests investment in the project. Similarly, a negative NPV will reject the project investment proposal. NPV = 0 is the breakeven point of a **no loss no gain** situation. Hypothetical cash flow data are computed in Table 11.6.

$$\begin{aligned}
\text{NPV} &= (-5) + (-10/1.1) + \left[(-20)/(1.1)^2\right] \\
&\quad + \left[(-20)/(1.1)^3\right] + \left[(5)/(1.1)^4\right] \\
&\quad + \left[(10)\Big/(1.1)^5\right] + \left[(20)\Big/(1.1)^6\right] \\
&\quad + \left[(20)/(1.1)^7\right] + \left[(30)/(1.1)^8\right] \\
&= -5 - 9.09 - 16.53 - 15.03 + 3.42 \\
&\quad + 6.21 + 11.29 + 10.26 + 16.33 \\
&= 1.86 \text{ million } \$ \text{ (marginal case)}
\end{aligned}$$

A positive NPV means a better return on investment. A negative NPV is a bad return, worse than the return from zero NPV.

11.4.2.2 Internal Rate of Return Method

IRR or **discounted cash flow rate of return** or **rate of return** is an alternative method used to evaluate investment

TABLE 11.6 Cash Flow Data for a Hypothetical Mineral Project

Year	Revenues	Expenditures	Net Cash Flow[a]	Activity
0	0	5	−5	Reconnaissance
1	0	10	−10	Prospecting
2	0	20	−20	Detailed exploration
3	0	20	−20	Development
4	10	5	+5	Initial production
5	20	10	+10	Production at 50% capacity
6	40	20	+20	Production at full capacity
7	40	20	+20	Production at full capacity
8	60	25	+35	Increase production, ore-man-shift, and cost cutting

[a] *Net cash flow in million US\$ = Revenues (earnings) − Cost (expenditures).*

opportunities. It is applied in capital budgeting to measure and compare project profitability. The principle and computation are similar to NPV. IRR is defined as the discount rate that equates the total discounted income with the total discounted costs of a project over the life period. It is the rate of return at which NPV equals zero.

$$\mathrm{NPV} = \sum_{n=0}^{n} \left(C_n/(1+R)^n = 0\right)$$

where C_n is the cash flow related to a particular period (n) usually in years (0, 1, 2, …, n)

or

$$\begin{aligned} \mathrm{NPV} &= 0 \\ &= (R_0 - C_0) + \frac{(R_1 - C_1)}{(1+\mathrm{IRR})} + \frac{(R_2 - C_2)}{(1+\mathrm{IRR})^2} \\ &\quad + \cdots \frac{(R_n - C_n)}{(1+\mathrm{IRR})^n} \end{aligned}$$

where R and C are revenues and costs, respectively, over the life of a project in year 0 through n. The investor accepts the project with IRR greater than its minimum acceptable rate of return. The IRR for the project data in Table 11.6 has been computed as 10.93%, greater than the discount rate of 10% assumed for accepting the proposal. The IRR value obtained is zero if and only if the NPV is zero. NPV and IRR yield the same conceptual decision of accept or reject for investing in a new project proposal. NPV and IRR are computed by numerical or graphical methods.

11.5 SOURCES OF INVESTMENT RISK

Activities and associated risks in the mineral sector are looked at in three broad ways, and are addressed for project evaluation and due diligence:

1. Scientific/technical aspect:
   a. Geological uncertainties: ore reserves and grade:
      - Reconnaissance (blind investment—success rate is 1 in 100 and even 1000).
      - Prospecting (ray of hope—success rate is 1 in 10−100).
      - Detailed exploration (better—success rate is 1 in 1−10).
      - Adequacy of drilling and core recovery.
      - Accuracy of sampling, assaying, and interpretation.
      - Check studies through quality control and quality assurance.
      - Mining: Selection of mining method and rate of production.
      - Mineralogical control on metallurgical responses of ore.
      - Equipment: Capital and operating costs, reliability, spares, and supplies.
      - Processing and extraction planned along with time component.
      - Environmental due diligence.
      - Magnitude of investment progressively increases and necessitates safeguarding.

- **b.** Staff competency:
  - Competency at all levels of technical, economic, commercial, and managerial staff of the highest standard.
- **c.** Economic viability:
  - Decision assumed to occur with certainty at the time of investment.
  - Revenue judged under ideal conditions without future variations of diversified activities responsible for discovery of deposit to marketing of end product.
  - Adverse change of even one variable upsets the entire decision of "win" or "lose."
  - Inherent risk to be addressed properly.

2. Market aspect:
- **a.** Variation in demand/supply scenario.
- **b.** Lower prices than expected.
- **c.** Foreign exchange rate on import and export of machineries and commodities.
- **d.** Future inflation.

3. Sociopolitical aspect:
- **a.** Future vision and commercial necessity for development of the country.
- **b.** Property transaction.
- **c.** Legal aspects.
- **d.** Export/import philosophy of the country.
- **e.** Political stability/instability of the government.
- **f.** Will of the government.
- **g.** Bureaucracy in licensing.
- **h.** Work culture and labor unrest.
- **i.** Sensitive environmental and forest issues.
- **j.** Excessive royalties, taxes, and other regulatory policies.

11.6 INVESTMENT RISK AND SENSITIVITY ANALYSIS

The undiscounted (payback period and AARR) and discounted (NPV and IRR) methods of evaluating mineral property for investment decision were assumed to occur under certainty at the time of investment. Cash flow is judged under ideal conditions without considering future variations for a series of diverse activities responsible for discovery of a deposit for the marketing of end products. Adverse change of even one variable will upset the entire decision for a profitable (win/win) or loss-making (lose/lose) venture. Therefore the inherent risks associated with the mineral industry have to be addressed properly. Adequate safeguards are to be taken well in advance to protect the investment and divert it to alternative opportunities.

There are technical risks during the exploration regime, including inadequacy of drilling, inaccuracy of sampling/analysis, unreality in interpretation, error in estimation of ore reserves and grades, selection of incorrect mining method, rate of production, process route, and extraction planned along with the time component. Market, economic, and business risks depend on variation in the demand/supply scenario, lower metal prices than expected, and change in foreign exchange rate on import and export of machineries and commodities. Political risks include instability of government, bureaucracy in licensing, labor unrest, sensitive environmental and forest issues, excessive royalties and taxes, and other regulatory policies. These factors will influence costs and revenues adversely.

The degree of uncertainty will vary between safe, low-, and high-risk investments. Investors in the high-risk category have to be compensated with additional premiums in profitability. Commonly used methods to minimize the risk are in a combination of gradually increasing or decreasing discount rates of individual variables while valuating future costs and revenues. If the discount rate is increased in steps, a set of cash flows will be generated that are negative in the beginning and generally positive at the end of the life of the mine. The resulting NPV will also gradually reduce to negative passing through zero (Table 11.6). The NPV is substantially and marginally positive at 10% and 13% discount rate. It changes to low and high negative at 16% and 20% discount rate. Investors have to accept or reject the project proposal based on their perception of risk absorption.

A second risk analysis method is to adjust cash flow by reducing the revenue by risk-free 10% over the base case with the discount rate unchanged at 10% (Table 11.6). This will provide a risk-adjusted NPV of (−) 4.94 with more certainty to reject the investment opportunity.

The third and most accepted method is **sensitivity analysis**. In addition to computing NPV using the most likely future cash flows, the sensitivity analysis method calculates a series of possible outcomes considering all possible variations of each variable and in combination. The outcome forms a corridor of cash flow analysis and NPV reflecting the best and worse combinations. The analysis identifies the critical variables, such as increase in capital and operating costs, capacity utilization, and decrease in grade, tonnage, and metal price that are sensitive to NPV and influence it most. Those critical variables are reviewed carefully to improve reliability for less risky decisions. Sensitivity analysis has been exemplified from Table 11.7 by three alternative scenarios: the base case (standard and simple), upside or best case (most optimistic), and downside or worse case (most pessimistic). NPV in the three options varies widely with expected high profit and high loss. Investors have to decide their game plan. It may so happen that all three scenarios would have been either positive or negative NPV, and then the decision would be straightforward.

TABLE 11.7 Risk Adjustments in Net Present Value (NPV) Computation

Adjust the Discount Rate	
Discount Rate (%)	**NPV (million)**
10 (risk free)	US$3.68
13	US$0.56
16	US$−2.03
20	US$−4.74

	Revenues		Expenditure		Net Cash Flow	
Year	**Unadjusted**	**Certainty Equivalent**	**Unadjusted**	**Certainty Equivalent**	**Unadjusted**	**Certainty Equivalent**
Adjust the Cash Flows						
0	0	0	5	5	−5	−5
1	0	0	10	10	−10	−10
2	0	0	20	20	−20	−20
3	10	9	5	5	+5	+4
4	20	18	10	10	+10	+8
5	40	35	20	20	+20	+15
6	40	34	20	20	+20	+14

NPV @ 10%	
Unadjusted	US$3.68 million
Certainty equivalent	US$−4.74
Sensitivity analysis	NPV (discount at 10%)
Upside case (increase revenue by 10%; reduce costs by 10%)	US$17.02 million
Base case	US$3.68 million
Downside case (reduce revenue by 10%; increase costs by 10%)	US$−8.93

Table format of Gocht et al. (1988) and computation by author.

11.7 ECONOMIC EVALUATION OF MINERAL DEPOSITS

Economic evaluation of mineral deposits at any stage of exploration and development is assessed based on technical (geology, mining, processing, and extraction), economic (cash flow, NPV, IRR, risk, and sensitivity), and sociopolitical needs. The degree of precision of evaluation depends on the adequacy of information gathered and due diligence at that point of the operation (Rudawsky, 1986; Sinclair and Blackwell, 2002; Wellmer, 1989). The following information is collected during geological (G), feasibility (F), and economic (E) studies:

1. Geological stage (G):
    - **a.** Location and access of the deposit.
    - **b.** Terrain.
    - **c.** Climate.
    - **d.** Regional and deposit geology.
    - **e.** Regional and deposit structure.
    - **f.** Country rocks and mineralogy.
    - **g.** Host rock and mineralogy.
    - **h.** Rock quality and strength.
    - **i.** Adequacy of drilling and core recovery.
    - **j.** Sampling, assaying, and interpretation.
    - **k.** Geotechnical characteristics of host rock.
    - **l.** Geohydrological characteristics of host rock.
    - **m.** Shape and size of the deposit.
    - **n.** Global tonnage and grade estimates with categorization.
2. Feasibility stage (F):
    - **a.** Infrastructural facilities.
    - **b.** Mining method planned.
    - **c.** Mining recovery and ore loss.
    - **d.** Mine entries—adits, inclines, ramps, shafts.

- **e.** Mine capacity.
- **f.** Mine dilution.
- **g.** Annual ore:waste ratio.
- **h.** Production schedule and mine life.
- **i.** Metallurgical test results.
- **j.** Metallurgical recoveries.

3. Economic stage (E):

- **a.** Market factors:
  - General economics.
  - Market competition.
  - Short- and long-term demand/supply trends.
  - Short- and long-term price fluctuation at the London Metal Exchange (LME).
  - Short- and long-term price fluctuation of foreign exchange.
  - Equipment availability.
  - Raw material availability.
- **b.** Cost factors:
  - Total investment required.
  - Capital expenditure (CAPEX).
  - Operating expenditure (OPEX)—mine/mill/smelter/refinery.
  - Transportation costs.
  - Tax and royalty.
  - Interest rate.
  - Depreciation criteria.
  - Cash flow.
  - Profit and loss.
- **c.** Government factors:
  - Foreign direct investment.
  - Mineral leasing policy.
  - Legal aspects.
  - Labor policies.
  - Environmental and forest policies.
  - Infrastructural support.
- **d.** Social factors:
  - Sustainability.
  - Infrastructure.
  - Human Resources Development (all categories and levels).
  - Safety regulations.
  - Education and vocational training.
  - Health care.
  - Industrial relations.
  - Social obligations.

11.7.1 Evaluation Process

Additional significant economic factors for understanding and evaluating a mineral/mine project are:

1. Gross in situ value

In situ valuation is a straightforward method of valuing mineral deposits. The in situ metal content is the product of geological reserves (Measured + Indicated + Inferred) and % metal grade of all commodities, including value-added elements like Au, Ag, PGE, etc. present in the deposit. Gross in situ value is the sum of each in situ metal content and respective metal prices.

2. Mining and milling losses

Mining and milling losses are due to the metals being left behind as pillars, grade dilution by mining of waste or low-grade material, and incomplete metal recovery during beneficiation. The value of the reserves blocked in pillars is added to revenue as and when recovered later. Recovery decreases with the complexity of the orebody and mineralogical control on metallurgical responses. In general, mining and beneficiation recoveries vary between 75% and 90%.

3. Smelting and refining charges

The value of the concentrate produced at the mine head is determined after subtracting the metallurgical losses during smelting and refining, treatment charge per tonne of concentrate, refining charges per tonne of contained metal, credit for precious metals, and penalty for deleterious contaminants. The metal loss, treatment charge, credit, and penalty will vary between metals.

4. Transportation cost

The cost of concentrate transportation from the mine head to the smelting point is deducted while valuing the concentrate. The transportation cost is a function of the distance to be transported, number of transfer points, and mode of shipment such as road, rail, or sea.

5. Capital expenditure

Capital cost or CAPEX is fixed assets or costs added to the value of an existing fixed asset like buildings, equipment, and other permanent facilities with a useful life extending beyond the taxable year. CAPEX includes all costs incurred and likely to be incurred up to production from the project. Capital investment includes exploration and delineation, mine development, utility plants, cogeneration plants, concentrate extraction/tailing management, infrastructure, upgrading facilities, environmental monitoring, turnaround, research, and miscellaneous items not associated with a specific category.

Preproduction capital components are development of physical facilities such as mine access systems (incline, shaft, ramp), mine and process equipment, workshops, stores, offices, townships, schools, human resource development, vocational training centers, industrial safety, community health care, and recreation. There are other essential infrastructures such as road, rail, power, and potable and industrial water.

The working capital component is a revolving fund required to operate the mine and process plant. The amount is returned as positive cash flow at the end of the life of the mine.

Sustaining capital is required for timely replacement of equipment and any other anticipated major modification in the mine and mineral processing system.

6. Operating expenditure

Operating cost or OPEX is the ongoing cost for running the system. OPEX is the cost of production per tonne of run-of-mine ore, waste, concentrates, and overheads. The operating cost relates to two components: fixed and variable. Fixed costs are the salary and amenities paid to the employees, property taxes, license fees, and overheads. Variable costs are directly associated with mining and processing activities for producing the ore, waste, and concentrates. Variable costs include all raw materials and consumables, power, water, chemicals, maintenance, royalties, and taxes. The annual operating costs will change with the volume of production. The operating cost will have a positive or negative effect under excess or low production on installed capacity.

7. Revenue and income

Revenue or turnover or sale or gross sale refers to all the money the project receives for the value of products or services to the customer during the life of active operation. Revenue at the mine head is the tip line of cash flow computation associated with the anticipated development of the mineral deposit.

Net income refers to profit and represents the amount of money the company has left over, if any, after paying all costs of production, payroll, raw materials, taxes, interest on loans, etc.

8. Inflation

Inflation is a rise in the general level of prices of capital and consumable goods and services over a period of time. It has a direct effect on economy and profits. The capital and infrastructure may be replaced at a later time with much higher costs. The inflation of consumables and services is a regular phenomenon in all activities at a rate between 5% and 10% (Fig. 11.2). An abrupt high rise in inflation due to whatever reasons renders adverse effects on the market economy with falling purchasing capacity for the general population. Many mining companies struggle with sharp increases in labor, energy, and raw material costs. The possible effect of inflation must be incorporated while evaluating the profit and loss of the project proposal.

9. Depreciation

Depreciation is the spread of CAPEX or assets over the span of project life, and is generally at a straight-line method of 10% or equal sum. The assets include machinery and permanent infrastructures, including entry systems like shafts. It is the method of reduction in the value of the asset across its useful life. The depreciation amount is deducted from the taxable income. Some mining companies follow accelerated depreciation of 20%—30% in the initial years for tax benefits. The depreciated sum is added back to the cash flow after tax deduction as it does not account for an actual flow of funds into or out of the project.

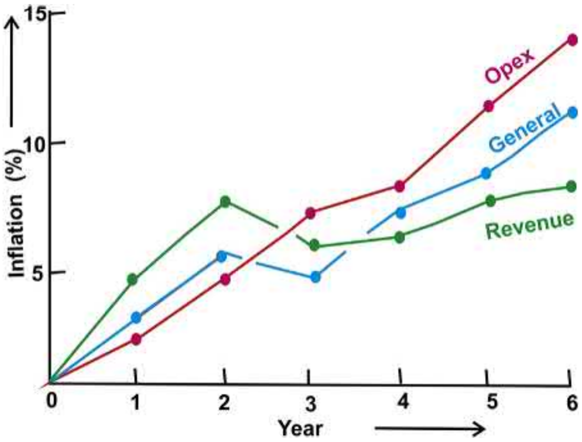

FIGURE 11.2 Differential inflation pattern of revenue, operating costs, and general services.

10. Depletion

Depletion is the value of ore (capital asset) mined each year and deducted from the taxable income. The depleted fund is added back to the after-tax cash flow on a similar ground of depreciation. The deduction of depreciation and depletion allowances from the taxable income reduces the effective tax rate and acts as relief or incentive to the investors.

11. Amortization

Amortization is the loan repayment instalment model consisting of both principal and interest. The simplest computation involves division of total amount by number of instalments for the duration of the loan period. The amount of the instalment gradually reduces over time due to lower proportion of interest on unpaid principal. Negative amortization or deferred interest is a complex process of repayment that does not cover the interest due. The remaining interest owed is added to the outstanding loan balance.

12. Mineral royalties

Mineral royalties are paid to the state/regional government by the mine owners once commercial production starts. Mineral production royalties follow one of four basic forms: (1) a flat rate unit of production royalty, (2) a gross or net smelter return royalty, (3) a net revenue royalty, or (4) a net profits royalty. The rate of royalty varies widely from country to country and mineral to mineral. **Ad valorem royalties** are levied as a percentage of the total value of minerals recovered or the ex-mine value.

TABLE 11.8 Annual Cash Flow Diagram in $

Item Head	Action
Gross sales revenue	(−) Transportation, smelting/refining, and downstream ore processing charges (−) Royalties (−) Less operating costs
Net operating revenue	(−) Noncash items (−) Depreciation (−) Depletion (−) Amortization
Net taxable income	(−) Taxes (+) Credit
Net income after tax	(+) Noncash items
Net operating cash flow	(−) Capital costs (initial and sustaining) (−) Working capital (−) Exploration costs (−) Acquisition costs (−) Land payments
Net cash flow	Investment decision, financial statement

13. Taxation payments
Tax payments are deducted as per corporate income tax to get an estimated time distribution of after-tax cash flow. The taxation rates vary widely between countries.

14. Cash flow
Cash flow is the movement of money into or out of a project. The cash flow statement or funds flow statement is financial accounting in the balance sheet showing the flow of cash in and cash out of the project. A schematic cash flow statement is given in Table 11.8.

The evaluation of a mining project under consideration determines the possibility of mining explored economic mineral reserves. The outcome will indicate either: (1) proceed to the next stage of detailed activities along with investments, or (2) withdraw from the venture. There are three mining investment evaluation models based on stages of exploration, resources/reserves adequacy, and project status. The studies include: (1) order of magnitude feasibility or scoping study, (2) prefeasibility study, and (3) feasibility study.

11.7.1.1 Order of Magnitude Feasibility or Scoping Studies

The **order of magnitude feasibility** or **scoping studies** are initial financial appraisals of indicated mineral reserves and resources. The scoping study is suitable for exploration projects under a reconnaissance permit and more often under a prospecting license. It is a conceptual type based on assumptions to decide further detailed exploration. One has to be optimistic regarding reserves and grades, mining and milling recoveries, and costs and revenues in contrast to very precise large volumes of actual test data. Information on detailed engineering design, mining method and beneficiation, and operating and capital costs is borrowed from experience, reports, case studies, and published literature on similar types of deposits. This type of economic review being conducted during exploration tenure forms a groundwork and acts as an excellent guide to improve the area of information base. The main purpose is to generate the capability of the investor for a **go or no-go decision**. The scoping study is reliable within 40%−50%. An order of magnitude study of a base metal deposit during exploration stages is discussed in Section 11.8.

11.7.1.2 Prefeasibility Study

The prefeasibility study is a detailed approach to firmer and more factual information with well-defined ore geometry, sampling and assaying with due diligence, reserve and grade with higher confidence at ∼80% accuracy, availability of infrastructure, proposed mining plans with scale of production, operating cost and equipment (not detailed engineering), bench-scale mineral process route, economic analysis, including sensitivity tests, environmental impact, and legal aspects. Experimental mining by opening a small pilot pit or developing a cross-cut underground for collecting representative samples, ore dressing pilot plant tests using bulk samples, and other relevant detailed information may be required as a follow-up. The prefeasibility study gives a more reliable picture of project viability with 70%−80% reliability. The project is either under a mining lease or ready to apply.

11.7.1.3 Feasibility Study

The feasibility study is the final phase of target evaluation based upon sound basic data with much greater detailed analysis of the property toward development of mine and plant leading to regular long-term production. All previous estimates are modified and finalized with the availability of every detail on geology, engineering, and economics. The majority of the ore reserves and grades are in the Partly Developed, Proved, and Probable category. The detail engineering on mining methods and beneficiation plant have been completed. The capital and operating costs are set. Cash flow analysis with NPV, IRR, and sensitivity to different assumptions regarding revenues, costs, discount rates, inflation is realistic and more authentic. Environmental impact and government formalities are expected to be cleared. The economic viability of the project is assured within 85%–90%. In fact, the feasibility report acts as a bankable document for sources of finance from potential financial institutions, equities, and joint ventures. The projects are often listed on the standard stock exchanges.

11.8 CASE STUDY OF ECONOMIC EVALUATION

11.8.1 A Zinc-Lead Project

The integrated geological, geophysical, and geochemical survey supported by drilling during the 1990s established a high-grade steeply dipping zinc deposit in India with 9 Mt of reserves at 15% Zn + Pb + Ag. Lithology structure-controlled mineralization occurs in graphite mica schist, calc-silicate, and quartzite, intruded by pegmatite. Pyrrhotite is predominant, followed by sphalerite, galena, pyrite, and chalcopyrite in decreasing abundance. Mining is only feasible by the underground method. An order of magnitude study (Fig. 11.3A and Table 11.9) conducted during 1995 at US$1100 per tonne metals ended with a high NPV of US$107 and US$34 million before and after tax.

Subsequent close-space drilling during 2000 split the orebody geometry and outlined three deep-seated en-echelon lenses separated by large waste partings. While the metal grades remain unchanged the reserve has been estimated at 3 Mt at 13% Zn, 2% Pb, and silver. Mine life is reduced from 24 to 8 years. NPV, at US$1200 per metric tonne metal, changed to US$14 and US$1 million before and after tax due to a major reduction of ore reserve (Fig. 11.3B and Table 11.9). The economic valuation at that time (2000) suggested that the deposit is sensitive to ore reserve and other technical parameters. The project is marginally viable and needs a more critical approach in decision-making.

Exploration continued in the deposit due to high metal content and higher metal price during 2009-2011. Hindustan Zinc Limited completed 53,000 m of surface drilling in 169 holes during the same period, and established 10.6 Mt at 10.6% Zn and 1.6% Pb (Kavdia et al., 2011). Metallurgical tests showed that the ore was amenable to conventional flotation and two stages of cleaning to produce a zinc concentrate grade of 53.5% Zn at 88% recovery, and lead concentrate grade of 63.8% Pb at 72.5% recovery. LME metal prices stood at US$1850/tonne for zinc and US$2000/tonne for lead (January 2012). The investment strategy competently changed in 2012 to mine the deposit with an additional premium of silver recovery. Status was concluded as a greenfield project, underground sublevel mining at ~US$12 million CAPEX at 0.35 Mt/annum ore production capacity, and 17-year mine life since 2014 (Box 11.1).

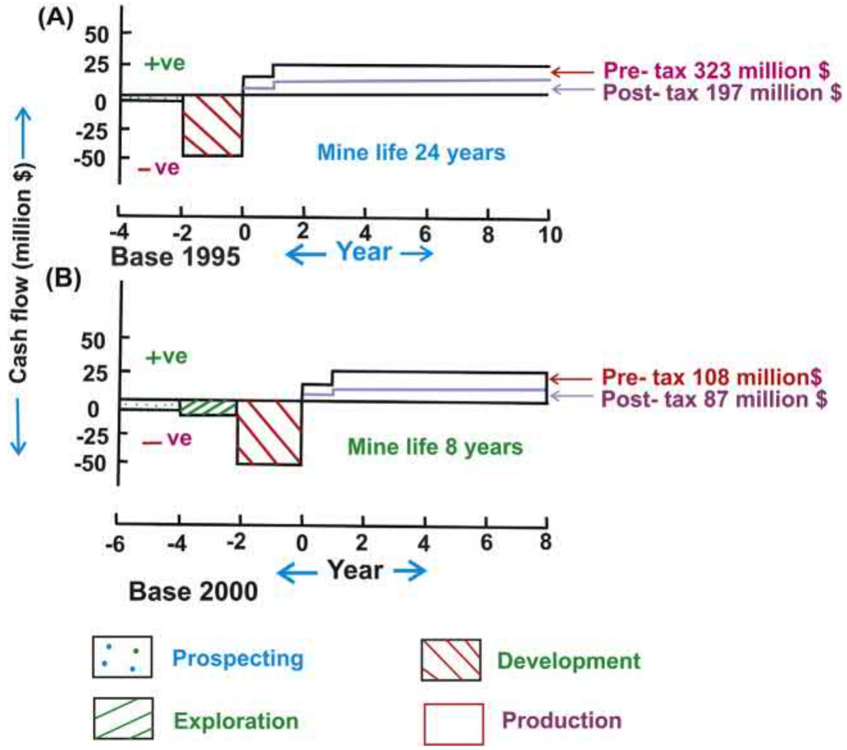

FIGURE 11.3 Phasing of investment and cash flow distribution of an exploration project during (A) 1995 and (B) 2000.

TABLE 11.9 Order of Magnitude Economic Study of a Zinc Deposit on Phased Exploration

	Parameters	Unit	A. 1995 Base	B. 2000 Base
	Ore reserves	(Mt)	9	3
	Grade (Zn + Pb) + Ag	%	13.28	15
	Mine capacity	(tpa)	300,000	300,000
	Mining recovery	(%)	80	80
	Mine life	Year	24	8
	Mine dilution	%	15	15
	Concentrate grade	%	52	
	Operating cost/tonne	$	40	
	Capital cost (CAPEX in million)	$	50	
	Treatment charges/tonne concentrate	$	180	
	Metal price	$	1100	1200
	Particulars		Million $	Million $
1	Gross in situ value			
	Zinc equivalent metal		1341.01	447
2	a. Mine and milling loss		377.92	126
	b. Smelting and refining charges		399.38	133
	c. Concentrate handling and transport cost		36.66	36.66
	d. (a + b + c)		813.96	271
3	Revenue at mine head (1–2)		527.05	176
4	a. Operating cost		189.85	63
	b. Capital sustaining cost		14	5
	c. Total (a + b)		203.85	68
5	Gross income (3–4)		323.20	108
6	Depreciation allowance		50.00	50
7	Taxable income (5–6)		273.20	58
8	Tax at 46%		125.67	27
9	Net income (7–8)		147.53	37
10	Cash flow			
	a. Before tax (5)		323.20	108
	b. After tax (6 + 9)		197.53	87
11	Capital costs		50.00	50
12	Exploration cost		1.30	2.30
13	Net present value			
	a. Before tax		107.17	13.69
	b. After tax		33.64	1.06
14	Remarks on investment		Viable	Marginal

BOX 11.1 Lesson

The lesson one learns from the foregoing comparative economic valuation of the same deposit at different stages of exploration reveals that investment decision is significantly sensitive to size and grade, mining method, process recovery, and metal price. Explored mineral deposits are never rejected, but shelved for the next opportunity.

11.8.2 A Zinc-Lead-Copper Silver Project

A massive polymetallic sulfide ore deposit in Mexico is exposed over 700 m in a NW—SE direction and dips 70° → SW, with a width ranging between 5 and 30 m, averaging 10 m. A large area of mafic volcanic rocks and associated fine sediments lies in contact with an irregular quartz-feldspar-porphyry intrusive. Systematic exploration established ore reserves of 2.4 Mt at 6.76% Zn, 2.95% Pb, 0.35% Cu, and 65.6 g/t Ag. The main ore horizon is accessed and developed through an adit and underground shaft. Mine production has been set at 2000 tonnes per day or 730,000 tonnes per annum for a 3.4-year mine life. Metallurgical recoveries were tested at 88.7% Zn, 86.3% Pb, 60.4% Cu, and 68.5% Ag. Total metal production has been estimated at 145,300 tonnes of zinc, 61,600 tonnes of lead, 5100 tonnes of copper, and 3.5 million oz of silver. The order of magnitude study is given in Table 11.10 for investment decision.

A comparative statement of cash flow on different alternatives is presented in Table 11.11 to attain the best option.

TABLE 11.10 Scoping Study and Financial Model of Polymetallic Zinc-Lead-Copper-Silver Deposit

Parameters	Unit	Total
Mining and Processing		
Ore reserves	Mt	2.42
Ore mined	Mt	2.42
Ore milled	Mt	2.42
Waste	Mt	0.56
Zinc grade	%	6.76
Lead grade	%	2.95
Copper grade	%	0.35
Silver grade	g/t	65.6
Contained zinc	Million lb	361.07
Contained lead	Million lb	157.38
Contained copper	Million lb	18.50
Contained silver	Million oz	5.11
Mine production and milling	At 2000 tpd/730,000 tpa/365 days	
Mine life	3.4 years	
Zinc Concentrate		
Zinc recovery	%	88.7
Zinc concentrate production	Tonnes	270,023
Zinc concentrate grade	%	53.8
Zinc contained in concentrate	Million lb	320.271
Lead Concentrate		
Lead recovery	%	86.3
Silver recovery	%	68.5
Lead concentrate production	Tonnes	123,212
Lead concentrate grade	%	50
Lead contained in concentrate	Million lb	135.818
Silver contained in concentrate	Million oz	3.499

Continued

TABLE 11.10 Scoping Study and Financial Model of Polymetallic Zinc-Lead-Copper-Silver Deposit—cont'd

Parameters	Unit	Total
Copper Concentrate		
Copper recovery	%	60.4
Copper concentrate production	Tonnes	22,043
Copper concentrate grade	%	23
Copper contained in concentrate	Million lb	11.18
Payable Metals in Concentrate		
Zinc	Million lb	272.23
Lead	Million lb	129.03
Silver	Million oz	3.32
Copper	Million lb	10.79
Income Statement		
Metal Prices		
Zinc	$/lb	1.13
Lead	$/lb	0.85
Copper	$/lb	2.78
Silver	$/oz	12.61
Revenues		
Zinc	Million $	307.62
Lead	Million $	109.67
Copper	Million $	29.99
Silver	Million $	41.91
Total revenues	Million $	489.19
Total capital costs (CAPEX)	Million $	219.07
Cash Operating Costs (OPEX)		
Mining	Million $	74.39
Process plant	Million $	28.13
General administration	Million $	11.21
Zinc concentrate treatment charge	Million $	55.36
Shipping	Million $	20.41
Lead concentrate treatment charge	Million $	19.71
Shipping	Million $	5.99
Silver refining	Million $	1.40
Copper concentrate treatment charge	Million $	1.32
Shipping	Million $	1.55
Total cash operating costs (OPEX)	Million $	219.47
Depreciation for 4 years (CAPEX)	Million $	219.07
Total production costs	Million $	438.54
Income from operations	Million $	50.65
Taxes at 28%	Million $	35.23
Net income after taxes	Million $	15.42

CAPEX, capital expenditure; *OPEX*, operating expenditure.

TABLE 11.11 Net Cash Flows at Different Alternatives

Year	Status	Revenue (Million $)	Net Cash Flow Before Depreciation and Tax (Million $)	Net Cash Flow Before Tax (Million $)	Net Cash Flow After 28% Tax (Million $)
0	CAPEX	(–) 219.07	0	(–) 219.07	(–) 219.07
1	Production	54.78	28.61	(–) 26.15	(–) 26.15
2	Production	196.93	105.60	50.84	36.60
3	Production	227.83	129.74	74.98	53.98
4	Production	9.65	3.75	(–) 49.01	(–) 49.01
Total		489.19	267.70	50.66	15.42
Payback period					2.9 years
IRR %			122.2	23.11	7.04
NPV at 10%			213.3	41.1	13.57

CAPEX, capital expenditure; *IRR*, internal rate of return; *NPV*, net present value.

The project is sensitive to low ore reserves and short mine life. Increasing the ore reserves from nearby deposits with further exploration will open an opportunity for extended mine life to take advantage of lower unit capital costs. The investment can be attractive by adding back the depreciation allowances to the after-tax fund.

11.9 SUMMARY

Investment in a mining project is a challenging opportunity with associated risks at every phase of the mineral supply process. The degree of risk varies with highest in the reconnaissance and prospecting stages due to inadequate information about the deposit. The investor has to accept the total risk of project failure during this phase as the probability of success of discovery of an economic deposit is very low. So the investor has to be judicious and may look for alternatives before stepping into a risk-prone venture. However, once the deposit is properly delineated with confidence and an investment decision is taken the risk shifts from geological aspects to technical, engineering, and managerial skills. This includes selection of technology, mine design, production capacity, time, and cost overrun. The project is exposed to various risks such as optimization of productivity, scheduling, price cycles, and other market factors during operating tenure. These risks can be conceptualized and minimized through adequate initial investment in a sequential manner toward generation and economic evaluation of information considering all expected sensitive issues.

The mineral deposits are immobile by nature, and continue to deplete unlike in agriculture. Mineral exploration should continue to find new deposits and develop to supply ore at increasing capacity and higher cost for future generations. The following are ideal parameters worth considering for a mineral deposit; however, they infrequently happen in real life:

1. Large size and high grade.
2. Easily accessible.
3. In great demand.
4. Favorable location at surface or shallow depth for low-cost open pit mining.
5. Strategic national importance.

Mineral economics plays a significant part by using various economic tests and sensibility analyses, and identifying the differential inflation patterns of recovery efficiency in mining, beneficiation, smelting, refining, revenue, operating costs, and general services.

A checklist of information collection norms for investment in new mineral projects is given in Table 11.12.

TABLE 11.12 **Checklist for Investment in a New Mineral Deposit**

1. **Deposit identity**
    - **a.** Name of the mineral deposit:
    - **b.** Country/state/province/district:
    - **c.** Location:
    - **d.** Nearest airport/seaport/railhead:
    - **e.** Approach road condition:
    - **f.** Climate:
    - **g.** Average rainfall:
    - **h.** Groundwater table:
    - **i.** Leasehold/freehold:
    - **j.** Licensing policy (RP/PL/ML)—transparent?
2. **Surface type**
    - **a.** Topography: plain land/undulation/hill:
    - **b.** Barren/vegetation/forest cover:
    - **c.** Mostly soil or rock cover:
    - **d.** Weathered/fresh surface:
    - **e.** Government or private land:
    - **f.** Any surface indication of mineralization:
3. **Brief geology**
    - **a.** Availability of geological map:
    - **b.** Regional geological setting:
    - **c.** Deposit geology:
    - **d.** Country rocks and host rock(s):
    - **e.** Regional/deposit structure:
    - **f.** Deformation:
4. **Deposit/mineralization**
    - **a.** Plan area covered by deposit:
    - **b.** Deposit boundary well defined?
    - **c.** Strike length:
    - **d.** Average width and range:
    - **e.** Vertical extension:
    - **f.** Exposed to surface/concealed in depth:
    - **g.** Dip of the orebody:
    - **h.** Rock-forming minerals:
    - **i.** Ore-forming minerals:
    - **j.** Gangue minerals:
    - **k.** Principal economic mineral(s):
    - **l.** Associated by-product mineral(s):
    - **m.** Economic trace elements:
5. **Exploration inputs**
    - **a.** Details of soil/rock samples:
    - **b.** Pits and trenches:
    - **c.** Chips and channel samples:
    - **d.** Number of boreholes drilled and interval:
    - **e.** Core recovery:
    - **f.** Borehole survey:
    - **g.** Average hole depth and drill interval:
    - **h.** Standard of laboratories where analysis undertaken:
    - **i.** List of elements analyzed:
    - **j.** Methods and instruments used for analysis:
    - **k.** % of duplicate samples cross-checked with actual record of deviations between original and duplicate values:
6. **Ore reserve/resources**
    - **a.** Reserve estimation methods followed:
    - **b.** Estimation cross-checked by other method:
    - **c.** Total reserve estimated:
    - **d.** Categorization of reserves (Proved/ Probable/ Possible) and proportion:
    - **e.** Average grade of the deposit with range (all commodities such as %Pb, %Zn, %Cu, Ag (g/t), Au (g/t), etc.:
    - **f.** Quantity of "float ore and average grade":
    - **g.** Plan area covered by float ore:

Continued

TABLE 11.12 Checklist for Investment in a New Mineral Deposit—cont'd

7. **Beneficiation test work**
   - a. Laboratory scale[a]
   - b. Pilot plant scale[a]
8. **Economic analysis**
   - a. Broad order of magnitude study conducted:
   - b. Scoping study/prefeasibility study conducted:
   - c. Feasibility study conducted:
9. **Infrastructure availability**
   - a. Power grid:
   - b. Water sources:
   - c. Modern workshop facility:
   - d. Housing:
   - e. Health care:
   - f. Educational and recreation facilities:
   - g. Shopping:
10. **Miscellaneous**
    - a. Political stability of the host country:
    - b. Relation between federal and state governments:
    - c. Will of each government:
    - d. Tax and royalty:
    - e. Skilled labor, policy, and work culture:
    - f. Environment and Forest Acts and Regulations:
    - g. Land protection for tribal inhabitants:
    - h. Environmental baseline and mining impacts:
    - i. Ecotourism:
11. **Special note**
    - a. Proposal for investment based on "in situ ore reserve" or "exclusively on float ore"?
    - b. Estimation actually on measured data or imaginary model?
    - c. Visit to any nearby mining activities possible?
    - d. Address/phone/email of geological survey of the country.

ML, mining lease; *PL*, prospecting license; *RP*, reconnaissance permit.
[a] *Result of test work if conducted: ore to concentrate ratio, concentrate grade, recovery.*

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Chapter 12

Elements of Mining

Chapter Outline

> *The principle of mining is not to maximize ore production but to aim at zero waste generation with long-term sustainable development for nonrenewable wasting assets.*
>
> Author.

12.1 DEFINITION

Mining is the process of excavating ore minerals along with minimum waste rocks from Earth's crust for the benefit of humankind. The activities consist of handling loose ground, drilling and blasting of hard rocks, removal of broken materials from the workplace, and supporting the ground for safe operations. Various mining methods are available to exploit different types of deposits (Deshmukh, 2010; Deshmukh, 2016a,b; Hartman and Mutmansky, 2002). The prime objective is to mine in the safest conditions and economically without sacrificing the interest of the conservation of minerals—a nonrenewable wasting asset. The choice of mining techniques depends on the following:

1. Nearness to surface.
2. Nature of overburden.
3. Shape, size, regularity, and continuity.
4. Strike, dip, thickness, and rock strength.
5. Nature of mineralization.
6. Host and wall rock condition.
7. Stripping/overburden and ore-to-waste removal ratio.
8. Possibility of minimizing internal and external dilution.
9. Availability of infrastructures.
10. Cost of mining and mineral dressing.

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00012-5

11. Production target and resource/reserve status.
12. Value of primary, associated commodities and value-added elements.

The first choice of hard rock mining is the adoption of open pit techniques if the orebody is exposed to or exists near to the surface. Underground mining methods are appropriate to that part of the orebody where open pit operation is uneconomic due to high ore-to-overburden ratio. Deep-seated deposits are exclusively mined by underground methods. An open pit mine continues and changes to the underground method at a later period if the orebody persists beyond the ultimate economic limit of the open pit option. Mining can be categorized as:

1. Small-/medium-/large-scale production.
2. Manual/semimechanized/fully mechanized operation.
3. State/private/joint venture ownership.

TABLE 12.1 Characteristic Features of Soft and Hard Rock Mining

Soft Rock Coal Mines	Hard Rock Metal Mines
Bedded, large horizontal extent, near uniform thickness, dip, and quality	Irregular in extent, thickness, shape, size, distribution, dip, and metal content
Sharp orebody contacts at footwall and hanging wall with waste rocks	Orebody contacts are generally defined by cut-off principles
RP, PL, ML at wide-spaced drilling, planning, 1–3 years development period	RP, PL, ML at close-spaced drilling, planning, 3–5 years development period
Limited sampling due to uniform nature of deposit	Detailed sampling from grassroots to throughout the life of the mine
Can accommodate minor surveying errors	High standard of surveying necessary to control undesired dilution
Soft rock mining often uses electrically operated drills	Hard rock mining requires compressed air power-driven drills
Simple mine design, <5% development in waste rock, less waste handling	Complex mining, +20% development in waste, more waste handling
Produce inflammable and explosive gas	Such problems are rare
Limited mechanization	High and sophisticated mechanization
In general, direct use of run of mine ore. Upgrade process is simple and handling of rejects is limited	Upgrade to concentrate by beneficiation and metal by smelting and refining. Tailing and slag disposal are critical

ML, mining lease; *PL*, prospecting license; *RP*, reconnaissance permit.

The underground soft rock mining of coal, lignite, rock salt, and potash possesses different characteristics to hard rock metal mining like iron ore, zinc-lead, copper, gold, chromium, platinum, uranium, and manganese (Table 12.1).

The mining methods are classified on the physical standing of surface and underground conditions. Underground methods are further divided into soft bedded deposits, hard veins, and massive type based on rock strength, mechanization, support system, and production capacity (Table 12.2).

12.2 SURFACE MINING

Surface mining is comparatively much cheaper than underground methods. It covers about 70% of global mineral production. The technique is most appropriate in case the orebody is either exposed or exists close to the surface. It can broadly be divided into several types depending on the nature of materials being handled. It can be unconsolidated placer (alluvial, colluvial, and eluvial deposits of gold, silver, tin, platinum, and gemstones), gravel and mineral sand, bedded coal seam, blanket-type bauxite, hard massive dipping copper, zinc and lead metals, iron ore, rock phosphate, limestone, marble, kaolin, and talc. The operation is manual digging with picks and hammers or advanced mechanized methods. The surface mining process deals with the removal of ore and large quantities of overburden in varying proportions. The ore-to-overburden ratio of bedded deposits is the proportion between the vertical thickness of the ore and that of the overburden. The ratio between ore mined and overburden actually removed is called the stripping ratio. The rule of thumb for planning ore and overburden ratio from past experience is assumed for a selected mining method as follows:

1. Manual quarrying-1:1.5.
2. Semimechanized quarrying 1:2.
3. Mechanized large-scale quarrying 1:4 to 10, and even occasionally >20 in the case of valuable noble metals.
4. Underground mining 1:<0.25, and further reduction with larger production.

12.2.1 Placer Mining

The placer deposits are loose unconsolidated and semi-consolidated materials. They are formed by surface weathering, erosion of the primary rocks, and the transportation and concentration of valuable minerals. The small deposits of gold, silver, tin, platinum, diamond, monazite, zircon, rutile, and ilmenite are common examples. These minerals are recovered by small-scale miners working in the informal sector often using primitive artisan mining techniques. The process involves digging and sifting through mud, sand, and gravel manually with bare hands or

TABLE 12.2 Classification of Stoping Methods by Physical Criteria, Rock Strength, Mechanization, Support System, and Production Capacity

Deposit Type/ Mining Methods	Strength and Support System	Mechanization and Capacity
Surface Mining—Open Pit		
Placer deposit	Loose sand, soft and unconsolidated, minimum support required	Total mechanization and high capacity—optional
Shallow deposit	Medium hard, waste backfill	Total mechanization and high capacity—optional
Massive deposit	Hard, massive, maximum waste backfill recommended	Total mechanization with high production capacity
Ocean bed mining	Soft and environment sensitive	High mechanization
Underground Mining Bedded Deposits		
Room and pillar mining	Medium, roof collapses, sand fill	Medium
Long wall mining	Medium, roof collapse, support by stone, sand, timber, and steel props	Total mechanization and very high capacity
Coal gas	Soft and medium, natural support	Low capacity
Coal bed methane	- Do -	Medium capacity
Shale gas	- Do -	Low capacity
Solution mining	- Do -	Low capacity
Underground Mining—Hard Rock		
Square set	Bad ground and pillar recovery, instant and total timber support	Labor intensive, high cost, low production
Shrinkage	Narrow steep veins, occasionally backfilling required	Less development, low mechanization, low ore-man-shift
Cut and fill	Bad ground, cable bolting, rib pillars, and cement mix backfill essential	Moderate mechanization and production
Sublevel	Steep and wide body, crown and sill pillars, occasionally fill support	Advanced mechanization and high production
Sublevel top slicing	- Do -	- Do -
Sublevellong hole drill	- Do -	Very high productivity
Vertical retreat mining	Massive orebody, mining in sequence of primary, secondary, and fill panels, and backfill essential	Advanced mechanization, low cost, large capacity, and high productivity
Block caving	Large, massive, conditional support	- Do -
Mass blasting	Pillars recovery, conditional support	- Do -

at best by using simple tools and equipment like shovels and sieves. This is similar to the cottage industries of rural areas and characterized by low productivity, lack of safety measures, high environmental impact, and low revenue for the government.

Production and productivity can be increased by bucket dredging with or without a centrifugal suction pump for large-sized properties of sand and gravel at sea coastal regions, and deep offshore and deeper seabed polymetallic nodules. The bucket dredge can operate down to 20—30 m. The modern dredge can produce between 600 and 1500 t/h. Mineral concentration is done with jigs, cyclones, spirals, and shaking tables. The bucket wheel excavator is appropriate for dry sand mining. The unit excavates mineral sand selectively, and continuously feeds the material to the hopper by a conveyor belt (Fig. 12.1).

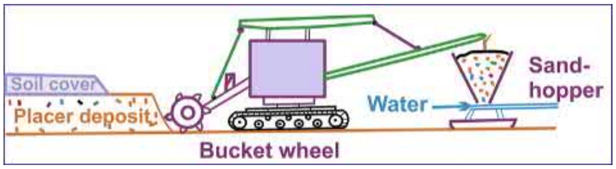

FIGURE 12.1 Schematic view of mechanized bucket wheel excavator in operation for beach sand mining to recover valuable minerals like gold, tin, diamond, monazite, zircon, rutile, and ilmenite.

12.2.2 Shallow Deposits

The strip mining process is suitable for fairly flat, shallow, single-seam coal, lignite, and other bedded deposits. The mineral layer is covered by an even thickness of overburden composed of soft top soil and weathered rocks in succession. The soft and unconsolidated overburden can be stripped and removed by dragline or shovel to expose a coal seam and metallic ore. The overburden might need drilling at grid spacings of 7.5 m × 7.5 m—15 m × 15 m depending on its hardness and thickness. The drill holes are charged with explosives and blasted. Production drilling and blasting continue in advance with the movement of dragline/shovel.

The surface soil is often stripped separately, removed, and dumped as stockpile. The excavators either dispose of the overburden to a suitable location for land reclamation or store the waste material for future backfill after the coal/minerals are removed. The top soil from the stockpile is spread back onto the reclaimed surface of the stripped mine. The new top soil is often protected by seeding or planting grass or trees on the fertilized restored surface. The coal/metallic ore is usually removed by an exclusive separate operation. It uses smaller drills capable of drilling entire thicknesses of the seam or at suitable bench height if necessary. The blast hole spacing must be closer than that of the overburden rocks. The process involves charging with ANFO explosive and light blasting. This will avoid pulverization of the coal. The broken coal or minerals are removed by shovel or front-end loader, crushed if required, screened to various size fractions, and transported to the beneficiation plant. The high wall of the mine opening is stable at 3 in 1, i.e., around 20 degrees from vertical. The lumpy stockpile heap of overburden waste is stable at 30—35 degrees for shale and 35—45 degrees for limestones and sandstones. All measurements are with respect to the horizontal surface. The total cycle of ore and waste mining is given in Fig. 12.2.

The overburden is removed by opening successive and progressive benches in the case of deep-seated bedded deposit within a permissible stripping ratio. It continues until sufficient area over the ore is exposed. Multiple seam mining is done by operating a first pair of overburden and coal beds, followed by second and third pairs in sequence. Finally, the total overburden rocks, stockpiled around the mine opening, is backfilled to reclaim the abandoned excavation.

12.2.3 Open Pit Mining for Large Deposits

The open pit or open cast mining method is the obvious choice for a property with a wide area of mineralization exposed or existing close to the surface and continuing to greater depths. The open pit exposes the orebody from the surface by separate removal of ore and associated waste rocks. It is the most economic option for a deposit up to that depth where the economic ratio of ore and waste can be sustained. There are many advantages to the open pit mining method, namely:

1. Full visualization of exposed orebody and negligible ore loss.
2. No ore reserve is blocked, except crown pillar at the ultimate pit bottom to continue to underground mining.
3. Greater concentration of operations, better grade control, and blending.
4. No need for artificial light in day shift, natural ventilation round the clock.
5. Greater safety, minimum mining hazards like gasification, roof and wall supports.
6. Easy draining of subsurface water.
7. No restriction on working with heavy and bulky machinery.
8. Lower capital and operating costs.
9. Minimum mine development work and higher ore-man-shift (OMS) leading to early production and quick return of capital invested (payback period).

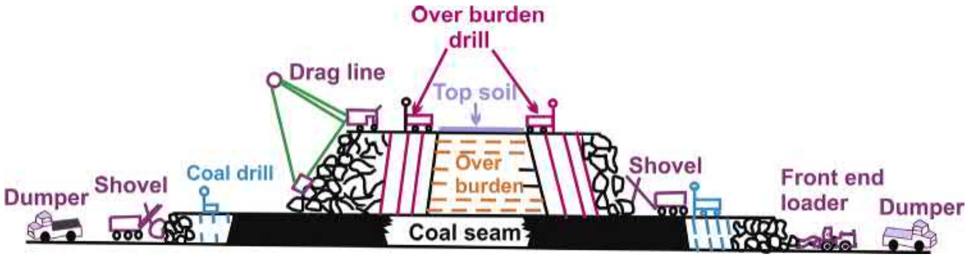

FIGURE 12.2 A schematic view of the complete operating cycle of mining for shallow-bedded deposits like coal and lignite seams.

The disadvantages are comparatively few

1. Acquisition of large surface right for open pit mining.
2. The land owners, often tribal population, and contractual farmers living within the Mining Lease area are rehabilitated and compensated by cash, separate housing, employment, health care, education, and other facilities.
3. Surface mining operations generate excessive waste rocks from overburden, footwall, and hanging wall. These huge waste rocks need to be removed carefully, transported and stacked by scientific and systematic manner at safe location.
4. Loss of production due to extreme summer and winter rain, and snow.

A short- and medium-term plan within the framework of a long-term plan is prepared based on surface topography and 3D configuration of the orebody with respect to its shape, size, inclination, depth, grade distribution, hydrology, etc. The first task in open pit mining is to remove the top soil, subsoil, and overburden rocks in sequence. The overburden is dumped separately. It can be reverted for replacement in reverse order. The next stage is to open the mineralized ground as the first slot, known as a box cut. The slot is then expanded to form a bench system. Mining continues by advancing the benches horizontally within the broad framework of the ultimate mine layout. The benches have two components, i.e., a floor for easy movement of labor and materials, and a face (wall) to prevent collapse. The pit maintains a critical slope angle, both at the footwall and hanging wall side, not exceeding 45 degrees from the horizontal. The slope at the footwall corresponds to the inclination of the orebody. The limit will be close to the orebody with minimum waste rock generation. The hanging wall slope is relatively shallow to reach the deepest level of the pit bottom (Fig. 12.3). The hanging wall benches generate the maximum waste rock from overburden.

The vertical height of benches varies between 5 and 10 m depending on the width of the orebody, type of machinery deployed, and to minimize footwall dilution. The minimum width of the benches is 18 m. The haul roads are 45−60 m wide at a gradient of 1 in <9, and permit easy movement of dumpers and other heavy machinery. The haulage road is connected to the main road for shifting ore to the surface stockpile, and subsequently to the process plant. The waste rock is moved to the waste dump at an appropriate location. The haul road runs along the periphery of the pit. It proceeds downward from upper to lower bench by developing ramps at suitable turnings making a total haulage system (Fig. 12.4).

Total pit development and production activities include drilling, blasting, excavation, loading, and transportation of broken ore (Fig. 12.5).

The overburden waste rock is dumped as a heap at a suitable location beyond the ultimate pit limit. The heap spreads both horizontally and vertically. The preferred location would be at the shortest distance over nonagricultural, nonforest land, with a nondrainage slope at the footwall side of the deposit. The dump material can be backfilled to the abandoned pit as the pit progresses or at the closure of the mine. The mine backfill process is the environmental reclamation of the worked-out area. A panoramic view of a large working rock phosphate mine is given in Fig. 12.6.

12.2.4 Ocean Bed Mining

Ocean water and the ocean floor cover 70% of Earth's surface and host a vast variety of mineral resources, namely, salt (NaCl), potassium (K), magnesium-calcium ($MgCO_3$ and $CaMg(CO_3)_2$), sand, gravel, gypsum, polymetallic manganese nodules (iron-manganese-copper-cobalt and nickel), phosphorite, and sea floor volcanogenic massive and rich copper and zinc sulfides, with associated lead, silver,

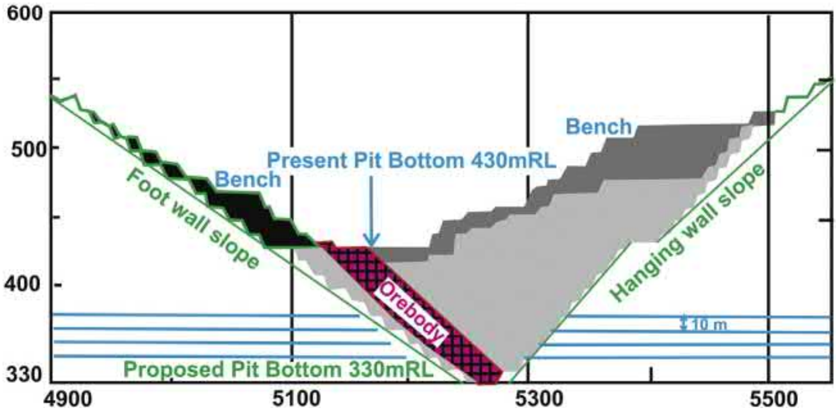

FIGURE 12.3 Schematic projection of open pit benches, footwall and hanging wall slope angle at technical stability and safety of miners and machineries. It depicts the ultimate pit bottom in surface mining beyond which ore production will be uneconomic. Mining will continue by underground methods if orebody persists in depth.

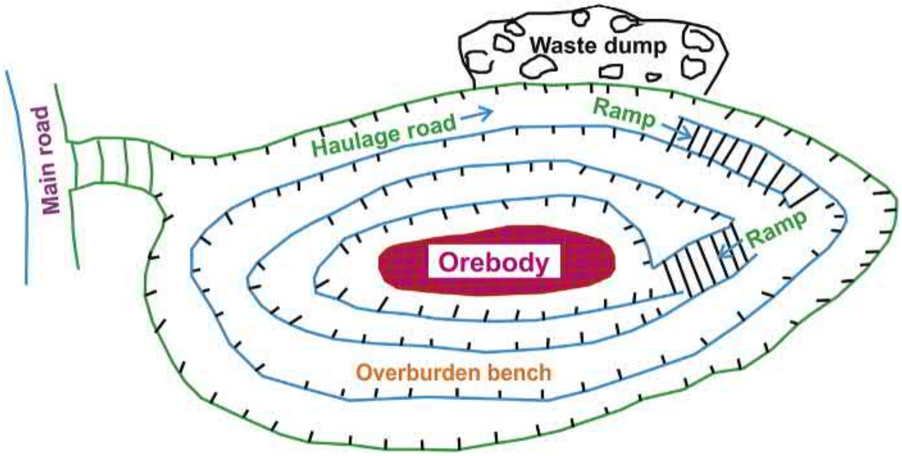

FIGURE 12.4 Sketch map to visualize the pit development plan showing the orebody at lower bench, selection of possible waste dump area, haulage road, and ramp.

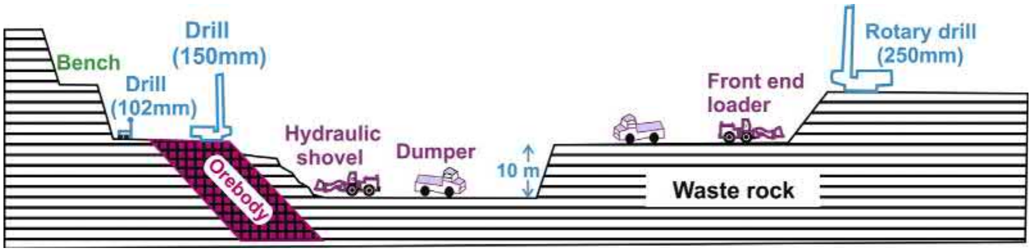

FIGURE 12.5 Schematic overview of mine activity schedule for ore and overburden drilling, shovel/dumper combination, and production movements.

FIGURE 12.6 View of Jhamarkotra rock phosphate mine with haulage road and series of overburden benches. The mine is planned to be 7 km long, 700 m wide, and 280 m with an ultimate open pit limit of 2 Mt ore and 16 Mt overburden waste per annum capacity (December 2008).

and gold. Ocean water contributes to the formation of placer gold, tin, titanium, ilmenite, zircon, diamond, and fresh water. The direct extraction of resources is limited to salt and potassium by evaporation, magnesium by electrolysis, and fresh drinking water by commercial desalinization systems. Fresh water is also produced by the reverse osmosis process. Ocean bed gold, tin, titanium, diamond, and manganese nodules (copper-nickel-manganese) are recovered by dredging technology from near-shore and deep-ocean sediments. The dredge is an excavator, and dredging is an excavation operation carried out underwater, in shallow or deep seas, with the purpose of collecting bottom sediments and disposing of them at a different location. A dredger is a ship or boat equipped with a dredge. The unit can be used for mineral exploration under water and sea bed mining for polymetallic polynodule survey recovery by dredging (refer to Chapter 5, Section 5.5.13, and Fig. 7.31).

The increasing population and the exhaustion of readily accessible terrestrial deposits will undoubtedly lead to broader exploitation of deep-seated land deposits, and increasing extraction directly from ocean water and ocean basins.

12.3 UNDERGROUND MINING

Underground mining is appropriate to that part of the orebody where open pit operation is uneconomic due to higher ore-to-overburden ratio. The deposit is either deep seated or has significant vertical continuity. The underground method recovers ore existing below the surface safely and economically (Hustrulid and Bullock, 2001). The technique generates as little waste as possible, and therefore waste handling and stockpiling are negligible, which makes activities environmentally friendly. The excavation of steeply inclined thin vein type and massive orebody proceeds either upward by overhand or downward by underhand stoping methods, and is broadly grouped under two categories:

1. Soft rock mining: Coal, potash, rock salt.
2. Hard rock mining: Copper, lead-zinc, gold, chromite, uranium, and platinum-group elements.

12.3.1 Mine Access

Mineralization is accessed from surface to underground by various ways depending on topography, orebody configuration, and stages of operation, i.e., detailed exploration, mine development, and routine mine production. The location point of access is planned at a minimum distance to reduce initial cost of development and movement of labor and materials throughout the operation. The selection of entry type should satisfy the best economic ore waste haulage scheme. An underground mine rarely has a single entry, and in general multiple types of entry systems are constructed. Care should be taken not to block valuable ore in essential pillars around the access route, because the ore may be overlooked. There must be at least two entry systems in combination for the safe return of miners trapped inside due to any accident. Multiple entries render air inflow and outflow for improved underground ventilation. The roof and walls of all mine entries passing through weak zones must be properly supported by timber, steel net/plate, rock and cable bolting, cement grouting, rocks, and concrete walls.

12.3.1.1 Adit

An adit is a doorway to reach the orebody located inside a hill. Entry is by excavating horizontal tunnels preferably from the footwall side of the orebody in the hill slope above the valley level (Fig. 12.7). Mine access through the adit can be from multiple levels depending on the height of the orebody above the valley level. A multilevel adit will reach the orebody in the shortest time to start early mine production and provide a shorter payback period. The dimension at the initial stage is 2 m × 2 m for exploration and delineation of orebody. The dimension is widened to 4 m × 3 m in the event of a viable mining proposition. The adit serves the purpose of development and production above the valley level. The broken ore from above the adit level is transported to the portal by rail, conveyor belts, and rubber-tired trucks. Any water seepage above the adit level is drained without pumping. The adit can be developed into an underground shaft, and function for improving underground ventilation systems. The walls and roof of adits are supported by concrete and painted white for better illumination. The cost of development is relatively much cheaper compared to any other entry system to underground mines.

12.3.1.2 Incline

An incline is a sloping road driven from or above the valley level to access an orebody at shallow depth in a short time. The adit should preferably be located on the footwall side of the dipping orebody It is a moderately dipping access at an angle of ~30 degrees from horizontal or 1 in 4 to 1 in 5 so that miners can negotiate the slope. Rail tracks are laid in the incline for the haulage of machines, ore, and waste rock in

FIGURE 12.7 An adit—horizontal entry above the valley level to reach the orebody at optimum distance for underground mining at Zawar Mala, India.

FIGURE 12.8 Mine entry systems by incline at a moderately steep angle of ~30 degrees to reach the orebody at the shortest distance, primarily preferred during exploration to confirm ore characteristics and sample for beneficiation test works.

buckets fitted to a mechanized headgear/pulley arrangement (Fig. 12.8). An inclined length beyond 150–200 m is not advisable due to strenuous effects on miners. The size may be 2 m × 2 m for exploration and initial mine development, and expand to 4 m wide × 2 m high for regular production. The roof and walls are supported for safety reasons. The cost of an incline is moderately higher than an adit. An incline is appropriate for quick access to the orebody, conducting underground drilling to confirm orebody boundaries, initiate rock mechanic studies, and generate a sufficient average type of ore for beneficiation test works. It is suitable for near-surface small-to-medium-sized deposits at low production targets. The incline serves as an intake or outlet for improving ventilation systems.

12.3.1.3 Decline

A decline or ramp is the fastest access road from the valley level at a slope of 1 in 9 to reach underground mine levels. The slope makes it possible to drive rubber-tired equipment like jeeps, heavy-duty dumpers, and earth-moving machinery. A decline is an ideal access for large, steeply dipping orebodies, and is designed to develop as a spiral tunnel moving downward that circles either the flank or around the orebody. The access road is connected to each mine level. The decline begins with a box cut at the surface, fully protected by iron structure, bricks, or concrete and acts as a portal (Fig. 12.9). It may also start from the wall of an open pit mine or underground working at a desired level. The dimensions can start from 4 to 5 m wide × 3 m high

FIGURE 12.9 Mine entry systems through decline or ramp at a slope of up to 1 in 9 with fastest development to the bottom-most levels and suitable for earth-moving machinery and heavy-duty dumpers.

and expand to a size suitable for the safe movement of heavy-duty dumpers and other machinery. The cost of development is moderately higher than an adit or incline, but much cheaper than a shaft. Moreover, this trackless mining can reach the orebody and mine levels at a much faster rate, and deliver a much higher rate of early production deploying heavy-duty, low-profile dumpers. Today, the decline is a globally adopted mine entry system, including at Kolihan Copper Mine developed in the early 1970s and Sindesar-Khurd zinc-lead-silver mine in the early 2000s, both in Rajasthan, India.

12.3.1.4 Shaft

Shaft mining is the earliest form of underground mining and is done by excavating a vertical or near-vertical tunnel from the top down. A shaft is created by sinking a well on stable ground adjacent to the footwall side of the dipping orebody continuing at depth (Fig. 12.10). A shaft located in the orebody or hanging wall side will require protective pillars to maintain stability as mining progresses. The ore blocked in shaft pillar will be lost forever. The shafts are sunk as circular, square, and rectangular openings. A shaft can be inclined following the dip of the orebody to avoid increasingly longer cross-cuts to the ore at greater depths. The vertical shafts are technocommercially preferred for better efficiency of ore hoisting. The shafts are permanently lined with concrete or steel. The finished diameter varies between 4.2 m (a single cage and tub) and 6.7 m (a pair of tandem cages accommodating two tubs). A mineshaft is frequently split into multiple compartments. The shaft compartment functions as a conveyance for miners and for moving supplies underground. The second compartment is used to hoist ore and waste to the surface. Large mines have separate shafts for cages and skips. A skip is a large open-topped container designed for automatic loading onto an ore bin. The system is equipped with multirope friction winders, one for the cage and the other for the skip with a counterbalancing weight. The cage has a payload of 3.5 t or 50 miners. The skip has a payload of 5 t. The cages run on rigid guides. The skip along with its balancing counterweights runs on guided ropes to prevent undue swinging. The third compartment is used for an emergency exit. It is equipped with an auxiliary cage or a system of ladders. An additional compartment houses mine services such as high-voltage

FIGURE 12.10 Main shaft with steel structure and conveyor belt at right-hand corner for ore transfer to mineral-dressing plant at Mochia Mine, Rajasthan, India.

cables and pipes for the transfer of water, compressed air, or diesel fuel and air intake and exhaust for ventilation.

The main shafts are designed for hoisting ore and waste to the surface, and lowering heavy machinery. The main shaft is located at the center of gravity of the orebody so that the distance of ore transportation is optimum from any point. The auxiliary shafts work for manual winding, material transport, stowing and backfilling material for open stopes, and ventilation. The shafts are protected from any damage by keeping a sufficient solid stable block of rock and even ore on all sides of the shaft pillar. The shaft usually starts from the valley level, ultimate open pit bottom, and underground working, that technically suits the best. The final shaft depth should be about 5 m below the bottom of the present minable *orebody*, and is extended with new findings or continuity of the existing orebody.

Eight of the 10 deepest mines in the world are in a particular region of South Africa, while the remaining two, Kidd Creek and Creighton, are both located in Ontario, Canada. The top 10 deepest underground mines are AngloGold Ashanti's Mponeng gold mine (3900 m), TauTona gold mine (3900 m), Savuka gold mine (+3700 m), Driefontein gold mine (3400 m), Kusasalethu gold mine (3276 m), Moab Khotsong gold mine (3054 m), South Deep gold mine (2995 m), Kidd Creek copper-zinc mine (2927 m), Great Noligwa gold mine (2600 m), and Creighton nickel Mine (2500 m). https://www.mining-technology.com/features/feature-top-ten-deepest-mines-world-south-africa/.

The deepest shafts in the world are reported to be Driefontein (4000 m) and Tau Tona (3900 m) gold mines, Johannesburg, Merensky Reef platinum-palladium mine (2200 m), South Africa, Timmins copper-zinc mine (2682 m), Ontario, Canada, and Mt. Isa copper-zinc-lead mine (1800 m), QLD, Australia. Notable depths of shafts in India are at Kolar gold mine, Champion Reef (2010 m), Mosabani copper mine (685 m), Jaduguda uranium mine (640 m), Rajpura-Dariba zinc-lead mine (600 m), Zawar Group (452 m, Fig. 12.10), and Khetri copper mine (475 m).

12.3.1.5 Raise and Winze

Raise and winze are miniature forms of shaft. The vertical internal connection between two levels and sublevels of a mine is called a winze if it is made by driving downward. A raise is made by driving upward (Fig. 12.11).

The downward excavation for a winze is carried out by hanging chain ladders or fixing iron ladders from the levels and sublevels. Upward driving is done by fixing iron ladders upward and making a temporary platform for overhand drilling and blasting. Development speed can be accelerated by employing mechanized raise climbers fitted with guide rails and temporary platforms for drilling upward (Fig. 12.12).

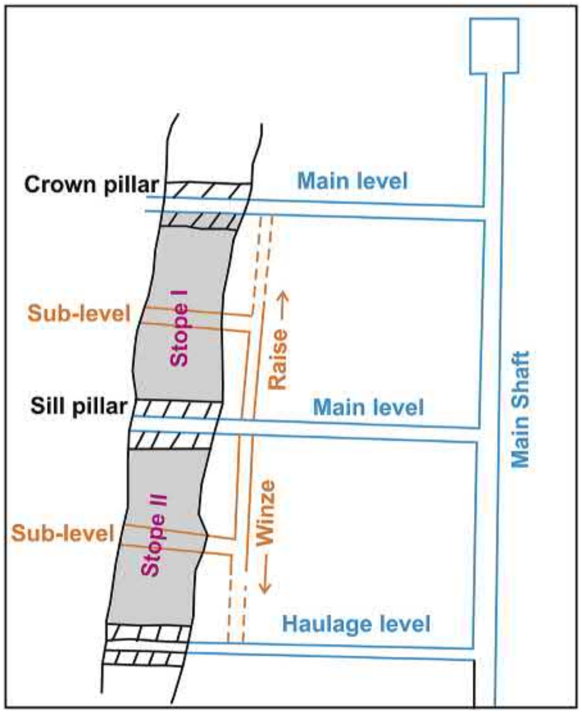

FIGURE 12.11 Schematic diagram showing the underground levels, sublevel, raise, and winze used for mine development and production.

FIGURE 12.12 Alimak raise climbers are often in use for vertical or inclined excavation to join between levels and sublevels.

12.3.1.6 Level

A typical underground mine has a number of near-horizontal levels at various depths, spread out from the main mine access to the orebody. The levels are designated as main, sub, haulage, and exploration depending on the purpose. The main levels are in vertical separations at an average height of 30, 60, and 120 m based on the mining method. The sublevels are intermediate levels for stope drilling at 10, 15, and 30 m. The haulage levels are used for the transportation of ore to the crushing chamber and ore bin for hoisting to the surface (Fig. 12.11). The exploration levels are used for diamond drilling to enhance the tonnage and grade with higher precisions at lower cost and accuracy. The exploration levels are planned to be utilized for mining purposes later.

12.3.1.7 Drive and Cross-Cut

Drives and cross-cuts are horizontal tunnels developed in a level with a cross-section of 2 m × 2 m to 4 m × 3 m. The drive is a tunnel run nearly parallel to the orebody, called exploration, sill, drill, ore, or haulage drive depending on the location and function (Fig. 12.13). The drives are used for exploring the orebody over the strike length from one end to the other, and serve the transport route of ore and development waste from the stopes.

The cross-cut is a tunnel running at right or acute angles across the elongation of the orebody with further classification as main (Fig 12.14), drill, ore, and exploration cross-cut. The cross-cuts are immensely useful for exposing the orebody across for true width, mine development, production, and ore transfer passage.

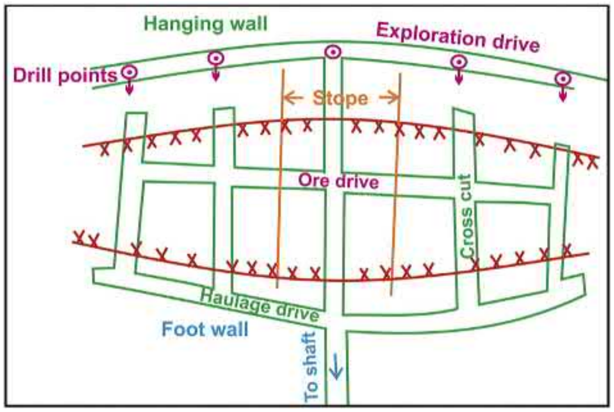

FIGURE 12.13 Schematic level diagram showing the various drives, cross-cuts, and mining stopes and their purposes.

FIGURE 12.14 View of a main cross-cut starting from the central main shaft to the orebody at Boula-Nausahi chromite deposit, main production haulage (December 2009).

12.3.1.8 Stoping and Stope

Stoping is the removal of the broken ore from an underground mine leaving behind an open space known as a **stope**. Stope is a 3D configuration of in situ ore material designed for mining as an independent subblock in underground mining. The stopes (Fig. 12.13) are excavated near perpendicular to the level into the orebody. They are often backfilled with tailings, development waste, sand, and rocks from nearby areas. The fill material is mixed with cement at various proportions to increase strength. There are various stoping methods.

12.3.1.9 Mine Pillar

Mine pillars are the solid part of ore blocks left in situ to support the ceiling (roof, floor, and side walls) of mined-out void spaces, and around the permanent mine access on various technical grounds. The pillars are of three main types, namely, crown, sill, and rib pillar. The crown pillar is the blocked ore and is left at the top of the stope to prevent the collapse of the upper level (Fig. 12.11). The sill pillar is the ore that is left below the stope to prevent the collapse of the working stope (Fig. 12.11). The rib pillar is part of the ore left between two adjacent stopes as in the vertical retreat mining (VRM) method or around a permanent structure like mineshafts. The majority of pillars, except around permanent structures, are recovered later after mining is completed between the two main levels, and void stopes are filled. The reserves blocked in mine pillars are of Proved category, and grouped as Other ore. The category upgrades to Developed status at the time of recovery.

12.3.2 Underground Mining of Bedded Deposits

The underground mining of bedded deposits deals with extraction of soft ore. It is largely done for coal, lignite, and sometimes for rock salts like halite (sodium chloride) and sylvite or sylvine (potassium chloride). The method in common practice is to drive through tunnels, passages, and openings. All are connected to the surface for the purpose of removal of broken ore. Excavating equipment cuts, breaks, and loads the soft coal to a size suitable for haulage. Continuous loading of coal, having low density and high bulk, on a conveyor belt is the best choice. Alternatively, the coal is drilled and the resultant holes are loaded with explosives and blasted to break the coal to the desired size. There are various methods for mining bedded deposits depending on the thickness and depth of the seam.

To protect miners and equipment in an underground coal mine, much attention is paid to maintaining and supporting a safe roof or overhead ceiling for the extraction openings. A long face or working section of coal, some 200 m in length, is operated at one time. The miners and machinery at the working face are usually protected by hydraulic jacks or mechanical props, which are advanced as the coal is extracted.

12.3.2.1 Room and Pillar Mining

Pillar mining, or room and pillar or board and pillar mining, is the most accepted type in underground coal mining due to flexibility and low capital cost. The method is appropriate for narrow (2–4 m thick) coal seams, free from stone bands, located at a moderate depth, and having strong supports for roof and floor, which can stand for long periods after development. Rooms are the entryways within the seam with series of equidistant square and rectangular pillars of coal supporting the roof (Fig. 12.15). A typical design would have entryways (rooms) with a width between 3 and 4.8 m employing coal-cutting machines. The pillars vary between 12 and 49 m from center to center depending on the size of the gallery, depth of mining, and rock condition. Pillars can be square and rectangular. The excavation height varies between 2 and 3 m. The nature of the immediate roof is the deciding factor. About 30% of planned production is obtained during the development stage once the seam is touched.

Mine development starts after the main connecting road reaches the mining horizon from the shaft/incline/decline. The mining excavation continues in a set of **Panels** confined within a **District**. Each district is separated from adjacent districts either by solid coal, brick, or a stone wall. Essential roads/galleries are developed between two panels for the passage of labor, machinery, drainage, ventilation, and stowage. The **dip gallery** or **dip** is a road driven along the dip of the seam. **Main dip** or **Main Rise** is one of the headings for movement of broken coal. **Level gallery** or **level** is a road driven along the strike of a seam. A **drift** or **stone gallery** is a roadway in barren rocks connecting two or more coal seams. **Heading** is a gallery in the process of being driven. **Face** is the moving form of any workplace.

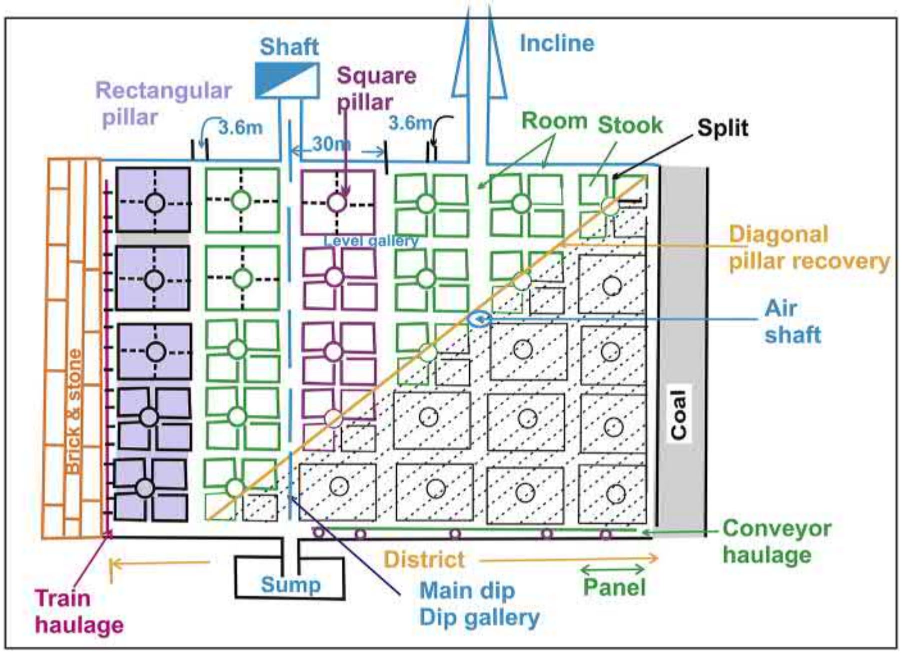

FIGURE 12.15 Schematic diagram of room and pillar mining method suitable for narrow coal and lignite deposits.

Panels are sealed off and isolated in case of any emergency arising out of spontaneous heating or fire in the panel.

The coal pillars are recovered in sequence on completion of development. Pillars are removed in the following order: coal cutters, loaders, shuttle cars, and train haulage. Continuous mining is performed by integration of cutting machine and conveyor haulage grouping. Continuous mining utilizes a large robust rotating steel drum fitted with tungsten carbide teeth to scrape coal from the seam. The roof breaks and collapses by natural caving into the voids or goafs. The pillars are split into small stooks and extracted diagonally. The surface is likely to develop cracks and subside. The goaf is completely packed with incombustible material by stowing. Filling is critical under surface water bodies or infrastructure or multiseam mining. The complete pillar mining activities and extraction are depicted in Fig. 12.15. Room and pillar mining is appropriate for mining any blanket deposit of iron ore, bauxite, base metals, stones and aggregates, talc, soda ash, and potash.

12.3.2.2 Long Wall Mining

Long wall underground mining removes 250–400 m of coal wall in a single slice. The method is suitable for thin seams of 1–2 m thickness extending over 3–4 km even at a greater depth. It requires high capital investment for large-capacity continuous coal cutters and self-advancing hydraulic roof support systems. Mine development is at a bare minimum to attain production at full capacity as quickly as possible. It provides maximum yield with the highest extraction of coal recovery.

The long wall mining method lays one long face extending the entire working section of the coal seam. The continuous coal-cutting machine removes the broken coal and transfers it to a series conveyor. The line of action is always in one direction leaving the void (goaf) behind. The roof over the goaf is allowed to collapse naturally or is partially/completely supported by stone and sand. A void strip 3–6 m wide immediate to the advancing face is supported by timber, steel props, bards, and chocks. The roof of the advancing face is propped by self-advancing hydraulic supports in modern large-scale mining. **Long wall advancing** extracts coal from the vicinity of the main entry point and proceeds outward to the panel boundary. The roadways are made in the mined-out area behind the face. **Long wall retreating** blocks the panels completely on all four sides, and the face retreats along the roadways toward the main entry point (Fig. 12.16). One of the two roadways at either end of the long wall face is called the **gate road** or **haulage gate** used for ore transport and air intake.

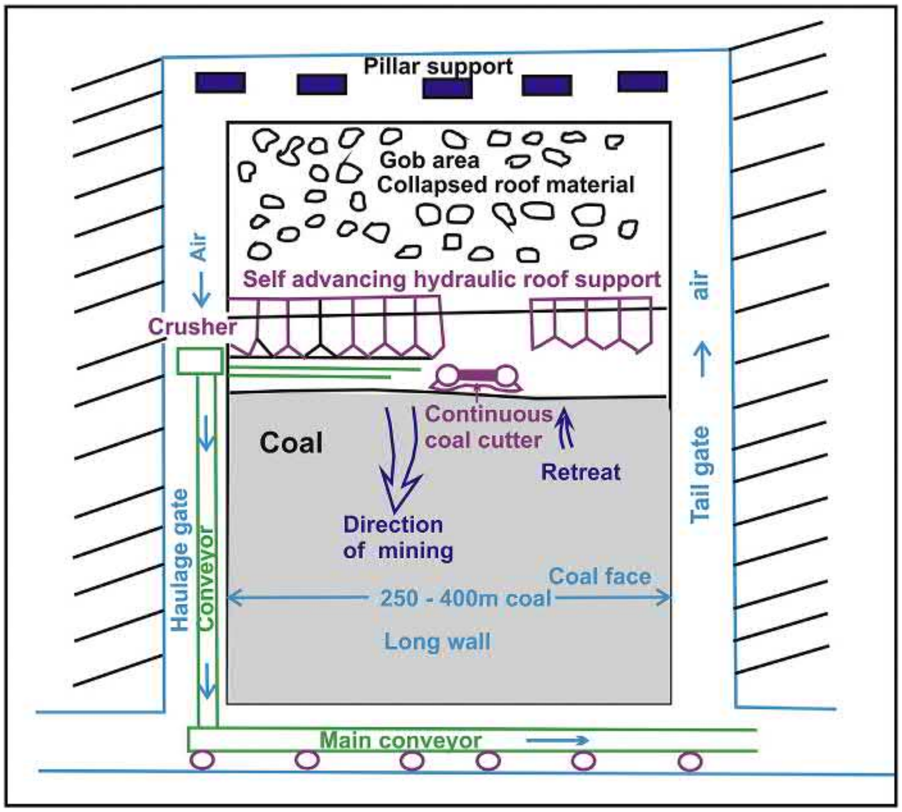

FIGURE 12.16 A general layout of long wall advancing with highly mechanized large production and simultaneous backfilling support system for coal and lignite deposits.

The other is the **tail gate** and serves as material supply route and air outlet.

Short wall mining is an alternative to the long wall mining method, and uses a continuous mining machine with moveable roof supports. The coal panel dimensions are about 500 m long and 50–60 m wide due to factors like geological discontinuity of coal slices. The mined coal is transferred to a face conveyor for haulage. The roof is supported by specially designed shields similar to long wall mining.

12.3.2.3 Coal Gas Mining

The coal seams, located at a greater depth of 500–800 m with better continuity and low calorific value, are prima facie uneconomic for mining. These coal resources can be converted to combustible gas by an in situ underground gasification process. The large quantities can be viable fuel for power generation. Natural methane gas also forms during compression and heating of organic matter over a geological timeframe, and is entrapped within the coal seam.

The underground coal gasification process includes drilling of one well into the nonmined coal seam for the injection of oxidants (water/air or water/oxygen mix). The production well is drilled some distance away to bring the gas to the surface (Fig. 12.17). The coal seam is ignited through the first well and burns at high temperatures, generating carbon monoxide (CO), carbon dioxide (CO_2), hydrogen, oxygen, and large quantities of methane (CH_4) at high pressure. The coal faces continue burning and oxidants are injected to spread the flames along the seam. The process continues laterally through the entire seam between the injection and production wells. The injected oxidants react with coal to form combustible gas, brought to the surface in a production well and cleaned to use as fuel. Coal burning and gas recovery form underground cavities triggering roof collapse. The operation is cost effective with greater lateral growth and longer gasification life. A new set of wells is developed in the nearby area after coal gasification is exhausted.

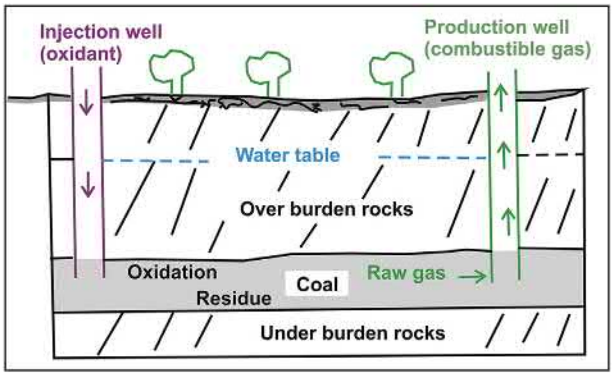

FIGURE 12.17 Schematic view of gasification process of deep-seated low-calorific coal seam through a series of injection and production wells.

12.3.2.4 Coal Bed Methane

Coal bed methane (CBM) is an unconventional form of natural gas found in coal deposits or coal seams. It is a primary clean energy source of natural gas. The development and utilization of CBM is of great social and economic benefit. It is a clean-burning fuel (compressed natural gas—CNG) for domestic and industrial uses. The extraction of CNG reduces explosion hazards in underground coal mines. Large amounts of methane (CH_4) are often associated with some coal seams. CBM is formed during the process of coalification by transformation of plant material into coal. It is generated by either a microbiological or thermal process as a result of increasing heat at greater depth during coal formation. The coal seams are often saturated with groundwater at high pressure. CBM is recovered by drilling a number of wells into the coal seam (Fig. 12.18). The methane can be readily separated by reducing water pressure with partial pumping of water. The gas moves to the well and is piped out to the surface. It is compressed and sold to market. The extraction process involves drilling hundreds of wells with extensive infrastructural support facilities.

The United States currently produces 7% of natural gas (methane) from CBM. India has the fifth largest proven coal reserves in the world, and thus holds significant prospects for exploration and exploitation of CBM. The prognosticated CBM resources in the country are about 92 trillion cubic feet or 2600 billion cubic meters in 12 states of India (http://www.dghindia.org/index.php/page). India is endowed with vast reserves of bituminous coal of Paleozoic and Tertiary ages within the CBM window at depths of nearly 250–1200 m. To harness CBM potential in the country, the government of India formulated a CBM policy

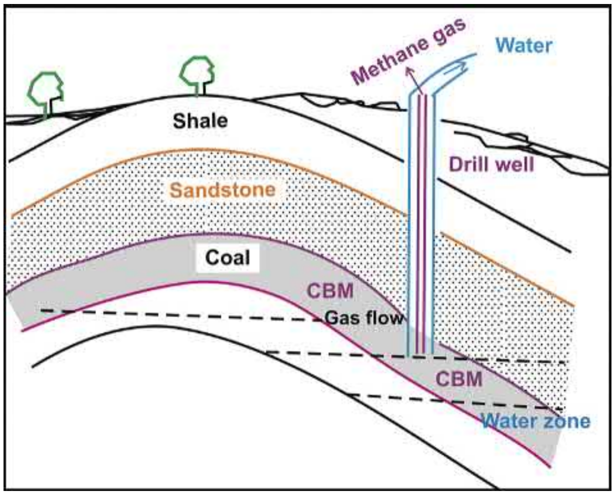

FIGURE 12.18 Schematic view of coal bed methane mining as a popular source of clean compressed natural gas used for domestic and industrial purposes. *CBM*, coal bed methane.

in 1997 wherein CBM being a natural gas is explored and exploited under the provisions of the Oil Fields (Regulation and Development) Act 1948 and the Petroleum and Natural Gas Rules 1959.

12.3.2.5 Shale Gas Mining

Shale gas and oil shale are formed due to significant enrichment of natural organic matter and its subsequent transformation into natural gas and oil under high pressure and temperature in fine-grained shale rocks. The favorable location is in various sedimentary basins between the Carboniferous and Cretaceous ages. Shale gas has been on the global energy map since the 1950s. The product has been technoeconomically accessible as an important source of natural fuel in the United States since the late 1990s. Interest in low-cost energy resources is gaining global prominence.

Shale rocks in general have low permeability to allow significant fluid/gas flow both horizontally and vertically. Therefore gas production of commercial quantities requires advanced hydraulic fracturing within the shale rock for additional permeability. Vertical holes are initially drilled to reach the target shale horizon, followed by multidirectional horizontal drilling from a single parent vertical hole. Hydrofracturing is done by introducing fluid, mainly water under high pressure, to force the gas to move to the production well (Fig. 12.19). Hydrofracturing has made shale gas profitable in the past decades, making shale gas an asset portfolio for energy companies. Shale gas in the United States is rapidly increasing as an available source of natural gas.

12.3.2.6 Solution Mining (In Situ Leaching/In Situ Recovery)

The deep-seated rock salts of halite (sodium chloride) and sylvite or sylvine (potassium chloride), low-grade copper, gold, lithium, and uranium deposits can be mined by introducing fresh water using a powerful pump with a large diameter double tube pipe into the orebody. The water is pumped through the outer pipe and flows into the ground, and salt is dissolved into the solution (brine). The brine solution is forced to the surface through an inner pipe and stored in a series of large tanks. The brine is finally pumped to the chemical plant for final recovery of clean and respective salts (Fig. 12.20). A series of holes with single pipes, some for water inflow and others for brine outflow, can be organized to cover a large area.

Solution mining (in situ leaching) has been extensively used in Colorado, USA, to extract nahcolite (sodium bicarbonate), Beverley and Honeymoon uranium mines in South Australia, San Manuel copper mine in Arizona, USA, Ajax gold mine in the Cripple Creek district in the United States, and most of the world's lithium producing areas in South America.

12.3.3 Underground Hard Rock Mining

Underground hard rock-hosted metalliferous mining deals with a wide range of diversely shaped and sized thin veins of gold, silver, and platinum and massive chromium, zinc-lead, copper, uranium, and manganese deposits. The underground stopes are developed with 3D perspectives. The drives and cross-cuts are developed at successive levels and connected vertically. Mining proceeds upward by overhand stoping and downward by underhand stoping. Hard rock fully mechanized underground mining generates minimum waste rock in comparison to open pit mines. Hard rock underground mining adopts many designs suitable for size, shape, location, nature of strata, thickness, dip, and grade variation of the orebody. The larger the ore handling, the greater the OMS.

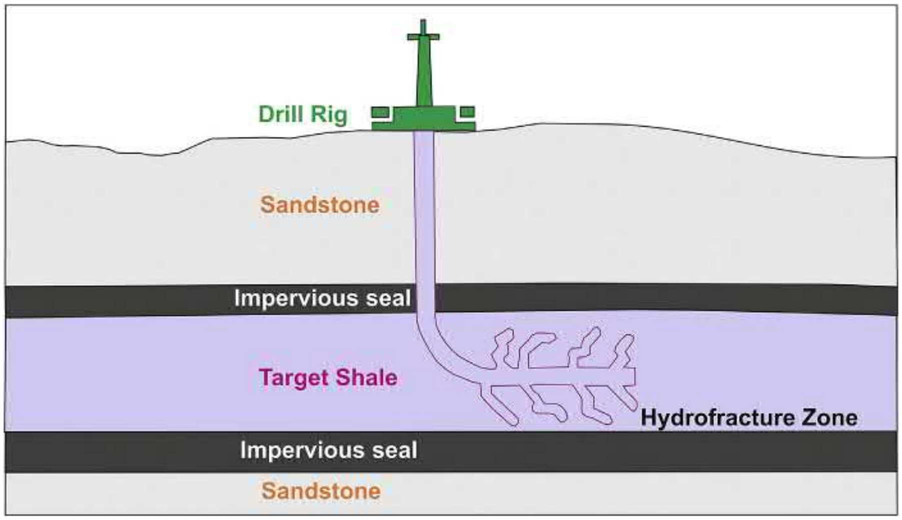

FIGURE 12.19 Schematic view of shale gas mining by hydro- or gas fracturing. The technique is becoming a popular source of energy today everywhere.

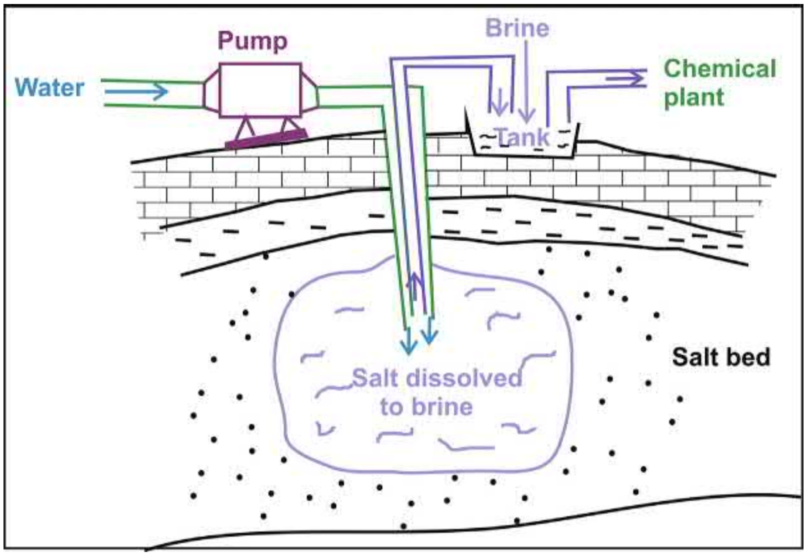

FIGURE 12.20 Schematic view of solution mining from deep-seated rock salt at low cost.

12.3.3.1 Square-Set Stoping

Square-set stoping is applicable for high-grade thin to medium orebody with weak walls and back needing an instant support system. It is suitable for the recovery of fractured ore leftovers and pillars with extremely bad ground conditions. The method is costly and labor intensive, but suitable irrespective of size, shape, and depth. Ore recovery is better with efficient grade control. The waste can selectively be left in the stope as filling. Timbering is a dominant feature in square-set stoping causing fire hazards and high accident rates.

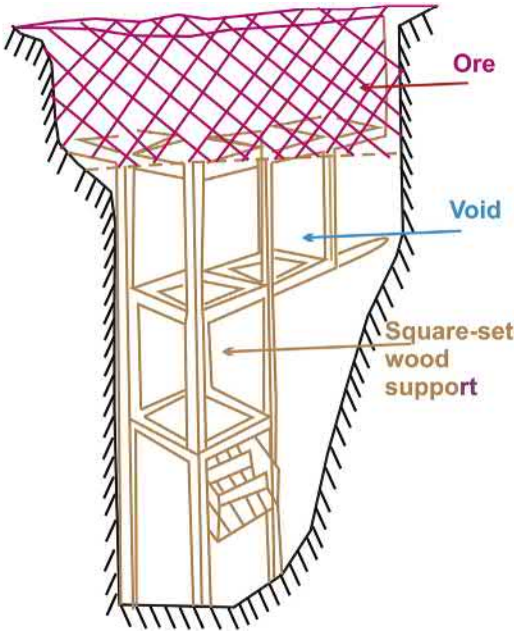

FIGURE 12.21 Square-set mining design is suitable to recover high-grade ore blocked in weak and fractured pillars needing instant support systems.

The concept of shrinkage stoping is similar to room and pillar soft rock mining. The square set indicates regular framed timber support of the void area immediately after the ore is removed. The ore is excavated generally by overhand drilling in small rectangular blocks large enough to be supported by a standard square set of timbers (Fig. 12.21). The broken ore is excavated in horizontal, inclined, and vertical panels. The square-set mining method has been adopted at Bawdwin zinc-lead-silver mine, Myanmar, Phoenix copper mine, British Columbia, Sullivan zinc-lead mine, Canada, Broken Hill zinc-lead mine, Australia, and Namtu-Bawdwin lead-silver-zinc mine, Myanmar.

12.3.3.2 Shrinkage Stoping

Conventional shrinkage stoping is suitable for steeply dipping (70—90 degrees) narrow veins with regular ore boundaries and thicknesses ranging between 3 and 12 m. The length of shrinkage stope varies between 50 and 100 m with heights between 40 and 60 m. The development work connects two main levels by raises/winzes at both ends that provide good ventilation for working, and man-ways at regular vertical intervals. The preparatory level is excavated at 5—10 m above haulage level. These two levels are connected by a number of conical box hole raises at 8—10 m centers for ore pass. The preparatory level is stripped up to the side walls exposing the whole width of the orebody.

The cycle of overhand drilling by 33 mm diameter jackhammer drills and blasting with ANFO explosive continues end to end in the strike direction. The average lift

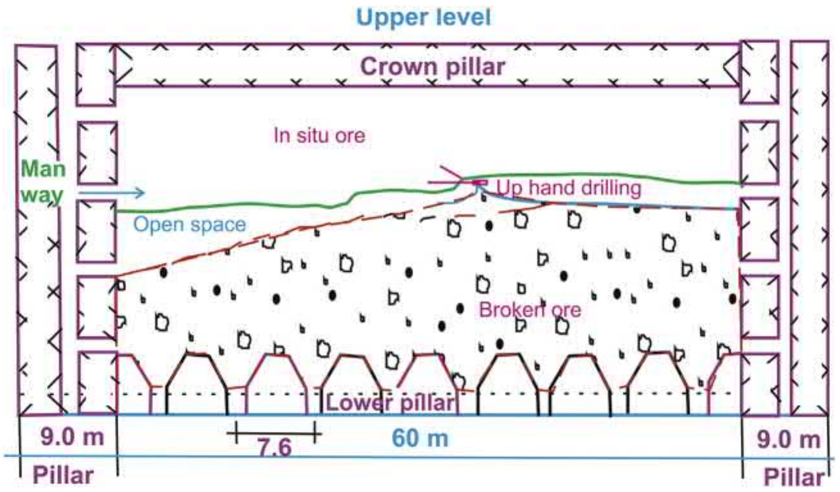

FIGURE 12.22 Schematic diagram of shrinkage stope in operation at Mochia mine, Zawar, India, to selectively recover high-grade vein-type sulfide ore.

in the stope is between 2 and 2.5 m/blast. The blasted ore makes greater volumes than in situ ore due to the swell factor. Therefore ~35%–40% of the broken ore is withdrawn (shrink) from the advancing stope. It provides a workspace between the muck pile and the new overhead face to drill for the next ore slice (Fig. 12.22). Upperhand drilling, blasting, and partial ore removal continue up to the upper pillar drive. The total ore is removed from the stope after reaching the top. The stope may be backfilled or left empty depending on rock conditions. The power factor is ~250 g/t of ore broken. Shrinkage stope yields stope productivity of 30–50 t/day.

The shrinkage stoping method was extensively used in the initial phase of thin vein-type orebodies at Balaria zinc-lead mine, Rajasthan, and Mosaboni copper mines, Jharkhand, India. This method is less used now due to low OMS.

12.3.3.3 Cut and Fill Stoping

Cut and fill mining is a highly selective open stope mining method considered ideal for steeply dipping high-grade deposits found in weak host rock. The horizontal flat back cut and fill mining method is applicable under a wide range of conditions from small to large deposits of irregular outline, and flat to steep dipping orebodies. The cost of preparation and development is comparatively lower. Mine production starts quickly with a smaller workforce. The cost of the filling operation is high. The development work involves preparation of a haulage drive along the orebody at the lower main level, and an undercut at 5–10 m above. There will be a number of separate raises for man-ways, ore pass, and filling material. Stopes are 90 m long, and divided into three panels of 30 m each, separated by 5 m thick rib pillars. The producing panel is excavated by overhand drilling using jackhammer drills of 33 mm diameter and wagon-mounted COP-89 drifters. Excessive damage to the roof is expected by vertical overhand drilling in poor rock conditions. The roof is presupported by 12 m long cable bolts at 2 m × 2 m grid, repeated every 7–10 m lift. Blasting is done in horizontal slices not exceeding 3 m in the roof leaving 5 m × 5 m post pillars at 15 m centers along the strike and 12 m across, if the ground condition dictates. During the mining sequence, the back of the excavation is temporarily supported using rock bolts before the stope is backfilled to form the floor of the next level of development. The backfill is designed to provide mild excavation support as well as to provide a strong working floor for the workforce and equipment.

Mucking is done by 1.3 m^3 electric load-haul-dump (LHD) machines operating on consolidated fill. These machines load and haul broken ore up to the nearest ore pass that opens at a track-facilitated haulage drive. A diesel- or battery-powered locomotive pulls a train of 5-t Grandby cars. The locomotive carries the ore up to the main ore pass over an underground jaw crusher with an output of −150 mm size. The primary crushed ore is hoisted to the surface in a 6-t skip driven by 697 kW Koepe winders. Stopes are backfilled with waste rock, sand, and +32 micron-sized classified mill tailings mixed with 5%–15% cement. The cyclic drilling, blasting, loading, and filling in three stope panels constitute the cut and fill mining operation (Fig. 12.23). Each stope can produce 200–250 t/day. The rib, crown, and sill pillars are recovered later. The post pillars are left inside the fill material.

The cut and fill method is widely deployed at the copper-zinc deposit at Cobar and zinc-lead deposit at New Broken Hill Consolidated, NSW, Australia, and zinc-lead deposit at Rajpura-Dariba, India.

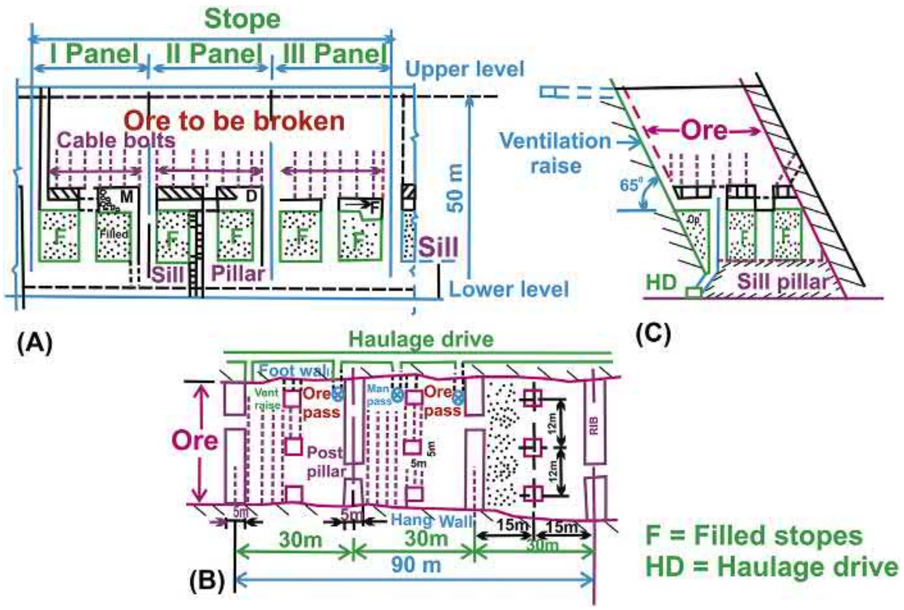

FIGURE 12.23 Schematic diagram of flat back cut and fill mining with post pillar stoping at Rajpura-Dariba mine, (A) Longitudinal section, (B) plan, and (C) cross-section. The operation is a cycle of drilling, mucking, and filling.

12.3.3.4 Sublevel Stoping

12.3.3.4.1 Conventional Sublevel Stoping

Sublevel open stoping originated in the early 1900s in iron ore mines in Michigan, USA. It was developed over the years from a method originally known as short hole bench and train mining. It is a large-scale open stoping method, and is often referred to as long hole or blast hole stoping. Conventional sublevel stoping (Fig. 12.24) is applicable for steeply dipping thick mineralized lenses with regular boundaries. The orebody is strong enough to separate from stable hanging walls and footwalls. The sublevel stope is designed between two main mine levels at a vertical separation of about 70 m. The haulage drive is at 20 m from the footwall of the ore contact. The drawpoint cross-cuts are at 9 m center to center at the bottom main level. The cross-cuts end with the development of undercut or trough or box hole for drawing broken ore. There are two raises on either end of the stope limit for development of three sublevels that act as drill drives within the orebody.

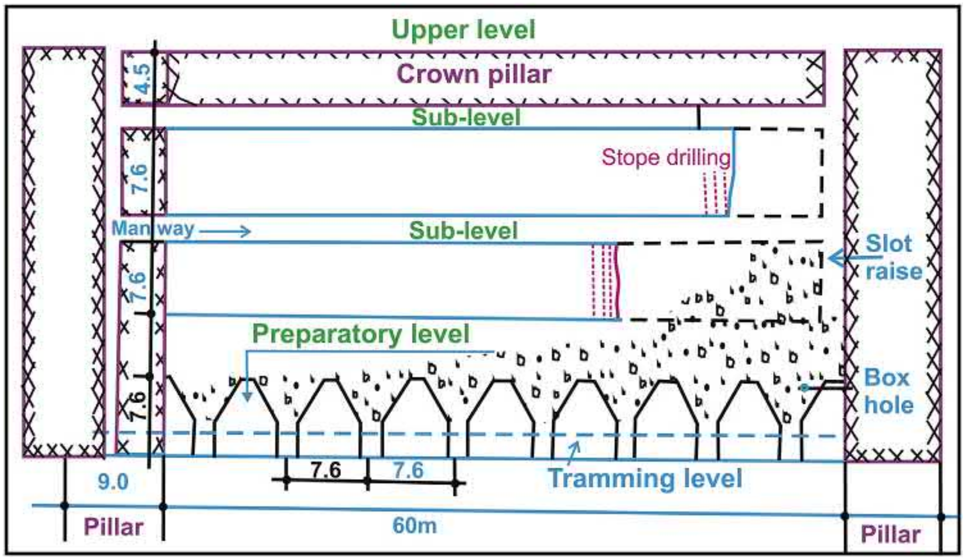

FIGURE 12.24 Conventional sublevel stoping is applicable for steeply dipping thick orebody under competent ground conditions.

Stope development involves driving the first sublevel (preparatory level) from the long pillar raise 10–12 m above ore drawpoint level. The second and third sublevels are developed at about 10 m vertical intervals leaving a 4–5 m crown pillar above the top most sublevel. One of the raises works as a service for a man-way, and the other opens the slot up to a height of about 4 m above the widened preparatory level. This follows stripping of the slot raise between preparatory level and second sublevel up to footwalls and hanging walls to create a free face for parallel downhole drilling of 7.6 m long and 36 mm diameter on a sublevel bench. Blast holes are drilled at 1 m spacing and 1.20 m burden. The powder factor is low at 125 g/t of ore broken, achieved in primary stoping-necessitated secondary blasting of large-sized boulders. Stope productivity is 100 t/day.

Sublevel stoping became prevalent with modifications because of the following advantages:

1. Maximum ore recovery with minimum unplanned dilution due to excess length and deviation of blast holes.
2. Recovery of ore blocked in pillars after stopes have been backfilled.
3. Large-scale blasting, increase in productivity and efficiency at lower mining costs.
4. Easy to mechanize and can use large equipment.
5. Low mine hazard at high safety.

The disadvantages are

1. Low selectivity of ore boundaries and high internal dilution.
2. Average orebody width of 6 m or more.
3. Extensive advanced precision of orebody delineation with closely spaced definition drilling based on complexity of mineralization.
4. Increased dilution for orebodies with lower dips.
5 Backfill of extremely large voids or poor fill quality may be disastrous.

12.3.3.4.2 Sublevel Top Slicing

Sublevel top slicing (Fig. 12.25) is the technical development of conventional sublevel stoping for increased level of production. Stope development starts with excavation of a set of 67 m long ore- and man-pass raises, located on either side of the haulage drive. The Alimak raise climber ensures high-speed raising with safety. The sublevels are driven from man-pass raise toward and up to within 5 m of the ore-pass raise. A finger raise is excavated from the ore-pass raise for the sublevel to puncture it. Each sublevel is developed by drives and cross-cuts at 10 m intervals between the rib pillars. Sublevel top slicing starts by stripping of a slot raise between two sublevels near the hanging wall. Blast holes, drilled in an upper-fan pattern covering the ore boundary between three sublevels, form a trough for ore withdrawal. The ore is blasted against broken material, retreating from the hanging wall toward the footwall. The sublevel interval would increase to 9.6 m between the sixth and seventh levels. This method yields an overall productivity of 1.66 t per man-shift against 0.85 t from a 6.7 m level interval stope. Ore recovery is high.

Stope drilling is upgraded to 57 mm diameter blast holes in a fan pattern, drilled by Simba Junior rigs in a

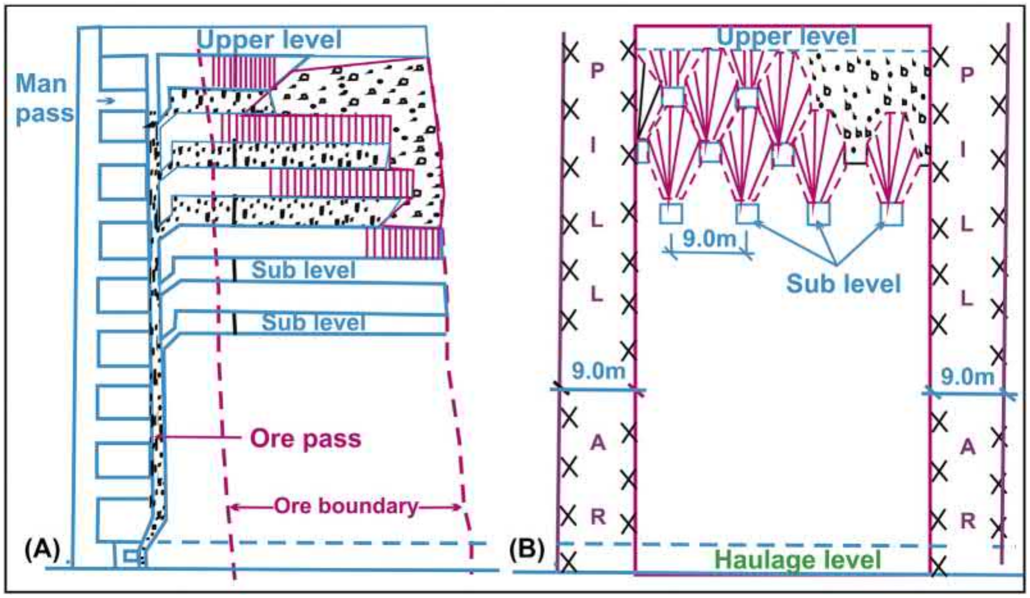

FIGURE 12.25 Conventional sublevel top slicing mining method yields high productivity.

sublevel top slicing. The explosives are a combination of ANFO and Anodets to achieve faster and more efficient blasting. A productivity improvement of 70 t/shift can be achieved by using 1.5 m^3 capacity diesel-operated LHDs, increasing productivity from each loader to 200 t/shift. The blasted ore, dumped from the levels into nearby ore passes, is drawn at the bottom through pneumatic chutes into 5-t capacity Granby mine cars to be hauled by a 5–8-t trolley wire locomotive. The Granby mine cars unload ore into a bunker over an underground double toggle jaw crusher.

12.3.3.4.3 Sublevel with Long Hole Drilling

Sublevel with long hole drilling (Fig. 12.26) is a further innovative modification of sublevel stoping. The stope starts from the extraction level, driven 13 m above the haulage level. An orebody/trough drive and an extraction drive, parallel to each other with interconnecting cross-cuts at a 10 m center, has been developed. The sublevels are driven at 25 m vertical intervals above the extraction level. A dog-legged raise, funneled at the top, between haulage and extraction level, serves as an ore pass. The inclined raises along the orebody are driven from extraction level to top level at both ends of the ~100 m long stope. A hanging wall raise is used as a slot raise. The footwall raise is used as a man/material-pass. The slot raise is located at the center of the stope that retreats on both sides. The slot is extended sideways by blasting against the slot raise to create a free face for sublevel ring blasting. Blast holes are drilled at 360 degree rings, 1.5 m spacing, and with a 1.5 m toe burden for stope blasting. Down-the-hole (DTH) hammer drills 150–200 mm in diameter and 60–70 m long for the level and Simba Junior drills (57 mm diameter) for the trough section are used.

The diesel/battery/electric-operated LHDs collect and transport broken ore from the stope and dump it into a nearby ore pass. However, the use of diesel-operated machinery in the underground mine operation is not encouraged due to environmental hazards. A ramp at a convenient location between haulage and extraction level can be developed for the movement of LHD and other material. The broken ore is loaded at the main haulage level through pneumatic chutes into a train of 5-tGranby mine cars, and hauled by trolley-wire locomotive. Overall productivity of 2.2 t/man-shift is achieved from these stopes. It reduces stope development from 2 to 0.7 m for every 100 t of production. Stope productivity increases from 3 to 16 t/m due to increased spacing and burden.

12.3.3.5 *Vertical Retreat Mining*

The vertical crater retreat (VCR) method was developed by the International Nickel Company Limited and CIL Inc., based on crater blasting theories. The method was first used in 1974 at the Levack nickel mine located in the North Range of Sudbury Basin, and it provided productivity benefits almost immediately. VRM, also known as VCR, is applicable to massive wide orebodies with moderate to steep extensive depth continuity at reduced cost. The method is globally accepted with the advent of high-speed large-diameter drill holes up to a length of ~125 m. A DTH and in-the-hole (ITH) drill unit with 150–165 mm

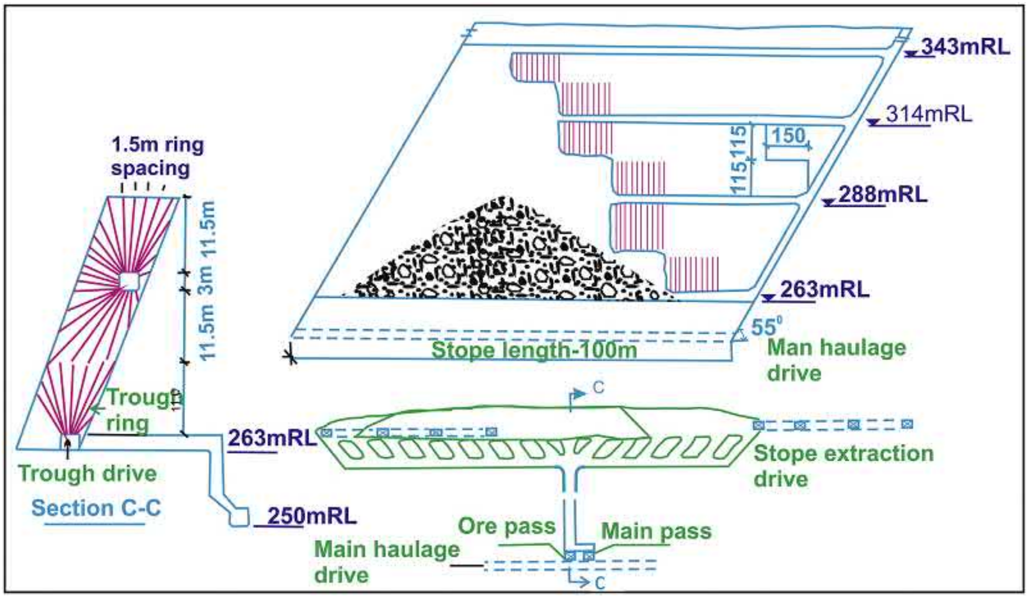

FIGURE 12.26 Sublevel stoping with long hole drilling is an innovative modification and mechanization for further higher productivity with or without backfill.

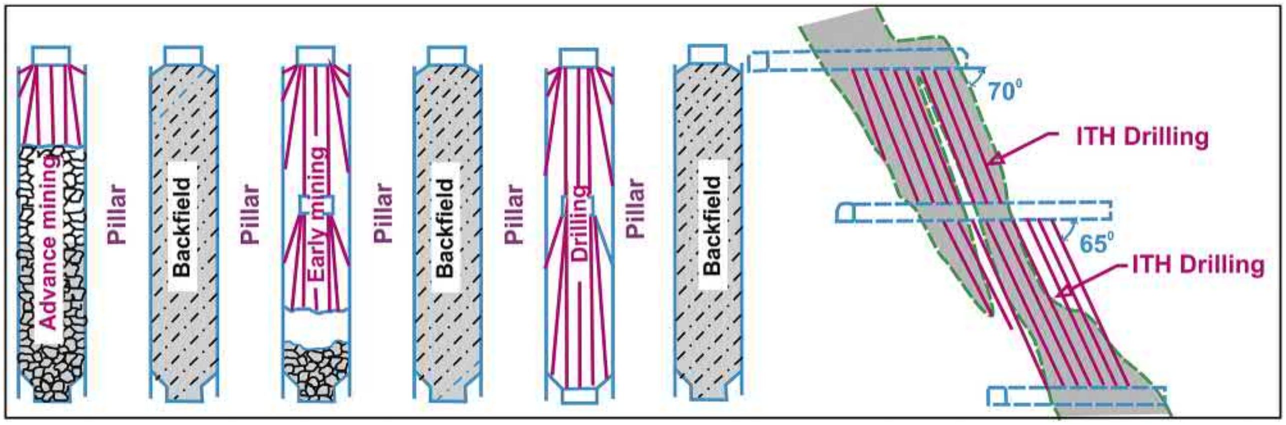

FIGURE 12.27 Schematic view of vertical retreat mining method with cyclic sequence of long hole drilling, mucking, and filling of alternate stopes and pillars for a vertical height of 60–100 m in large volume regular orebody.

diameter works in both vertical and inclined planes. The stope portrays a uniform shape and designs a relatively smaller stoping panel of 15–30 m along the strike of the orebody (Fig. 12.27). The vertical height can be 100 m, including crown and sill pillars of 12 m each. Stope development starts with excavation of a haulage drive at the main level, an extraction drive 12 m above, and two drill drives at 40–45 m vertically above. A ramp, 1 in 7, connects the uppermost drill drive and extraction drive for movement of the workforce, heavy equipment, like DTH, ITH, and radio remote-controlled LHDs, and material. Access to each panel is made at extraction and drill drives through 3.5 m × 3 m cross-cuts developed at 15 m intervals.

The VRM method is an application of spherical charge blasting. The ore cross-cuts at the extraction level serve as an initial free face for spherical blasting, while those at drill drives accommodate the drill unit. Blast holes (15–16.5 cm diameter) are drilled by a CD 360 ITH-type machine. Drilling is done downward in a planned design pattern from drill cross-cuts. Few holes penetrate the lower cross-cut opening, followed by flank holes to cover the 15 m stope width. The holes drilled in the section up to the lower cross-cut are utilized for spherical charging and blasting at the start. Explosive is loaded only at the bottom of each hole for each successive blast. No slot raise is required. The broken ore slice drops into the draw point at the extraction level, and partially removes enough ore to create a sufficient void for the following blast. The ore left in panel acts as support to the walls, and controls wall dilution. The remaining ore is quickly removed after the last blast in a panel. Radio remote-controlled LHD removes the last chunks of ore without exposing the operator to the empty stope. The large void is backfilled with sand, a mixture of cement and sand, and cement and rock or classified tailings mixed with 5%–15% cement for consolidation. The sequence of mining would be excavation of 60 m center primary blocks, leaving strong pillars 45 m wide on either side, followed by the secondary pillar and finally the rib pillar.

The method is extensively used for recovery of ore blocks at lower levels of Rajpura-Dariba and Rampura-Agucha unground mines, Rajasthan, India, yielding a tonnage factor of 20 t/m of drilling along with better fragmentation and higher ore recovery and productivity. This method is safe to the workforce and machinery because drilling/loading/blasting is done from the top levels, ore is drawn using radio remote-controlled LHDs, and finally backfilling/ground support is controlled from the upper levels.

12.3.3.6 *Block Caving*

Block caving is applicable to sufficiently large, amply massive, and often uniformly low-grade orebody usually with steep to vertical dips. The ore mass should be naturally fractured and week enough to cave under gravity. Block caving is a mass-mining method at low cost that allows for bulk mining and extraction of large quantities at a time. Block caving can handle existing large crown pillars between open pit and underground operations. The development, drilling, and blasting requirements are minimal. Development includes excavation of haulage drive, drawpoints with a set of finger raises, and an undercut. The ore above the undercut is fractured, motivated by initial long hole blasting. Thereby large blocks of ore and overburden move downward under gravity, and crush each other to grind the ore into smaller sizes. In-stope secondary blasting or hydraulic breaking may be required to treat the boulders. Run-of-mine ore quantity and grade is monitored. The drawl is discontinued in the event of excessive dilution by wall collapse or mixing of overburden waste rocks. Block caving is an economical and efficient mass-mining method, where rock conditions are favorable.

12.3.3.7 *Mass Blasting*

Underground mining practices have witnessed a large quantity of ore to the tune of 0.5−1.0 Mt being blocked in various pillars that provide mine stability, support, and safety for the future. This valuable ore blocked in pillars is extracted by mass blasting (open stoping), increasing mine life and safe conditions at reduced cost. The stability of the mine, in the light of pillar blasts, can be evaluated using geotectonic software to decide the sequence of extraction of pillars. The study can predict mine conditions likely to prevail after the mass blast.

A large underground mine pillar blast was conducted in 1994 at Mochia mine, Zawar Group, India, consuming 145 t of explosive and yielding 0.55 Mt of ore. The pillars were composed of 48 m thick crown and complementary 43 m thick rib. The crown pillar was split into 24 horizontal slices by drilling fan rings of 115 mm diameter. The rib pillar was split into 10 vertical slices by drilling fan rings of 165 mm diameter. The crown pillar was fired downward, and the rib pillar laterally in one go into the preexisting stoping voids of 2W and 3W stopes (Fig. 12.28). The powder factor was 3.79 t/kg at a cost of US$1.5/t of ore.

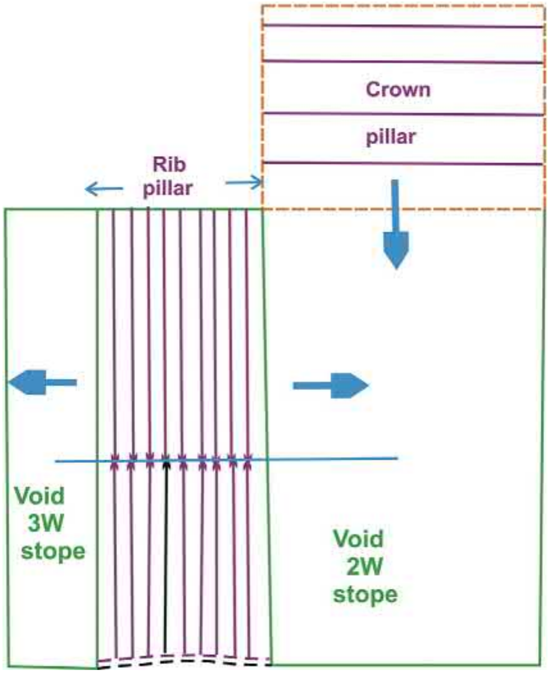

FIGURE 12.28 Schematic firing of crown and sill pillars by relay mass blasting.

12.4 MINE MACHINERY

Contemporary open pit and underground mines perform on sophisticated high-end advance mechanization. Multiple large diameter DTH and ITH drill units, diesel-, compressed air-, and electric-powered radio remote-controlled large capacity loaders, +85 t rubber-tired dumpers and trucks, conveyors, rails, and aerial ropeways for ore transportation are common appliances. Mine machinery can be classified based on operations such as development, production drilling, collection, loading, and transportation.

12.4.1 Drilling

Mining operates with drilling, blasting for development, and producing broken material. There are various drill machines available based on hole diameter and capacity to drill, and are essentially noncore with hard steel and/or tungsten carbide cutting bits. Drilling operates on combined percussive and rotary actions. The energies required are compressed air, electric power, and diesel. The common branded drill units are jackhammer, wagon drill, DTH hammer, and ITH hammer.

The jackhammer is a compressed air-operated, light-weight (15−25 kg) device, and is operated by a single person. The hole diameter varies between 30 and 38 mm and it drills depths between 3 and 6 m. Common applications are development of benches in small open pit mines, regular use in underground mine face development, and overhand drilling in shrinkage stopes.

Wagon rock drills operate by compressed air and are mounted on a portable frame fitted with three rubber-tired wheels, crawler chain (Fig. 12.29), or tractor for easy movement to the hole site during active mine operation. The hole diameter varies between 50 and 115 mm for a depth of 3−40 m. The drifter mast is 3 m long and can be changed as per requirement. The mast can rotate from vertical to horizontal to drill at any angle. Conventional wagon drills are modified to heavy duty using hydraulic pressure, and are used for surface and underground mine production.

FIGURE 12.29 Compact crawler chain-mounted pit drill in operation at Sukinda chromite mine in India, to drill 5−10 m bench height and for easy movement to hole sites.

FIGURE 12.30 Column-mounted pneumatic screw feed Simba Junior drills suitable for underground mines to drill in 360-degree rotation at Rajpura-Dariba mine, India.

FIGURE 12.32 Close view of single hand-operated face drilling by Tamrock single boom electric-powered jumbo drill with straight 14 feet steel feed operation at Sindesar-Khurd mine, Rajasthan, India.

The Simba Junior, manufactured by M/s Atlas Copco, is a pneumatic screw feed unit, designed especially for underground mines to drill in 360 degree rotations. The hole diameter varies between 51 and 57 mm with a maximum drilling length of 25 m. The drill unit is attached with two columns, and it is easy to move from one place to another. The Simba Junior series is suitable for tunneling, drifting, long hole stope drilling, and mines of low to medium production (Fig. 12.30).

The challenges of extremely high-speed mine development and large production are met by extra heavy-duty, innovatively designed, mechanized drill jumbo rocket boomer rigs (Face Master by GHH and Mine Master by Atlas Copco) with a single boomer (Fig. 12.31), twin and three boomers for drilling blast holes of diameters between 41 and 76 mm, and net lengths up to 3.8 m. The unit can move 12 km/h by hydrostatic or mechanical power shift tramming systems up to 15 degrees gradeability. The unit is used in underground workings for both coal and metal mining. The design allows effective drilling of blast holes in underground workings of heights up to 3.6 m. Similarly, automatic rock bolting machines are available.

Drill jumbo boomers move easily to sites, set the direction and angle of boom quickly and accurately, and have a superfast rate of penetration and simple operation by a single person with high productivity (Fig. 12.32).

A DTH drill is meant for drilling holes in hard compact rock formations (Fig. 12.33). It combines both percussive and rotary actions, and is powered by compressed air. DTH units are provided with mud pumps for negotiating overburden. The hole diameter varies between 115 and 165 mm

FIGURE 12.31 Single boom jumbo drill with basket diesel-powered articulated chassis with permanent four-wheel drive.

FIGURE 12.33 Tire-mounted down-the-hole hammer drill rigs in operation for drilling 60 m vertical height of vertical retreat mining stopes at Rajpura-Dariba mine during the 1990s.

for a depth of 125 m. The drilling tool is a cross/button bit. A DTH hammer consists of a drill bit and a short length of pipe. The lowering and hoisting of drill rods is operated by a chain. The drill is leveled with three hydraulic jacks. Drilling is usually vertical with a possible swing of 20 degrees on either side from vertical in some models. DTH hammer rock drills have led the way in performance, reliability, and longevity since their introduction 20 years ago.

The ITH drill, similar to the DTH drill, is especially useful for the VRM method, and drills at compound angles from vertical and horizontal directions. Low headroom is achieved by the employment of a double-acting hydraulic cylinder. ITH drills are extensively used in massive mineralization for quick evaluation.

A rock breaker is not a drilling unit. It works on percussive motion, and is an important piece of equipment of the mining machinery family. It is essentially used to break oversized boulders before feeding to a standard crusher. It is powered by diesel oil. The machine is mounted on crawler chains (continuous tracks), and can move to any desired location (Fig. 12.34).

12.4.2 Mucking

Muck is loose rock/ore/clay material that has been fragmented as a result of blasting in a working face or stope in an open pit and underground mining excavation. **Mucking** is the process involved in loading, hauling, and transporting the muck away from stockpiles, mine dumps, mine advancing faces, active or passive stopes, and worksites. The mucking of broken ore and waste rock from a small or large mine is carried out by various types of machines. The size of mucking units changes with respect to the bulk of material to be moved from the open pit and underground operation.

A bulldozer is a diesel power-driven unit mounted on rubber-tired wheels or crawler chains. It has a pusher blade at the front fitted with a bucket. It is used in the initial

FIGURE 12.34 Crawler-mounted (continuous tracks) hydraulic hammer-type rock breaker in operation to break large-sized stones of run-of-mine ore at Sindesar-Khurd mine, Rajasthan, India.

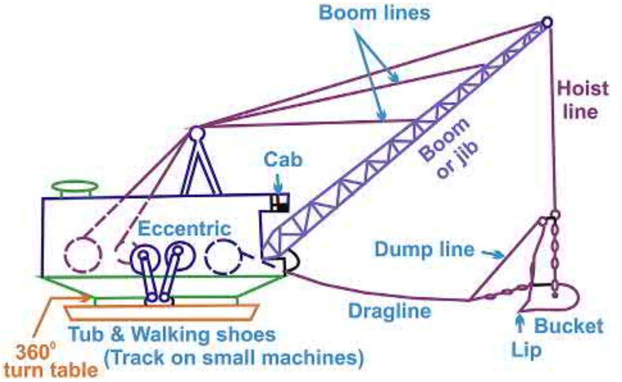

FIGURE 12.35 Schematic diagram showing the function of a dragline to remove the broken ore and waste at a mine operation site.

development of open pit mines to level the ground by dozing for setting infrastructure. It is also used for digging soft earth or weathered profile. **Scrapers** are diesel-operated tire-wheeled units with a cutting blade at the bottom. The blade cuts and pushes thin slices of soft material in open pit mining. A **ripper** is an attachment in place of a blade and cuts deep furrows in the ground as it moves. Scrapers and rippers work in combination with bulldozers.

Power shovels and **draglines** (Fig. 12.35) are diesel/electrically powered heavy-duty machines mounted on a revolving deck/crawler. They have a long light boom, crawler chain, and bucket controlled by cables. The bucket is lowered down in soft earth, blasted loose rock, coal, and other ore. The unit works from upper bench/level and successively moves to lower benches. The bucket digs and drags by controlling the cable to load materials. The bucket is hoisted by cable and unloads the contents to suitable locations by a swinging movement of the boom.

LHD units represent a total on-site solution to ore transportation, particularly for underground mining. It is essentially a tire-mounted tractor with a bucket as a front attachment. The bucket can be lowered to the ground, pushed to load broken ore, and raised to dump hydraulically/mechanically. It is also known as a **front-end loader** or **pay loader**. These units run on compressed air or electric power and rarely by diesel because of environmental restrictions. The capacity of each unit varies widely depending on the quantity of ore to be handled in a day. LHDs load ore from the mine face or stope draw points, haul it a few tens of meters, and dump it to a low-profile dumper, rail, or ore pass. The LHD is driven by an operator or by remote control for drawing leftover ore from open stopes. The capacity and technology vary from a compressed air-driven 1 m^3 CAVO-310 hopper loader (Fig. 12.36), to a diesel or compressed air-driven 1.5 m^3 LHD (Fig. 12.37), to a 2.7 m^3 electric-powered radio remote-controlled operation (Fig. 12.38) and these machines are the mainstay of ore transport for VRM/bulk mining. The other common mucking machines are the **bucket wheel excavator** and **bucket chain excavator**.

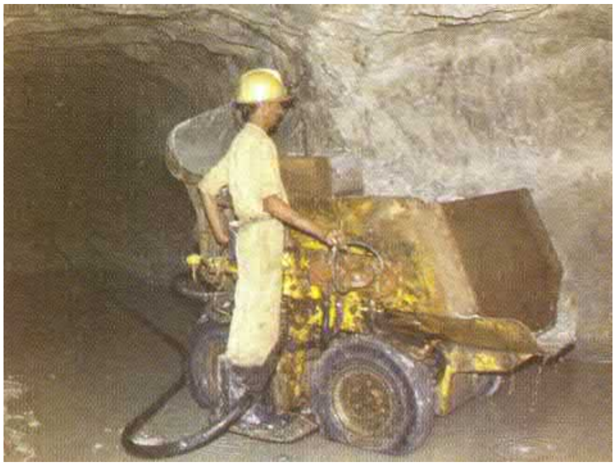

FIGURE 12.36 Compressed air-driven four-wheel drive Cavo loaders on four extra rubber-molded tires with 1 m^3 capacity are useful in small-scale underground mine transportation.

FIGURE 12.37 Diesel/compressed air-driven 1.5 m^3 load-haul-dump machine transporting the broken ore from working stopes to loading points.

12.4.3 Transporting

The small and large volume of broken ore from open pit mine benches is transported to the ore stock pile in a combination of trucks, loader, and dumpers. The size of the machines changes accordingly. Capacities range between 25 and 85 t (Figs. 12.39 and 12.40). Low-profile dumpers are used in underground mines with access by decline. Conveyer belts are used in underground mines with access by shaft or incline. The environmentally friendly battery-operated locomotives are suitable for moving ore to the shaft for hoisting it to the surface in buckets and/or skips. The ore is emptied mechanically into bins beneath the surface head frame for transport to the mill.

FIGURE 12.38 Electric-powered radio remote-controlled operation of 2.7 m^3 capacity.

FIGURE 12.39 Hydraulic crawler-mounted medium-sized mucking and loading unit in operation at Sukinda chromite mine bench.

12.5 MINE EXPLOSIVES

An explosive is a solid or liquid chemical substance that can instantly produce a sudden expansion of material accompanied by the development of high temperature and pressure. Explosives explode with high vibration and loud noise when ignited by flame, heat, and sudden shock. The detonator gives a violent shock to the explosives to create an explosion. The process is called detonation. The explosion breaks and shatters a large volume of rock mass depending on the type, power, quantity, and design of the blast. The commonly used commercial explosives are:

1. Gun (black) powder: Potassium nitrate (75%), charcoal (15%), and sulfur (10%).
2. Flash powder: Fine metal powder (aluminum or magnesium) and a strong oxidizer (potassium chlorate or perchlorate).
3. Ammonium nitrate: Ammonia gas with nitric acid.
4. Nitroglycerine: Gelatinous, semigelatinous, and powdery.
5. Armstrong's mixture: Potassium chlorate and red phosphorus.
6. Trinitrotoluene (TNT): Yellow insensitive crystals that can be melted and cast without detonation.
7. ANFO: Ammonium nitrate mixed with diesel fuel oil.
8. Slurry explosive: A mixture of TNT and ANFO in water.
9. Emulsion explosive: An oxidant, a fuel, and an emulsifier.
10. Gelatin: Nitrocellulose in nitroglycerine and mixed with wood pulp and sodium nitrate or potassium nitrate.

12.6 ROCK MECHANICS AND SUPPORT SYSTEMS

Rock mechanics is the study of geotechnical responses of geological phenomena. It involves measurement of the stability of rock strata and soil deposited within mined-out voids. The knowledge and indication of geotechnical characteristics, including rock strength parameters, is evidently the first step, and is further supplemented by the study of weathering, joints, shears, faults, and other rock deformations. The critical parameters are determination of **rock-quality designation** (RQD), and **rock-mass rating** (RMR) from drill core. Measurements include laboratory testing of the strength of various rocks likely to be encountered during mining. The observations are processed by numerical modeling to conceptualize support systems to protect mines, miners, equipment, and underground infrastructures. Roof support is accomplished with timber, concrete, steel columns, rails, bars, and roof bolts. **Roof bolts** are long steel rods used to bind the exposed roof surface to the rock behind it (Gundewar, 2014).

The local ground support prevents rockfall from roof and walls. Standard metal wire mesh of 10 cm × 10 cm openings is attached to the roof or walls by pointed anchor bolts grouted with cement. **Shotcrete** is another process that sprays/injects concrete/mortar with high pneumatic

FIGURE 12.40 Hydraulic large shovel mucking and loading and 85-t Haulpac dumper at Jhamarkotra rock phosphate open pit mine, Rajasthan, India (December 2008).

FIGURE 12.41 Timber chock support system to prevent collapse of bad ground.

FIGURE 12.42 Cable bolting is suitable to bind large rock masses for extended periods and is adopted as an appropriate support system in bad ground.

velocity through the nozzle of a hosepipe onto the loose fractured surface. Concrete is a mixture of cement, sand, gravel, stone chips, fly ash, chemicals, and water. Shotcrete undergoes placement and compaction due to projected force. It can impact onto any type or shape of surface, including vertical or overhead. The mixture coats 50–100 mm thick layers on roof and walls preventing the fall of rock fragments.

Roof subsidence can be prevented by easily available seasoned timber supports at low cost. The timber bars are arranged as a prop between the floor and roof of the mine opening (Fig. 12.41). However, the use of timbers is seriously discouraged because it generates deforestation in the long run.

Rock bolting prevents major ground failure. The holes are drilled into the roof and walls. Long metal bars are inserted to hold the ground together. The point anchor and expansion shell bolt are metal bars of 20–25 mm in diameter and 1–4 m in length. As the bolt is tightened the expansion shell located at the top end expands and the bolt tightens to hold rock together. The cable bolts bind large rock masses in hanging walls and around large excavations. The cable bolts are 10–25 m long, much larger than standard rock bolts, and grouted with cement (Fig. 12.42).

12.7 MINE VENTILATION

Mine ventilation is a significantly important aspect of underground mining. Improved ventilation clears methane and other toxic gases found in coal and metal mines, removes fumes from blasting, and exhausts diesel fumes produced by equipment. Ventilation provides fresh air to underground mines and removes noxious gases, as well as dusts that might cause lung disease like silicosis. In deeper mines, ventilation is necessary to cool the workplace for miners. The primary sources of heat in underground hard rock mines are depth factor from surface, blasting, rock temperature, machinery, autocompression, and fissure water. Underground mine ventilation is regulated by air intake through one of the inclines or the main shaft, and air outlets through other inclines or ventilation shafts fitted with exhaust fans.

12.8 MINE CLOSURE

All mines are closed either completely at some point due to complete removal of ore (Fig. 12.43), or temporarily due to fall in demand, fall in metal prices, uneconomic operations, natural calamity, and legislative order. The closure of a mine has significant social and economic implications for the surrounding regions and people, employees, and dependents. A Final Mines Closure Plan should be submitted 1 year prior to proposed closure. A Progressive Mine Closure Plan is to be submitted within 180 days from the date of notification in the amended format and guidelines in Mineral Concession Rules and Mineral Conservation and Development Rules. It requires effective planning of landscape covering land, mine, river, water, waste dump, and tailing disposal. The program must satisfy the ongoing rehabilitation process to restore to a level acceptable to society as a self-sustained ecosystem, and not become an undesirable burden.

The Mine Closure Plan includes an outline describing the lease areas affected by mining, impacted communities and stakeholders, decommissioning and infrastructure plan, mine area rehabilitation, and finally the social and economic impacts of mine closure. The closure plan must highlight a brief narrative of the deposit, available mineral reserve and resources, mining method and mineral processing, and reasons for closure. It should include reclamation and rehabilitation of mined-out land, water and air quality, waste, top soil and tailing dam management, existing infrastructure, disposal of mining machinery, compensation and alternative restoration, time schedule, and costs.

12.9 MINING SOFTWARE

Computer applications in geological data processing and mine design have become a boon to the mineral industry. In-house software development is time consuming and requires availability of expertise. Even then it can only be satisfactory to a limited extent. Vendor software is user friendly. Continuous development over the last three decades has enabled software to handle the simplest to the most complicated of situations. Vendor software takes into account all possible needs encompassing all possible global users engaged in multipurpose facets of work, and is continuously updated online to satisfy worldwide customers.

In-depth knowledge of computers and the intricacy of software are not essential for their use. Adequate training and especially practice can enhance the skill of the user. It is important that the user is well versed in the subject, data input, and possible results expected at the end of processing. One should never blindly depend on the black box. No single item of software can provide the total solution to the mining industry. A combination of in-

FIGURE 12.43 The Sullivan zinc-lead-silver-tin mine in Kimberly, British Columbia, Canada, was discovered in 1892 and closed after 105 years. It was Canada's longest surviving continuous mining operation, and produced 16 Mt of lead and zinc metals, as well as 9000 t of silver. *Image credit: Kimberly Daily Bulletin, December 21, 2001.*

house and vendor software can take care of all possible alternatives, including influence of criteria. There is a selection of geology, mine planning, and processing software readily available at a cost, and commonly used packages are mentioned without any prejudice or degree of qualitative position. Each one has its strengths and deficiencies. One has to pick the software that best suits the requirement. No hardware and software will work unless trained human resources are at hand with the zeal to work. It is essential to include an onsite professional staff training component with its own database to ensure software competency, and annual or long-term online maintenance of software updates. Staff training by the vendor should be an integral component when selecting the software.

The format of data collection should be standardized during exploration. There are five files: four for raw data and the fifth is processed information. The file format is in ASCII/Excel/Dbase with standard decimal specified. The exploration companies capture detail drill core description including chemical analytical values of samples at remote camp site, and electronically upload to the central process computer at head quarter for evaluation. The data collection files are:

1. COLLAR file
   A COLLAR file contains data related to the starting point of a borehole. Latitude and longitude coordinates can be global or local following the Universal Transverse Mercator system. Z coordinates represent levels with respect to mean sea level. The borehole number must be unique all through the database.

Borehole No.	X or Longitude/ Easting (m)	Y or Latitude/ Northing (m)	Z or Level (m)	Borehole Depth (m)
RA080	55.00	−700.00	384.42	110
RA065	115.00	−150.00	387.50	210

2. SURVEY file
   A SURVEY file contains survey or deviation data along the borehole course

Borehole No.	Depth (m)	Angle (°)	Bearing (°)
RA080	0	−50	320
RA080	50	−51	321
RA080	90	−51.5	321

3. ROCK file
   A ROCK file contains alphanumeric codified rock type intersected in the borehole

Borehole No.	From (m)	To (m)	Rock Type
RA080	0.00	11.50	SOIL
RA080	11.50	23.25	GBSG
RA080	23.25	60.00	GBMS
RA080	60.00	110.00	GBSG

4. ASSAY file
   An ASSAY file contains chemical analysis of samples conducted at unequal length during the early stage of exploration. The original sample lengths, if unequal, are transformed to equal length for statistical analysis, and composited to larger lengths for reduction of variance.

Borehole No.	From (m)	To (m)	% Pb	% Zn	g/t Ag
RA080	28.50	29.50	0.50	1.25	10
RA080	29.50	31.00	1.90	15.25	45
RA080	31.00	32.25	2.10	12.00	55
RA080	32.25	34.00	1.55	9.50	40

5. SAMPLE file (desurveyed)
   A SAMPLE file is a processed file sample of unequal, equal, or composite length with desurveyed central coordinates and corresponding chemical values.

Borehole No.	X	Y	Z	% Pb	% Zn	g/t Ag
RA080	40.00	−700	370.00	0.50	1.25	10
RA080	39.35	−700	369.50	1.90	15.25	45
RA080	39.10	−699	368.10	2.10	12.00	55
RA080	38.90	−699	367.80	1.55	9.50	40

The following list of software vendors is alphabetically arranged:

1. Geology and mine planning:
   a. DATAMINE International, UK, is the world's leading developer, trainer, and maintainer of integrated technology for total solutions to the mining industry, encompassing geological data capture, geostatistical evaluation, mine planning, production scheduling, and environmental issues with a full virtual reality system.

- **b.** GDM BRGM, France, provides 3D GeoModeler for processing geological, geochemical, and geophysical data integrated with geographic information system applications.
- **c.** GEMCOM-SURPAC International Inc., Australia, develops software designed to automate and integrate key operations for exploration, resource evaluation, mine planning, mine design, and mine operations.
- **d.** GEOVARIANCES is a French independent software vendor that develops and maintains geostatistical data modeling related to mining and environmental issues.
- **e.** LYNX, Vancouver, Canada, provides site setup and configuration functions along with real-time monitoring, control, logging, automatic report printing, and on-screen history of customizable user interface of geological information. It has the ability to create multiple screen displays with critical information in plain view with the option to view details. Drilldown displays provide an intuitive means to monitor many sites.
- **f.** MEDSYSTEM, Tucson, Arizona, USA, develops and supports software for mine design, evaluation, geologic modeling, surveying, geostatistics, and scheduling in open pit, underground, coal, metal, and nonmetal mines.
- **g.** MINEX 3D, Australia, an associate of GEMCOM, is a comprehensive software package that synthesizes the geological data to arrive at 3D modeling.
- **h.** PC MINE, Vancouver, Canada.
- **i.** SURPAC, Australia, is a strong survey cum open pit package that extends to a total system covering geological assessment, survey, mine planning, scheduling, grade control, and reconciliation.

2. Rock mechanic
- **a.** NFOLD is numerical analysis software for rock stress and strain (RQD, RMR, and other related factors) that arrives at a solution for rock support and void filling in mining.
- **b.** ROTOMAP is a 3D model that is used for rockfall analysis, and the design of rockfall protective systems. It simulates the isomap contour lines of the minimum travel times of the blocks, with a simple chronometer and a standard video camera. It is possible to compare the real and simulated times in correspondence with predetermined checkpoints.
- **c.** ROCK3D is a program for stability analysis of removable blocks on planar rock slopes. It identifies and analyses all the blocks that have formed under each kinematic mode. Once the geometry of the rock blocks has been identified, the bolt forces necessary to reach a required safety factor are calculated.

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Chapter 13

Mineral Processing

Chapter Outline

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00013-7

> *Minerals are wanted in the highest state of purity for their end uses.*
>
> Author.

13.1 DEFINITION

All minerals, by definition, are naturally occurring substances possessing definite chemical composition, atomic structure, and physical properties. Minerals, in general, occur in certain heterogeneous associations of varied physical and chemical properties, and complex interlocking boundaries. The properties of common metallic and nonmetallic minerals have been summarized in Table 2.2. Metal content and other chemistries vary widely between minerals. Minerals are wanted in the highest state of purity (say, 99.99%) for their end uses.

Mineral processing, also known as **ore dressing**, **mineral beneficiation**, or **mineral engineering**, is defined as the science and art of separating valuable metallic and nonmetallic minerals from unusable gangues. Mineral beneficiation and extractive metallurgy are postmining activities that promote liberation and separation between ore minerals (valuable concentrates) and unworthy waste (rejects/tailings). This is achieved by exploiting characteristic differences in physical and chemical properties of minerals, and applying suitable techniques (Ammen, 1997; Fuerstenau and Han, 2003; Grewal, 2010; Wills, 2015). The processing of raw materials (run-of-mine [ROM] ore) produces marketable intermediate (copper concentrate) or finished (silica sand) products. ROM ore components consist of the following:

1. Building and decorative stones: Granite, marble, and limestone.
2. Industrial minerals: Calcite, fluorite, apatite, barite, wollastonite, bauxite, diamond, and gemstones.
3. Metalliferous minerals: Chalcopyrite, sphalerite, galena, bauxite, and hematite.
4. Precious metals: Gold, silver, platinum, and palladium.

The process should not under any circumstance, and even at any intermediate stage, alter the physical and chemical identity of the parent minerals for subsequent treatment (smelting). The metalliferous concentrate is further treated by extractive metallurgy, either **hydrometallurgy** or **pyrometallurgy**, and **electrometallurgy** for extraction of metals in their purest form.

Mineral beneficiation includes four prime activities:

1. **Comminution**, **liberation**, or **particle size reduction**.
   Liberation is the release of valuable minerals between themselves and from the associated gangues at the coarsest possible particle size. The optimum particle size for best liberation is seldom achieved due to complexity of intermixing natural characteristics. When valuable minerals and gangues are interlocked in a particle, they are known as **middlings**.
2. **Sizing** and separation of particles by **screening or classification**.
   Sizing is the separation of particles according to their size using nets or screens of desired and industry standard perforation.
3. **Concentration** by taking advantage of physical and surface chemical properties.
   Concentration is the separation of minerals into two or more products such as valuable minerals in concentrates, gangues in tailing, and locked particles in middlings. Middlings are misplaced particles and often associate with either concentrates or tailings.
4. **Dewatering** or **solid/liquid separation**.
   Moisture reduction reduces the cost of long-distance shipment and prevents hazards during transportation.
   The mineral beneficiation technique is oriented to the conservation of mass (material balance) and accepts the best possible grade of concentrate at the highest possible recovery efficiency of each mineral (mineral balance).

13.2 ORE HANDLING

Ore handling at the mine site, open pit, or underground is one of the important activities prior to mineral beneficiation. Several tasks are generation of the proper size of broken ROM material, cleaning, removal of harmful substances, transportation to plant site, creation of stockpiles with even size and grade, and analysis of mill feed. Ore from various sources of mines, stopes, and draw points is successively reduced to a smaller size. The intermixing of material by blending of ores from different sources maximizes homogeneity and consistency before feeding to the process operation.

13.2.1 Cleaning

ROM ore contains pieces of iron and steel broken from mine machinery, drill rods and bits, pieces of wood from mine support arrangements along with clays and slimes from nonmetallic gangue minerals. These materials are harmful to the process system because they can jam and damage the crusher-grinder-pulverizer, chock the screens, and clog the flotation cells and filtration media. They must be removed at an appropriate stage of operation. Removal is done by hand sorting, electromagnetic separation over a conveyor belt, and washing of clays and slimes.

FIGURE 13.1 Standard open surface rubber belt conveyor system with support rollers at the bottom of the belt for ore transportation over kilometers.

13.2.2 Transportation

ROM ore is transported to the mineral processing plant by various means. It depends on the size of operation, say 1000 to 10,000 t/day, and the distance to be covered between the mine and the plant, which can vary from a few hundred meters to tens of kilometers. In the case of long-distance transportation, aerial ropeways and heavy-duty trucks and dumpers are used. If the distance is short, the standard rubber belt conveyor with support rollers at the bottom of the belt (Fig. 13.1) is the most widely used method of handling loose bulk material. A set of conveyors negotiates the distance, sharp turns, and gradients. The basic principle is to operate a continuous transportation system in the direction of the gravitational movement at the shortest possible distance between supply and delivery points.

13.2.3 Stockpile

The directly saleable ROM ore is stockpiled (Fig. 13.2) at the mine head in various size fractions and grades, directly loaded to transport vehicles, and delivered to the customer's destination.

The storage of raw material as buffer stockpile is also necessary for uninterrupted operation of a continuous process plant. The ore is stocked as reserve at every stage of output/input of stope draw points, mine dispatch sites, and crusher/grinder/feeder for uninterrupted feeding in the likelihood of any breakdown at any unit of operation. The quantity of storage depends on the size of operation, frequency of unexpected breakdown, and shutdown of individual units for routine maintenance. As a general practice, 3–6 days of requirements are stocked at every site. The stockpiles can be flat, conical, and elongated stacks with chutes at the bottom for autofeeding to conveyor belts or loading equipment (Fig. 13.3). The feeder mechanism regulates an even flow of ore movement from storage bins to the delivery point in an automatic conveyor network. Many types of feeders are used: chain, apron, roller, rotary, revolving disc, and vibratory.

13.2.4 Weighing, Sampling, and In-Stream Analyzer

The physical weighing of ore and moisture, sampling, and chemical analysis is required at every stage of operation, namely, mill feed, concentrate, and tailing, to estimate the quality of end products and metallurgical accounting.

13.2.4.1 Weighing

The weighing of moist ore is conducted at every stage of ore movement from mine draw point, surface transport system, and conveyor belts at the process plant. It is done by multiplying the number of ore-filled mine cars, trucks and dumpers, and aerial ropeway buckets with the tonnage factor of broken ore. The weights are compared by physically surveying the volume/tonnage of the stockpiles and results of continuous automatic weighing devices fitted with the conveyor. The moisture content is determined by randomly taking grab samples from different parts of stockpiles, dumpers, mine cars, and conveyors. The samples are heated on an open oven or by thermal dryer to evaporate the moisture. The weights of moist and

FIGURE 13.2 Screen-sorted chromite ore stockpiles of different specifications for direct sale and transportation to a ferrochrome plant.

FIGURE 13.3 Close conveyor system (top) transporting run-of-mine (ROM) ore automatically unloaded from shaft cage to ore bin, and interim stockpiles (right) with chutes (bottom) for autofeeding to the mineral process plant.

subsequent dry ore are obtained for the same grab sample. The moisture content is determined by:

% Moisture = {(Wet weight − Dry weight)/(Wet weight) × 100}

The weight of the concentrate is determined by deducting the moisture factor. The weight of the tailing is the difference between the weight of feed and concentrates. This is compared by estimation of tailing flow over the running hours of the flotation plant.

13.2.4.2 Sampling

Grab sampling of ROM ore is regularly done to assign the mine a production grade. However, the grade of assorted broken ore and fine fragments cannot be précised due to the wide range of particle sizes and heterogeneity of the material. A better sample grade is expected from mill feed material at −12 mm size. The best possible grade representation is at the mill discharge point of −75 μm size when it becomes extremely homogeneous. Samples of fine fragments can be manually collected at regular intervals of 15, 30, or 60 min in two ways: by taking a grab of mill feed (−12 mm) from the conveyor belt or by collecting a mug full of slurry (−75 μm) at the ball mill discharge of feed, concentrates, and tailings. Modern mineral process plants are equipped with automatic samplers at the incoming and outgoing product flows at preferred preset time intervals. The device (Fig. 13.4) is a simple collector or cutter that moves mechanically at constant speed and intervals across the whole stream of material either in dry or slurry form. The sample container is large enough to hold material for an operating shift. The samples are analyzed through facilities available at the operating unit.

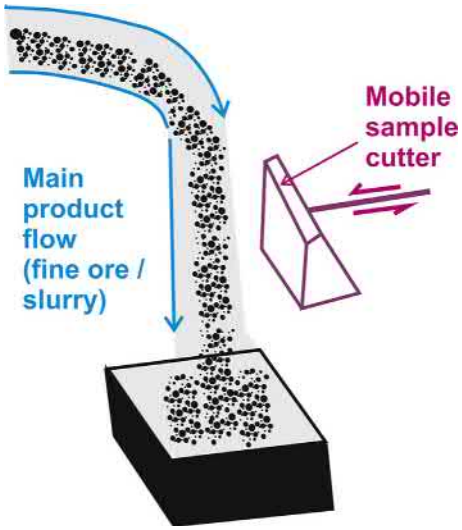

FIGURE 13.4 Schematic diagram of automatic unbiased mill sampling arrangement of pulverized slurry ball mill product flow (top) by to-and-fro moving cutter (middle) at certain time intervals.

13.2.4.3 In-Stream Analyzer and Process Control

Mineral beneficiation, particularly base and noble metals, is sensitive to optimum use of reagents, recovery of metals, and clean concentrate. High fluctuation of feed grade at flotation cells yields loss of metals to tailing. The offline analytical procedures discussed at Chapter 7, Section 7.5, are not appropriate under changing feed grade. The process is not capable of continuous in-stream detection and spontaneous corrective measures. This is surmounted by complete concentrator automation. The circuit is comprised

FIGURE 13.5 Mill sampling system by in-stream analyzer. The probe is installed in the slurry stream of feed (conditioner) and reject (tailing) for continuous sensing of metal grades and simultaneous digital process control of reagents.

of three major integrated units: probe or sensor, in-stream analyzer, and digital process control module.

The in-stream X-ray analyzer (Fig. 13.5) employs sensors acting as a source of radiation, which is absorbed by the sample causing fluorescent response of each element. The analyzer probes are installed in feed, concentrates, and tailing streams. The metal content (Pb, Zn, Cu, Fe, Cd, Ag, Au, etc.) and pulp density, in the form of electrical signals from the probes (sensors), are conveyed in electronic circuits (detectors generating a quantitative output signal) to a digital computer in the control room. A continuous screen display and/or printout showing the elemental dispersion at every minute is available for manual or automatic control of reagents in the flotation process. The field instruments for the flotation circuits comprise pH and metal probes and magnetic flow meters with control valves for reagent dosing pumps. The system improves the recovery of each metal as well as concentrate grade. The regulated feed reagents, apart from improved metallurgy, result in significant savings of reagent cost.

13.2.5 Particle Size Analysis

Mineral processing techniques depend a great deal on the particle behavior, which in turn varies with its size. Therefore size analysis is of great significance to determine the quality of grind and establish the degree of liberation of valuable minerals between them, as well as from the gangue at various particle sizes. Sizing is the general expression for separation of particles. The simplest of sizing process is screening, i.e., passing the particles to be sized through a sieve or series of sieves. Sieves consist of nets made of iron rails, rods, and wire having specific apertures so that preferred size fractions can pass through them. Sieves are designated by standard mesh numbers with aperture sizes expressed in microns (μm) as given in Table 13.1. (A micron or μm = one millionth of a meter = 10^{-6}).

TABLE 13.1 Standard Wire Mesh Sieve Size (BS 1796) Uses in Various Industries

Mesh Number	Nominal Aperture Size (μm)	Mesh Number	Nominal Aperture Size (μm)
3	5600	36	425
3.5	4760	44	355
4	4000	52	300
5	3350	60	250
6	2800	72	212
7	2360	85	180
8	2000	100	150
10	1700	120	125
12	1400	150	106
14	1180	170	90
16	1000	**200**	**75**
18	850	240	63
22	710	300	53
25	600	350	45
30	500	400	38

Bold represents suitable Mesh Number and Aperture size suitable for zinc, lead and copper flotation.

13.3 COMMINUTION

Mineral deposits are composed of ore and gangue minerals intimately associated in an intricate mosaic. The minerals are assembled in various proportions with forms varying between very fine and extremely coarse grain size depicting layered, veins, stringers, and complex structures (Fig. 13.6).

An individual mineral may occur as an inclusion within another type and often with interlocking boundaries (Fig. 13.7). Until and unless the individual minerals are unlocked and totally liberated from each other the concentration process of minerals rich in value cannot be perceived. This is achieved by comminution (particle size reduction).

The particle size of ore is progressively reduced to an optimum fraction for separation by a method suitable to the physicochemical properties of the minerals. The initial comminution process begins during the mining operation through blasting of in situ orebody, drawing by excavators or scrapers, and moving out to the stockyard as ROM ore. Fragment size at this stage is heterogeneous, varying anywhere between 1.50 m and fines. Large boulders are

FIGURE 13.6 Camera image of polished surface of rich run-of-mine (ROM) ore showing yellow-brown sphalerite, gray-black galena, and gangue minerals (white calcite, dolomite, and quartz crystals).

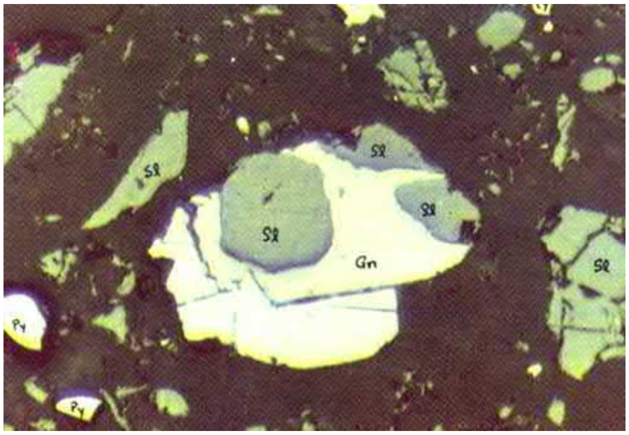

FIGURE 13.7 Polished thin section under microscope showing coarse inclusion and interlocking gray sphalerite (Sp) and white galena (Ga) in the matrix of host rock.

reduced by a rock breaker (refer Fig. 12.34) at the ore dumpyard or on the grizzly feeder and by the onsite crusher. Ultimate size reduction in a successive sequence of crushing, grinding, and pulverizing is an integral part of the process plant. The individual mineral grains are liberated (Fig. 13.8) to the highest extent and are ready for froth flotation or any suitable beneficiation technique.

13.3.1 Crushing

Crushing is accomplished by compression of the ore against a rigid surface or by impact against a surface in a rigidly constrained motion path. Crushing is usually a dry process and carried out on ROM ore in succession of two or three stages, namely, by (1) primary, (2) secondary, and (3) tertiary crushers.

FIGURE 13.8 Final milling completes the liberation of free sphalerite, galena, pyrite, graphite, and gangues, ready for froth flotation or any suitable process.

13.3.1.1 Primary Crusher

Primary crushers are heavy-duty rugged machines used to crush ROM ore of (−) 1.5 m size. These large-sized ores are reduced at the primary crushing stage for an output product dimension of 10−20 cm. The common primary crushers are of jaw and gyratory types.

The **jaw crusher** reduces the size of large rocks by dropping them into a "V"-shaped mouth at the top of the crusher chamber. This is created between one fixed rigid jaw and a pivoting swing jaw set at acute angles to each other. Compression is created by forcing the rock against the stationary plate in the crushing chamber as shown in Fig. 13.9. The opening at the bottom of the jaw plates is adjustable to the desired aperture for product size. The rocks remain in between the jaws until they are small enough to be set free through this opening for further size reduction by feeding to the secondary crusher.

The type of jaw crusher depends on input feed and output product size, rock/ore strength, volume of operation, cost, and other related parameters. Heavy-duty primary jaw crushers are installed underground for uniform size reduction before transferring the ore to the main centralized hoisting system. Medium-duty jaw crushers are useful in underground mines with low production (Fig. 13.10) and in process plants. Small-sized jaw crushers (refer to Fig. 7.32) are installed in laboratories for the preparation of representative samples for chemical analysis.

The **gyratory crusher** consists of a long, conical, hard steel crushing element suspended from the top. It rotates and sweeps out in a conical path within the round, hard, fixed crushing chamber (Fig. 13.11). The maximum crushing action is created by closing the gap between the

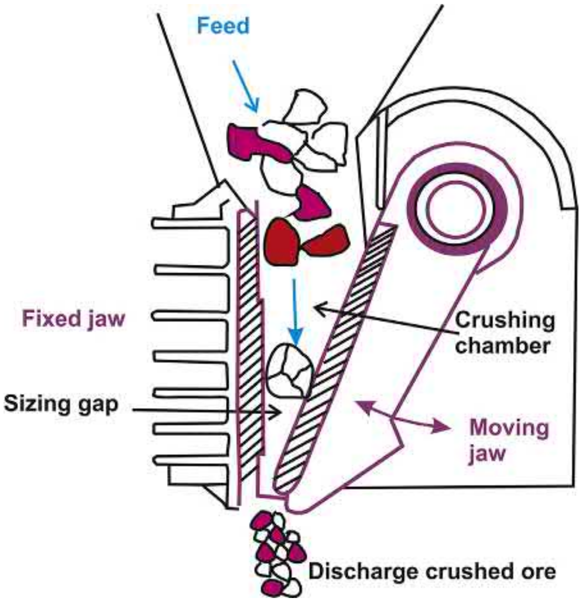

FIGURE 13.9 Schematic diagram showing principle of jaw crusher showing the path of lumpy feed ore to fragmented product crushed under high pressure of fixed and moving jaws.

FIGURE 13.10 Medium-sized jaw crusher in operation in underground mine for crushing run-of-mine (ROM) ore before transferring to the surface.

hard crushing surface attached to the spindle and the concave fixed liners mounted on the main frame of the crusher. The gap opens and closes by an eccentric drive on the bottom of the spindle that causes the central vertical spindle to gyrate.

13.3.1.2 Secondary Crusher

The secondary crusher is mainly used to reclaim the primary crusher product. The crushed material, which is around 15 cm in diameter obtained from the ore storage, is disposed as the final crusher product. The size is usually between 0.5 and 2 cm in diameter so that it is suitable for grinding. Secondary crushers are comparatively lighter in weight and smaller in size. They generally operate with dry clean feed devoid of harmful elements like metal splinters, wood, clay, etc. separated during primary crushing. The common secondary crushers are cone, roll, and impact types.

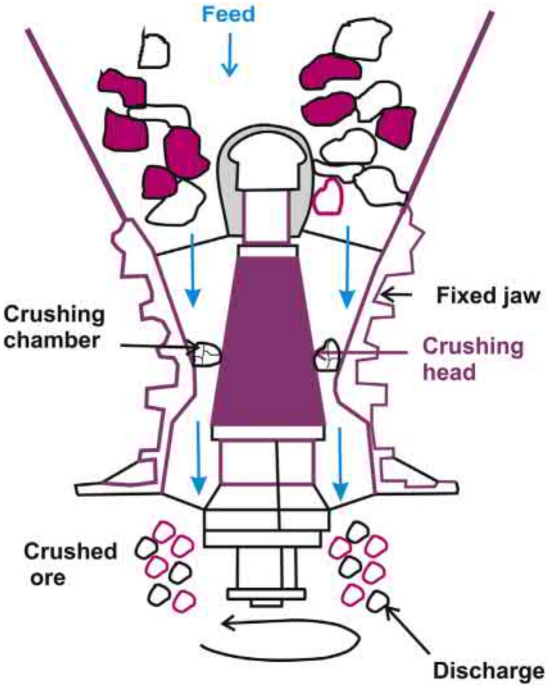

FIGURE 13.11 Working principle of gyratory crusher for breaking lumpy ore pressed between a fixed jaw and rotating conical head.

The **cone crusher** (Fig. 13.12) is very similar to the gyratory type, except that it has a much shorter spindle with a larger-diameter crushing surface relative to its vertical dimension. The spindle is not suspended as in the gyratory crusher. The eccentric motion of the inner crushing cone is similar to that of the gyratory crusher.

A working cone crusher (Fig. 13.13) can perform as a tertiary crusher when installed in a close circuit between secondary crusher and ball mill to crush any overflow material of vibratory screening.

The **roll crusher** consists of a pair of horizontal cylindrical manganese steel spring rolls (Fig. 13.14), which rotate in opposite directions. The falling feed material is squeezed and crushed between the rollers. The final product passes through the discharge point. This type of crusher is used in secondary or tertiary crushing applications. Advanced roll crushers are designed with one rotating cylinder that rotates toward a fix plate or rollers with differing diameters and speeds. It improves the liberation of minerals in the crushed product. Roll crushers are very often used in limestone, coal, phosphate, chalk, and other friable soft ores.

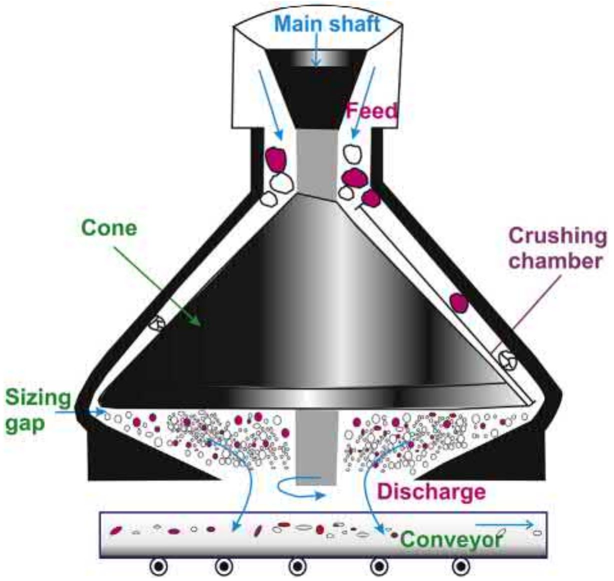

FIGURE 13.12 Schematic diagram depicting the basic elements and function of a cone crusher.

The **impact crusher** (Fig. 13.15) employs high-speed impact or sharp blows to the free-falling feed rather than compression or abrasion. It utilizes hinged or fixed heavy metal hammers (hammer mill) or bars attached to the edges of horizontal rotating discs. The hammers, bars, and discs are made of manganese steel or cast iron containing chromium carbide. The hammers repeatedly strike the material to be crushed against a rugged solid surface of the crushing chamber breaking the particles to uniform size. The final fine products drop down through the discharge grate, while the oversized particles are swept around for another crushing cycle until they are fine enough to fall through the discharge gate. Impact crushers are widely used in stone quarrying industry for making chips as road and building material. These crushers are normally employed for secondary or tertiary crushing.

FIGURE 13.13 A working cone crusher in a mineral process plant operation, performing both secondary and tertiary crushing functions.

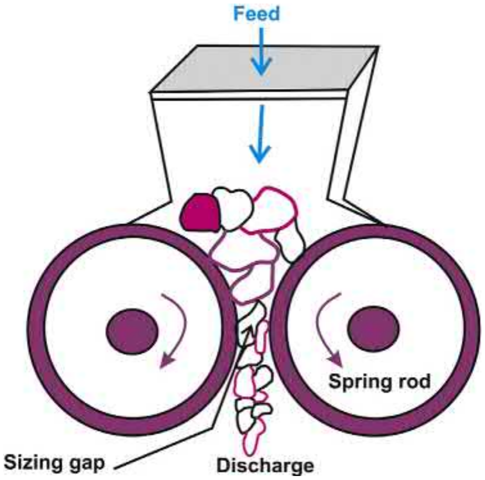

FIGURE 13.14 Conceptual diagram depicting the basic elements of a roll crusher.

13.3.1.3 Tertiary Crusher

If size reduction is not completed after secondary crushing because of extra-hard ore or in special cases where it is important to minimize the production of fines, tertiary recrushing is recommended using secondary crushers in a close circuit. The screen overflow of the secondary crusher is collected in a bin (Fig. 13.16) and transferred to the tertiary crusher through a conveyer belt in close circuit.

13.3.2 Grinding Mill

Grinding is the final stage used in the process of comminution. It is usually performed in rotating, cylindrical, heavy-duty steel vessels either dry or as a suspension in water. The loose crusher products freely tumble inside the rotating mill in the presence of agitated grinding medium. Grinding takes place by several mechanisms such as a combination of impact or compression due to forces applied almost normally to the particle surface, chipping due to oblique forces, and abrasion due to forces acting

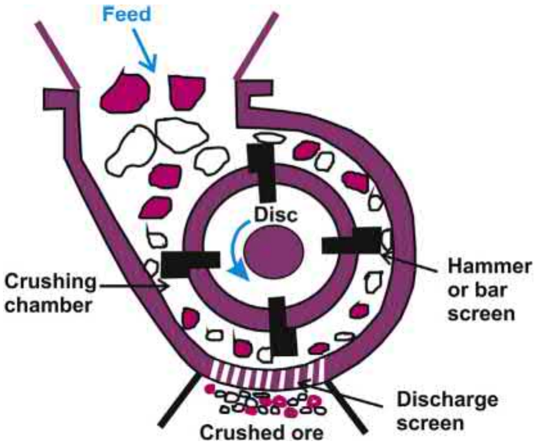

FIGURE 13.15 Schematic diagram showing the basic elements and function of an impact crusher.

FIGURE 13.16 Close circuit transfer of oversize material from secondary crusher collected in an ore bin (top) and autotransfer to tertiary crusher by a conveyor belt (bottom).

parallel to the surfaces. Grinding inside a mill is influenced by the size, quantity, type of motion, and space between individual pieces of medium within the mill.

There are five types of grinding mill: ball mill, rod mill, pebble mill, autogenous mill, and semiautogenous mill. The primary differences between these mills are the ratio of diameter to the length of the cylinder and the type of grinding media employed. The grinding media can be steel balls, steel rods, hard rock pebbles, or the ore itself, and the mill is classified accordingly. The grinding mill reduces feed particles of 5−20 mm to optimum sizes between 40 and 300 μm as required for beneficiation.

13.3.2.1 Ball Mill

Ball mills (Fig. 13.17) are short cylindrical vessels with a shell-to-diameter ratio of 1.5 to 1 and less. When the length-to-diameter ratio varies between 3 and 5 it is called a tube mill. The grinding medium is high-carbon or cast alloy steel balls. The particle size of the feed usually does not exceed 20−25 mm. Grinding is caused by balls being moved up the side of the mill in such a way that they release and fall to the point where they impact the ore particles in the trailing bottom region of the slurry. Ball mills are operated at higher speed so that the balls can be thrown up and strike back to the other wall with increased speed to hit the ore particles. Ball mills are suited for finer grinding of hard and coarse feeds. They are better suited for grinding base metals and phosphate, and operate in close circuit with the flotation cells.

13.3.2.2 Rod Mill

Rod mills are long cylindrical vessels with the length of the shell 1.5 to 2.5 times longer than their diameter. The breaking medium is steel rods. The rotating drum causes friction and attrition between steel rods and ore particles. As the mill rotates, the rods cascade over each other in relatively parallel mode to prevent overgrinding of softer particles. Product discharge is either through central or end peripheral or overflow types. Rod mills can take feed particles as coarse as 50 mm to produce material as fine as 300 μm. Rod mills are suitable for the preparation of feed to gravity and magnetic concentration.

FIGURE 13.17 Standard grinding ball mill plays a significant role in completing the liberation of ore and gangue minerals. It is in operation at Zawar Mine, India.

13.3.2.3 Pebble Mill

Pebble mills are similar to ball mills except that the grinding media are closely sized, suitably selected rocks or pebbles. The rotating drum causes friction and attrition between rock pebbles (quartz or quartzite pebbles) and ore particles. The pebble mill operates at low cost with respect to grinding media, power consumption, and maintenance. It has wide application in gold mines.

13.3.2.4 Autogenous Mill

Autogenous mills pulverize due to self-grinding of the ore without any additional breaking media. The drum is typically of large diameter with respect to its length, generally in the ratio of 2 or 2.5 to 1. The rotating drum throws larger ore particles in a cascading motion, which causes impact breakage of larger sizes and compressive grinding of finer sizes. It operates at a lower cost. Autogenous mills are often integrated in large mineral-processing operations. However, if the hardness and abrasiveness of the ore varies widely then it may result in inconsistent grinding performance.

13.3.2.5 Semiautogenous Mill

Semiautogenous mills are essentially a variation of autogenous mills with the addition of steel balls along with the natural grinding media, which rectify the problem of inconsistency in grinding. The total amount of balls in these mills ranges between 5% and 15% of volume. Many of the present-day plants install semiautogenous mills as primary- or first-stage grinding in combination with ball mills. They reduce the cost of media and replacement of rods. Maintenance cost in general is low. Semiautogenous mills are primarily used in the gold, copper, platinum, lead, zinc, silver, alumina, and nickel industries.

13.4 SCREENING AND CLASSIFICATION

Particle size plays a critical role in mineral processing for the beneficiation of valuable minerals suited during any particular downstream operation. Screening and classification are two distinct techniques of particle separation based on size. The relatively coarser particles are separated by screening. The screens are attached to all types of crushing units at feed and discharge stages. The oversized materials are diverted to recrush and regrind devices. The undersized materials pass to the next finer stage for crushing or grinding. The particles that are considered too fine to be sorted efficiently by screening are separated by classification. The classifiers are attached to the grinding units in close circuit for treating over- and undersized particles accordingly.

13.4.1 Screening

The crushed particles are separated using a hard metallic screen having a perforated surface with dimensions of fixed and uniform aperture. The crushed rock fragments are dropped to the screen surface. Particles finer than the openings pass through the screen. The oversized particles are conveyed to the discharge end for recrushing. Screening is generally difficult for very fine material and operated under dry conditions or with less moisture content. The efficiency of screen performance is judged by the recovery of desired size and misplaced material in each product. The factors affecting screen performance depend on particle size, shape, orientation, feed rate, angle of discharge, % open area, types of vibration, moisture content, and the feed material. Different types of industrial screen are available each suited to handle a particular type of material. The screen may be a nonvibrating or vibrating type. The vibrating type is more frequently used. Grizzly is an example of the nonvibrating type. Trammel screens, vibratory and gyratory, are examples of the latter.

The **grizzly** is used for primary screening of very coarse materials. It is generally installed for sizing the feed to the primary crusher. A grizzly is fundamentally a horizontal or inclined set of heavy wear-resistant manganese steel rails or bars set in a parallel manner at a fixed distance apart (Fig. 13.18). Finer materials fall through the spacing of the bars. Oversized materials slide on the surface of the bars

FIGURE 13.18 Run-of-mine ore is transported to a beneficiation plant and uploaded on a grizzly separator for preventive screening before feeding to a primary crusher.

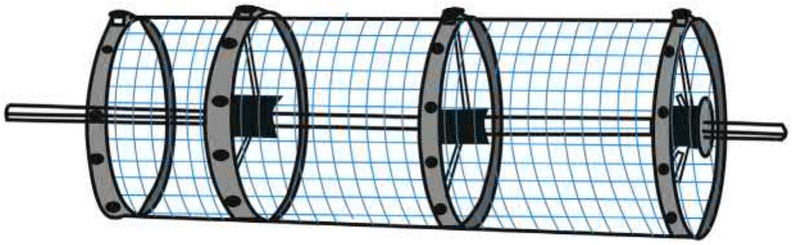

FIGURE 13.19 Trommel drum separator revolves in horizontal- or low-angle axis to separate the size fractions.

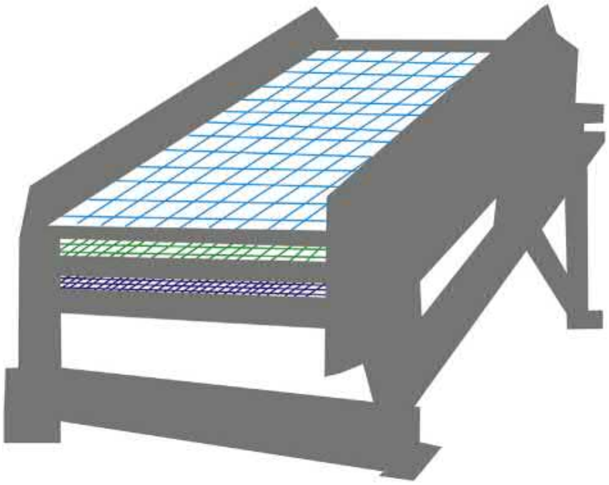

FIGURE 13.20 Schematic view of vibratory screen separator with multiple screen deck used to reduce size fractions.

and are reduced on site by manual hammering, power pack rock breaker (Fig. 12.34), or local explosive pop blasting. Screens are static for very coarse materials. A grizzly can incorporate a mechanism to shake or vibrate the screen to improve performance.

The **trommel** or revolving screen or drum separator is a horizontal or slightly inclined rotating cylindrical screen (Fig. 13.19). The feed material enters at one end of the cylinder, undersized particles fall through the screening surface, and oversized particles move by a rotating motion to the discharge end. A trommel can separate several sized fractions by using a series of screens with coarsest to finest apertures. It can handle both dry and wet feed material. Trommel separators are low-cost equipment, and suitable for soil washing in coal and iron ore industry as higher end applications. Screening of aggregates and road materials is at the lower end application.

The **vibratory** screen is the most common screening device found in mineral-processing applications for the various types of material and particle sizes encountered. It works on the shaking motion of the surface and the resulting action is imparted on the material being screened (Fig. 13.20). It can be arranged as multiple decks so that different particle size products can be obtained from a single feed.

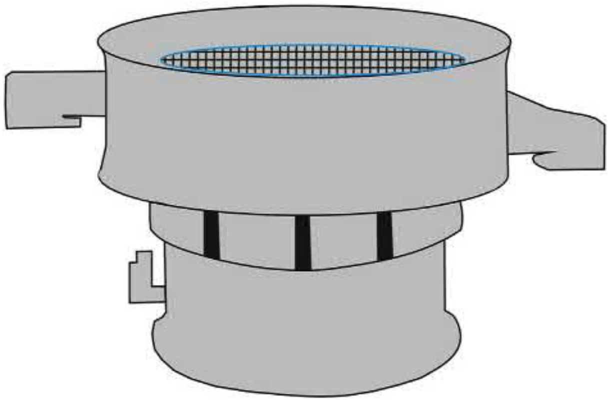

FIGURE 13.21 Conceptual diagram of gyratory screen separator with various available models.

Gyratory screen separators (Fig. 13.21) are removable and replaceable circular multiple decks or trays for different-sized products. They work on both gyratory and slight vertical motions. Gyratory separators are ideal for large and fine solid particles and solid/liquid applications. They operate by a specially designed motor mounted vertically at the center of the baseplate of the screen.

13.4.2 Classification

The separation of particles by screening is not effective for exceptionally fine materials composed of different mineral mixtures. Sorting between two or more mineral products of similar size is possible on the basis of the velocity with which the grains fall through a fluid medium. This method of separation and concentration by difference in the settling rates due to variable particle size, shape, and density in a fluid medium is known as **classification**. The fluid medium in general is water under modified conditions such as rising at a uniform rate, changing density, addition of suitable reagents, and passing air bubbles. The classifiers consist of a sorting column in which a fluid rises at a uniform rate. Particles introduced into the sorting column sink and are classed as underflow if their terminal velocities are greater

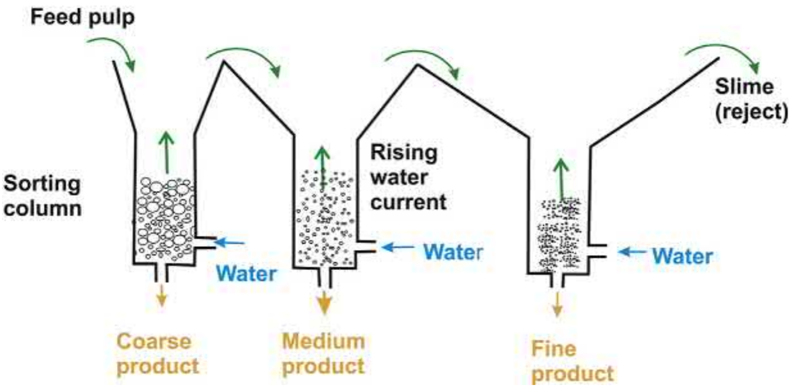

FIGURE 13.22 Schematic diagram showing the principle of a hydraulic classifier in a series of successively larger cone sizes with relatively lower current velocity.

than the upward velocity of the fluid. On the other hand, if their terminal velocity is less than the upward velocity of the fluid, they rise and are classed as overflow. The classification equipment includes hydraulic classifiers, horizontal current classifiers, spiral and rake classifiers, and hydrocyclones.

13.4.2.1 Hydraulic Classifier

The hydraulic classifier works on the differences in settling rates of particles of feed pulp against the rising water current. The unit consists of a series of conical sorting columns of successively larger size with relatively lower current velocity. The relative rate of settling against up-flow of water current accumulates coarsest particles in the first to finest in the last conical vessel (Fig. 13.22). The sediments are removed from the bottom of the settling zone and treated accordingly. The very fine slimes overflow at the last column.

13.4.2.2 Spiral Classifier

Spiral classifiers are typically mechanically driven devices. The unit drags coarse sandy sediment from the settled feed pulp by a continuously revolving spiral along the bottom of an inclined surface to a higher discharge point at one end of the settling tank (Fig. 13.23). The fines overflow at the other end. The **rake** classifier is a variation in the mechanism of shifting the coarser component. The rakes dip into the feed pulp, move in an eccentric motion along an inclined plane for a short distance, and then lift it up and go back to the starting point to repeat the operation. Spiral classifiers are usually preferred to the rake type as material does not slide backward. The backward sliding of material happens when the rakes are lifted between strokes.

13.4.2.3 Hydrocyclone

The **hydrocyclone** is a widely used classifier in the mineral-processing industry. It is installed in close circuit between the grinding and conditioning paths for flotation of complex base metal ore. It consists of a cylindrical section at the top connected to a feed chamber for continuous inflow of pulp, which is then expelled through an overflow pipe. The unit continues downward as a conical vessel and opens at its apex to the underflow of coarse material (Fig. 13.24). The feed is pumped under pressure through the tangential entry that imparts a spinning motion to the pulp. The separation mechanism works on this centrifugal force to accelerate the settling of particles. The velocity of slurry increases as it follows in a downward centrifugal path from the inlet area to the narrow apex end. The larger and denser particles migrate nearest to the wall of the cone. The finer/lighter particles migrate toward the center axis of the cone, reverse their axial direction, and follow a smaller

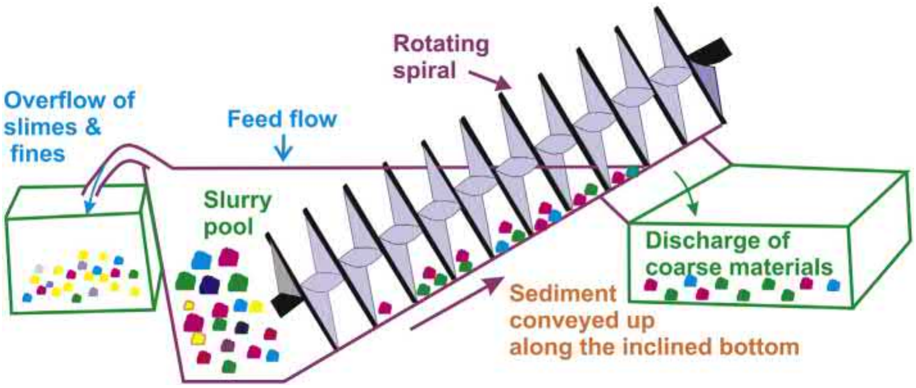

FIGURE 13.23 Principle of mechanical spiral classifier separating coarse materials from fines.

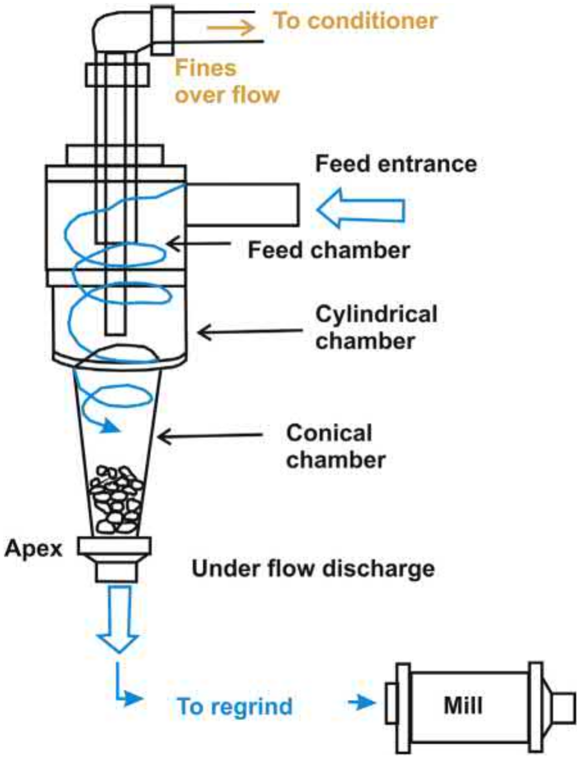

FIGURE 13.24 Sketch diagram showing the working principle of a hydrocyclone in close circuit classification.

diameter rotating path back toward the top. The oversized discharge fractions return to the mill for regrinding, while the undersized fractions move to the conditioning tank for flotation. Hydrocyclones perform at higher capacities relative to their size and can separate at finer sizes than other screening and classification equipment.

13.5 CONCENTRATION

Minerals rarely occur in their purest form and are seldom used directly. Most of the nonmetallic and all metallic orebodies contain valuable elements in widely varying states between parts per million and percentage. The ore as produced from the mine head needs to be beneficiated or upgraded to an intermediate stage or final form for industrial uses. The process of upgradation is called **concentration** and the upgradation product is called the **concentrate**. Concentration is performed by various methods of exploiting the physical and chemical behaviors of the feed materials to the process plant. Beneficiation processes are many, such as leaching, sorting, gravity, magnetic, electrical, dense media, and flotation (Rao et al., 2017).

13.5.1 Leaching

Leaching is a process that extracts metals directly from low-grade ores, often in oxide form and old tailing pads. This is a slow process and can take several months for metal extraction. Sometimes leaching is economically effective to convert unviable property to a profitable venture. The main leaching reagents are diluted hydrochloric, sulfuric, and nitric acids. Acid leaching of low-grade Cu, Au, Ag, Pt deposits and tailing pads is done without incurring much cost in mining, crushing, and milling. The cleaning of iron ore or limonitic-stained quartz sand by diluted sulfuric acid is a common industrial practice.

FIGURE 13.25 Copper heap leaching at Whim Creek, Philbara, Australia (Haldar, 2013).

The low-grade ore, generally from open pit overburden, is blasted, loaded, and transported to the primary crushers. The coarse ore goes to the heap leach pad. The leach pad is covered by a series of pipes and hoses that sprinkle a shower of diluted acid solution onto the ore. The metal is dissolved and flows to a pond at the bottom of the pad (Fig. 13.25). Leached solution containing the dissolved metal is pumped to the solvent extraction (SX) circuit, which looks like a series of agitation tanks or cells. The SX process concentrates and purifies the metal leach solution. Metal is recovered by the electrowinning cells at high electrical current efficiency. The adding of special chemical reagents to the SX tanks binds the metal selectively. The metal is stripped and separated easily from the reagent for reuse.

13.5.2 Ore Sorting

The process of mineral concentration and cleaning was conceptualized centuries earlier by selective hand sorting of desired or undesired particles of lumpy size by mere appearance, color, texture, heaviness, etc. Hand sorting was common practice to separate rich ore as concentrate and

FIGURE 13.26 Hand sorting and commercial sizing by manual works at low cost in small-scale mining operation at Nausahi chromite mine, India.

wood or iron pieces as a cleaning process from ROM ore. Hand sorting is still a popular method in small-scale mining operations for the separation of waste rock and specific sizing of ore for commercial purposes (Fig. 13.26).

The sorting techniques are changed to mechanical mode by adopting optical, electronic, and radioactive properties for large-scale industrial applications. This is possible due to the distinct contract between the valuable ore and waste gangue minerals with respect to their physical properties. The critical attributes are light reflectance (base metals and gold ore, limestone, magnesite, barite, talc, and coal), ultraviolet ray (wolframite and sheltie), gamma radiation (uranium and thorium), magnetism (magnetite and pyrrhotite), conductivity (sulfide ores), and X-ray luminescence (diamond). The main objective of mechanical sorting is to reduce the bulk of the raw ROM ore by rejecting large volumes of waste material at an early stage. The process utilizes a two-stage separation process. The first stage involves primary crushing of feed that liberates pre-concentrate and barren rejects. The second stage performs recrushing, grinding, and processing to produce final concentrates and tailings. This two-stage operation will substantially lower the cost of large volumes of crushing and grinding, and the subsequent process of upgradation to produce marketable final concentrates.

A fully automatic electronic sorting device is comprised of an integrated circuit of an energy source, a process computer, a detector, and an ejector (Fig. 13.27). ROM ore at desired fragment size, preferably washed, moves on a conveyor belt or vibrating feeders at uniform speed and is released, maintaining a natural flow of the stream of ore particles. The energy elements like light rays, laser beams,

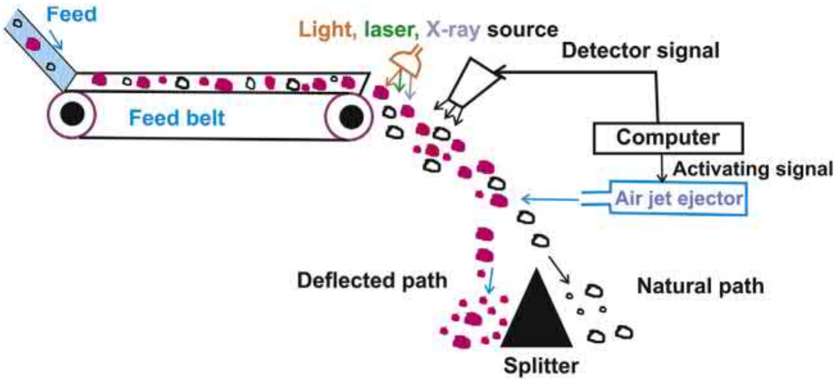

FIGURE 13.27 Schematic diagrams showing the principle of an automatic electronic ore sorter for separation of ore and gangue in lumps and coarse form at reduced cost.

and X-rays converge from the source and reflect from the surface of the rocks passing through the sorting zone. The nature of reflectance is sensed by the detector system, which sends signals to the computer. The amplified signal activates an air jet at the right instant and intensity to eject the particle from the stream. The accepted and rejected particles are dropped in separate stacks around a conical splitter.

13.5.3 Gravity Concentration

Gravity concentration is a proven process for mineral beneficiation. Gravity concentration techniques are often considered where flotation practice is less efficient and operational costs are high due to extremely complicated physical, chemical, and mechanical considerations. Gravity separations are simple and separate mineral particles of different specific gravities. This is carried out by their relative movements in response to gravity along with one or more forces adding resistance to the motion offered by viscous media such as air or water. Particle motion in a fluid depends on specific gravity, size, and shape of the moving material. Efficiency increases with coarser size to move adequately, but becomes sensitive in the presence of slimes. There are many types of gravity separators suitable for different situations and many devices for gravity concentration. The common methods are manual pans, jigs, pinched sluice and cones, spiral concentrators, and shaking tables to name a few.

13.5.3.1 Panning

Panning as a mineral/metal recovery technique was known to many ancient civilizations. Gold panning was popular and extensively practiced in California, Argentina, Australia, Brazil, Canada, South Africa, and India during the 19th century. Panning is the manual shaking of a tray containing river bed sand and gravel, and alluvial soil containing precious metals like gold, silver, tin, tungsten, and native platinum. The shaking tray separates sand, stones, and fine-grained metals into different layers by differential gravity concentrations (Fig. 13.28). The undesired materials are removed. This is a primitive practice used by remote tribal people on a small scale and at low cost.

13.5.3.2 Jig

Jigs are continuous pulsating gravity concentration devices. Jigging for concentrating minerals is based exclusively on the differences in density of the particles. The elementary jig (Fig. 13.29) is an open tank filled with water. A thick bed of coarse heavy particles (ragging) is placed on a perforated horizontal jig screen. The feed material is poured from the top. Water is pulsated up and down (the jigging action) by pneumatic or mechanical plunger. The feed moves across the jig bed. The heavier particles penetrate through the ragging and screen to settle down quickly as concentrate.

FIGURE 13.28 Gold panning in the Gold Rush Era: with gold pans in hand, fortune seekers crossed the country in the mid-1800s to secure their fortunes in the newly acquired territory of California. It is extensively practiced today in remote tribal areas.

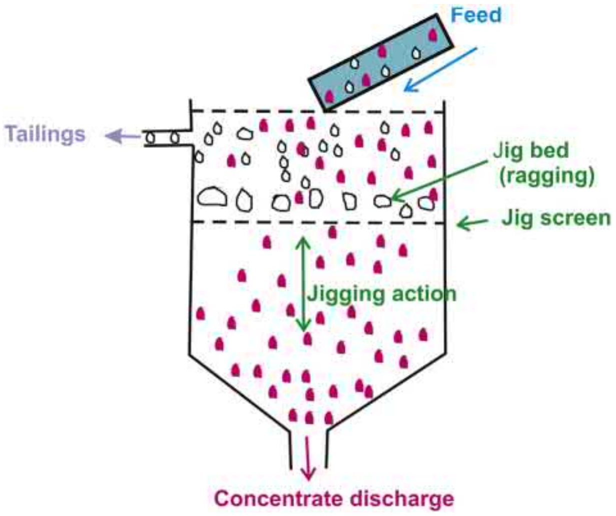

FIGURE 13.29 Conceptual diagram illustrates the basic principles of a jig concentrator.

The concentrate is removed from the bottom of the device. The jigging action causes the lighter particles to be carried away by the crossflow supplemented by a large amount of water continuously supplied to the concentrate chamber. Jig efficiency improves with relatively coarse feed material having wide variation in specific gravity. Jigs are widely used as an efficient and economic coal-cleaning device.

13.5.3.3 Pinched Sluice and Cones

Pinched sluice and cones is an inclined trough made of wood, aluminum, steel, and fiber glass, 60–90 cm long. The channel tapers from about 25 cm in width at the feed end to 3 cm at the discharge end. Feed consisting of 50%–65% solids enters the sluice and stratifies as the particles

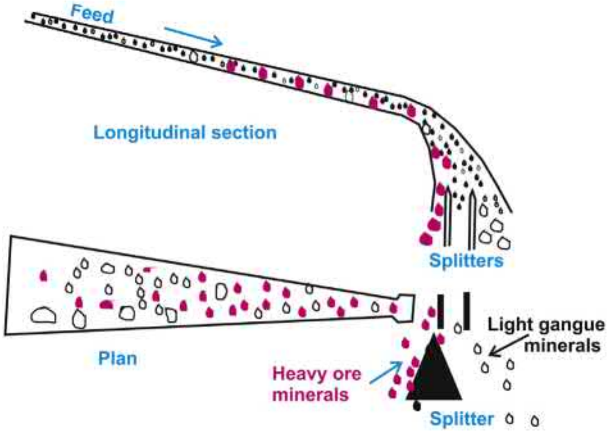

FIGURE 13.30 Conceptual diagram portrays the basic principles of a pinched sluice concentrator.

flow through the sluice. The materials squeeze into the narrow discharge area. The piling causes the bed to dilate and allows heavy minerals to migrate and move along the bottom. The lighter particles are forced to the top. The resulting mineral strata are separated by a splitter at the discharge end (Fig. 13.30). Pinched sluices are simple and inexpensive. They are used for the separation of heavy mineral sands. A large number of basic units and recirculation pumps are required for an industrial application. The system is improved by the development and adoption of the Reichert cone. The complete device comprises several cones stacked vertically in integrated circular frames.

13.5.3.4 Spiral Concentrator

The spiral concentrator is a modern high-capacity and low-cost device. It is developed for concentration of low-grade ores and industrial minerals in slurry form. It works on a combination of solid particle density and its hydrodynamic dragging properties. The spirals consist of a single or double helical conduit or sluice wrapped around a central collection column. The device has a wash water channel and a series of concentrate removal ports placed at regular intervals. Separation is achieved by stratification of material caused by a complex combined effect of centrifugal force, differential settling, and heavy particle migration through the bed to the inner part of the conduit (Fig. 13.31). Extensive application is the treatment of heavy mineral beach sand consisting of monazite, ilmenite, rutile, zircon, garnet, and upgrade chromite concentrate. Two or more spirals are constructed around one central column to increase the amount of material that can be processed by a single integrated unit.

13.5.3.5 Shaking Table

The shaking table consists of a sloping deck with a rifled surface. A motor drives a small arm that shakes the table along its length, parallel to the rifle pattern. This longitudinal shaking motion drives at a slow forward stroke followed by rapid return strike. The rifles are arranged in such a manner that heavy materials are trapped and conveyed parallel to the direction of oscillation (Fig. 13.32). Water is added to the top of the table and perpendicular to table motion. The heaviest and coarsest particles move to one end of the table. The lightest and finest particles tend to wash over the rifles and to the bottom edge. The intermediate points between these extremes provide recovery of middling (intermediate size and density) particles. Shaking tables find extensive use in concentrating gold, tin, and tungsten.

These devices are often used downstream of other gravity concentration equipment such as spirals, Reichert cones, jigs, and centrifugal gravity concentrators for final cleaning prior to refining or sale of product.

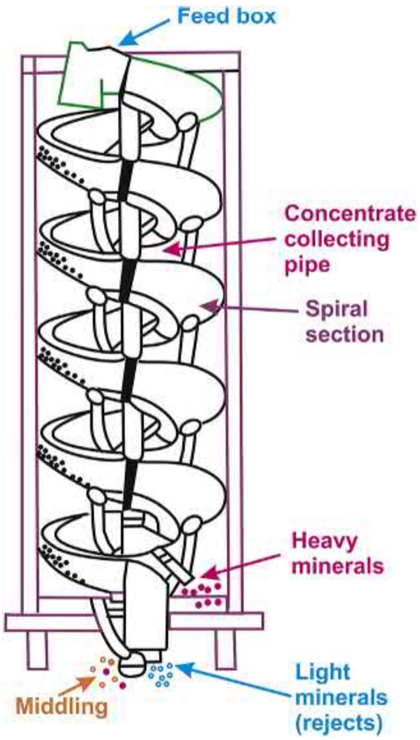

FIGURE 13.31 A typical sketch diagram of a standard spiral concentrator working at chromite process plants, Sukinda layered igneous complex, India.

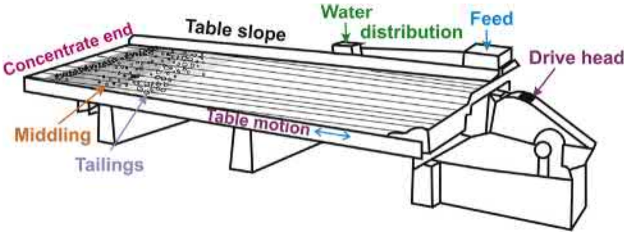

FIGURE 13.32 A typical model diagram of a shaking table in the recovery of gold, platinum, etc.

FIGURE 13.33 Multigravity separators at Rajpura-Dariba mineral process plant in India during the early 1990s.

13.5.3.6 Multigravity Separator

The multigravity separator (MGS) is a new development in flowing film concentration expertise utilizing the combined effect of centrifugal force and shaking (Fig. 13.33). The centrifugal force enhances the gravitational force and obtains better metallurgical performance by recovering particles down to 1 μ in diameter, which would otherwise escape into the tailing stream if other conventional wet gravity separators (jigs, spirals, and table) are used. The principle of the system consists essentially in wrapping the horizontal concentrating surface of a conventional shaking table into a cylindrical drum, which then rotates. A force, many times greater than the normal gravitational pull, is exerted on particles in the film flowing across the surface. This enhances the separation process to a great extent. MGS in close circuit with lead rougher cells of graphite schist-hosted sulfide ore improves the lead concentrate metallurgy from 20% to +40% Pb. The graphitic carbon content reduces simultaneously from >10% to <3%. The presence of graphitic carbon interferes with the flotation of sulfide ore resulting in low metal recovery and unclean concentrate.

MGS improves the metallurgical recovery and quality of concentrate for graphite carbon-bearing sulfide ore and high alumina-bearing fine iron ore. The MGS technique works successfully at Rajpura-Dariba zinc-lead plant and all iron ore plants in India by decreasing graphitic carbon and alumina, respectively. MGS improves 42.9% Cr_2O_3 with 73.5% recovery from the magnetic tailings of Guleman-Sori beneficiation plant in Turkey.

13.5.4 Magnetic Separation

Magnetic separation takes advantage of natural magnetic properties between minerals in feed. The separation is between economic ore constituents, noneconomic contaminants, and gangue. Magnetite and ilmenite can be separated from their nonmagnetic rock-forming minerals of host rock as valuable products or as contaminants. The technique is widely used in the beneficiation of beach sand. All minerals will have one of the three magnetic properties: ferromagnetic (magnetite, pyrrhotite), paramagnetic (monazite, ilmenite, rutile, chromite, wolframite, hematite, etc.), or diamagnetic (plagioclase, calcite, zircon, apatite, etc.). Commercial magnetic units follow a continuous separation process on a moving stream of dry or wet particles passing through a low or high magnetic field. The various magnetic separators are drum, cross-belt, roll, high-gradient magnetic separation, high-intensity magnetic separation, and low-intensity magnetic separation types.

13.5.4.1 Drum Separator

The drum separator consists of a nonmagnetic drum fitted with 3%–6% magnets composed of ceramic or rare earth magnetic alloys in the inner periphery. The drum rotates at uniform motion over a moving stream of preferably wet feed. The ferromagnetic and paramagnetic minerals are picked up by the rotating magnets and pinned to the outer surface of the drum. As the drum moves up, the concentrate is compressed, dewatered, and discharged leaving gangue in the tailing compartment. Drum rotation can be clockwise or counterclockwise and the collection of concentrate is designed accordingly. A drum separator produces extremely clean magnetic concentrate. It is suitable for the recovery of precious minerals from beach sand.

13.5.4.2 Cross-Belt Separator

The cross-belt separator consists of a suspended magnet fixed over a continuously moving belt carrying feed. The magnet attracts and lifts magnetic minerals, and strips off captured trap minerals/metal, and discharges off the side or end of the conveyor leaving gangue to tailing. It is widely used in the mineral beach sand industry for separation of ilmenite and rutile. However, it is being replaced by rare earth roll magnetic and rare earth drum magnetic separators.

13.5.5 Electrostatic Separation

Electrostatic separation works on the natural conductivity properties between minerals in feed. Separation is between economic ore constituents, noneconomic contaminants, and gangue. The common units are high-tension plate and screen electrostatic separator. The electrostatic plate separators work by passing a stream of particles over a charged anode. The electrostatic minerals lose electrons to the plate and are pulled away from other particles due to induced attraction to the anode. The dry stream of moving particles is preferred between 75 and 250 μm, with close size distribution and uniformity of shape for efficient separation. It is used for separating monazite, spinel, sillimanite, tourmaline, garnet, zircon, rutile, and ilmenite from heavy beach/stream placer sand. The electrostatic technique with local modification is extensively used in Australia, Indonesia, Malaysia, and India bordering Indian Ocean for separation of mineral sands.

13.5.6 Dense Medium Separation

Dense medium separation (DMS) or heavy medium separation works on the sink-and-float principle of minerals with variable specific gravities as in the case of coal and shale, and sulfide ore in carbonaceous host rock. DMS in industries uses organic liquids, aqueous solutions, and thick suspensions in water or the pulp of heavy solids in water. This is the simplest method following wet gravity separation. Minerals lighter than the liquid medium will float and those denser than it will sink (Fig. 13.34). It assists greatly in the precomminution rejection of bulk of gangue material and preconcentration of low-grade ore. DMS technology is being favorably adopted in the investment of mining by preconcentration of minerals from as low as 1%−2% zinc grade. The technique helps in the rejection of bulk of the gangue minerals prior to grinding for final liberation.

One of many good examples is Pering zinc open pit mine, South Africa, with 50 Mt reserves at 1.4% in situ Zn + Pb grade. The simplified DMS process reduces ROM volume by a preconcentrate mass pull of 22% at 5.2% Zn + Pb.

13.5.7 Flotation

Since the beginning of the 20th century, the flotation concept was the most flexible and adaptable mineral beneficiation technique. Selective mineral separation by flotation works on physical and chemical surface properties of valuable and unwanted gangue minerals. It is being continuously modified for low-grade complex sulfide ores like lead-zinc, lead-zinc-copper, nickel-platinum-gold, tin, fluorite, phosphate, fine coal, and iron ore at a lower cost with better recovery. The processes are known as froth and column flotation.

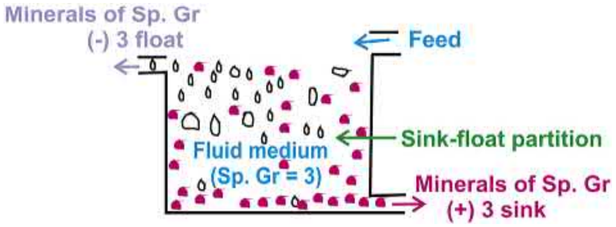

FIGURE 13.34 Conceptual diagram illustrating the principles of the density media separation process to separate coal and shale, and promote preconcentrates from low-grade sulfide ore from carbonate gangue minerals.

13.5.7.1 Froth Flotation

The froth flotation process produces froth of selective mineral agglomerates and separates them from other associated metallic components and gangue minerals. The physical and chemical surface properties of optimum fine size fraction make some specific minerals hydrophobic. The particles become water repellent by coming in contact with moving air bubbles in the presence of certain reagents. The froth portion moves up leaving the gangue (tailing) below, stabilizes for a while, and collects as concentrate for further cleaning (Fig. 13.35).

The mineralized froth (concentrate) stabilizes for a while at the top of the cell (Fig. 13.36), overflows, and moves to a cleaner cell, filter, and dryer in sequence to form mature saleable product for smelting to produce pure metals. The concentrate is the raw material for extracting metals by smelting and electro- and chemical refining.

The continuous process of separation in commercial plants occurs in a series of containers called **cells** forming a **bank** (Fig. 13.37). The final products of the grinding mill pass through a conditioner tank where the pulp is

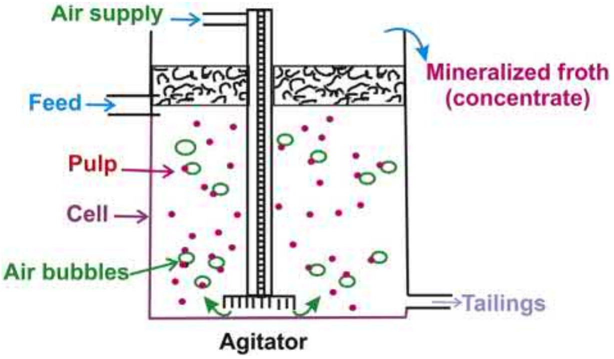

FIGURE 13.35 Schematic diagrams showing the principle of froth flotation and total function inside a flotation cell.

FIGURE 13.36 Formation of mineralized froth (lead concentrate) from an active flotation cell and that subsequently moves to lead cleaner, and concentrate stockpile.

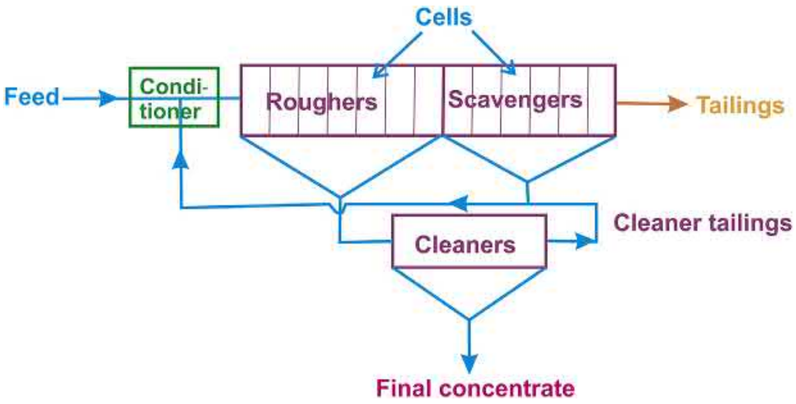

FIGURE 13.37 Schematic diagram of process flowsheet illustrating conditioner-rougher-scavenger-cleaner cells, including formation of concentrate and reject.

conditioned in a few seconds to a couple of minutes in the presence of xanthate and methyl isobutyl carbinol (MIBC). The conditioned pulp enters the first few cells ("rougher cells") charged with reagents. Some of the hydrophobic ore minerals attach to air bubbles and move up as rich froth (concentrate). Rougher concentrate moves downstream to **cleaner cells** to produce the highest-grade concentrate. The last few cells in the bank (**scavengers**) process low-grade pulp along with gangue and recover the remaining ore mineral froth and clean it. New feed enters the conditioner → rougher cells → scavenger cells → cleaner cells until the tailing underflows the last cell in the bank.

The bank of flotation cells is placed in rows on the floor of the ore-dressing plant in close circuit to recover multiple concentrates of respective minerals (Fig. 13.38).

Three main group of reagents used in flotation are collectors, frothers, and regulators. Each set of reagent plays a specific role in mineral processing.

13.5.7.1.1 Collector

Collectors or **promoters** are organic compounds that make the surface of certain selected minerals water repellent. These reagents are added to pulp in the conditioner tank and ball mill. The mineral surface absorbs collectors during the conditioning period making them hydrophobic. Hydrophobic particles come in contact with flowing air bubbles and float to the surface forming froth. Sodium isopropyl xanthate and potassium amyl xanthate are commonly used collectors.

13.5.7.1.2 Frother

Frothers are surface-active chemicals that concentrate at the air—water interface. They prevent air bubbles from coalescing or bursting by lowering the surface tension of slurry. Frothing properties can be persistent or nonpersistent depending on the desired stability of the froth. Pine oil and alcohols such as MIBC are commonly used frothers.

FIGURE 13.38 A typical bank of flotation cells in an operating circuit.

13.5.7.1.3 Regulator

Regulators or **modifiers** are used to modify the action of the collector by intensifying or reducing the water-repellent effect of mineral surface conditions. This is done to assist in the selective flotation of minerals. Regulators can be classed as activators, depressants, or pH modifiers. The regulators may activate poorly floating minerals such as sphalerite by adding readily soluble copper sulfate. Similarly, regulators can depress certain minerals rendering them hydrophilic and preventing their flotation. Minerals like pyrite and arsenopyrite can be depressed by adding sodium cyanide or lime, so that a differential flotation can be performed on a complex ore. The nigrosin reagent is used for maximum depression or elimination of graphitic carbon from zinc-lead sulfides in graphitic host rock. The separation of graphitic carbon aids in producing high-quality clean zinc and lead concentrates. The chemicals that change the pH of the slurry are also used as modifiers. A medium alkaline condition is preferable in the flotation process where most of the collectors are stable. The alkaline environment minimizes the damage done by corrosion of cells and pipelines. The pH modifiers include lime, soda ash, and sulfuric acid. They can act as activators and/or depressants by controlling the alkalinity and acidity of the slurry. The modifiers can also counteract interfering effects from the detrimental slimes, colloids, and soluble salts that can absorb and thereby reduce the effectiveness of flotation reagents.

The design of a mineral processing circuit requires integration and assembly of various unit operations. It starts from crushing/grinding/flotation with the generation of valuable concentrates and rejection of tailing in a continuous process. It is desirable to conduct laboratory, bench, and pilot plant-scale test works at the appropriate stages of exploration and mine development activities. This is done before adopting a commercial plant flow diagram of complex mineral assemblages. The representative sample is obtained by compositing duplicate mineralized core covering the entire deposit and bulk sample collected from the initial mine development. The grind size, concentrate grades, recovery of valuable minerals, type of reagents, and cost parameters are optimized.

13.5.7.2 Flotation of Zinc-Lead Ore

The majority of zinc-lead deposits belong to the Paleoproterozoic age hosted by dolomite, calc-silicate, and mica schist ± graphite. The feed grades are 3%−15% Zn, 1.0%−2.5% Pb, and 40−150 g/t Ag with varying amounts of pyrite and pyrrhotite. The typical grade components are approximated: lead concentrate (<65% Pb), zinc concentrate (<55% Zn), and tailing (~0.20% Pb and ~0.50%−1% Zn). Silver and cadmium are recovered in lead and zinc concentrates, respectively.

ROM ore is crushed by the primary jaw crusher to yield a product size of −150 mm. The fraction between 150 and 50 mm is fed to the secondary cone crusher. The −50 mm size fraction of the secondary crusher discharge and the screen undersize is fed to the tertiary cone crusher. The final crusher product of −12 mm fraction size is fed to the ball mill for wet grinding. The ball mills run in close circuits with hydrocyclones and yield a product containing 68% of −74 μm size particles. The specific particle size is essential for optimum liberation of valuable minerals from gangue material (Fig. 13.39). Zinc sulfate and sodium cyanide are added to the ball mill for the depression of sphalerite and pyrite, respectively.

FIGURE 13.39 Dry zinc-lead ore grinded to 68% of −74 μm particle size to yield the highest liberation of ore and gangue minerals.

The ball mill cyclone overflow moves to the lead rougher and scavenger flotation cell via the conditioner, where sodium isopropyl xanthate and MIBC acids are added as collector and frother, respectively, for lifting galena. The lead concentrate (Fig. 13.40) from lead rougher and scavenger transfers to lead cleaner cells for washing until a specific quality is achieved. Sodium cyanide is added to lead cleaner for further depression of pyrite. The scavenger concentrates and cleaner tailing are recycled to lead rougher cells.

FIGURE 13.40 Dry lead concentrate with grade up to 65% Pb is achieved based on feed quality.

The overflow from the lead scavenger cells is fed to the zinc conditioner. The various reagents are added for specific purposes. These are sodium cyanide for pyrite depression, copper sulfate as sphalerite activator, sodium isopropyl xanthate as collector, and MIBC as frother. Zinc flotation is achieved in two stages of rougher and scavenger cells. The zinc rougher concentrate is transferred to the cleaning circuit for further upgrade. The scavenger concentrate and tailing of cleaner cells are recycled to the zinc rougher cells. The total zinc concentrate moves to the zinc cleaner cell to achieve clean concentrate with grades up to 55% Zn (Fig. 13.41).

The final underflow of the zinc bank moves out of the cells as rejects (Fig. 13.42), and is transferred to tailing ponds or void fillings in underground mines.

FIGURE 13.41 Dry zinc concentrate with grade up to 55% Zn is achieved based on feed quality.

FIGURE 13.42 Dry tailing from a Zn—Pb process plant with grade around 0.20% Pb; 0.50%—1.00% Zn is lost based on feed quality.

Typical process flow charts of a zinc-lead beneficiation plant and products are illustrated in Fig. 13.43.

The concentrates of lead and zinc are thickened in respective thickeners and pumped to individual filtration plants. Filtration is done either by disc vacuum, drum, or belt filters. The concentrates are dried using a rotary thermal dryer or exposed to natural drying. The final lead and zinc concentrates are transported to respective smelters by road, rail, and sea routes. The eventual reject of the flotation plant (tailing) is pumped either to a nearby tailing dam or to the underground stopped-out voids for filling as support systems to prevent them from collapse. To strengthening the underground fill, 5%—10% cement is added. The tailing is allowed to settle in the dam. The water is reclaimed through a network of percolation wells and pumped back to the water treatment plant for industrial reuse. A typical analysis of low-grade ore and process products is given in Table 13.2.

Zinc and lead metals are extracted by **pyrometallurgical** or **hydrometallurgical** processes, and electrochemical refining to the level of 99.99% metals. The precious elements recovered by electric refining are silver, cadmium, cobalt, and nickel. The other important by-product recovered during smelting is sulfur to produce sulfuric acid.

13.5.7.3 Flotation of Copper Ore

Copper ore usually contains about 0.5 to 2% copper that occurs in the form of disseminated and stringers. The run of mine ore is reduced from 150 mm to 25 mm size in Jaw and Cone crushers. The crushed ore is grinded in ball mills to −74 μm size. The ore is processed by froth flotation comprising rougher and scavenger cells. The common reagents for copper ore flotation are xanthates as collector, pine oil as frother, sodium cyanide as depressant, and lime to maintain slurry alkalinity. The concentrate in the form of froth and slurry contains +20% copper. It is thickened in a rake-type unit from a level of 30% solid content to 60%. The concentrate grade can further be elevated to 30% Cu. The recovery of associated molybdenum is achieved by integrated column flotation using cleaner concentrate. The thickened concentrate slurry is treated in vacuum disc filters to remove water. The powder concentrate contains about 10%—12% moisture. The moisture content in concentrate is further reduced to a level of 0.2% before charging to a flash and anode furnace. The final treatment is electrochemical refining to obtain copper cathode of 99.99% purity. The precious metals recovered during electrorefining are gold, silver, tellurium, and selenium. The other important recovery during smelting is sulfur gas to produce sulfuric acid. A typical flow chart is given in Fig. 13.44.

The multimetal copper-zinc-lead ore is treated by integration of three complete banks in series, each one for copper, lead, and zinc to produce respective concentrates. In the case of complex ore metallurgy, bulk concentrate is produced containing all three primary metals and value-added elements like gold, silver, cadmium, cobalt, molybdenum, selenium, and tellurium.

13.5.7.4 Flotation of Iron Ore

Iron ore minerals, particularly hematite and goethite, are beneficiated by a combination of size fraction, preconcentration, and flotation in stages (Fig. 13.45). Iron ore requires removal of silicate impurities of a finer size by flotation for higher-grade products of +60% Fe. ROM ore at 400—600 mm is fed to a primary crusher with product set

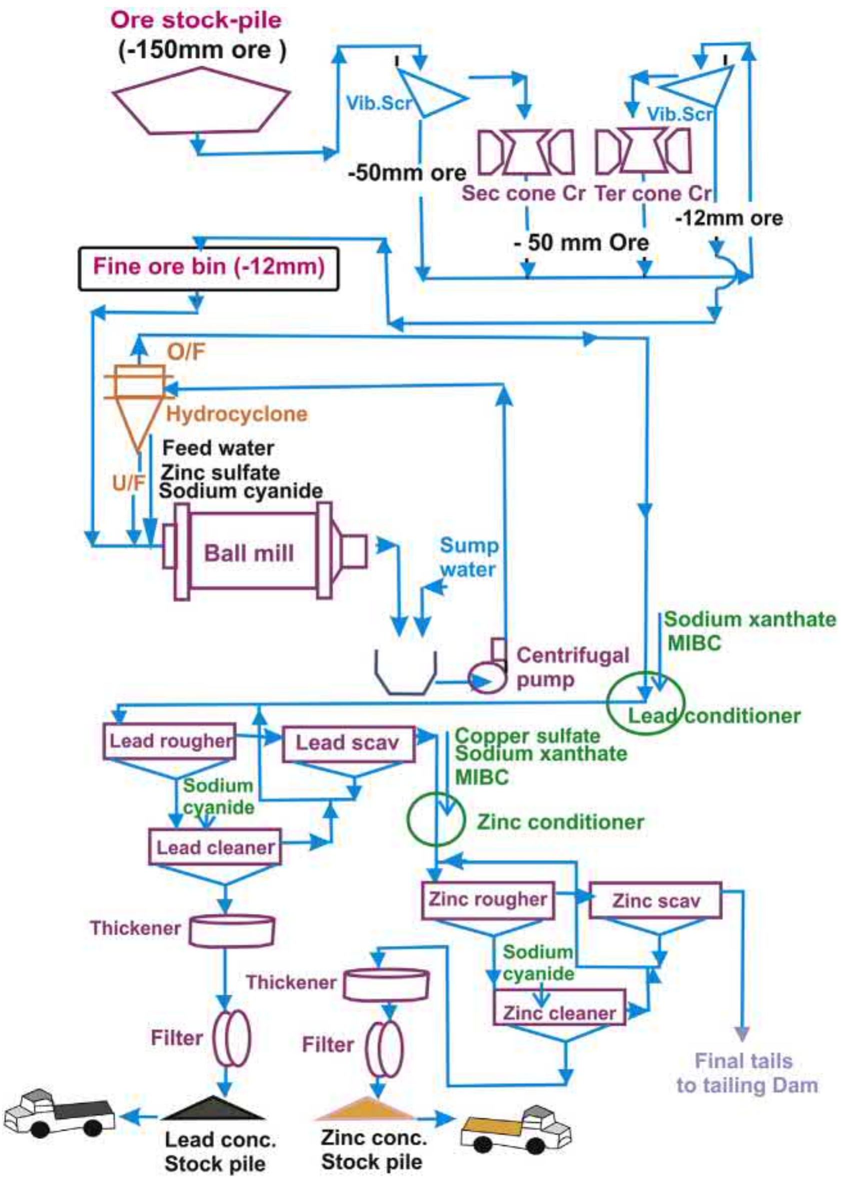

FIGURE 13.43 A standard process flow chart of a zinc-lead beneficiation plant. *O/F*, over flow; *U/F*, under flow.

TABLE 13.2 Typical Analysis of Low-Grade Ore, Lead, Zinc Concentrate, and Tailings

Parameters	Ore	Lead Conc.	Zinc Conc.	Tailings
% Pb	2.0	65	1.5	0.13
% Zn	4.0	3.5	55	0.36
% Fe	5.50	5.5	6.5	4.5
Ag g/t	40	800	90	9
Cd g/t	200	160	2300	24
% Ca	12			15
% Mg	6			7
% Acid insol.	28	1.30	1.20	28

Ore-to-concentrate ratio: 1:15. Lead recovery is 85% and zinc recovery is 91.66%.

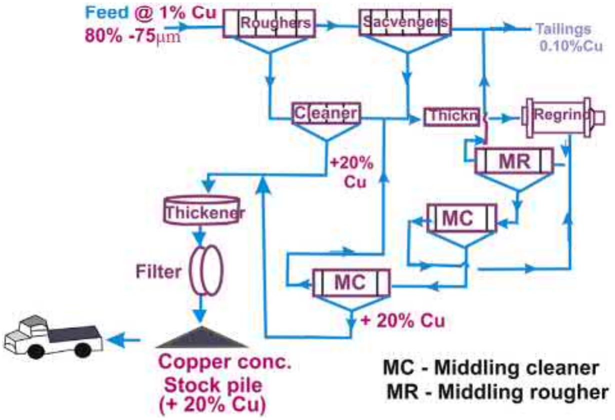

FIGURE 13.44 A typical process flow diagram of copper ore beneficiation.

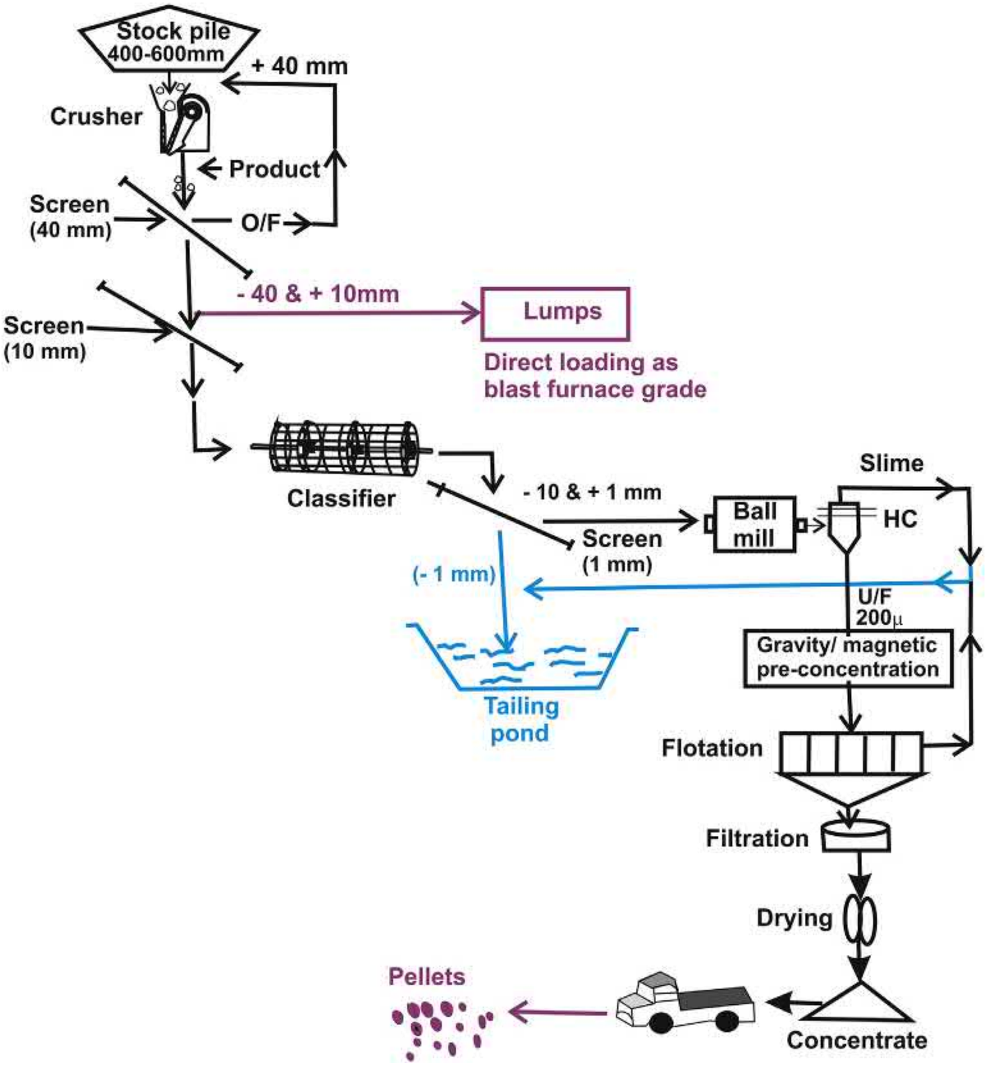

FIGURE 13.45 A complete flow chart of iron ore beneficiation. *O/F*, over flow; *U/F*, under flow.

at −40 mm. The crushed product is screened in two stages. The overflow of the first screen (+40 mm) is recrushed. The underflow of the first and overflow of the second screen, i.e., −40 and +10 mm size, are directly sent for loading as blast furnace grade. The underflow (−10 mm) is passed through a classifier. Undersized particles of −1 mm are sent to a tailing pond. The overflow of −10 and +1 mm is grinded in a ball mill to produce 200 μm product size. The pulp is subjected to hydrocyclones for separation of slimes and removal of silica. Collectors such as amines, oleates, sulfonates, or sulfates are used for the flotation of silica. Magnetic or gravity separation is introduced at any suitable stage for preconcentration. The final iron ore fines are converted to pellets.

13.5.7.5 Flotation of Rock Phosphate Ore

Rock phosphate, the primary raw material for fertilizer and phosphoric acid, occurs as high-grade ore (+30% P_2O_5), medium-grade ore (20%–30% P_2O_5), and low-grade ore (15%–20% P_2O_5). The very high-grade ore blends with medium-grade ore for direct sale. The high-grade ore is mined, crushed, and sold to various fertilizer plants. The low-grade ore is beneficiated by reverse/inverse flotation techniques.

The low-grade ore is crushed/grinded to −74 μm size for liberation of phosphate, carbonate, and silica. The fine product is subjected to flotation after conditioning with fatty acid salt as collector and reduction of silica content in an alkaline circuit at the first stage. An addition of phosphoric and sulfuric acids in the second stage acts as Ph controller for the removal of carbonate in froths. The phosphate component is depressed in an acid environment, and moved to thickeners/filters/dryers to form a final concentrate at +30% P_2O_5 at an ore-to-concentration ratio of ~2.5.

13.5.7.6 Flotation of Coal

Present-day highly mechanized coal mining (long-wall mining) generates up to 25% fines of around 250 μm to 20 mm size. These fine fractions require upgradation by separation of high ash content. The flotation and dense media separation are effective to recover fine coal. Petrochemical products such as diesel oil, kerosene, and liquid paraffin are the best collectors. The inputs in coal processing are high-value coking coal for pyrometallurgical industries and low-value thermal coal for power generation.

13.5.7.7 Column Flotation

The concentrates are often contaminated with excess undesired elements in zinc (silica), lead (graphitic carbon), copper (silica), molybdenum, chromium, fluorite, manganese, platinum, palladium, and titanium. The flotation column is a significant development in the mineral-processing industry on account of an efficient single-step cleaning action to upgrade fine-sized concentrate. It offers improved metallurgy at low cost, simplified circuit, and easy control compared to conventional cells.

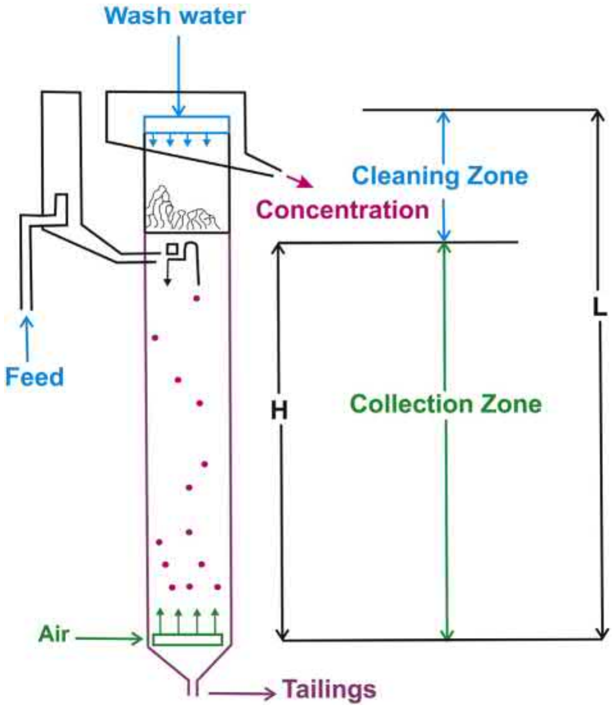

FIGURE 13.46 Basic features of a flotation column collection zone and cleaning zone, where the rejects move to the tailings. Column flotation improves the final concentrate grade.

Column flotation works on the countercurrent principle. The pulp moves down. The rising swarms of fine air bubbles, generated by a gas sparger installed at the bottom, carry valuable mineral particles to froth at the top of the column. The distinct design features different from conventional flotation are: (1) addition of wash water at the top of froth, (2) absence of mechanical agitator, and (3) bubble generation system (Fig. 13.46). Column flotation consists of two distinct zones: collection and cleaning. The falling particles from feed slurry contact the countercurrent of rising bubbles as they swarm and drop in the collection zone. Hydrophobic particles collide and attach to air bubbles and are transported to the cleaning zone. Hydrophilic and feeble hydrophobic particles are removed from the bottom of the column. In the cleaning zone, water sprinkles over froth providing a clean wash of concentrate, further liberation of fine gangue particles, and transfer to the tailing zone.

The columns are installed and integrated between concentrate cleaner tanks and thickener. The columns are effective for cleaning and achieve upgrade in a single stage with improved metallurgy as seen in copper in Zambian, molybdenum-copper in Canada, chromium and coal in the United States, and zinc-lead in Australian and India. Industrial flotation columns are round (Fig. 13.47) or

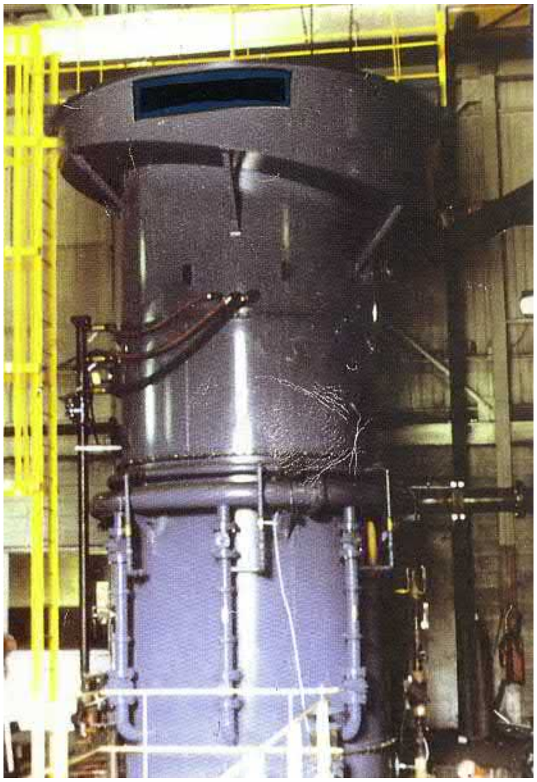

FIGURE 13.47 Industrial flotation column in operation at Rajpur-Dariba plant, India, with advantages like better recovery and higher concentrate grade at lower operating costs. The column reduces silica content from zinc concentrate and graphite content from lead concentrate.

square in cross-section, 5−8 m in diameter, and 10−15 m height. Column flotation improves zinc concentrate metallurgy from 48% Zn with 5%−7% SiO_2 at 80% recovery to +50% Zn with <3% SiO_2 at 85% recovery.

13.5.8 Dewatering

Most ore beneficiation methods require large volumes of water for separation of ore and gangue minerals, leaving a high proportion of moisture in the final concentrates. The smelters, captive or custom base, are located at long distances from mining beneficiation sites. Long-distance shipment of concentrate in pulp form by road, rail, and/or sea routes is unsafe at high cost. Therefore dewatering or solid/liquid separation is done to generate dry concentrate. However, partially moist concentrate between 5% and 10% is desirable for easy handling and safe transport. Metal losses are expected when moisture content is too low or totally dry. This may be a serious environmental issue due to the spreading of air-driven concentrate in dry and dust forms. Dewatering is done at successive stages of (1) sedimentation or thickening, (2) filtration, and (3) thermal drying.

13.5.8.1 Sedimentation

Sedimentation or thickening is the natural gravity settling of the solid portion of the concentrate pulp. It takes place in a cylindrical thickening tank in the form of layers (Fig. 13.48). The pulp is fed continuously from the top of the tank through a pipe. The clear liquid overflows out of the tank. The thickened pulp that settles at the bottom is taken out through a central outlet. The deposition process can be accelerated and the settled solids can be pushed toward the central outlet by rotating suspended radial arms performing as an automatic rake mechanism. The sedimentation process would produce thickened pulp of 55%−65% solids by weight.

FIGURE 13.48 A view of a thickener with a rake mechanism in the first phase of dewatering of concentrate by sedimentation or gravity settling of solids.

13.5.8.2 Filtration

Filtration is the second stage of solid/liquid separation, normally after thickening, by means of a porous medium. The most common filter medium is cotton fabrics, but can be extended to any one of jute, wool, linen, nylon, silk, and rayon. The filter pads allow liquid to percolate and retain the solid on the outer surface. The filter medium is washed and cleaned at regular intervals for better performance and longevity. Several types of filter mechanism are in use. The most widely used filters in mineral-processing applications are the disc, drum, and horizontal types. Filtration produces moist filter cake of 80%−90% solids.

Disc filters are used with vacuum filtration equipment. They comprise several large discs (Fig. 13.49). Each disc consists of sectors that are clamped together. The ribs between the sectors are designed in a radial fusion, narrowing at the center. The semidry feed enters from the side. The disc rotates slowly so that cake forms on the face of the disc and semidry cakes are lifted above the slurry. The cake is suction dried. It is removed by scraper blades fitted on the side of each disc and pushed to discharge chutes. Generally, disc filters are used for heavy-duty applications such as dewatering of lead-zinc-copper concentrate, low-grade iron ore-taconite, coal, and aluminum hydrate.

The **horizontal belt filter** consists of a highly perforated horizontal rubber drainage conveyor deck fitted with filter media. The slurry moves from the start to the other end. Filtration starts partly by gravity and partly by a vacuum mechanism attached to the bottom of the moving drainage deck. The cake discharges as the belt reverses over a roller.

The **drum or rotary drum filter** works on the same principle as that of a disc filter. The drum is mounted horizontally and rotates in slow motion (Fig. 13.50).

FIGURE 13.49 A view of a disc filter in the second phase of dewatering of concentrate.

FIGURE 13.50 A view of a drum filter, an alternative process of dewatering concentrate.

The surface of the drum is tightly wrapped with filter media and divided into several compartments, each one attached with drain lines. The filter is partially submerged in slurry feed. The drum rotates slowly through the slurry and produces filtered cakes while moving out of the submergence level. Partially dried cakes are removed by a combination of reversed air blast and automatic scraper knife.

13.5.8.3 Thermal Drying

The **drying** of concentrate is done prior to shipment to distance smelters. The rotary thermal dryers are widely used for production of final saleable concentrate. They consist of a long cylindrical shell mounted on a roller at a slight slope to rotate the unit at uniform speed. Hot air at about 980°C is passed inside the cylinder through which the wet feed moves from the feeding point to the discharge end by gravity. The dry concentrate at 5%—10% moisture moves on a conveyer to the stockyard before being loaded onto trucks or rail wagons as required for shipment.

13.5.9 Tailing Management

The ore-to-concentrate ratio ranges between 5:1 and 10:1 and even more depending on the richness of the deposit. The quantity of fine rejects or tailing is between 5 and 15 t to produce 1 t of concentrate. A mine with annual production of 1 Mt ore will generate fine tailing anywhere between 0.80 and 0.90 Mt. This huge amount of fine tailing is to be handled and disposed of carefully without disturbing the ecological balance of the surroundings. Tailings from the scavenger bank are pumped to a tailing thickener. The underflow of the tailing thickener, at maximum attainable density, is pumped to the tailing dam (Fig. 13.51) located at a nearby suitable distance from the plant. Modern tailing dams are constructed with deep-rooted walls and cement spread on the floor to prevent any leakage of tailing water through cracks and fissures. The dam on the downstream is erected on alternate layers of gravel and sand so that water percolates through the bottom and settles in a tank.

The tailing thickener overflow, excess water from the tailing pond, and the underflow of the tailing dam are reclaimed and recycled on a continuous basis following the principle of zero discharge. The reagent mixed water is pumped to the plant for industrial reuse after lime treatment. A thin layer of gravel is placed directly over the tailings surface for dust mitigation. The top surface of the tailing pond is reclaimed by direct vegetative stabilization after the dam is full and dried up. This is done by growing grasses, shrubs, and trees to arrest the blowing of dry sand, a source of air pollution. The vegetated cover aims at shedding rainfall runoff during the humid season.

The alternative management of tailing disposal is to pump the dense slurry to the open underground voids of cut and fill, sublevel, and vertical crater retreat stopes. The tailing in the initial fill is mixed with 10% cement to make a strong barricade at the stope mouth and subsequently by 3%—5% cement for a strong stabilized support system.

13.6 METALLURGICAL ACCOUNTING

Process plant performance is judged by the cost of operation, quantity, purity, and recovery of the valuable products. Metallurgical accounting is important to control the operation at every stage. These key parameters are

FIGURE 13.51 A panoramic view of a tailing dam in a hilly terrain that would eventually be filled over time, and rehabilitated by vegetative stabilization.

identified and computed by material balance using simple equations of two products (Eqs. 13.1 and 13.2) for a single metal. The single metal may be zinc and two products are zinc concentrate and tailing. The equation can be extended for calculation of multiproducts of multimetal deposits, including recovery of value-added by-products. The multimetals may be from zinc, lead, and copper deposit producing multiproducts of three concentrates: zinc, lead, and copper. The value-added by-products of cadmium, silver, and gold are recovered with zinc, lead, and copper concentrate, respectively. The procedure utilizes a few basic inputs of the process plant. The model is demonstrated by the plant parameters given in Table 13.2. The steps are illustrated considering only zinc metal for simplicity. The zinc-lead deposit in clean dolomite host rock is designed for a 3000 tpd mine and matching milling capacity. The average feed, concentrate, and tailing grades are 4.00% Zn, 55% Zn, and 0.36% Zn.

The material balance by equalizing input and output is:

$$T_f = T_c + T_t \tag{13.1}$$

The metal or mineral balance by equalizing total metal or mineral input and output is:

$$T_f \times G_f = T_c \times G_c + T_t \times G_t \tag{13.2}$$

where T_f = weight of feed in tonnes, G_f = % grade of metal or minerals in feed, T_c = weight of concentrate(s) in tonnes, G_c = % grade of metal or minerals in concentrate, T_t = weight of tailing in tonnes, and G_t = % grade of metal or minerals in tailing.

13.6.1 Plant Recovery

Plant recovery is the percentage of total metal recovered in concentrates from feed ore. A recovery of 86% means that 86% of metal has been recovered in concentrate and 14% metal is lost in tailing. If the ore contains more than one metal (say Pb, Zn, and Cu) then weighted cumulative recovery in concentrates and loss in tailing is to be noted.

$$\text{Plant recovery} = (T_c \times G_c/T_f \times G_f) \times 100\% \tag{13.3}$$

$$\text{Or } [\{(G_c \times (G_f - G_t)\}/\{G_f\,(G_c - G_t)\}] \times 100\% = 91.60\%$$

13.6.2 Ore-to-Concentrate Ratio

Ore-to-concentrate ratio is the ratio between weight of feed and weight of concentrates produced. The higher the grade of deposit, the lower will be the ratio and vice versa. The concentrate grade and recovery are metallurgical efficiency factors. From Eq. (13.2):

$$F/C = (G_c - G_t)/(G_f - G_t) \tag{13.4}$$

where F/C represents the ratio between concentrate and feed

$$= 15, \text{ i.e., 15 t of feed will yield 1 t of concentrate}$$

$$= (55 - 0.36)/(4.00 - 0.36)$$

13.6.3 Enrichment Ratio

Enrichment ratio is the ratio between concentrate and feed grade, and is expressed as G_c/G_f, i.e., $55/4.0 = 13.75$.

13.6.4 Metal Balancing

Metallurgical accounting or metal balancing is computed on a shift/day/week basis with automatic samplers at feed, concentrate, and tailing points. Mineral beneficiation is a continuous process linking flow of material at crushing, grinding, flotation, concentration, tailings, thickener, filters, dryers, and stockpiles. The weight of final concentrate is measured in stockpiles at regular intervals. Metallurgical balance at a short time interval, say shift, day, or week, is an approximation to take preventive measures in the plant. The results of cumulative long-term tenure, such as monthly/quarterly/yearly are more authentic. The computation is done with Excel spreadsheets using a two-product formula. It can be programmed for cumulative results and performances. Commercial software is available. Plant performance and metal balance of a single metal and concentrate for a day's production is given in Table 13.3. Metallurgical balance for multimetal deposits is complicated and expanded in the same way.

TABLE 13.3 Plant Performance and Metal Balance of a Zinc-Lead Mine

Item	Weight (Tonnes per Day)	% Zn Metal	Weight of Zinc Metal (Tonnes)	Distribution % Metal
Feed	3000	4.00	120	100
Concentrate	200	55.00	110	91.66
Tailing	2800	0.36	10	8.34

13.6.5 Milling Cost

The milling cost covering all individual subdivision is critical in identifying high cost centers where improvements in performance would be beneficial to project profitability. The cost cannot be generalized due to local variable costs on labor, energy, and water. It will also be affected by type and complexity of the ore being processed. Standard fixed and variable process plant operating costs are summarized in Table 13.4.

13.6.6 Concentrate Valuation

The prime objective of mineral beneficiation is to optimize financial return of ore at various combinations of recovery efficiency and grade of concentrates. This will depend on average values of metals at international markets (e.g., London Metal Exchange), transport charges to smelters, and costs of metal extraction. The harmful impurities (Hg, As, and U) and precious trace/rare earth elements (Au, Ag, Cd, and Co) will affect the value of concentrate either as a penalty or a bonus. The net smelter return (NSR) is calculated for any combination of recovery efficiency and grade as:

NSR = Value of contained metal − (Smelter/Refinery charges + Transport costs + Bonus − Penalty)

The metal production cost includes the cost of concentrate and conversion to metal (smelter + refinery). These costs are affected by energy and labor costs at mine, beneficiation, and smelter locations.

TABLE 13.4 Operating Cost Summary (%) per Metric Tonne of Ore Beneficiated by Froth Flotation

Item	% Cost
Fixed Costs	
Manpower	30
Overheads	1
Sub-total	31
Variable Costs	
Power	20
Water	2
Reagents	20
Grinding media (crushing and grinding)	3
Crusher liners	2
Mill liners	2
Thickening and filtration	1
Tailing disposal	2
Laboratory costs	5
Maintenance costs	7
Concentrate transport	5
Subtotal	69
Total	100

13.7 SMELTING AND REFINING

Smelting is a branch of extractive metallurgy that produces metal from ore/concentrate, and **refining** is upgradation to purest metal (99.99%) and separation/recovery of precious metals (Ammen, 1997).

13.7.1 Smelting

Smelting maximizes the separation of ore from gangue minerals. The concentrates undergo smelting and converting in a furnace at a high temperature to produce a silicate melt (slag) and an immiscible melt (matte) due to density differences. The flux (limestone) is added to the furnace to reduce the melting temperature in the matte. The two broad divisions of the smelting process are pyrometallurgy and hydrometallurgy.

13.7.1.1 Pyrometallurgy

Pyrometallurgy works on the thermal treatment of ores and concentrates resulting in physical and chemical transformations in parent minerals and enables the recovery of valuable metals. The treatment produces saleable products (metals) or intermediate compounds/alloys (impure metals) for further processing (refining). The pyrometallurgical process is suitable for iron ore, chromite, lead, zinc, copper, tin, and tungsten. Pyrometallurgy follows one or more of the following processes.

13.7.1.1.1 Calcination

Calcination is the thermal decomposition of a sulfide/carbonate ore. The decomposition of calcium carbonate to calcium oxide and carbon dioxide as well as iron carbonate to iron oxide is:

$$CaCO_3 \rightarrow CaO + CO_2$$

Calcination processes are carried out in a variety of furnaces, namely, shaft furnace, rotary kiln furnace, and fluidized bed furnace.

13.7.1.1.2 Roasting

Roasting drives out unwanted sulfur and carbon from sulfide/carbonate ore in the oxidizing environment, leaving an oxide. The chemical reaction inside the roaster is:

$$2ZnS + 3O_2 \rightarrow 2ZnO + 2SO_2\uparrow + \text{Heat}$$

A **roaster** is a large-diameter vertical furnace comprising a mild steel plate at the lower portion with fire-insulating brick lining at the top (Fig. 13.52). Concentrate is fed into the roaster maintaining a temperature of 950°C. The hot gases from the roaster pass through a waste heat boiler and are cooled to 350°C. **Calcine** is separated from the boiler, gases passes through cyclones, moves out at 320°C, and finally enters a wet scrubber (Peabody scrubber). The solids from the gases are scrubbed at 45°C. Sulfur dioxide gases end their journey in a conventional sulfuric acid plant to produce 98.5%.

13.7.1.1.3 Reduction

Reduction is a type of thermal application at temperatures above melting point of the metal, with at least one product in the molten phase. The metal oxide is heated with coke/charcoal, a reducing agent that liberates oxygen as carbon dioxide leaving a refined metal. The common iron ore hematite (iron oxide) changes to metallic iron at ~1250°C, 300°C below the melting point of iron (1538°C).

Addition of **flux** helps the melting of oxide ores, chemically reacts with unwanted impurities (silicon compounds), and assists in the formation of **slag**. Calcium oxide, in the form of limestone, is commonly used as flux. It reacts with carbon dioxide and sulfur dioxide produced during roasting and smelting to keep them out of the working environment as rejects.

13.7.1.2 Hydrometallurgy

The hydrometallurgy extractive technique involves the use of aqueous chemistry for the recovery of metals from ores, concentrates, and recycled/residual materials. Hydrometallurgy includes the following three broad areas.

13.7.1.2.1 Leaching

Leaching uses aqueous acidic (lixiviant) solutions that vary in pH, oxidation/reduction potential, and temperature-optimized selectivity of dissolution-desired metal from in situ and heaps of broken ore.

In-situ leaching involves drilling holes into orebody, fracturing by explosive/hydraulic pressure for acidic solution to penetrate into orebody, collection of leached solution, and finally processing. Honeymoon uranium mine, South Australia, operates leaching since 2011. Copper heap leaching at Whim Creek, Philbara, Australia has

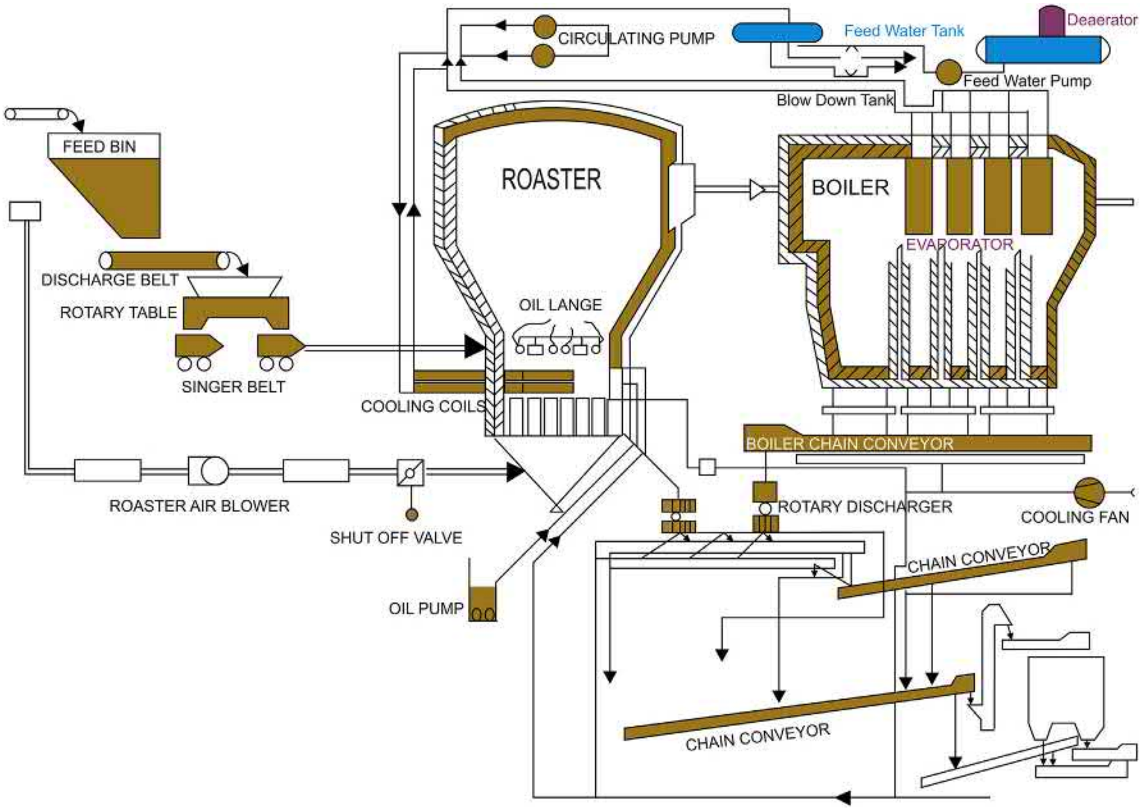

FIGURE 13.52 A complete flowsheet of roasting in hydrometallurgy.

been discussed at Chapter 13, Section 13.5.1. Autoclave leaching reactors are used for reactions at higher temperatures to enhance reaction rate (e.g., zinc smelter recovery in Rajasthan, India). The ore/concentrate is fed as slurry/pulp into stirred agitation leaching tanks to mix with lixiviant aqueous solution (solvent). The agitation enhances reaction kinetics by enhancing mass transfer.

13.7.1.2.2 Solution Concentration and Purification

The leach liquid concentrates metal ions and recovers by selective precipitation and removal of impurities. Copper precipitates as its sulfide as a means to purify nickel leachates. **Solvent extraction** or **liquid/liquid extraction** is another method to separate compounds based on their relative solubility in two different immiscible liquids: water and an organic solvent.

13.7.2 Refining

Refining is the process of purifying an impure metal to its purest form (99.99%). The final metal is usually chemically identical to the original one. The various types are: cupellation, electrolytic refining, and wrought iron.

13.7.2.1 Cupellation

Cupellation is the refining process that separates noble metals from impure metals/alloys treated under very high temperatures and controlled operations. Lead melts at 327°C, lead oxide at 888°C, silver at 960°C. The impure lead metal/alloy is melted at a high temperature of 960−1000°C in an oxidizing environment. Lead oxidizes to lead monoxide (litharge), which captures oxygen from other metals present. The liquid lead oxide is removed or absorbed by capillary action into hearth linings separating silver.

13.7.2.2 Electrolytic Refining

Electrolytic refining is the process of purifying impure metals by electrolysis that uses electrical current to drive an otherwise nonspontaneous chemical reaction. A slab of impure metal and a fine sheet of pure metal are made as anode and cathode, respectively. Both are kept in a close cell/container/chamber dipped in a solution of metal salt as electrolyte. The impure metal from the anode dissolves in electrolyte and an equal amount of pure metal from the electrolyte deposits on the cathode as electric current passes through the cell. Soluble impurities dissolve in solution and insoluble impurities settle at the anode bottom (anode mud having precious metals). Electrolytic refining for copper with an impure copper anode slab, pure copper sheet cathode, and copper sulfate electrolyte is a globally used commercial application. Pyrometallurgical zinc (98.50%) is refined to 99.99% purity by refluxing.

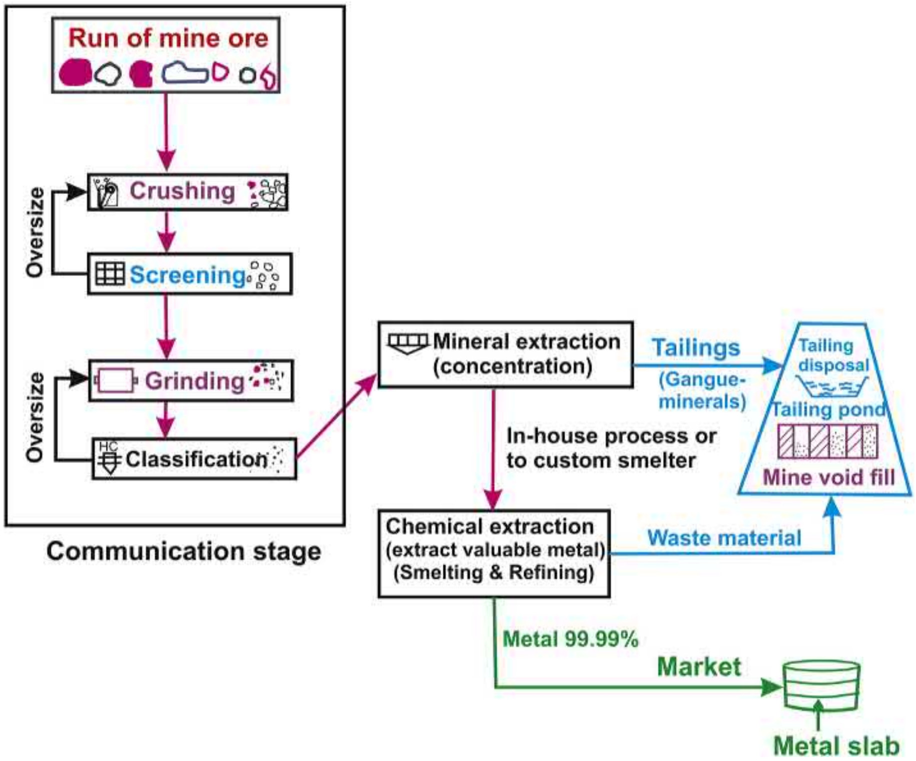

FIGURE 13.53 A holistic conceptual flow diagram showing the journey from run-of-mine ore to concentrate, and ultimately to metal production at 99.99% grade.

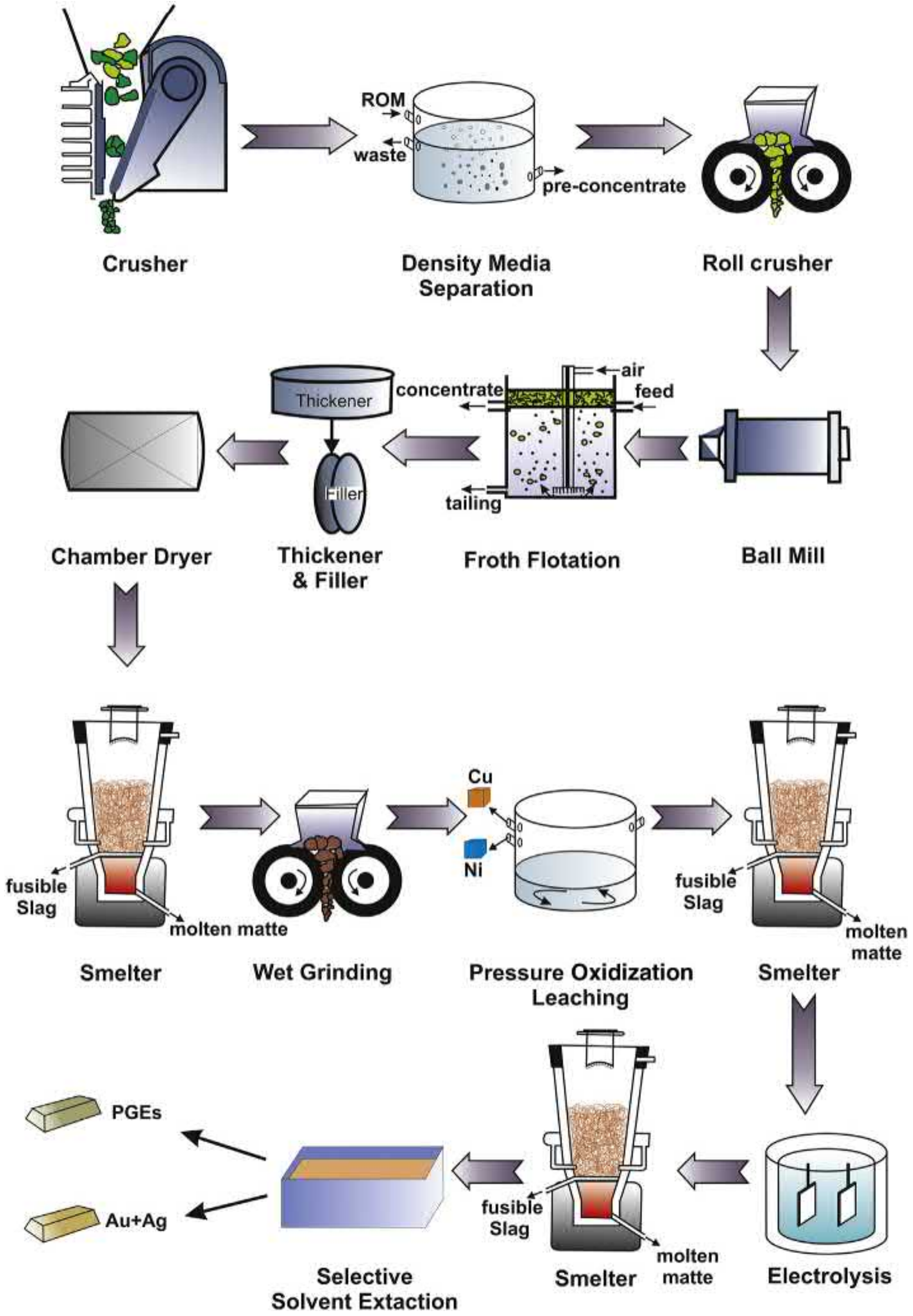

FIGURE 13.54 A complete flow diagram, including crushing, grinding, density media separation, froth flotation, and pyrometallurgical and hydrometallurgical process route to achieve the highest purity of metals. *PGE*, platinum-group elements.

13.7.2.3 Wrought Iron

Wrought iron is a refined blast furnace product (pig iron) containing 4%—5% carbon and some silicon. The harder and stronger steel is alloy mixed with chromium, nickel, and manganese.

13.8 ORE TO CONCENTRATE AND METAL

Mineral processing, mineral beneficiation, or upgradation involves handling three primary types of ROM material, which have been blasted, fragmented, and brought out from

FIGURE 13.55 Panoramic view of hydro-metallurgical smelter of Hindustan Zinc Limited at Rajpura-Dariba, Rajasthan, India. The smelter has an annual production capacity of 210,000 t zinc and 100,000 t lead metal, and 160 MW captive power plant.

an in situ position. These materials can be used directly or by simple or complex processing and even by applying extractive metallurgy like hydrometallurgical or pyrometallurgical methods. The categories are:

1. Rocks: Granites, marble, limestone, building stones, sand, coal, and clays.
2. Industrial minerals: Quartz, diamond, gemstones, fluorite, apatite, zircon, garnet, vermiculite, barite, and wollastonite.
3. The metalliferous deposits: Gold, platinum, chromite, chalcopyrite, sphalerite, galena, bauxite, hematite, and magnetite.

The journey from ROM ore to concentrate and finally metal travels through many operations of liberation, separation, concentration, and extraction before it reaches the end users. These activities have been diagrammatically summarized in Figs. 13.53 and 13.54. A panoramic view of State of the Art zinc and lead smelting is depicted in Fig. 13.55.

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Chapter 14

Environmental System Management of Mineral Resources and Sustainable Development

Chapter Outline

> *A miner shall leave the mining area in a better form than he found it.*
>
> Author.

14.1 DEFINITION

Mineral wealth is finite and a nonrenewable asset with high cost and risk in prospecting. Mining is a land-based activity in general and an offshore activity for oil and gas. Accelerated industrial and economic growth necessitates rapid development of the mineral sector to support the basic manufacturing industries. Developed and developing countries are in a race to achieve the highest level of economic and social progress. The speed of this development needs to be checked to safeguard the environment and maintain quality, ecofriendly living conditions on a continuing and sustainable basis. Development, environment, and sustainability are complementary to each other, keeping an optimum balance between development and environment. Policymakers and the mineral industry must promote social well-being of the people living in and around mining areas, including those local inhabitants who may/may not be concerned directly with mining.

Environmental system management (ESM) is a powerful tool for handling the adverse impacts of environment aspects. ESM provides a structured approach to plan and implement environmental protection measures. Large organizations adopt ESM to improve environmental performance and enhance business efficiency. ESM integrates environmental management into daily operations as well as long-term planning and other quality management systems.

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00014-9

The adverse impact of exploration, mining, and related activities on the environment and the disruption of the ecological balance worldwide came into focus only a few decades ago. Developing countries are equally responsible due to ignorance and the consequences of long-term neglect. Remedial measures have resulted in stringent enactments and rules to negotiate bumpy roads, though some degradation effects are inevitable and unavoidable. The mineral sector has to address a methodology that causes least damage to natural resources such as air, water, soil, and biomass, and to human communities and lifeforms. Sustainable mining with an integrative approach is critical and significant for the growth of the mineral sector.

14.2 ESM IN THE MINERAL INDUSTRY

Environmental pollution by the mineral industry degrades the quality of land, soil, vegetation, forest, air, water, human health and habitation, and ecosystems, making it a matter of serious concern (Saxena et al., 2002). The magnitude and significance of the impact varies from mineral to mineral, geographical position, and size/type of operation. Mineral sectors follow the framework of the National Mineral Policy, Mineral Concession Rules, and Mines and Minerals (Development and Regulation) Act. Prior permission from state and central Departments of Mines and Geology, Bureau of Mines, Ministry of Finance, Forest and Environment is mandatory at every stage of activity.

Functional areas in the mineral sector can broadly be grouped based on purpose, type of operations, end products, and activities that cause degradation, identify hazards, and suggest remedies. Each area will be discussed separately with respect to activities causing expected sources of environmental degradation, hazard identification, and suggested remedies. The causes, impacts, and remedies are, in general, interrelated and overlapping. The functional areas are:

1. Exploration.
2. Mining and beneficiation
3. Smelting and refining.

14.2.1 Exploration

The environmental effect is minimal during exploration activities, which include surface mapping, airborne and ground geophysical survey, geochemical study of soil, rock, and water samples, excavations (pits, sumps, and trenches), and drilling to various extents and magnitudes. These activities are conducted in such a way as to minimize their impact on the environment. Appropriate compensation and rehabilitation are undertaken to satisfy the local inhabitants. A focus on the community engagement process by facilitating employment opportunities to locals is important. The exploration program includes support, services, training, and welfare to the community as a whole, and youth in particular. This relation development model during exploration stages will pay dividends for future mining and related operations. This is the ideal time for the development of empathy and confidence building with the local administration and community. Prevailing natural conditions should be maintained. The compilation and evaluation of existing and new data on satellite images, topography, geological maps, sample locations, geochemistry (the presence of mercury and other toxic metals), mineral occurrences, and quality of air, water, vegetation, and forests will be of great value for creating the environmental baseline. It will help to guide the future course of the environmental management program during and after project life.

14.2.2 Mining and Mineral Processing

Environmental impacts and consequential damages are by and large high during mining and beneficiation. These operations must focus on safety, environment, economy, efficiency, and the community for a successful venture. The possible impact areas and their management can be grouped as:

1. Baseline monitoring.
2. Land environment management.
3. Waste management.
4. Mine subsidence and management.
5. Mine fire and management.
6. Airborne contaminations and management.
7. Noise pollution and management.
8. Vibration and management.
9. Water management.
10. Hazardous process chemicals and management.
11. Biodiversity management.
12. Social impact assessment and management.
13. Economic environment.
14. Environmental impact assessment (EIA).
15. Environmental management plan (EMP).
16. Mine closure plan and management.
17. Mine rehabilitation and management.

14.2.2.1 Baseline Monitoring

Baseline monitoring is a significant component of environmental management that commences at the reconnaissance phase, and continues to incorporate feasibility studies. It includes all relevant environmental, economic, and social issues. Baseline information identifies the possible impact areas that need attention during operating stages and their management. The system is continuously updated with periodical assessments to evaluate the extent of mining-related impacts and recovery following control of the impact or rehabilitation.

14.2.2.2 Land Environment Management

Land, in various forms, is a finite natural resource. The necessity of land is ever increasing due to rapid population growth in developing countries and per capita enhanced industrial growth. One must analyze and understand that the quantum of land requirement during actual mining, beneficiation, smelting, and refining (Table 14.1) is small in comparison to other industries. The minerals are mined at the sites where they exist. Mining and mineral processing activities occur in remote places far away from cities. The possibility of land and soil degradation is expected at these remote locations.

The types of impact on land, topography, and soils, and suggested environment management, are:

1. Loss of agricultural and forest land
   In the case of opencast mining there will be complete loss of agricultural and forest land, and deforestation in and around the pit. Underground mining uses limited surface land for the entry system and infrastructure development. In either situation, adequate compensation is provided to landowners with cash, employment, and rehabilitation. New agricultural land is developed, and afforestation done under overall land-use planning. Mining in unreserved forest land is replanted with sufficient plantations in nearby areas. No mining is permitted in reserve forest areas under normal circumstances, other than precious metals and minerals of strategic importance. The area around is afforested covering a much larger space. The choice of plants is a critical issue. The plants should easily grow in the type of soil and rocks faster and require less upkeep. Common plants are neem (*Azadirachta indica*), babul (*Vachellia nilotica*), Indian khus (vetiver grass family), and Jatropha (nettlespurge), mostly medicinal herbs.
2. Topsoil and subsoil degradation and management
   The types of mining activities, particularly open pit, affect the topsoil and subsoil to a great extent by changing natural soil characteristics (texture, grain size, moisture, pH, organic matter, and nutrients). In an ideal open pit situation it is desired that the topsoil horizons within the selected mining limits are clearly defined. The topsoil and subsoil are removed separately, preferably by scraping, and stockpiled on easily accessible stable land. These soils can selectively be relaid simultaneously to reclaim degraded land for agriculture, or reused in the future at the time of mine closure. As far as practicable the removed vegetation from the mining zone should be replanted in suitable areas.
3. Changes of drainage pattern by blocking water and flash flood
   The effect of unplanned mine waste dumping will change the surface topography and thereby the local drainage pattern. The waste dumps will act as a barrier to the natural flow of rainwater resulting in water logging and flash floods causing damage to agriculture and local properties downstream. It will also affect seasonal filling of local reservoirs and recharging of groundwater. Changes in drainage pattern can be anticipated from expected postmining surface contours. A suitable action plan for surface drainage patterns can be designed accordingly. This planning is required particularly from the view of total water management and erosion control.

TABLE 14.1 Norms of Land Area Permissible for Exploration and Mining Lease in India

Stage	Land Area (km^2)	Duration (Years)	Anticipated Activities
Reconnaissance permit	<10,000	3 (nonrenewable)	Limited excavation for pitting, trenching, and diamond drill site for sampling with no impact. No land requirement
Large prospecting lease	500–5000	3–6	
Prospecting license	1–500	3 + 2	
Mining lease (ML)	0.10–100 (actual mining and processing in less than 1 km^2)	>20	1%–10% of ML area acquired with clearance from MOM, MOF, and MOE. Creation of lumpy and fine waste. No reserve forest land permitted for mining and waste dumping
Beneficiation/ smelting/refining	Limited area for process plant	Life of mine	Generation of fine waste, fluid, solid impurities, and gases

MOE, Ministry of Environment; *MOF*, Ministry of Forest; *MOM*, Ministry of Mines

4. **Landslide**
   Opencast mining on hill slopes, particularly in areas of heavy rainfall, is vulnerable to landslides causing loss of human life and property, and deforestation. This can be controlled by the geotechnically designed slope of the mine and adequate support systems.
5. **Unaesthetic landscape**
   Mining activity changes the land-use pattern and alters the surface topography by increased surface erosion and excavations. If proper reclamation is not done, this can result in an unaesthetic landscape. Open pit mines must be filled with mine waste rock as reclaimed land. They can be filled with rain- or floodwater for fisheries and water sports.
6. **Land-use planning and management**
   The methods and procedures of land use are planned before the mining starts. The status is periodically compared during active mining to maximize the benefits of better land use and to incorporate remedial measures in case of deviation. The mine area should be reclaimed to the best possible scenario at the time of mine closure. It is the responsibility of the mining company to take into account the cost of reclamation in project costs. The reclaimed land should preferably be reverted back to the erstwhile landowners under mutual agreement. The land can be developed for the local community based on overall planning of the region. The method can be decided by representatives from the mining company, local inhabitants, local authorities, and state planning department.

14.2.2.3 *Waste Management*

The type of waste and quantity likely to be generated during mining, beneficiation, smelting, and refining can be visualized from Table 14.2.

The management of waste handling can be organized as:

1. **Lumpy waste**
   The coarse lumpy waste generated due to open pit or underground mining can be used for reclamation of unused land in and around the mining area. This reclaimed land can be made into offices or industrial (Fig. 14.1) or community buildings.
   The low-lying uneven lands around the industrial area can be converted to amusement parks and playgrounds (Fig. 14.2) using lumpy mine waste. It can also be used as solid waste fill in open pit mined-out voids.
2. **Fine waste**
   The bulk of fine waste generated is in slurry form or tailings during mineral beneficiation. The tailing is transferred through pipelines to the tailing ponds for settling. The top of the tailing pond can be developed as a grassy park, playground, or picnic spot or for other use. Tailing mixed with 5%—10% cement can be directly diverted underground as void filling for ground support.

TABLE 14.2 **Likely Waste Generation, Coarse and Fines, During Mining and Beneficiation**

Parameter	Open Pit Mine	Underground Mine (%)
Ore-to-waste ratio	1:4, 5, ..., 10	<25
Beneficiation (converted) fine waste (tailing in slurry form)	<90%	<90
Computation at 1000 tpd mine or 300,000 tpa ore production		
Coarse lumpy waste	1,200,000 t	<75,000 t
Fine waste (tailing)	270,000 t at 90% of ore treated	
Smelting waste (reject)	Limited slag generation with value-added recoverable metals	
Refining waste (reject)	Limited fluid impurities with value-added trace elements	

14.2.2.4 *Mine Subsidence and Management*

Mine subsidence is the movement of ground, block, or slope caused by readjustment of overburden due to collapse and failure of underground mine excavations (Fig. 14.3), unfilled and unsupported abandoned mines, and excessive water withdrawal. It can be natural or manmade. Surface subsidence is common over shallow underground mines. The sudden subsidence of ground causes injury to local inhabitants and damage to material, the topography, and infrastructure, and can even cause mine inundation and the development of mine fire.

Mine subsidence movement can be predicted by instrumentation, monitoring, and analysis of possible impacts. The modification of underground extraction planning may minimize possible subsidence impact. Subsidence can be prevented by adequate support systems, e.g., rib and sill pillars, steel and wood, cable and rock bolting, plugging of cracks, and backfilling with sand, cement-mixed tailing, and waste rock.

14.2.2.5 *Mine Fire and Management*

Mine fire (Fig. 14.4) is a common phenomenon in mining. This is especially true in many coal seams and high sulfide (pyrite)-rich deposits. A coal mine fire occurs due to the

FIGURE 14.1 Reclaimed land used for building a zinc smelter at Visakhapattanam, India.

FIGURE 14.2 Reclaimed land used for community and industrial sports and recreation at a remote tribal hamlet of Zawar Group of zinc-lead-silver mines, India.

presence of high methane gas, instantaneous oxidation property of coal when exposed to open spaces, and generation of excessive heat. The intensity of fire depends on the exposed area, moisture content, rate of air flow, and availability of oxygen in the surrounding area. The nature of the fire may be confined to surface outcrop, mine dump, open pit benches, or be exclusively underground, and may even spread to the surface. Fire in sulfide ore and concentrate occurs due to high pyrite-bearing dry stockpiles exposed to an open environment for some time under the sun and heat.

A mine fire is a matter of serious concern and causes enormous impact with loss to the economy, as well as social and ecological upheaval. Losses are burning and

FIGURE 14.3 Surface subsidence from operating underground zinc-lead open stopes without any loss of life or material.

locking of valuable coal reserves and polluting of the atmosphere with excessive carbon monoxide, carbon dioxide, and nitrogen. The surface temperature rises causing inconvenience to residents nearby and damage to land, surface properties, vegetation, as well as the lowering of the groundwater level. The common diseases that affect local inhabitants are tuberculosis, asthma, and related lung disorders.

The nature of the fire can be delineated showing precise location, boundaries, intensity, and direction of movement (Fig. 14.5). Change of temperature and gas levels can be recorded and measured by surface instrumentation or airborne thermal scanner. Surface thermal infrared measurements are more commonly used. The temperature anomaly is measured by a handheld infrared gun in the affected area on the surface or underground from various locations. The measurements are recorded at prespecified times to minimize the effect of solar radiation. Prediction is achieved by simple contouring of the temperature gradient or by applying different mathematical models. Depth and extent are determined by lowering probes into fissures or along boreholes. The temperature gradient is recorded by a digital recording unit connected by a long data transmission cable. This is less preferred due to expensive drilling and frequent damage to transmission cables. Drill holes act as catalysts for additional air supply to fire activity. The third technique is airborne infrared survey. The region is mapped by low-flying aircraft or helicopters fitted with an infrared scanner. Airborne interpretation is refined by simultaneous collection of ground information on weather, soil moisture, and vegetation. The low-flying survey is being replaced by the availability of precision data from satellite images and high-end geographic information system processing software.

FIGURE 14.4 Coal mine fire is a common phenomenon in open pot and underground mines due to the burning of natural gases and temperature recorded by infrared gun at Jharia coalfields, India.

The fire can be either stopped or checked from spreading further after it is precisely delineated. The possible remedies are:

1. Stripping or digging the fire out physically.
2. Injecting filling material like fly ash, water, mud, cement, and sand into nonworking mines and voids through fissures, boreholes, and other openings.
3. Isolating by large-scale trenching, fireproof foam blanketing, impermeable layers of sand and debris, inert gas infusion, dry chemicals, or foams.
4. Grow trees as much as possible to balance the environment.
5. Acting quickly to prevent the fire spreading and change of fire position.

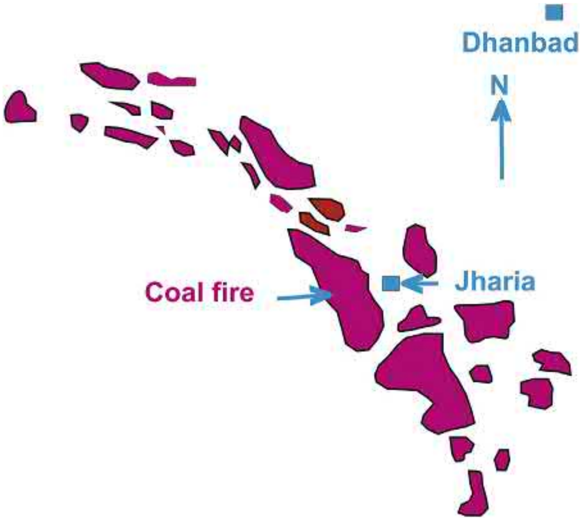

FIGURE 14.5 Schematic map of mine fire depicting the nature and movement of fire and planning for remedies at Jharia coal field, India.

14.2.2.6 Airborne Contaminants and Management

Airborne contaminants related to emissions of particulate matters during exploration, mine production drilling and ore/waste handling, mineral processing, and pyrometallurgical smelting produce significant sustainability impacts. Suspended particulate matter are fine discrete masses of solids, gases, and liquids, such as fine dust, asbestos, smoke, fly ash, lead, mercury, arsenic, and other toxic metals. The gaseous pollutants are molecules of CO, SO_2, metal fumes, hydrocarbon vapor, and acid mist. The sources of air pollution are mine production (drilling and blasting, particularly in open pit mines) (Fig. 14.6), mineral processing plants (crushing and grinding), ore and waste handling, workshops, and large numbers of transport vehicles (Fig. 14.7). Air pollution causes injury to eyes, throat, and the breathing passage and lungs of workers and local inhabitants, animals, and plants. Chemical pollutants are responsible for serious diseases like birth defects, brain and nerve damage, pneumoconiosis, tuberculosis, and cancer.

Air pollution in mining, mineral processing, smelting, and cement complexes is controlled by:

1. Wet drilling applications in mining and grinding.
2. Dust suppression through mobile sprinklers along haulage roads and fixed sprinklers in waste dumps and stockpiles.
3. Chemical treatment at haul roads.
4. Selection of superquality mine explosives.
5. Use of face masks.
6. Installation of dust/gas extraction systems at crushers.
7. Ventilation fans and bag filters for cleaning of exhaust gases from refineries.

FIGURE 14.6 Open pit mine blasting of rock phosphate, India, generates toxic/nontoxic gases harmful to any living entity. The effect is controlled by better quality explosives, blasting between shift intervals, and nonexposure of miners to gas.

8. Tall chimneys to disperse residual gases after scrubbing, conversion, and/or cleaning.
9. Systematic stacking of waste and vegetation over inactive benches.
10. Aforestation/greenbelt development around the mine peripheries.
11. Routine medical tests, monitoring, and treatment of affected people.

Dust extraction and de-dusting facilities are installed in the areas of high dust creation (crushing, grinding, and pulverizing) inside the mine but invariably in the mineral dressing plant (Fig. 14.8). The gas cleaning system and double conversion double absorption sulfuric acid plant are set up in the smelter to minimize emission and prevent sulfur dioxide and other intoxicating gases escaping to the environment. Mercury removal plants aid in keeping away the ingress of mercury in sulfuric acid and/or its entry into

FIGURE 14.7 A huge fleet of heavy-duty trucks move in and out daily from Sukinda chromite mining belt, India, for ore transportation causing high pollution of dust and diesel exhaust.

FIGURE 14.8 Air pollution control by a dust extraction system installed at an ore-dressing plant, India.

the biocycle. A notable way of controlling dust and gas can be effected by using tall chimneys and greenbelt development (Fig. 14.9).

14.2.2.7 Noise Pollution and Management

Workers and residents in and around mining complexes deserve noise levels within acceptable standards in their workplace and residential areas. Ambient noise level is recorded as part of the environmental assessment process at an early stage of project formulation. Measurements are conducted by automatic noise loggers over adequate times, ideally during exploration. The recording is repeated prior to the mine being operational and nonworking days to reflect natural conditions. Excessive noise by industrial machinery, transport vehicles, and other associated sources beyond acceptable levels is identified. The noise legislative framework is developed to combat problems caused by excessive noise. Routine monitoring is conducted at workplaces, schools, hospitals, places of worship, surrounding residences, and other noise-sensitive locations for corrective measures. Optimum noise levels with variation around the standard are given in Table 14.3. The warning and danger limits are specified as 85 and 90 dB(A), respectively. No worker should be allowed to enter a workplace with a noise level of 140 dB(A). All these standards are based on exposure during an 8-h workshift. Continuous exposure to high noise levels causes deafness, nervousness, irritability, and sleep interference. It also disturbs wildlife and the ecosystem.

The source of noise is identified for corrective measures at the manufacture level. Systematic monitoring of noise levels is done with a modular precision sound level meter, which has a wide range of measurement capabilities. The suitable remedies are:

1. Community liaison and involvement in the decision-making process.
2. Periodical measurements and monitoring.
3. Control measures at the manufacture level.
4. Change of blasting design and explosive control.
5. Evacuation of people from the blasting area.
6. Regulation of vehicular movements, including night air traffic.
7. Acoustic barrier and greenbelt development.
8. Use of ear protection devices (earplugs, ear muffs) at the workplace to reduce noise level exposure beyond 115 dB(A).
9. Location of residential and resettlement colonies away from noise-generating sources.

FIGURE 14.9 Air pollution control by erecting tall chimneys and green belt development, Paris, October 2009.

TABLE 14.3 Ambient Noise Standards at Various Places

	Limits in dB(A)	
Area Category	**Day (06–21 h)**	**Night (21–06 h)**
Industrial area (mine, plant)	75	70
Commercial area (office, market)	65	55
Residential area	55	45
Silence zone (hospitals, schools, churches)	50	40

14.2.2.8 *Vibration and Management*

The major sources of vibration in the mining sector are drilling and blasting in open pit and underground operations, heavy machinery deployed for breaking and transporting ore, and high-capacity crushing and grinding units at the beneficiation plant. The increasing size and depth of open pit and large-diameter long hole blasting in underground mines further aggravates vibration. Other sources are movement of heavy vehicles around the workplace and workshop noise. The environment and mine safety authorities have laid down standards of acceptable vibration levels to protect damage to existing structures and associated health hazards. The average ground particle velocity may not exceed 50 mm/s for soil and weathered and soft rocks. The upper limit for hard rocks is 70 mm/s. Any deviations in vibration level from the standards may cause nervousness, irritability, and sleep interference. Routine ground monitoring equipment can identify the sources and nature of vibration.

The suggested remedies are:

1. Modification measures at the manufacture level.
2. Change in blasting design by hole spacing, diameter, and angle.
3. Avoiding overcharging, using delays, and improving blasting techniques.
4. Use of superior quality explosive, explosive weight per delay, and delay interval.
5. Control of fly rocks.
6. Greenbelt development.

14.2.2.9 *Water Management*

Water is a life indicator and is essential to sustain life. An adequate, safe, and accessible supply must be available to all. Water can be classified into various groups depending on its source, use, and quality. The primary sources of water are mostly from the surface: oceans, rivers, streams, reservoirs, and natural or manmade lakes. The other source is from subsurface aquifers that come to the surface as springs. It can also be tapped by tube wells. In addition to the survival of humans, animals, and plants, water is also necessary for agriculture, industry, and developmental activities. Water is rarely available in its purest potable form. It is usually polluted by various sources mainly through microbial, chemical, and radiological aspects. Pollutants in the form of physical, chemical, and biological waste make it unsuitable for use. The physical pollutants are color, odor, taste, temperature, suspended solids, and turbidity. The chemical pollutants are primarily related to geology and mining. The chemical contaminants are hardness, acidity/alkalinity, dissolved solids, metals (Fe, Pb, Cd, As, and Hg), and nonmetals (fluorides, nitrates, phosphate, organic carbon, calcium, and magnesium). Microbial hazards cause infectious diseases by pathological bacteria, viruses, parasites (protozoa and helminthes), microorganisms, and coliforms. The chances of dissolved pollutants like Fl, Pb, Cd, As, and Hg are high in water bodies in the vicinity of mining and beneficiation industries. This is due to the presence of pollutant elements in the ore-bearing host rocks and discharge of industrial effluents to the surface. Radiological hazards may derive from ionizing radiation emitted by radioactive chemicals in drinking water. Such hazards are rare and insignificant to public health. However, radiologic exposure from other sources cannot be ruled out. Mining operations frequently cause lowering of the groundwater table due to pumping of water to make mining safe.

The World Health Organization (WHO) defined the guidelines for safe drinking water quality standards with variations in acceptable limits from country to country in 2008. Recovered mine, plant, and smelter water quality results from Indian zinc mines are given in Table 14.4. The mine water is treated and used for industrial purposes. The presence of pollutants causes poisonous and toxic effects to all living beings when concentrations are more than the permissible limits. Polluted water may risk the survival of aquatic flora and fauna, and needs treatment before use and preferably before industrial purposes.

Water, being a scarce and essential material, needs to be used in association with a long-term water management plan. The program must satisfy the industrial requirements as well as take care of domestic and agricultural needs of the surrounding villagers. The water balance exercise should cover the study of the requirements and availability of both quantity and quality for respective uses. The following water management program can be envisaged:

1. Identify all surface and subsurface sources of all types of water for adequate availability.
2. Introduce oil and grease traps and separators.

TABLE 14.4 Provisional Guideline Values for Drinking Water Quality by the World Health Organization (WHO) Versus Analysis of Typical Water Sample From Zinc-Lead Mines and Smelters, India

Parameters	Provisional Guideline Values for Drinking Water by WHO 2008	Recover Water Analysis From Zinc-Lead Mines and Smelters, India
Color	Colorless	Yellowish
Odor	Odorless	Pungent sulfur smell
Taste	Decent	Bad and rough
pH value	6.5–8.5	7.2–9.0
Total hardness (mg/L)	300	170–1000
Suspended solids (mg/L)	100	30–130
TDS (mg/L)	500–2000	400–2000
Arsenic as As (mg/L)	0.01	Nil
Barium (mg/L)	0.7	Not available
Boron (mg/L)	0.5	Not available
Cadmium as Cd (mg/L)	0.003	0.002–0.90
Chromium (mg/L)	0.05	Nil
Chlorides (mg/L)	250–1000	35–450
Copper as Cu (mg/L)	0.05–2.0	0.01–0.5
Cyanide (mg/L)	0.07	Not available
Fluoride as F (mg/L)	1.0–1.5	0.01–1.5
Iron as Fe (mg/L)	0.3–3.0	0.2–2.0
Lead as Pb (mg/L)	0.1	0.01–0.15
Manganese (mg/L)	0.4	Below detection
Mercury as Hg (mg/L)	0.006	Tr – 0.009
Molybdenum (mg/L)	0.07	Nil
Selenium (mg/L)	0.01	Nil
Sulfates (mg/L)	150	310–730
Uranium (mg/L)	0.015	Nil
Zinc as Zn (mg/L)	5.0	0.003–0.42
Remarks	Desirable/ permissible limit	Needs treatment for industrial reuse only
Source	WHO report 2008 and others	Compiled from various sources

TDS, Total Dissolved Solids; *Tr*, Traces

3. Construct check dams and garland drains all around the mine pit, and use waste dumps, soak pits, septic tanks, and domestic sewage water and other water harvesting practices to arrest seasonal rainwaters and any discharge of industrial effluent water for reuse in industry and plantation.
4. Implement "zero" discharge water management for mine pumps and recoup from tailing dam followed by sand bed filtering, treatment for pH, and recycling mainly for industrial uses.
5. Insert low-density polyethylene lining for seepage control in and around the tailing dam and other mine water storage facilities.
6. Minimize application of fertilizers, herbicides, pesticides, and other chemicals.
7. Dam and reservoir water (Fig. 14.10) is used for both industry and domestic purposes of a township. A major portion is diverted to the surrounding villages for agriculture and drinking through a long-term water management master plan.

14.2.2.10 Hazardous Process Chemicals and Management

Various process chemicals are used in the froth flotation of metallic ore of uranium, copper, zinc, lead, and iron. The flotation chemicals are mainly isooctyl acid phosphate, sodium isopropyl xanthate, and potassium amyl xanthate as conditioners and collectors, methyl isobutyl carbinol as frother, and sodium cyanide and copper sulfate as depressor. The cyanide extracts gold. Acid leaching of low-grade Cu, Au, Ag, Pt ore and tailing pad is a common practice. The primary leaching reagents are diluted hydrochloric, sulfuric, and nitric acids. These hazard process chemicals, disposed to the tailing dam, are fast-acting poisons. The intake of these diluted chemicals over a long time by gas inhalation, skin contact, and through water, milk, vegetables, and food pose toxic effects on humans, animals, birds, insects, and plants. Chronic sublethal exposure, above the toxic threshold or repeated low doses, may cause significant irreversible adverse effects on the central nervous system.

Acid mine drainage from complex sulfide deposits is a naturally formed chemical hazard associated with the weathering of hard rock metalliferous mines. It can also manifest itself in pyritic black shale-hosted sulfide ore, coal, and mineral sand mines.

The following actions are suggested for managing the chemical hazards of acid mine drainage:

1. Geological mapping, modeling, and control are used to separate acid-generating rocks. Risk of miners can be avoided by the use of safety shoes and a mine dress code.

FIGURE 14.10 Water management by sharing between industry, domestic, and agricultural purposes from Jhamri dam at Jhamarkotra rock phosphate mine, India.

2. Many gold mines practice cyanide destruction methods to reduce the risk of environmental impact in tailing storage facilities or mined-out pit voids.
3. The bottom and side walls of tailing ponds are sealed by concrete to arrest any percolation of water to surrounding water channels.
4. All seepage water passing through the sand/gravel bed below the dam is collected, treated, recycled, and reused for industrial purposes.
5. Tailings production should be reduced and reused wherever possible.
6. Routine sampling of water bodies of 10 km around mine-tailing ponds should be assessed for contamination and remedial measures taken.
7. The hazardous chemical management code should be implemented.

14.2.2.11 Biodiversity Management

Ecology is concerned with relations between living organisms and their changes with respect to changes in the environment. The direct ecological impact of mining to the surface of the land is usually severe due to the removal of natural topsoil that affects humans, animals, and plants. The net consequence is the likelihood of destruction in biodiversity within natural ecosystems. Natural plantations and forests are likely to be destroyed due to removal of topsoil and cutting of forest for infrastructure development. The composite effect of mining changes the wildlife ecology, causes species to become endangered, and changes the travel routes of wild animals and migratory birds. The social and legislative context of mining in many parts of the world enforces and sets some form of land rehabilitation goals in mine closure situations. It is often anticipated prior to the granting of a mining lease. Rehabilitation considerations are incorporated into mine planning such that they become a major governing factor during routine mining operations and waste disposal.

The management of ecosystem restoration involves the following:

1. Encouragement and data sharing between governments, mining organizations, and universities for research in biodiversity.
2. Community liaison and involvement to address the issue.
3. Topsoil restoration by removal, storage, and replacement with technical and scientific skill.
4. Planned waste disposal with stabilizing and binding of the dump slopes by low-cost ecofriendly biodegradable jute or coir mat cover and plantation to protect the movement of fines to nearby land and drainage.
5. Minimization of plant cutting and growing more plantations all around for beautification, including open pit benches, waste dumps, and overdried tailing ponds.
6. Bauxite mining at Western Australia, and coastal dune mining for heavy minerals at South African perform routine restoration and development of forest to restore biodiversity.
7. Ensuring the availability of sufficient safe potable water.
8. And, finally, “Ecological awareness is truly spiritual.”

14.2.2.12 Social Impact Assessment and Management

Most mineral deposits occur in remote inaccessible locations inhabited by tribal or less-developed societies. The people residing within mining lease areas are directly affected. People living outside the mining areas face the indirect impact of activities. The livelihood of these groups depends on farming their land as tenants, share-croppers, or as landless farm laborers. Most of the tribal people depend on forest products. Many of them are homeless. However, mining activities make marked differences across all levels of society. The socioeconomic profile is assessed before the mine starts. The compensation packages that are framed include:

1. Assessment of possible general social impact with respect to particular affected communities and regions.
2. Assessment of social impact due to mining operations, expansion, and closure of the associated community and region.
3. Compensation and rehabilitation of affected families.
4. Imparting formal education and vocational training with particular reference to younger generations.
5. Direct and indirect employment with first preference to displaced persons and then to engineering, skilled, semiskilled, and unskilled workers from nearby localities.
6. Community development and better living conditions, housing, roads, and transport facilities.
7. Improved health care and hygiene, and potable water.
8. Community participation in sports and recreation.
9. Support for women's literacy, welfare, community participation, and child care.
10. Improvement in the quality of life in many respects; however, an affluent industrial environment causes addictions like smoking, alcohol and drug abuse, and increased crime rates.

14.2.2.13 Economic Environment

The impacts of mining are believed to be harmful in general. It is partly applicable in comparison to overall necessity. Damage is prevented with due care and in a timely manner. Economic issues can be addressed by covering the broad aspects of land, water, ecosystem, and society. In most cases, mining is beneficial to society with measurable economic parameters. The project cost invariably includes large amounts of resources for environmental management and mitigation measures. The affected and related people of the mining area can benefit from rehabilitation and resettlement programs in self-sustained, pollution-free townships, community development with essential amenities like potable water, health care, educational, banking, sports, recreational, and other high-quality infrastructural facilities. This improves the standard of living compared to others in rural areas. On-the-job vocational training and managerial skill development programs improve the efficiency of workforces resulting in higher efficiency and productivity at less cost. Environmental economics provide the road map to achieve sustainable uses of mineral resources.

14.2.2.14 Environmental Impact Assessment

Environmental impact assessment (EIA) is systematic evaluation and identification of potential environmental changes to establish a new project (mine, smelter). EIA is conducted during the overall investment decision on the mining project, as well as at the planning and design stages. The broad impact areas of the mineral industry can be envisaged for land use, landscape, alternative mining technology, waste assimilation, ground subsidence, mine fire, air quality, dust and noise pollution, vibration, water resource and quality, ecology (flora and fauna), public health, safety, activity-related risk and hazards, and socioeconomic setting. The individual areas have been discussed in the previous paragraphs along with remedial measures to mitigate environmental impacts.

It is desirable to identify, well in advance, the public's psychology and their interests or fears about the proposed development and local needs to safeguard long-term interest in the project. It is always better to educate and counsel them about the benefits of the project, e.g., general improvements to quality of life. Management integrates the affected people into the project to create an inherent feeling about their profound responsibility in program formulation and successful implementation. Assistance can be taken from experts in the trade and nongovernmental organizations. A public hearing can be arranged to ensure the involvement of locally elected representatives and local people, and major issues can be debated. The participation of local residents and elected representatives, including state administrative authorities, will defuse misunderstanding, confusion, and conflict.

Monitoring mechanisms are evolved to effectively implement and introduce corrective measures for an ongoing mining project. There are various ways of monitoring measures (Sen, 2009):

1. Ad hoc method
   The ad hoc method is a preliminary and general type, and identifies broad areas of possible impacts and states in subjective and qualitative terms such as "low," "moderate," "high," "significant," "insignificant," "no effect," and "beneficial." It does not quantify the impacts.
2. Checklist method
   The checklist method primarily lists all possible broad potential impact areas that can exist in a given situation. The list extends by identifying subareas under each major heading. A major area can be water resource with subareas such as source (surface, lakes, rivers, and groundwater), quantity, and quality. The measure of impact is subjective and qualitative like the ad hoc method. Each item will be identified as "adverse," "beneficial," or "none."

3. Overlay method
   The overlay method prepares a series of base maps of the project area. Maps display the georeferenced distribution of physical, demographic, social, ecological, and economic aspects of the area. The individual impact layers are overlaid on transparent sheets or digital layers to produce composite scenarios of the regional environment.
4. Matrix method
   The matrix method is an open-cell matrix approach with identified project activities and possible magnitude and significance of environmental impact. The magnitude can be subjective and expressed by numbers between 1 and 10. It can be expressed as a judgment using + or − signs. It is a relatively complex algorithm of impact assessment based on facts and judgments.

14.2.2.15 Environmental Management Plan

EMP ensures control measures for all identified problems by using better technology alternatives. The report is prepared by interdisciplinary groups involved in all activities. The group includes persons from planning, execution, research and development, finance, and the board of management. Clearance from respective authorities like the Ministry of Environment and Forests is obtained and attached to the mining lease application.

Industrial development or development of the nation and protection of the environment are the two sides of the same coin. A judicial balance is to be made between environmental damage and opportunity lost for the progress of human society—every living and nonliving entity. Each member of society is to share the responsibility.

14.2.2.16 Mine Closure Plan and Management

The mine closure plan is a long-term process. A primary closure plan is required by the regional and state regulatory authorities as part of the mine lease approval process. The mine closure plan has two components: (1) progressive or concurrent, and (2) final. The progressive mine closure plan is integrated into the total program of the mine operating life cycle, and activated at an appropriate stage rather than being attended to at the end of all activities. It includes various land-use activities to be performed continuously and sequentially during the entire period of mining operations.

Final mine closure activities start toward the end of the life of the mine. The process will continue even after the last tonne of ore is produced and will carry on until the mining area is restored to an acceptable level of a self-sustained ecosystem. All mine owners, even if they have accorded approval along with the mining lease, are required to obtain the approval of the final mine closure plan as per the guidelines and format by the competent authority within a period of 1 or 2 years in advance. The continuity of orebody in the strike, depth, and nearby area must be fully explored before the final closure decision. Alternative opportunities must be examined to rehabilitate the community. The mine closure plan and procedures should be imparted to the community and stakeholders well in advance.

14.2.2.17 Mining Rehabilitation and Measurement

Mining rehabilitation and measurement is the process implemented to mitigate the impacts of mining on the environment at the time of closure. The rehabilitation process varies between converting the mining area to a safe and stable condition, and restoring the premining conditions as closely as possible to support the future sustainability of the site. The key rehabilitation processes are:

1. Land rehabilitation is the process of returning the land in a given area close to its former state to bring some degree of restoration. Current methods attempt to restore the land to an improved condition after treatment.
2. Topsoils and overburden are characterized at early exploration and continue through prefeasibility and feasibility phases as a basis for mine planning. The topsoil and overburden are preserved at a suitable place, protected by adding organic fertilizer, and reverted to their original place and form at mine closure.
3. Waste dumps are flattened to stabilize conditions. The bulky broken dumps are protected against erosion by spreading biodegradable nets and planting vegetation all around the slope.
4. Waste dumps, open pits, and underground entries are fenced off to prevent endangering livestock.
5. Open pit mines are filled either with mine waste rocks for stability or with water (Fig. 14.11) for agriculture, fisheries, and water sports. The underground mine voids with incompetent rocks are filled with either sand, waste rocks, cement-mixed tailings (Rajpura-Dariba zinc-lead-silver mine, Rajasthan, India), or wood support (Sullivan zinc-lead-silver-tin mine, Kimberly, British Columbia, Canada) for ground stability or for storing water, particularly in dolomite countries (Lennard Shelf zinc-lead-silver mine, northwestern Australia), for agriculture and drinking purposes.
6. Leftover sulfide ore is usually covered with a layer of clay to prevent access of oxygen from air and rainwater that oxidizes sulfides to produce sulfuric acid.

FIGURE 14.11 An abandoned open pit magnesite mine stores rainwater for agriculture and fisheries.

7. The mine spoil area is vegetated by fast-growing pasture, vetiver grass, popularly known as "khus" in India (Fig. 14.12), a perennial grass of the Poaceae or Gramineae family, and shelter trees with tolerance to extremely high levels of nutrients as a rehabilitation program.

   The vertiver grass family grows in hostile dry and hot climates with low rainfall. The plants develop quickly, stabilize the soil, and protect it against erosion, pests, and weeds. The grass is favored for animal feed. This species with all its qualities and minimal care is preferred along with shelter trees to cover adverse surfaces in remote areas (Fig. 14.13).
8. Tailing dams are mainly pumped out for water recycling and reuse and left to partially evaporate. The top surface is covered with waste rock and a thin soil layer, which is planted to stabilize the area (Fig. 14.14).
9. The removal of townships, hospitals, schools, colleges, and other educational institutions, recreation centers, markets, banks, workshops, mine infrastructures, and beneficiation plants is not always part of the rehabilitation program. These establishments possess heritage and cultural values, and are used by the local municipality for tourism and alternative purposes.
10. Rehabilitation of the community is provided by alternative employment nearby or remotely.

FIGURE 14.12 Vetiver grass family ("khus" in India) grows quickly in hostile climates, stabilizes soil, and protects from erosion, pests, and weeds with minimal care, Lennard Shelf zinc-lead deposit, Australia.

14.2.3 Smelting and Refining

1. Smelting waste

   Smelting waste is generally in solid form (slag) containing precious metals. In such a case the slag is stored carefully for future recovery of value-added elements. Otherwise it is used as waste filling or road material. A small amount of fine dust passes though gas chimneys. The dust can be arrested by installing electrostatic precipitators, waste heat boilers, and cyclones. The other smelting waste is in gaseous form. Sulfur dioxide (SO_2) is a major air pollutant emitted during roasting, smelting, and the conversion of zinc, lead, copper, and nickel sulfide ore. Sulfur dioxide emission is controlled by conversion to sulfuric acid or recovery as liquid sulfur dioxide or elemental sulfur. The remaining part of the gas is dispersed and defused to the atmosphere through extra-tall chimneys. A large amount of solid waste is generated by the leaching process of low-grade copper and gold ore (Fig. 13.25) and tailing from gold recovery. The final waste is disposed of carefully and separately.

FIGURE 14.13 Six to eight-month-old plantation of vetiver grass and shady trees to cover the surface at Lennard Shelf zinc-lead deposit, Australia.

FIGURE 14.14 Plantation of vetiver grass and tall shady eucalyptus trees (Myrtaceae family) over abandoned old tailing dam at Zawar Group of mines, India.

2. Refinery waste

Refinery waste is generally in fluid form containing precious trace elements like Ag, Au, Co, Pt, and Pd. The value-added metals are recovered by an electrolytic metal/acid refinery process. The refinery discharge water contains large quantities of arsenic, antimony, bismuth, mercury, and other hazardous elements. It must be neutralized and treated for effluent removal. The effluent water treatment plant (Fig. 14.15) is designed to remove heavy metals and other toxic components. The water discharged from various plants is collected in ponds, tanks, and chambers. The water is often recycled for industrial purposes after neutralizing with lime following environmental compliance.

FIGURE 14.15 Effluent treatment plants to recover metals and recycling of water for industrial uses, Rajasthan, India.

14.2.4 Hazards of the Mining Industry and Human Consequences

Mining has always been among the most hazardous of occupations, and safety in mines assumes even greater importance. The environmental hazards and human consequences due to inappropriate mining and processing practices cause immense damage in the mineral industries. These accidents are prone primarily to both surface and underground mining, as well as mineral processing. Major accidents cause loss of human life, which is beyond value, and property worth millions/billions of dollars, including loss of production.

1. Mining
    - **a.** A massive mound of earth came crashing down onto a crew of 25 miners and 13 excavators and dump trucks at Lalmatia opencast coal mine of Eastern Coal Field at Rajmahal area, Goda district, Jharkhand, India, on December 28, 2016, due to negligence and the ignoring of mine safety norms. A round-the-clock rescue operation recovered 18 dead bodies and machinery (source: https://timesofindia.indiatimes.com/india/jharkhand-mine).
    - **b.** The San José Mine is a small copper-gold mine located 45 km northwest of Copiapó in the Atacama Desert of northern Chile, and has been operating since 1889. Copiapó became internationally famous for a massive cave-in accident on August 5, 2010, that trapped 33 miners 700 m underground. Rescue efforts began the next day. All the entries to the underground mine were blocked by rockfall. The rescuers used heavy machinery to gain access through a ventilation shaft, which further deteriorated the ground. Several exploratory holes were drilled at 16 cm diameter to reach the target point of 33 trapped miners. All holes drifted off-track due to extreme depth and rock hardness. On August 19 one of the probes reached a space where the miners were believed to be trapped, but found no sign of life. The eighth borehole broke through at a depth of 688 m on August 22 at a ramp near the shelter where the miners had taken refuge, and all were found alive. Communication and limited food supply were established. The first miner was rescued 69 days after the collapse on October 13, 2010. It was a commendable job in the history of mining rescue (source: https://en.wikipedia.org/wiki/2010_Copiapó_mining_accident).
2. Mineral processing

   The failure of tailing dams is a major concern in mineral processing activity. It occurs due to design failure or structural complexity.
    - **a.** The Samarco open pit iron ore mine in Brazil is a joint venture between the English/Australian BHP Billiton and Vale. Samarco is the second largest iron ore mine in the world with estimated reserves at 2.97 billion tonnes, and initial production of 19 million tonnes/year. The mine tailing dam disaster on November 5, 2015, caused a huge mudslide that killed 19 people, polluted the nearby Doce River, and devastated the livelihoods of local residents. The downstream town of Paracatu de Baixo was encrusted under the mudflow. Dam failure was assumed to be a design fault (source: https://www.theguardian.com/.../2015/.../brazil-iron-mine-dam-bursts-floods-nearby-h).
    - **b.** Mount Polley is an open pit copper-gold mine with an underground component located in south-central British Columbia, Canada. The ore reserves have been estimated at 34.96 million tonnes at 0.324% Cu, and mining/milling of 2.50 million tonnes (2015). The mine environmental disaster started on August 4, 2014, with a partial breach of the tailings pond dam, releasing 10 million cubic meters of water and 4.5 million cubic meters of slurry into Lake Polley. Authorities declared a local state of emergency in several nearby communities with concerns over the quality of drinking water affecting 300 residents. Mine management submitted an interim plan to mitigate ongoing erosion and sediment transport downstream. An independent investigation reported that the construction was on underlying earth containing a layer of glacial till that had been unaccounted for by the company's original engineering contractor (source: https://en.wikipedia.org/wiki/Mount_Polley_mine_disaster).
    - **c.** Ok Tedi open pit copper-gold mine in Oceania, Papua New Guinea, is located near the headwaters of Ok Tedi River. The deposit was discovered in 1968, producing gold since 1984 and copper concentrate since 1987. The mine is a major supplier of copper concentrate to international markets in Germany, India, the Philippines, Korea, and Japan. The open pit and two underground mines will be in operation until 2025. The Ok Tedi mine tailing dam was in fear of rupture/collapse since the beginning of 1984. A lack of a proper waste retention facility caused severe harm to the environment along 1000 km of the Ok Tedi and Fly rivers. The livelihoods of 50,000 people around the area were disrupted. The Tedi tailing dam failure was a human consequence of the discharge of about 2 billion tons of untreated polluted mining waste/slurry into the river system, ranking it one of the worst human environmental disasters ever (source: https://en.wikipedia.org/wiki/Ok_Tedi_environmental_disaste).

14.2.5 International Organization for Standardization

The International Organization for Standardization (ISO) is the world's largest and most accepted developer and publisher of international standards. ISO is a voluntary nongovernmental organization with a network of 164 member countries with a central secretariat operating from Geneva. ISO is developed to focus on "excellency" in industries and forms a bridge between public and private sectors. The standard framework for certification of total quality achievement and long-term sustained maintenance is assured. ISO facilitates an agreement to be reached on solutions that satisfy both the business houses and consumers, or society as a whole.

The model certifications that are commonly adopted by the exploration, mining, and smelting companies are:

1. ISO 9000 Series of Quality Manual and Certifications ensures quality management systems and is designed to help organizations satisfy the needs of customers. ISO 9001:2000 ensures a quality management system to demonstrate its ability to consistently provide products that fulfill the regulatory requirements and customers' needs. It aims to enhance customer satisfaction throughout by effective application of the system.
2. ISO 14000 families of certifications ensure the framing of "excellency" in ESM of organizations to minimize the negative effect of operations on environmental aspects and comply with applicable laws, regulations, and other environmentally oriented mitigations. The model endeavors to continually improvement the system. ISO 14001 addresses exclusively environmental issues and assists organizations to achieve environmental and financial gains through the implementation of effective environmental management. The standards provide both a model for streamlining environmental management and guidelines to ensure that environmental issues are considered within decision-making practices. Many large business houses have obtained certification under ISO 14001 for their EMSs. IS 10500:1991 deals with Indian standards of drinking water specifications in line with WHO.

   The benefits of ISO 14001 or IS 10500 certification are mainly realized by large organizations. Small-to-medium enterprises (SMEs) have a smaller turnover and thus a correspondingly small return on the costs of certification. A fully certified ISO EMS may not be suitable for smaller organizations. However, the system provides guidelines that assist them (each of the entrepreneurs) to consider all relevant issues and thus gain the most benefit from their ESM. SMEs can use ISO 14001 as a model for designing their own ESM.
3. The ISO 18000 family covers occupational health and safety management systems to assist business houses to focus their concern toward the protection of employees. It also ensures that they are operating according to their stated health and safety policies.

   Larger organizations find certification more valuable when considering the potential trade and market advantages of an internationally recognized and certified ESM. This is a significant factor for companies seeking certification under the ISO 9000, 14000, and 18000 families for quality assurance standards, and is likely to be a factor in decisions regarding ISO 14001.

14.2.6 Benefits of ESM

ESM requires the spirit of an organization to take active participation in reviewing the existing mitigation practices, compensation packages, and results. The implementation of an ESM is essentially a voluntary initiative jointly for management, workers, and communities. It can act as an effective tool for governments to protect the environment through regulatory systems. The benefits of ESM can be summarized as:

1. ESM minimizes the environmental liabilities through well-designed mitigation procedures.
2. It maximizes the efficient use of resources.
3. It reduces waste generation by proper planning.
4. It demonstrates a well-accepted corporate image.
5. It motivates awareness of environmental concern among all levels of employees.
6. It increases better understanding of environmental impacts of business activities.
7. Finally, a good work environment and quality workforce increase skill and efficiency resulting in higher productivity at less cost and higher profits.

14.3 SUSTAINABLE DEVELOPMENT IN MINING

Primitive people struggled for their existence, and in the process discovered food, shelter, security, and movement for own survival. The mining of minerals and other natural resources became significant for human survival and progress. The mining industry is vital for economic growth. It generates wealth and employment, and adds value to the economic well-being of the country as a whole and daily life in particular. Yet, the notion persists that the mining industry is environmentally destructive, socially irresponsible, and often illegally rampant in developing and underdeveloped countries. The large and multifaceted mining industry can be made sustainable, minimizing its harmful impacts and maximizing its social and economic contributions (Laurence, 2011). Sustainability is a concept of optimum conservation of resources, and a balance between the prosperity level of well-being for present and future generations. The concept of sustainable development is a dynamic fine-tuning of institutional, economic, scientific, and technological factors satisfying needs and aspirations. The widely accepted definition of sustainable development by the World Commission of Environment and Development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The principle of sustainable development promotes the thought of optimal resource utilization and leaves behind adequate resources for future generations (David, 2011). The concept works on six key words: "Resource, Regenerate, Reduce, Reuse, Recycle, and Replace," as articulated by a little girl (Box 14.1).

1. Resource
   Mineral resources and reserves are natural concentrations of inorganic and organic substances, including major and minor minerals and their by-products, fuels, and underground water on Earth. These resources cannot be renewed in the laboratory, and are forever lost once taken out of the ground. The quantity of mineral resources is finite as outlined by exploration. Some mineral commodities are rare. The resources, in raw form or processed, are the source of supply for the consumption and benefit of society.
2. Regenerate
   In biological science, "regeneration means the continuous process of renewal, restoration, reproduction, and growth of organisms. In the case of mineral science, regeneration is unlikely in the true sense. Minerals cannot be regenerated. However, the resource can be augmented by extension of existing mineral bodies and identification of new areas, formed by geological processes over millions of years in Earth's crust.
3. Reduce
   Because mineral resources are nonrenewable, rare, and scarce natural commodities with finite quantities, their consumption must be reduced to a minimum to satisfy the most select necessity. One has no option left but to waste this valuable asset and make a balance between demand and supply. A small reduction in use can make everything different, as echoed by our childhood rhymes:

   Little drops of water

   Little grains of sand

   Make the mighty ocean

   And the pleasant (beauteous) land…

   Mrs. Julia A. Carney (1845).

   Mines must reduce the amount of waste generation by innovative technology to reduce waste handling and improve environmental damage control. An annual waste audit is common practice in the mining industry.
4. Reuse
   In the pursuit of sustainable development, adaptation of "reuse" by the community must be encouraged to move toward the lowest consumption of material.
5. Recycle
   Recycling of process water by chemical treatment and conditioning is common practice and used for industrial purposes. The wastewater from mines, workshops, process plants, and tailing dams is reclaimed as zero discharge. Similarly, all metallic scraps of copper, zinc, lead, aluminum, iron, etc. are reclaimed and metals recovered.
6. Replace
   The use of metals can be substituted by alternatives. Many home appliances, machine parts, and automobile bodies are being replaced by plastics and other by-products of refined petroleum. This will reduce the consumption of primary metals.

BOX 14.1 Our Earth!

Across the vast seas and around the globe
Among many gifts from nature itself
People are living on Earth, our adobe
Taking resources from Earth to our shelf.
Water's abundant but freshwater is rare
Non-renewable resources slip away
And all of these resources we must share
For this everyone must have a say.
To harness power from the sun and wind
To stand up against the corporate men
Save our planet with both action and mind
To create futures, for our grandchildren.
Let us take simple and drastic measures
So that we may save all of our treasures.

Srishti Hazra, Class-X,
Taft Charter High School,
LA, November, 2017.

Man was born as part of nature. However, with more and more development, comfort/convenience, and a luxurious lifestyle he is unable to appreciate the role of mineral resources in day-to-day life. In the process he moves away from nature, i.e., the three fundamental ingredients comprising air, water, and minerals. Excessive development, production, and consumption have ultimately become self-destructive, gradually depriving future generations of those

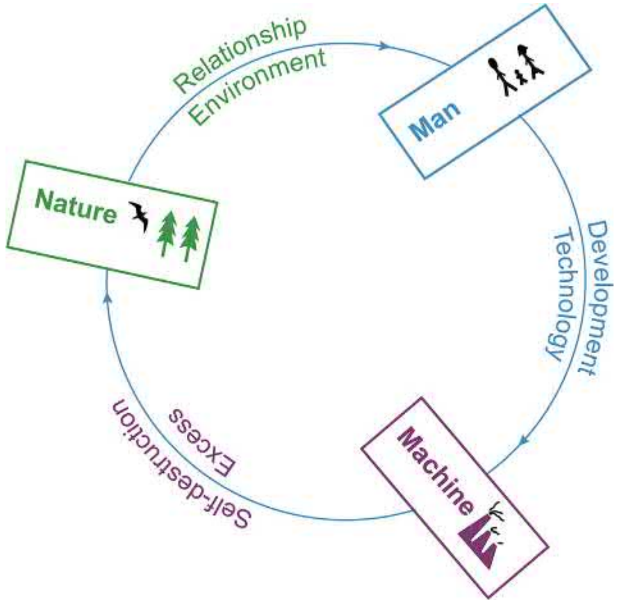

FIGURE 14.16 Nature, man, and machine: a continuous circle for survival and/or destruction.

three fundamental gifts of nature. The gravity of the situation should be realized, respected, and resolved by accepting sustainable development.

Technology and economic development must never destroy the environment, but sustain the continuity of the human race as a whole (Chamley, 2003). The binding relation between nature and man is the environment. Man develops technology using machines for his growth, making a full circle: nature/man/machine (Fig. 14.16). Sustainable development is a pattern of social and structured economic transformations.

14.3.1 Indicators

Standard indicators specify the status of sustenance of a country as a whole and society in particular.

- Gross national product (GNP) or gross domestic product (GDP) is the universally adopted yardstick or indicator for quantifying the economic development of a nation. Other alternative indexes are per capita income and per capita consumption.
- Manmade or natural calamities, e.g., tsunamis/wars, add spending to GDP.
- Loss to society or emotional traumas of individuals are never accounted for in this system.
- Indicators provide information inherent in long-term sustainability.
- The role of minerals and mining endorses major contributions to achieving sustainable development.
- Nonrenewable natural resources play a significant role in the following five indicators.

1. Environmental indicator
   The status of reserves (million tonnes/billion gallons) of all minerals, including groundwater, annual withdrawals, depletion of resources, rate of erosion/removal of topsoil, reckless mining, generation of industrial and hazardous waste, waste disposal, wastewater treatment (total and treatment type), industrial discharges into fresh water, land-use changes, protected area as % of total land area, use of fertilizer, deforestation rate, and emission of CO_2, SOx (sulfur oxides), NOx (nitrogen oxides), will depict a clear picture of the environmental standard in a region.
2. Economic indicator
   Economic indicators include GDP growth rate, gross export, gross import, reserve of natural resources (oil, natural gas, coal and lignite, major and minor minerals), minerals/concentrates/metals produced and transacted in the market, contribution to GDP, per capita energy consumption, energy used from renewable resources, distribution of jobs and income in mineral sectors, and annual growth rate of mining sectors. Energy minerals are significant to economic growth and the environment.
3. Social indicator
   Social indicators related to mining sectors are employment/unemployment rate, poverty ratio, population growth rate and density, migration rate, adult literacy rate, % GDP spent on education/health care, females per 100 males, primary/secondary school, college, university, % of people with access to safe drinking water, infant mortality rate, life expectancy, child abuse/neglect/abandonment, crime rate/damage/money spent, incidence of environment-related diseases, motor vehicles in use, loss of leisure due to extra hours of work, and travel time to workplace.
   The mining industry improves standards of living by providing potable water, food, shelter, health care, education, sports, and recreation to the ethnic inhabitants. However, exposure to mining and processing of galena, uranium, asbestos, fluorite, silica, and mica can cause tuberculosis, pulmonary and kidney disorders, cancer, restlessness, and insomnia. High income and incentives invite addiction to alcohol and drugs with increases in crime rates and abuse.
4. Institutional indicator
   The federal and state government institutions and mine owners formulate strategies for sustainable development and programs for information on national environmental statistics. General awareness is growing with research and development on the treatment of solid, liquid, and gaseous effluents, and prevention of forest and wildlife degradation. National and international seminars and research publications are organized for the growth and harmony of sustainability.

FIGURE 14.17 Human happiness and well-being: a new thinking in indicator. *Source: Times of India.*

5. Human happiness: a new concept
   The relationship between human happiness and economic well-being in the mission for environmental sustainability needs to be understood. The assessment of human happiness is designed to define an indicator that measures quality of social progress in more holistic and psychosocial terms than only the economic indicator. The relationship between economic growth measured by GDP and personal levels of happiness indicates that happiness increases with GDP up to a certain level. The increase of GDP beyond this level does not reflect increased personal happiness. This was well realized and sermonized by ancient philosophers traversing various countries and religions. Happiness is a function of nonmaterial factors and "very happy people" belong to a certain annual per capita income in purchasing power parity (Fig. 14.17). Jigme Singye Wangchuk, king of Bhutan, quotes "Gross National Happiness (GNH) is more important than Gross National Product (GNP)." Research into this aspect is continuing all over the world and includes a project survey of the United States, Japan, and remote rural villagers in Andhra Pradesh, India.

14.3.2 Minerals and Mining as Means of Achieving Sustainable Development

1. Science and technology
   - **a.** Focus on pollution prevention, energy saving, and health care.
   - **b.** Clean technology minimizes undesirable effluents, emissions, and waste from products and process.
   - **c.** Deficiency/excess of calcium, magnesium, potassium, iodine, zinc, selenium has to be optimized through grains, vegetables, and fruits avoiding chemical fertilizers and insecticides.
2. Fiscal measures
   - **a.** Tax formula aims at minimizing damage to environment and ecological balance.
   - **b.** Incentives seek to encourage reinvestment of income generated from mining in other mineral enterprises for sustainability.
3. Legislations
   Legislation is a universal means to enforce any policy.
4. Preservation of environment and forest
   - **a.** Clean Water (Prevention and Control of Pollution) Act 1972.
   - **b.** Clean Air (Prevention and Control of Pollution) Act 1970.
   - **c.** The Environment (Protection) Act 1986.
   - **d.** The Forest Act 1927.
   - **e.** Wildlife Protection Act 1972.
   - **f.** Tribal communities in mining projects.
   - **g.** The Environment and Sustainable Development Act.
5. Regulated exploitation of mineral resources: sustainability and longer life
   - **a.** National Mineral Policy.
   - **b.** Mineral Concession Rules.
   - **c.** Mines Act.
   - **d.** Mines Rules (Health and Safety).
   - **e.** Mines and Minerals (Development and Regulation) Act.
   - **f.** Mineral Conservation Act.
   - **g.** Oilfields (Regulation and Development) Act 1948.
   - **h.** Coal Mines (Conservation and Safety) Act 1952.

Sustainable mining is not merely about complying with the applicable regulations. Compliance is just the basic foundation of sustainability and more often it remains hidden from the eyes of most of the community and stakeholders. The visible issues are superstructure, track record of environmental care, biodiversity conservation, sociocommunity development efforts, transparency, and delivery of good governance. All these dimensions are relevant and integral to sustainable mining. The key management tasks in achieving sustainability in the mining industry are:

1. Mining sustainability focuses around two themes: (1) concern about the well-being of future generations and (2) community development with humility.
2. Let us live with happiness for the present and leave enough for future generations.
3. Mineral resources are limited, finite, and nonrenewable. Once out of the ground—lost forever.
4. Mineral exploration is a continuous process to augment the resources within certain limits.

FIGURE 14.18 "Little deeds of kindness, little words of love, make our earth an Eden, like the heaven above," Julia A. Carney (1845).

BOX 14.2 Prayer

May God protect us together?
May God nourish us together
May we work conjointly with great energy
May our study be brilliant and effective
May we not mutually dispute
(or may we not hate any)
Let there be Peace in me
Let there be Peace in my environment
Let there be Peace in the forces that act on me
Peace must be our ideology, progress our horizon.
Lead us from the unreal to the real
Lead us from the darkness to the light
Lead us from the death to the immortality
Let there be 'Peace, Peace, and Peace'.

Upanishad.

5. Promote environmental awareness within exploration and mining companies. Spread the message to the community through programs. Share the concerns and commitments with them.
6. Educate and train employees and contractors. Adopt the method in practice.
7. Educate the local community for an economically sustainable program to achieve self-support in a short period.
8. Early dialog for community development to establish trust and confidence. Encourage to work together. Build partnerships between different groups and organizations so that there is a sense of integrity, cooperation, and transparency for a shared focus to achieve mutually agreed common goals.
9. Develop a community engagement plan involving employment with flexible work rosters, collaborative participation in decision-making, services to society, health care and medical advice, women's education and child care, participation in the community and spiritual festivals, and have a deep sense of humility.
10. Ensure sustainable postmine closure uses of land and all infrastructures toward the creation of alternative employment.
11. Full adaptation of compliance of national and international impact management codes supported by independent audit.
12. Transparency and good governance must be reflected in every plan and action.
13. Research, publication, knowledge-sharing seminars, and participants in workshops.
14. Leave the area much more environmentally beautiful, progressive, and sustainable.
15. Let future generations grow in an environment of love, affection, compassion, happiness, trust, genuineness, and transparency… (Fig. 14.18).
16. And, finally, sustainability leads us to long-term prosperity and eternal peace. Let us repose our faith in the invocation and verses from ancient Indian philosophy (Box 14.2).

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Chapter 15

Mineral Exploration: Case Histories

Chapter Outline

Mineral Exploration. https://doi.org/10.1016/B978-0-12-814022-2.00015-0

Exploration case histories enrich our knowledge base for future mineral search.

Author.

15.1 DEFINITION

Case histories of mineral exploration, mining, mineral processing, extraction, conventional and geostatistical evaluation, and environmental sustainability help the concept of possible mineral occurrences in matching settings.

The following sections present case histories of several zinc-lead-copper-platinum-nickel-chromium and rock phosphate deposits. Each one has its own unique characteristics and represents a type. The topics are wide ranging and encompass ancient mining heritage in India and present-day activities, such as the largest zinc deposit in Australia, the single largest porphyry copper-molybdenum deposit in India, identification of deep-seated silver-rich deposits in India, geophysical success to identify deep-seated hidden polymetallic orebodies in Portugal, the largest-ever platinum-chromium deposit in South Africa, the largest nickel-copper-platinum deposit in Canada, geostatistical estimation and sampling optimization of exploration data in India, the largest platinum deposit in China, geological model-based discovery of phosphate deposits in India, and finally the setting of a country-based mineral discovery trend that can be extended to a global perspective.

15.2 ZAWAR GROUP, INDIA: AN ANCIENT ZINC-LEAD-SILVER MINING/SMELTING TRADITION

15.2.1 An Ancient Mining Tradition

An impressive and traditional ancient mining and smelting history was well developed in the vicinity of the major mining center of modern India, namely, Zawar (180 ± 35 BC), Rajpura-Dariba (1300−350 ± 120 BC), Rampura-Agucha (860 ± 100 BC), Ambaji-Deri zinc-lead-silver deposits, Khetri (3000−1500 BC), Singhbhum (~3000 BC) copper deposits, and Kolar (second century AD) gold deposit. The presence of extensive mine workings and debris, large heaps of slag and retorts (Figs. 4.1 through 4.4), smelting furnaces (Figs. 4.5 through 4.7), and ruins of temples and townships (Fig. 4.8) bear mute testimony to the art of exploitative acumen and extractive metallurgy during the early periods. Ancient openings are in the form of open pits, inclines, shafts, open stopes, chambers, and galleries. The technology was probably developed around 3200−2500 BC. The importance of mining was well established as a source of revenue for states around 1000 BC and distinct urban economies from 600 BC.

Ore-bearing mineralization was usually identified on or near the surface based on the presence of a multicolored, weathered profile, exposed mineralized veins, and the striking of lightning during thunderstorms. Miners manually excavated and followed a downward extension of the ore shoot (Figs. 4.1 and 4.2) and developed huge stopes.

Mining was carried out by fire setting and supported by arcuate rock pillars (Fig. 4.3), timbers as ladders, baskets for ore carrying, and launders for underground drainage. Conical clay pots were used as lamps to illuminate underground workings. Mineral processing was done by manual crushing in hard rock mortars (Fig. 4.4). Metal extraction was done by traditional shaft furnace (Figs. 4.5 and 4.6) in which the smelted metal settled at the bottom. Mining traditions were discontinued from time to time due to feudal wars, droughts, and epidemics. These remnants are significant for future rediscovery. The American Society of Metals International (ASM) recognized the process and designated a zinc distillation furnace, a historical landmark, with a plaque reading: "This operation first supplied the brass for instrument making in Europe, a forerunner of the industrial revolution."

15.2.2 Location and Discovery

The Zawar group of deposits (24°20′56″N, 73°42′49″E) is one of the oldest zinc-lead-silver mines in the world, located 40 km south of Udaipur City, Rajasthan, India (Fig. 15.1). The group of mines at Zawar is connected by road, railway, and airport at a road distance of 90 km. The economic mineral-bearing belt extends over 16 km and comprises four mining blocks: Balaria mine in the east (Fig. 15.2), Mochia in the west, and Baroi and Zawar Mala mines in the south. Mineralization is manifested by long abandoned workings.

In the present phase of mining, the Geological Survey of India (GSI) started exploration in 1942. Mewar Mineral Corporation India Limited (MCIL) revived the Mochia mine by reopening it for 175 tpd after a dormant period of more than a century. MCIL increased capacity to 500 tpd mine and beneficiation in 1945, and this remained until the formation of Hindustan Zinc Limited (a government of India enterprise) in 1966. Hindustan Zinc Limited obtained a mining lease for 52 km^2 and continued underground exploration and ore production at 1 Mt/a. The disinvestment process completed in favor of M/s Sterlite Opportunities (Vedanta Resources Limited) in 2002. Current production capacity is 1.5 Mt/a.

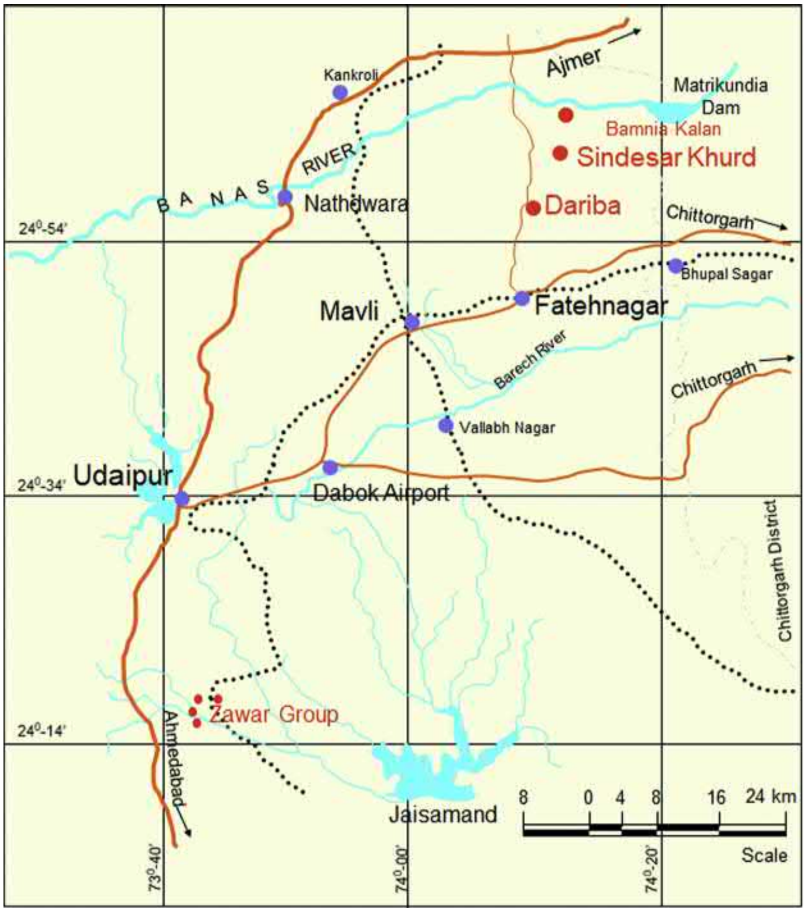

FIGURE 15.1 The Zawar group of mines is one of the oldest zinc, lead, silver mining sites in the world, and located about 40 km south of Udaipur city, Rajasthan, India.

FIGURE 15.2 Topography of Balaria Mine Block in the center, the Aravalli Mountain range in the far background, and undulating landscape in the foreground with scattered residential houses. *Image taken in 1978.*

15.2.3 Regional Setting

The geology is represented by metasedimentary rocks of the Middle Aravalli Group, resting over a banded gneissic complex (BGC) in a sequence of phyllite, greywacke, dolomite, quartzite, and phyllite. The sediments, deposited in a basin marginal environment, were subjected to multiple phases of deformation. The regional fold of Balaria-Mochia-Sonaria-Ruparia along with a north plunging major fold at Zawar Mala was formed in the second stage of deformation (F_2) on bedding and axial planar schistosity (Fig. 4.10).

15.2.4 Host Rock

The principal host rock throughout the belt is pure dolomite and partially black phyllite. The footwall and hanging wall rocks are represented by greywacke and phyllite/quartzite, respectively.

15.2.5 Mineralization

There are numerous ore lenses extending for 100−200 m and disposed in an en echelon pattern with steep dips (Fig. 15.3). Variation in grade and metal zoning exists in individual blocks. The principal ore-forming minerals are sphalerite, galena, and pyrite in different proportions at different mine blocks. Arsenopyrite is a minor but ubiquitous mineral. There are traces of chalcopyrite and pyrrhotite present. Silver and cadmium are two value-added by-products obtained from Zawar ore. Cadmium occurs exclusively in sphalerite structures. Silver occurs with galena and as minute native flakes (Fig. 1.2C).

15.2.6 Genetic Model

Mineralization is exclusively hosted by pure dolomite, hanging wall carbonaceous dolomite, and pyrite-rich phyllite. The grade of metamorphism is low. Mineralization is placed in sedimentary exhalative (SEDEX) type of 1710 Ma. The host rock, depositional features, rift-related intracontinental basin structure, exclusively stratabound and occasionally stratiform nature, size and grade, and high process recovery are comparable with the Mississippi Valley-type (MVT) area of the United States. The Zawar zinc-lead-silver belt resembles very well the MVT type of Lennard Shelf zinc-lead-silver deposits of North Western Australia, comprising multiple small discrete deposits located within a broad mineralized district.

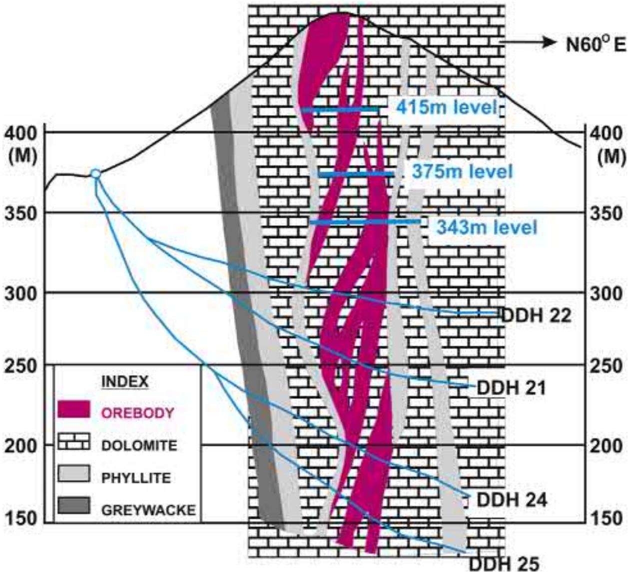

FIGURE 15.3 Cross-section of Balaria Mine Block showing the prototype orientation surface diamond drilling during the initial phase of exploration.

15.2.7 Size and Grade

The present mining lease of Zawar group of mines is spread over 36.20 km^2. Zawar Group has reserves of 9.50 Mt and resources of 82.30 Mt, with average grades of 3.40% Zn and 1.70% Pb as of April 1, 2017. Annual ore production capacity is 1.20 Mt (source: Hindustan Zinc Limited Annual Report, 2017).

15.2.8 Salient Features of the Mine Blocks

Summary information of individual mine blocks comprising exploration type, host rock, mineralization, metamorphism, surface oxidation (gossans), metal zoning, halos, genesis, age, deposit size and grade, contained metal, minable reserve, capacity, and life of mining is given in Table 15.1.

Zawar group of zinc-lead-silver deposits has a mining heritage of over 4000 years and will continue mine production for the next 50 years.

15.3 BROKEN HILL, AUSTRALIA: THE LARGEST AND RICHEST ZINC-LEAD-SILVER DEPOSIT IN THE WORLD

The Australian zinc-lead-silver deposits are hosted by Middle Proterozoic metasediments with exhalative association (SEDEX) restricted to McArthur-Mt. Isa basin across Northern Australia and Broken Hill in New South Wales. The former intracontinental sedimentary basin system is exposed over 1200 km in a NW—SE trend with Mt. Isa in

TABLE 15.1 Salient Features of Four Mining Blocks at Zawar Group

Features	Balaria	Mochia	Baroi	Zawar Mala
Strike length	1000 m			
Exploration	21 km surface drilling, underground drilling at 15 m	Development and underground drilling	Surface and underground drilling	Surface and underground drilling
Host rock	Dolomite, carbon phyllite	Pure dolomite	Pure dolomite	Pure dolomite
Mineralization	En echelon, stratbound, and often stratiform, Sp, Ga, Py	Stratabound and often stratiform, Sp, Ga, Py	Stratabound, fine/medium-grained, Ga, minor Sp, Py	Stratabound and often stratiform, Sp, Ga, Py
Metamorphism/deformation	Penetrative deformation under green schist facies	Penetrative deformation under green schist facies	Penetrative deformation under green schist facies	Penetrative deformation under green schist facies
Gypsum, baryte	Gypsum, baryte	Gypsum, baryte	Gypsum, baryte	Gypsum, baryte
Surface oxidation	Fresh sulfide exposed to surface	Fresh sulfide exposed to surface	—	—
Zoning	Metal zoning	Metal zoning	Metal zoning	Metal zoning
Halos	Rich pyrite	Pyrite	—	—
Genesis	SEDEX/MVT	SEDEX/MVT	SEDEX/MVT	SEDEX/MVT
Age (Ma)	1700	1700	1700	1700
Size and grade (March 2011)	16 Mt at 5.8% Zn, 1.2% Pb, 40 g/t Ag	17 Mt at 4.26% Zn, 1.7% Pb, 40 g/t Ag	6 Mt at 1.7% Zn, 4.6% Pb, 40 g/t Ag	7 Mt at 5.0% Zn, 2.2% Pb, 40 g/t Ag
Contained metal	1.12 Mt	1.01 Mt	0.38 Mt	0.50 Mt
Minable reserves	Estimated at 30.866 Mt at 3.67% Zn and 2.05% Pb			
Mining lease	Total mining lease of Zawar group of mines is 3620 ha (36.20 km^2)			
Infrastructure	Water requirement is met from captive Tidi dam. Power is adequately sourced from 80 MW coal-based captive thermal power plant and 6 MW diesel generator set, and shortfall, if any, is met by the state grid			
Mining methods	Sublevel open stopping ± paste, rock, and cemented filling			
Modernizations	Jumbo drill with LPDT/LHD combination for mechanized faster mine development, operational efficiencies, cost reduction, and improved safety			
Depth of mine	418 m	422 m	86 m	260 m
Mine capacity	0.350 Mt/a	0.450 Mt/a	0.400 Mt/a	0.300 Mt/a
Life of mine	+20 years			

LPDT/LHD, low-profile dump truck/load-haul-dump; *MVT*, Mississippi Valley type; *SEDEX*, sedimentary exhalative.

the south and McArthur in the north. The 5−10 km thick basin formation was active through a series of rift-sag cycles between 1800 and 1550 Ma. The basin hosts five world-class stratiform deposits (from south to north: Mt. Isa, Hilton, George Fisher [1653 Ma], Century [~1575 Ma], and HYC [1640 Ma]), each with over 100 Mt of ore reserves at +10% Zn + Pb. There are a few other deposits, namely, Lady Loretta, Dugald River, Cannington, Grevillea, Mt. Novit, Kamarga, and Walford Creek either with low tonnage and high grade or no published reserve available (Ross et al., 2004). The Broken Hill Zn−Pb deposit consists of a cluster orebodies within the Willyama Supergroup having large global reserves of +300 Mt. Roseberry silver-lead-zinc deposit was discovered in 1893 at Tasmania's west coast on the slopes of Mt. Black.

15.3.1 Location and Discovery History

The Broken Hill deposit (31°56′S, 141°25′E) is located 511 km northeast of Adelaide (NH-A32) and 1160 km west of Sydney (NH-32). Broken Hill (the Silver City) is an isolated mining city, far west of the state of New South Wales.

The deposit was discovered by Charles Rasp, a boundary rider, while mustering sheep around the Broken Hill area in 1883. Trained in chemistry, Charles was fascinated by the mineral appearance and formation of the gossans' profile. Joined by other team members, he submitted a mining lease and initiated prospecting for tin in surface gossans. The initial assaying from a small shaft indicated a low grade of lead and silver, but in 1885 a rich quantity of silver and lead was found. The Broken Hill Proprietary Company Limited (BHP) was incorporated in 1885 for operating silver and lead mines. BHP ceased its connection with Broken Hill in 1939. BHP Billiton emerged in 2001 and became the largest global mining company measured by revenue in 2011. Rio Tinto had a long connection with Broken Hill through its Australian subsidiary CRA.

15.3.2 Regional Setting

The Willyama Supergroup (7−9 km thick) has been divided into six principal packages defined by lithostratigraphy (Table 15.2) deposited on existing continental crust. The mineralized packages form an arcuate belt of deformed, high-grade amphibole granulite rocks of Paleoproterozoic age representing the regional setting of Broken Hill deposits.

Mineralization occurs within the BH Group and is marked by a widespread development of metasediments, interpreted as a sudden deepening of rift and onset of more significant hydrothermal activity giving an interpretive magnetic age of 1680−1690 Ma (Page and Liang, 1996), which is widely quoted as the inferred age of mineralization.

TABLE 15.2 Stratigraphy of the Willyama Supergroup Showing Depositional Trend and Mineralization and Exalites

	Depositional Trend	Mineralization and Exalites
Paragon Group	Platform deposition	
Sundown Group	Rift fill	
Broken Hill Group	Rift stage	Broken Hill-type Pb−Zn−Ag
Thackaringa Group		Banded iron formation
Thorndale Composite Gneiss	Early rift stage	
Clevedale Migmatite		

15.3.3 Host Rocks

The orebodies are confined within a single unit of mine sequence (lode-horizon) and subdivided into four units of clastic and calc-silicate, garnet quartzite, C-lode, and mineralization horizon. The orebodies are rich in calcite, fluorite, lead, and rhodonite, and in a clastic and calc-silicate horizon, a unit dominated by clastic-psammo-pelitic to pelitic rocks with well-developed calc-silicate layers, weak amphibolite, and Potosi gneiss.

15.3.4 Mineralization

Mineralization is essentially stratabound and stratiform, and can be traced for 25 km along the strike and up to a depth of 2000 m. Broken Hill mineralization interacts with exhalites of quartz-magnetiet ± Fe, Cu sulfides, quartz-Fe oxide/sulfide ± Cu, and scheelite. The orebodies are divided in two categories: lead lode and zinc lode, based on Pb:Zn ratio. The lead-rich types are calcitic-containing calcite, rhodonite-bustamite, apatite, garnet, and fluorite, and are largely hosted within clastic metasediments. The zinc-rich types are the primary quartz orebodies and rich orebodies containing quartz, garnet, gahnite, and cummingtonite, and mostly lie in the upper part of the sequence. The calcitic orebodies lie in the lower part (Fig. 15.4). The Thackaringa Group hosts banded iron tourmaline ore.

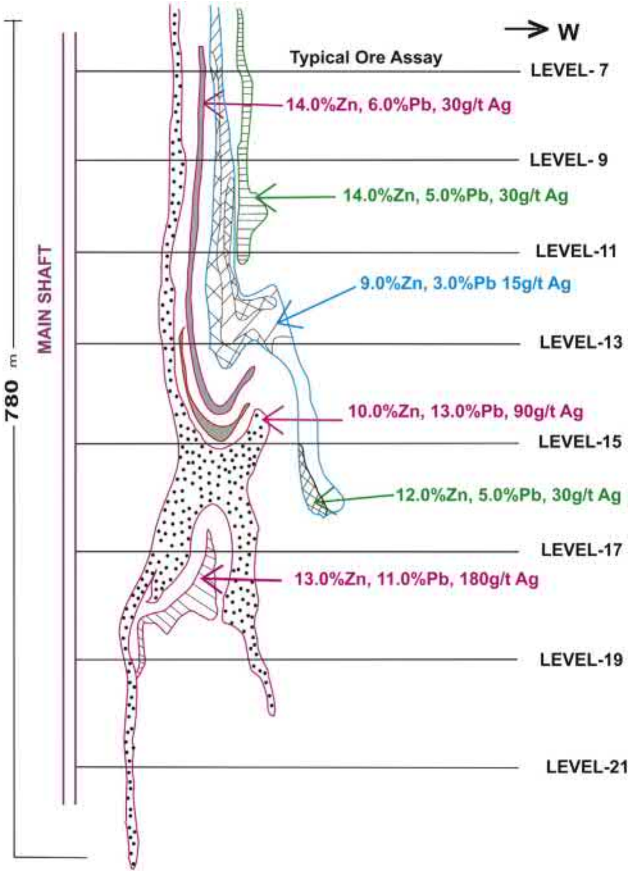

FIGURE 15.4 Schematic geological cross-section No. 3C through the main shaft, S150 E, at Broken Hill deposit. *Haldar, S.K., 2007, Exploration Modeling of Base Metal Deposits, Elsevier Publication, p. 227.*

15.3.5 Genetic Model

Regional field relationships have established an essentially stratabound and stratiform syn-SEDEX model of Broken Hill type. Metal deposition has been conceptualized as a result of high heat flow within the sedimentary basin in which the Willyama Supergroup was deposited. This high heat flow eventually led to high-grade regional metamorphism of the enclosing sediments.

15.3.6 Size and Grade

There are nine separate but closely related orebodies stacked within a single package of the stratigraphy. The preproduction reserve was estimated at +300 Mt at 12.0% Zn, 13.0% Pb, and 175 g/t Ag. There are seven mine blocks from SW to NE: Southern Operations, North Mine, Potosi North, Silver Peak, Central Block, Flying Doctor, and Henry George.

The combined mineral resources (Measured, Indicated, and Inferred) of the BHP operation as of June 2011 stand at ~22.7 Mt at 9.0% Zn, 7.0% Pb, and 86 g/t Ag. Ore reserve, which applies to southern operations, stands at 14.7 Mt at 5.3% Zn, 4.0% Pb, and 43 g/t Ag. The statement is based on the Joint Ore Reserves Committee Code and expected mine life is +10 years. Resource and reserve drilling is recommenced to increase confidence in existing resources and reserves (source: ASX and Media Release December 28, 2011).

The Broken Hill zinc-lead-silver deposit is known in the mineral industry as a huge reserve base of the richest grade, having over 150 years of large mine production from surface and underground.

15.4 MALANJKHAND: THE SINGLE LARGEST PORPHYRY COPPER–MOLYBDENUM OREBODY IN INDIA

India is not self-sufficient in resources of copper ore, and the domestic demand of copper metal is met through the import of metal and concentrate. Hindustan Copper Limited, a public sector undertaking incorporated in 1967, is the only integrated producer of refined copper. The two other producers in the private sector, namely, Hindalco Industries Limited and Sterlite Industries Limited, import copper concentrate for smelters.

The major copper deposits are located at Shingbhum Copper Belt (Jharkhand), Malanjkhand (Madhya Pradesh), Khetri Copper Belt (Rajasthan), and Rongpo polymetallic deposit (Sikkim). The copper deposits at Khetri and Singhbhum are medium to low grade. The Singhbhum orebodies are no longer supporting large-scale mechanization in underground mines due to narrow width and flatter inclination. Malanjkhand ore is exposed to the surface and was initially developed by low-cost, high tonnage, open pit mining with future adaptation to underground mining.

Total in situ copper resources have been estimated at 712 Mt (9.4 Mt Cu metal). Malanjkhand alone contributes 295 Mt (3.9 Mt Cu metal, 45% share of resource, and 80% share in production). This is followed by 195 Mt (2.5 Mt Cu metal) from Rajasthan and 179 Mt (2.3 Mt Cu metal) from Jharkhand.

15.4.1 Location and Discovery

The Malanjkhand copper project (22°12′N, 80°42′E) is a classic porphyry type, and is the single largest copper-molybdenum orebody in central India. The deposit is exposed to the surface and located 90 km from Balaghat, 182 km from Gondia, Madhya Pradesh, and 259 km from Nagpur, Maharashtra, at an altitude of 576 m above mean sea level.

The deposit was discovered by Colonel Bloomfield in 1889. GSI initiated exploration as late as 1969. Hindustan

Copper Limited assessed the property based on seven drill holes totaling 613 m, and submitted a mining lease in 1970. Detailed exploration continued with 101 km of surface drilling up to a depth of 700 m from the surface. This resulted in delineation of orebody with high confidence. The orebody dips 65−70 degrees → east (Fig. 15.5) and extends over 2.60 km (Fig. 15.6). The deepest intersection is at 900 m vertical depth from the surface.

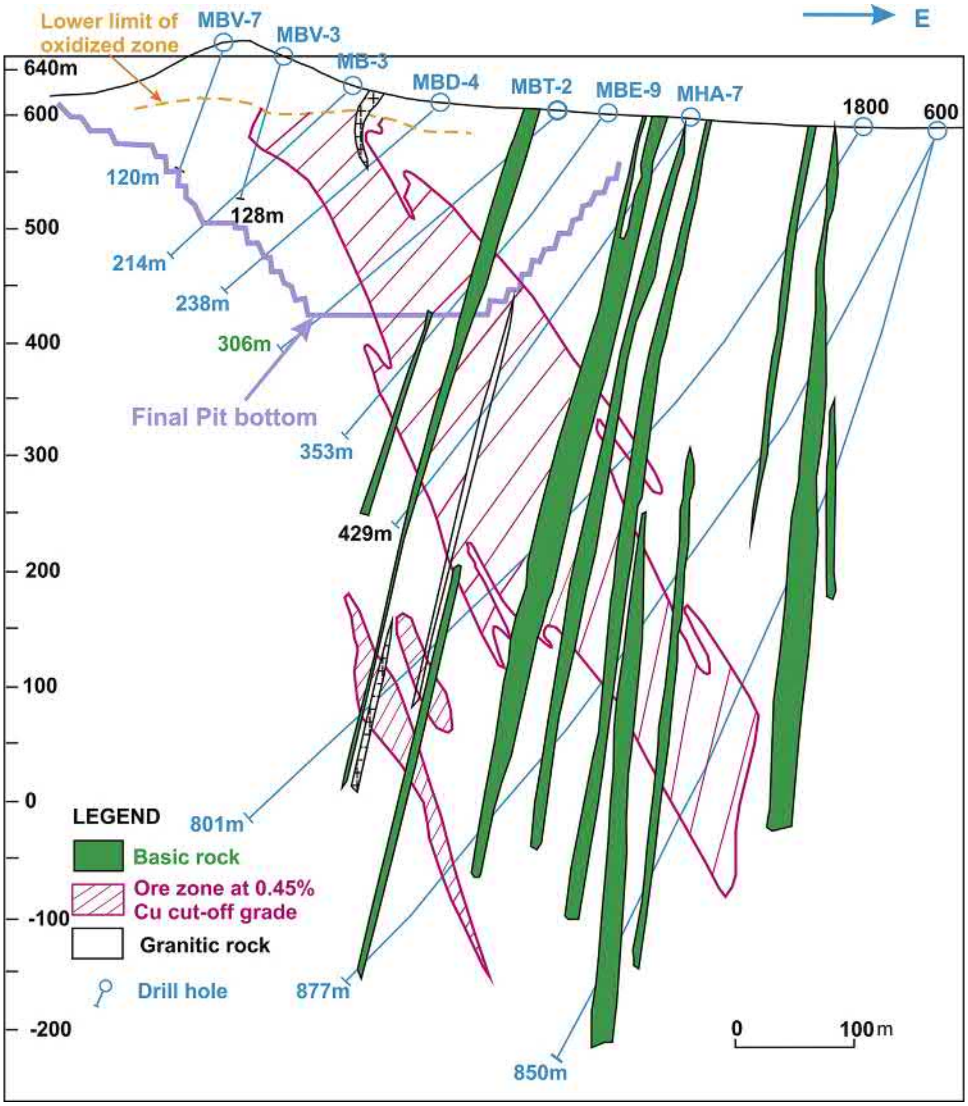

FIGURE 15.5 Geological cross-section of Malanjkhand copper orebody showing the surface drilling pattern and ultimate open pit bottom.

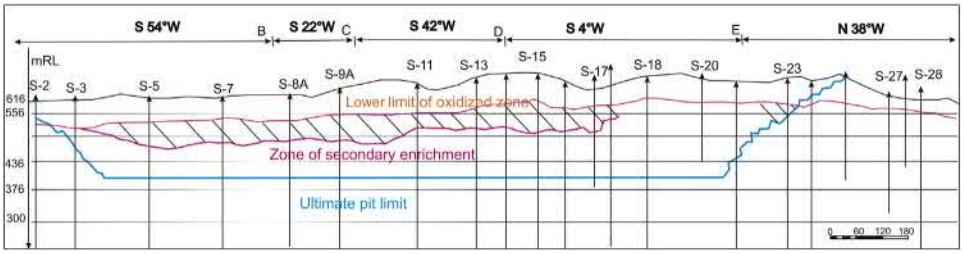

FIGURE 15.6 Composite longitudinal section along Malanjkhand copper orebody showing the surface drilling interval and ultimate open pit bottom.

15.4.2 Regional Setting

The host/country rocks are granodiorite and quartz monzonite pluton comprising biotite granite and tonalite. The granite along with mineralized quartz veins and basic dykes directly underlie the basal conglomerate of Chilpi Ghat Group. The deposit occurs at the intersection of two major sets of lineaments trending N—S and E—W. The N—S lineament within the pluton represents the major mylonitized, sheared, and crushed zone, and acts as a favorable structural loci for emplacement of ore-forming hydrothermal fluids to ascend, some of which are mineralized for varying extents. The deposit represents an elongated oval-shaped dome.

15.4.3 Mineralization

Mineralization occurs as a stockwork of thin quartz veins in granitoids and thick veins emplaced in sheared and mylonitized zones within the pluton. The reef varies with attitude from a single thin tabular body at the northern end to a composite of parallel-sheeted interconnected veins at the central and southern parts attaining a maximum width of 200 m. The orebody has been oxidized near the surface at the south with complete removal of copper and reconcentrated as supergene sulfide enrichment at deeper levels. In the northern side, copper is retained in the form of cuprite, chalcocite, covellite, and native copper within the oxidation zone without any supergene enrichment. Cu—Mo mineralization occurs extensively in the entire Malanjkhand pluton in the form of reef quartz-, stringer-, and pegmatitic-disseminated ore.

The ore minerals in the primary zone are chalcopyrite, pyrite, magnetite, molybdenite, sphalerite, and gold. Limonite, hematite, and goethite occur along fractures in the oxidation zone. Chloritization, sericitization, epidotization, potassic alteration, and silicification are present.

15.4.4 Genetic Models

The entire magmatic episode has been emplaced as a single large pluton with progressive differentiation and repeated tectonic activity causing variation in composition and generation of sheared lineaments. The last but one phase of differentiation resulted in Cu—Mo-bearing quartz veins of economic significance located at structure-controlled fracture zones. This is evidenced by field relation and geochemical analysis of granitoid. The likely age ranges between 2270 ± 90 Ma and 2458 ± 26 Ma using the Rb—Sr method.

15.4.5 Size and Grade

The preproduction ore reserve at Malanjkhand deposit was estimated at 145 Mt at 1.35% Cu, which includes 20 Mt at 1.13% Cu in open pit limit and 125 Mt at 1.39% Cu between ultimate open pit bottom and 0 m level. The ore contains 100 g/t Mo, <1 g/t Au, and <10 g/t Ag. The orebody is open at depth.

M/s Hindustan Copper Limited has been mining since 1972 by mechanized open pit method up to a depth of 200 m at an ore:waste ratio of 1:5.75. The heap leaching of oxidized and disseminated ore from the hanging wall zone is planned to augment production to 3 Mt/a. Production is enhance to 5 Mt/a from combined mining operations up to a depth of 1000 m.

Malanjkhand porphyry copper deposit initiated mining by open pit since the early 1970s, and converted to the underground mining method, ore handling, and beneficiation after reaching the optimum pit bottom in 2013—14.

15.5 SINDESAR-KHURD: ROUTINE DRILLING DISCOVERED CONCEALED ZN—PB—AG DEPOSIT IN INDIA

The state of Rajasthan contributes more than 95% of zinc-lead-silver reserves and resources in India. The large deposits occur in groups along an NE—SW lineament with nonmineralized partings in between. The major clusters are: (1) Zawar Group (Balaria, Mochia, Baroi, and Zawar Mala) in the extreme southwest, (2) Rajpura-Dariba (Dariba, Mokanpura, Sindesar-Kalan [E], Sindesar-Khurd, Bamnia, and Bethumni) in the center, and (3) Rampura-Agucha in the northeast. There are a couple of isolated small deposits, namely, Debpura, Dewas, Pur-Banera, Ghugra, and Kayar. The Kayar deposit is located at the northeast end and has been producing since 2014.

15.5.1 Location and Discovery

The Rajpura-Dariba, Sindesar-Khurd, Sindesar-Kalan, and Bamnia zinc-lead-silver belt is located at a road distance of 75 km northeast of Udaipur city (Fig. 15.1). The nearest rail station, Fateh Nagar, and airport, Dabok, are at distances of 22 and 50 km, respectively.

Ancient mining, beneficiation, and smelting manifestations at Rajpura-Dariba belt were rediscovered by GSI as early as 1934. The presence of unique surface gossans, ancient open pit and underground workings, grinding potholes, heaps of mine debris, and slag serves as an excellent guide. GSI initiated exploration as late as 1962 at the southern closure and completed surface drilling by 1970. Hindustan Zinc Limited acquired a mining lease (11.42 km^2) and commencement of underground mining. Surface and underground drilling are 34,100 and 68,700 m, respectively. Routine drilling continued and discovered concealed dolomite-hosted deposits at Bamnia-Kalan in 1982.

The investigation so far has been planned by tracing the signature of surface oxidation (gossans), host rock assemblages, and ancient mining/smelting remnants between Rajpura-Dariba in the south and Bethunni in the north. The orebodies are expected to trend NE—SW and dip toward E—SW as experienced for all zinc-lead-copper deposits of the Aravalli Mountain Range hosted in Aravalli and overlying Delhi Supergroup. Exploration drilling was designed accordingly and identified deposits like Mokanpura, Sindesar-Kalan (E), and Bamnia-Kalan. Most of the drill holes were terminated as soon as quartzite/quartz-mica schist was encountered at the footwall beyond the east dipping mineralization. The existence of Sindesar-Khurd was unknown until 1987—88.

15.5.2 Regional Setting

The metallogenic belt comprises medium- to high-grade metavolcano-sedimentary equivalent to orthoquartzite, carbonates, and carbonaceous deposits metamorphosed to amphibolite facies of Proterozoic. BGC of the Archean age unconformably underlies the cover sequence. The belt extends over 19 km in an N—S direction as a crescent-shaped regional synform with closure at the south of Dariba. The axial trend is NNE—SSW with a sharp easterly dipping axial plane. The Dariba syncline with NNE—SSW axial trace belongs to the second phase of deformation and exhibits a steep plunge (55—60 degrees) → NE.

15.5.3 Host Rocks

Zinc-lead deposits of various sizes and grades occur throughout the belt in calc-silicate-bearing dolomite and graphite-mica schist, the latter in general represents low-grade disseminated sulfides of large volumes.

15.5.4 Mineralization

Mineralization shows a similar assemblage of the Aravalli belt but differs in relative proportions from deposit to deposit. The stratabound and stratiform orebodies are comprised of sphalerite, galena, chalcopyrite, pyrite-pyrrhotite, arsenopyrite, and some fahlore (tetrahedrite-tennantite) with a preferred concentration of silver. Sindesar-Khurd and Bamnia-Kalan have an excessive predominance of pyrrhotite. The other deposits are dominated by pyrite. Rajpura-Dariba deposit is characterized by the presence of different varieties of laminated sphalerite, such as light brown, dark brown (Fig. 1.3F), and lemon yellow (Fig. 1.3G).

15.5.5 Genetic Model

Sulfides are deposited in shallow marine, volcano-sedimentary basins, formed as part of the larger intracontinental incipient rift. The stratiform sulfides are sedimentary diagenetic and hydrothermal emissions of metal-rich brines in which the sulfur was derived from thermochemical reduction of circulating seawater, and partly leached from a mafic source. The deposits of this metasedimentary basin are metamorphosed to medium-grade amphibolite facies, exhibit characteristic features of SEDEX class mineralization, and are dated at 1804 Ma.

15.5.6 Size and Grade

Total resources of the Rajpura-Dariba belt are estimated at 290 Mt at 3%—4% Zn + Pb. In situ gossan reserves, up to 40—50 m, over Dariba south lode are estimated at 32 Mt, grading 1.2% Zn, 0.4% Pb, 0.27% Cu, 200 g/t Ag, 500 g/t Hg, 1000 g/t Sb and As, and less than 0.5 g/t Au.

15.5.7 Rajpura-Dariba Mine Block

Rajpura-Dariba Mine (24°56′51″N, 74°7′53″E) is an underground mine commissioned in 1983, located at the southern extremity of the belt. Surface manifestations are well-developed gossans (declared as **National Gossans Monument**), and ancient open-pits with revetment supports to hold collapsing walls. The large number of narrow access and ventilation channels witnessed a prolific underground mining activities up to a depth of 170 m from surface. The deep seated large mine openings are timber-supported, with baskets, launders, and slag spread around. This is testament to the ongoing skills first practiced by ancient miners. This mine is perhaps one of the oldest zinc mining and smelting operations in the world.

The calc-silicate dolomite and graphite-mica schist host the stratabound and stratiform mineralization with sharp contacts. Quartz mica schist and quartzite are on both sides. The overall formation strikes NE—SW with a moderate to steep easterly dip.

The main lode extends over 1700 m and is separated into two orebodies, south and north, by a barren stretch of 300 m. The south lode strikes N—S and dips 60—70 degrees → east (Fig. 15.7). The south lode extends over 500 m and continues below the 0 m level at reduced width. Dolomite is siliceous at the footwall with dominance of chalcopyrite, followed by enrichment of sphalerite and galena, and concentrations of pyrite and pyrrhotite toward the hanging wall graphite-mica schist. The north lode is hosted by calc-silicate dolomite with a strike length of 900 m, with N—S strikes and dips 70—75 degrees to the east. The east lode, with a length of 600 m, strikes N—S and dips easterly at 60—70 degrees. It is located about 150—200 m away on a hanging wall of the south lode. The average widths of the south, north, and east lodes are 24, 18, and 18 m, respectively.

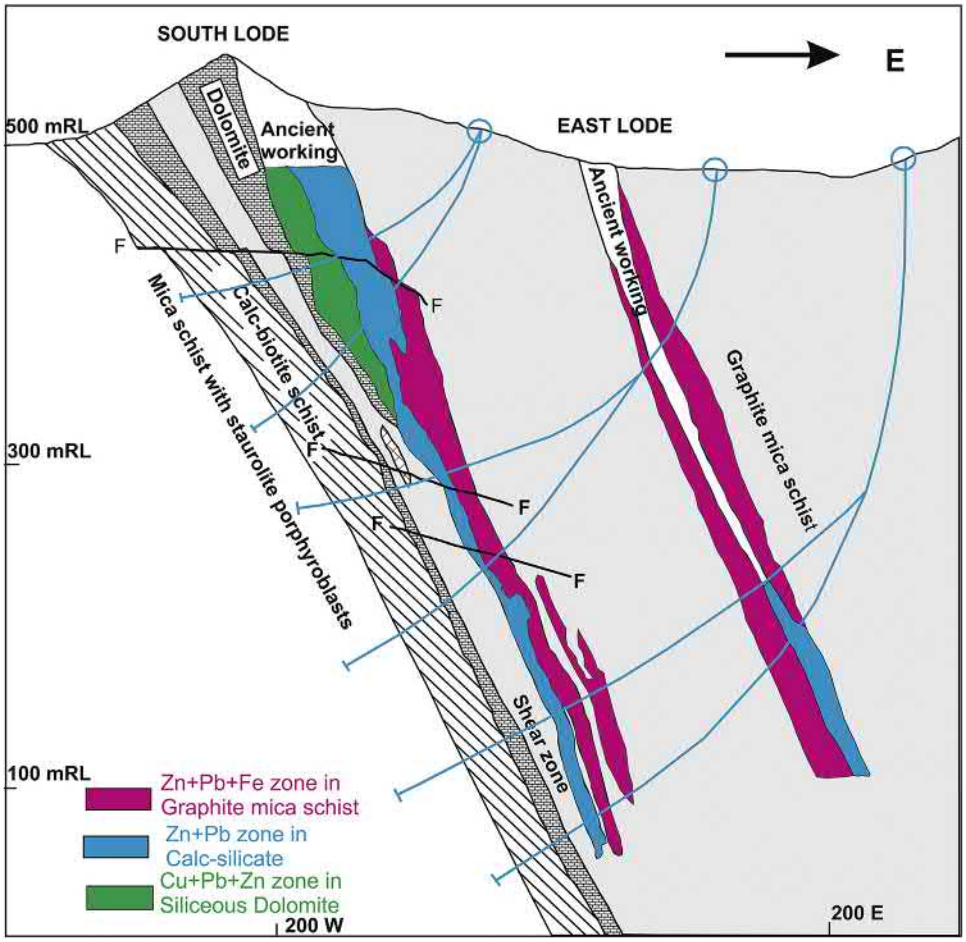

FIGURE 15.7 Geological cross-section of Rajpura-Dariba south and east lodes showing the prototype of orientation surface diamond drilling.

Rajpura-Dariba Mine Block has current reserves of 9.3 Mt and resources of 49.4 Mt at 6.3% Zn, 1.6% Pb as of April 1, 2017, and ore production capacity of 0.90 Mt/a (source: Hindustan Zinc Limited Annual Report, 2017).

15.5.8 Sindesar-Khurd Mine Block

The silver-rich Sindesar-Khurd deposit (25°01′, 74°08′, 45 K/4) is 6 km north of the Rajpura-Dariba mining town. The block constitutes a ridge of stony barren quartzite rising to an elevation of 570 m, showing no indication of mineralization.

As it happened, one of the drill holes in Mokanpura, east of Sindesar-Khurd, terminated in a calc-silicate-bearing dolomite horizon with rich sulfides similar to Bamnia-Kalan underneath the quartzite ridge. Subsequent routine drilling intersected huge zinc-lead-silver-rich mineralization beneath the stony barren massive quartzite ridge. The orebody represents the single western dip in the Aravalli Range. The massive (61 Mt, March 2012) silver-rich (+200 g/t Ag), zinc (6.8% Zn) and lead (2.9% Pb) deep-seated hidden Sindesar-Khurd was discovered by chance in 1987. Hindustan Zinc Limited explored the deposit, obtained a mining lease (1.96 km^2), and in 2006 finally commissioned trackless underground mining with a main pathway for the workforce, materials, machinery, and ore. Sindesar-Khurd will be the richest source and main producer of silver in India.

The stratabound single massive orebody is located in the central part of the western limb of the regional fold. The best-exposed rocks are interbanded mica schist/chert/quartzite, and form a prominent NNE–SSW-trending ridge. Calc-silicate-bearing dolomite horizon, the principal host rock, is completely concealed under the quartzite/chert and interbanded mica schist at a depth of about 120 m (Fig. 15.8). The hanging wall graphite-mica schist and calcareous quartz-biotite schist are intersected only in drill holes.

The average strike is N10°W. The orebody constitutes the steeper western limb of the antiformal structure. The westerly disposition of orebody is in sharp contrast to the usual easterly dips and exhibits all Aravalli-Delhi deposits.

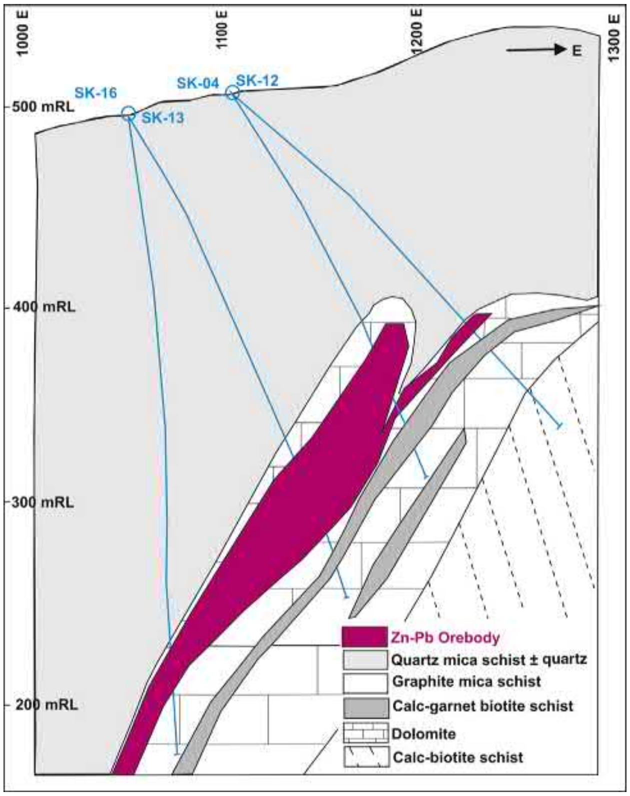

FIGURE 15.8 Geological cross-section of Sindesar-Khurd deposit showing hidden orebody 120 m below the surface and steep westerly dip in sharp contrast to the usual easterly dip.

GSI drilled 9267 m in 29 boreholes at 200 m intervals. Hindustan Zinc Limited commenced surface drilling in December 1992 and completed 6786 m in 22 holes over a 400 m strike extension up to a depth of 350 m from the surface. An additional 64,884 m of surface drilling was completed between 2005 and 2010 establishing continuity of mineralization at a depth of +800 m from the surface.

The strike extension has been traced over 1000 m. Principal ore minerals are sphalerite and galena. Pyrrhotite is an abundant sulfide gangue, while pyrite and arsenopyrite are rare.

The Sindesar-Khurd mine has a current reserve of 33.2 Mt and resources of 76.3 Mt at 4.7% Zn, 3.3% Pb, and 215 g/t silver as of April 1, 2017. Underground ore production capacity is 3.0 Mt/a (source: Hindustan Zinc Limited Annual Report, 2017).

15.5.9 Salient Features of the Leasehold Blocks at Rajpura-Dariba Belt

Summary information comprising exploration, host rock, mineralization, metamorphism, surface oxidation/gossans, metal zoning, halos, genesis, age, deposit size and grade, contained metal, minable reserve, capacity, and life of mining is given in Table 15.3.

The other two leasehold blocks await either a decision (Bamnia-Kalan, 25°03′, 74°09′, 45 K/4) or will be kept in abeyance (Sindesar-Kalan [E], 25°01′, 74°09, 45 K/4) due to low-grade ore (LGO) and excess graphite content in run-of-mine ore.

Rajpura-Dariba belt exhibits the best possible gossan on top of the orebody. It is supported by ancient mine entries up to a depth of 270 m from the surface and has a number of smelting slag heaps. These surface signatures made it easy to design exploration program. However, routine surface drilling intersected a deep-seated silver-rich zinc-lead deposit at a depth of 120 m from the surface.

15.6 NEVES CORVO, PORTUGAL: DISCOVERY OF A DEEP-SEATED ZN–CU–SN DEPOSIT: A GEOPHYSICAL SUCCESS

Portugal or the Portuguese Republic is the southwestern most country in Europe. Its capital is Lisbon. It is situated on the Iberian Peninsula bordering the Atlantic Ocean to the west and south and Spain to the east and north. Portugal is essentially an agricultural country. In terms of production, its mineral industry is modest by world standards. Economic growth became significant with the discovery and development of rich copper-zinc-tin deposits at Neves Corvo by Sociedade Mineira de Neves Corvo SA (Somincor). Mineral industries are copper (São Domingos open pit mine), zinc-lead (Aljustrel mine), copper-zinc-tin (Neves Corvo), tungsten (Panasgueira), gold (Góis region), and coal (Guimrota). Two metal mines are in operation: (1) Neves Corvo in Castro Verde, the largest producer of mined copper in the European Union, and (2) Panasgueira in Covilhã, Castelo Brancho, one of the largest tungsten mines in world. The discovery and successful implementation of the Neves Corvo project brought significant benefits to the local and regional communities in southwestern Portugal.

15.6.1 Location and Discovery

The Neves Corvo copper-zinc-tin deposit (25°01′, 74°08′, 45 K/4), Castro Verde, Beja District, Portugal, is located 220 km southeast of Lisbon and 100 km north of Faro. Neves Corvo has good connections to the national road network that connects Faro and Lisbon. The mine has a dedicated rail link to the Portuguese rail network. The deposit forms part of the 250 km long and 30–50 km wide Iberian Pyrite Belt that trends NW–SE from Alcácer do Sal (Portugal) to Sevilla (Spain). The Iberian Pyrite Belt in Spain has been known for more than 250 pyrite deposits/active mining for over 1000 years. Neves Corvo in the Portuguese part is the highest-grade copper-zinc-tin deposit ever found in the Iberian Pyrite Belt (Fig. 15.9).

TABLE 15.3 Salient Features of Four Mining Blocks at Rajpura-Dariba Belt

Features	Rajpura-Dariba	Sindesar-Khurd	Bamnia	Sindesar-Kalan
Location	75 km northeast of Udaipur city	6 km northeast of Rajpura-Dariba	4 km northeast of Sindesar-Khurd	1 km east of Sindesar-Khurd
Exploration	34 km surface and 75 km underground drilling	81 km surface drilling by GSI and HZL	17 km surface drilling by GSI and HZL	Surface drilling at 100 m by GSI
Host rock	Calc-silicate, dolomite, GMS	Calc-silicate, dolomite, GMS	Calc-silicate and dolomite	Graphite-mica schist
Mineralization	Stratabound and stratiform, Sp, Ga, Ag, Cu, Py	Stratabound, Sp, Po, Ga, Ag, Py, Cp	Stratabound, Sp, Ga, Po, Py	Stratabound and lensoidal, Sp, Ga, Po, Py, As
Metamorphism/ deformation	Strong deformation, amphibole facies	Strong deformation, amphibole facies	Strong deformation, amphibole facies	Strong deformation, amphibole facies
Gypsum present	Gypsum present	Gypsum	Gypsum	Gypsum
Surface oxidation	Excellent oxidation, multi-color gossans	Ore at 120 m below massive barren quartzite	Ore at 120 m below 20 m thick soil	Near surface, oxidation present
Zoning	→Cu–Zn–Pb–Fe	Metal zoning	–	–
Halos	Pyrite at hanging wall	Pyrrhotite	Pyrite present	Pyrite present
Genesis	SEDEX	SEDEX	SEDEX	SEDEX
Age (Ma)	1800	1800	1800	1800
Size and grade, March 31, 2017	42.2 Mt at 6.6% Zn, 1.7% Pb, 82 g/t Ag	110 Mt at 5.8% Zn, 3.8% Pb, 215 g/t Ag	3 lenses,4 Mt at 5.7% Zn, 2.5% Pb, 100 g/t Ag	Near surface, 94 Mt at 0.6% Pb and 2.1% Zn
Contained metal	2.05 Mt	10.55 Mt	0.33 Mt	2.54 Mt
Mining lease (ha/km^2)	1142.21 ha (11.42 km^2)	199.84 ha (2 km^2)	–	Abeyance due to uneconomic metal grade
Infrastructure	Water requirement is met from Matrikundia dam on Banas River. Power requirement is met by captive power plants and shortfall is met by state grid			
Mining methods	Vertical crater retreat and blast hole stopping mined-out stopes backfilled with cemented tailings			Open pit
Modernization	Equipped with world-class infrastructural facilities, including the latest and best machinery			NA
Depth of mine	500 m	500 m	300 m	40 m
Mine capacity	0.900 Mt/a	1.500 Mt/a	0.300 Mt/a	1.500 Mt/a
Life of mine	+20 years	+20 years	+10 years	+40 years

GSI, Geological Survey of India; *HZL*, Hindustan Zinc Limited; *SEDEX*, sedimentary exhalative.

Discovery of the Neves Corvo deep-seated, concealed, rich polymetallic deposit can be credited to the success of sophisticated geophysical techniques and interpretive confidence. A joint venture consortium between BRGM, Penarroya, and the Portuguese states mineral company Empresa de Desenvolvimento Mineira carried out the first phase of prospecting between 1969 and 1973 in the southern half of Iberian Pyrite Belt. The investigation was mainly by geological mapping and gravimetry survey leading to identification and ranking of several anomalies. The first exploratory drill hole was sunk in 1973 achieving nothing of any significance. This negative drilling result held the project in abeyance. However, exploration team members were not in agreement with the setback, and sanctioned a second phase, including diamond drilling between 1973 and 1977. They accumulated data from the rest of Baixo Alentejo province, and compared it with drill information and the reinterpreted geophysical anomalies. The team was seriously convinced that the holes so far drilled had not gone deep enough. The fifth drill hole of the third phase intersected 50 m of massive sulfide from the Neves orebody. Discovery of the Neves orebody at a depth of 330 m from the surface was a gift to the country in April 1977. Drilling continued and identified three other

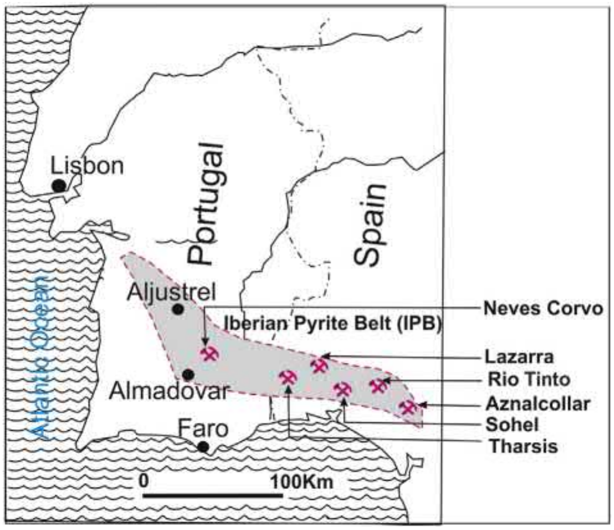

FIGURE 15.9 Location map of Iberian Pyrite Belt in Portugal and Spain showing Neves Corvo polymetallic deposit.

orebodies starting at a depth between 250 and 630 m, namely, Corvo, Zambujal, and Graca during 1977 and 1978. Tin orebody was discovered during mine development that led to the construction of a tin plant. Routine surface exploratory drilling close to the mine discovered a new high-grade copper-rich massive sulfide deposit in October 2010 and was named Semblana.

The company SOMINCOR (Sociedade Mineira de Neves Corvo SA) was formed in 1980 as operator. A total of 150 km of surface and 50 km of underground drilling, delineation, and evaluation identified copper-rich Corvo and Graca to be viable. Rio Tinto Zinc Corporation acquired a share of Penaroy and BRGM in 1985. In March 2004 EuroZinc acquired 100% of SOMINCOR, giving it full ownership of the Neves Corvo mine. EuroZinc merged with Lundin Mining in October 2006.

A 3.50 km decline ramp for the workforce and services, and a 500 m vertical shaft for ore hoisting, started in 1981 and 1982, respectively. Mine ventilation is supported by two vertical shafts. Mine design was completed between 1983 and 1984. The underground mine was commissioned on December 10, 1988, and commercial production of metal commenced in January 1989. The company made small copper biscuits from the first batch of copper metal to commemorate the occasion. The author is privileged to have received one such memento during his visit to the mine (Fig. 15.10A and B) in 1990. A tin plant was commissioned in 1990. The copper and tin concentrate were processed at the site and shipped to smelters overseas until 2006 with the commencement of the treatment of zinc ore. Zinc metal production was restarted at a limited rate in 2010 and a new zinc expansion project was completed in July 2011. The expanded plant has the flexibility to process zinc or copper ores.

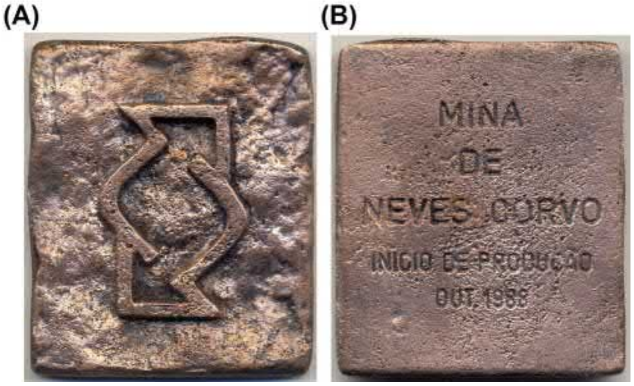

FIGURE 15.10 Small slab of first copper metal produced from Graca orebody, Neves Corvo mine, in 1988 commemorating the occasion: (A) emblem of the owner Somincor and (B) year of production.

15.6.2 Regional Setting

The Neves Corvo deposits occur within a volcanic sedimentary complex (Iberian Pyrite Belt). The host rock sequence comprises acid volcanic rocks separated by shale units. A discontinuous black shale horizon lies immediately below the ore horizon. There is a thrust-faulted repetition of volcano-sedimentary units above the mineralization. The whole assemblage has been folded into a gentle anticline oriented NW–SE and plunges → SE. This has resulted in orebody distributed on both limbs of the fold (Fig. 15.11). The entire sequence has extensively been affected by both subvertical and low-angle thrust faults causing repetition.

15.6.3 Exploration

Surface and underground exploration drilling is an ongoing operation for sustainable reserve creation. Drilling is carried out both in-house and contractually. Surface drilling of NQ series is spaced at either 100 or 75 m. Underground drilling is in a fan pattern with intersections at either 17.5 or 35 m spacing (Fig. 15.11). All drill holes are surveyed by a multishot reflex camera at 30 m intervals for an accurate location of drill intersections. Average annual surface and underground drilling are in the order of ~50,000 and ~25,000 m, respectively.

15.6.4 Mineralization

Six laterally linked, massive stratiform, sulfide orebodies have been defined, namely, Neves (north and south), Corvo, Graça, Zambujal, Lombador (north, south, and east), and Semblana. The orebodies are a deeply rooted stockwork and stringer system. Metal grades are segregated by strong zoning into copper, tin, and zinc, as well as barren massive pyrite (Fig. 15.12). The sulfide deposits are typically underlain by stockwork sulfide zones that form an important part of copper orebodies. The ore-forming minerals are

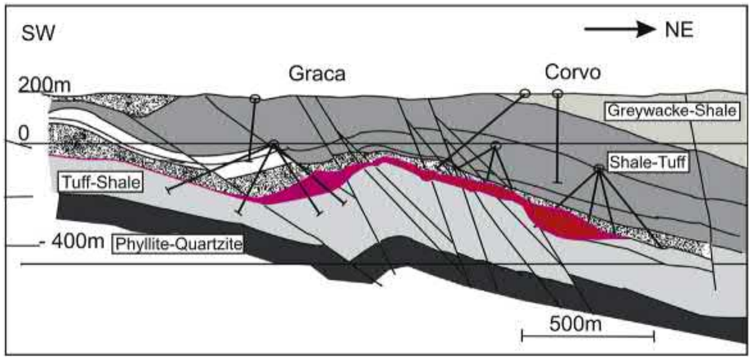

FIGURE 15.11 Surface and underground exploration by fan drilling design at Neves Corvo mine.

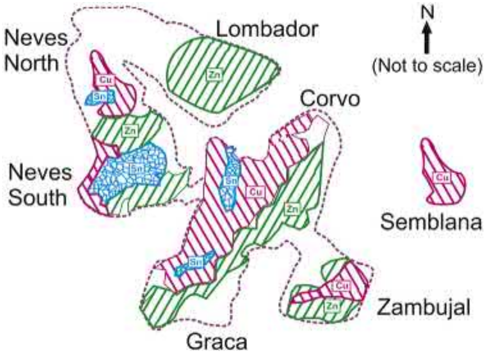

FIGURE 15.12 Distribution of orebodies and metal concentration at Neves Corvo group of orebodies

pyrite, chalcopyrite, sphalerite, galena, cassiterite, and silver minerals. The primary and secondary commodities from mine production are copper and zinc with subsidiary products of tin and silver.

The Corvo orebody has a strike extension of ~1100 m and dips at 10−40 degrees → NE. Orebody appears at a depth of 280−630 m below the surface with maximum true thickness of 95 m. The massive sulfide lens consists of a basal layer of copper ore up to 30 m thick, overlain by barren pyrite. The orebody is overlain by a complex mineralized sequence called Rubane. This consists of an assemblage of chloritic shale, siltstone, and chert-carbonate breccias, which are all mineralized with cross-cutting and bedding parallel veins and occasional thin lenses. The sulfides are cupriferous over much of their occurrences and Rubane copper ore constitutes over 15% of the total cupriferous content of Corvo.

Tin occurs closely associated with copper ore, both as massive sulfide lens and Rubane. Massive sulfide tin ore containing high copper grades is distributed through the copper ores of Corvo defining a trend from north to south. The Rubane orebody and the underlying stockwork are mineralized with high grades of tin ores at the north end of the massive sulfides.

The Graca orebody lies on the southern flank of an anticline and dips at 10−70 degrees → S. The orebody extends over 600 m along the strike and 450 m in the dip direction. The orebody appears between 250 and 480 m from the surface. The lens is up to 80 m thick and linked to Corvo by a bridge of continuous thin sulfide mineralization. Much of the copper ore occurs as a basal layer overlain by barren pyrite.

The Neves orebody consists of two lenses, north and south, joined by a thin bridge and dips at 5 and 25 degrees → N. The orebody extends over 1500 m in the strike direction and 700 m in the dip direction with maximum thickness of 50 m. The southern lens contains mostly zinc with significant lead, silver, and copper, and is underlain by tin-bearing copper ore. The northern lens contains a significant resource of massive copper sulfide with minor complex zinc ore. There is a thick zone of cupriferous stockwork underlying the northern lens.

Zambujal is a small, thin, flat, dipping massive sulfide orebody containing some low-grade zinc, minor copper, and barren pyrite.

The Semblana deposit is located 1.3 km northeast of Zambujal at a depth of 850 m. Exploration drilling outlined an area of 600 m by 250 m of massive sulfide and stockwork in seven drill holes. This new deposit remains open in all directions and appears to be flat lying. Mineralized thickness varies between 4 and 36 m. It is copper rich with grades varying between 1.5% and 4.5% Cu, 0.2% and 2.6% Zn, 0.1% and 1.0% Pb, and 0.1% and 0.3% Sn.

15.6.5 Genetic Model

The Iberian Pyrite Belt was formed 350 million years ago on account of active hydrothermal volcanism forming a volcano-sedimentary complex. Volcanic activity in the region led to several giant volcanogenic massive sulfide (VMS) ore deposits associated with polymetallic massive flanks of volcanic cones. More than 250 deposits of the Iberian Pyrite Belt are placed at volcanic sediment-hosted massive sulfide deposits, a complementary between the VMS and SEDEX types.

15.6.6 Size and Grade

The proved and probable ore reserves as of March 2011 stand at:

Copper-rich ore	27.7 Mt at 3.0% Cu, 0.9% Zn, 0.3% Pb, and 44 g/t Ag
Zinc-rich ore	23.1 Mt at 7.3% Zn, 0.4% Cu, 1.7% Pb, and 66 g/t Ag
Tin-rich ore	2.68 Mt at 13.62% Cu, 1.27% Zn, and 2.42% Sn*

The Neves Corvo mine produces copper, zinc, and tin ores. The tin resource (*) is nearing exhaustion, and forms no part of future mining plans.

Underground mining is based on mechanized stoping using primarily "bench and fill" and "drift and fill" methods with sand and paste backfill. The processing facilities are: (1) a copper plant with 2.5 Mt/a capacity at 25% Cu in concentrate, (2) a zinc plant with 1 Mt/a capacity at 50% Zn in concentrate, (3) a tailings impoundment, and (4) backfill plants. Mine life is +10 years at current minable reserves.

The Neves Corvo deposit is certainly the most significant, rich copper mine in the world and will remain Europe's El Dorado (the golden one) for many years (Lundin, 2011). The discovery of a single Neves Corvo polymetallic deposit has changed the national economy of the country in Europe.

15.7 BUSHVELD, SOUTH AFRICA: THE LARGEST PLATINUM-CHROMIUM DEPOSITS IN THE WORLD

The resource base and production of platinum-group of elements (PGE) and chromium in South Africa rank number one in the world. South Africa produced 120 t of platinum, 73 t of palladium metal, and 14 Mt of chromite ore in 2016 (U.S. Geological Survey, 2017). The world's share of platinum, palladium, and chromium production was 70%, 35%, and 43%, respectively, during 2016. Three of the five largest PGE-chromite deposits of the world occur near the stratigraphic middle of large layered intrusions, namely, Merensky and the Under Ground-2 (UG2) Chromitite Reefs of Bushveld Complex, South Africa, and the Main Sulphide Zone of The Great Dyke, Zimbabwe.

15.7.1 Location and Discovery

The Bushveld Igneous Complex (BIC) (25°S, 29°E) is the largest layered igneous intrusive in the world. The complex is located at about 100 km northwest of Johannesburg, South Africa, and hosts some of the richest and largest chromium-PGE deposits on Earth.

BIC was discovered in 1897 by Gustaff Molengraff, a Dutch geologist, biologist, and explorer. He discovered BIC while mapping the Transvaal region as a working state geologist. Chromite mining started thereafter. The igneous complex had been tilted, eroded, and outcropped around the edge of a great geological basin. Merensky Reef was an outstanding discovery of platiniferous orebody in the Eastern Bushveld Complex in 1924 by Dr. Hans Merensky and Andries Lombaard. Dr. Hans discovered another promising orebody in the northern limb in 1925, and named it Platreef. A UG2 chromite layer, discovered in the 1970s, surpassed the Merensky Reef in platinum reserve. Mining of these lodes was started from 1970 by Lonmin, Anglo American Platinum Ltd., using the underground method.

15.7.2 Exploration

The chromium-PGE group of deposits has extensively been drilled over the years from surface and underground. Continuity and delineation have been established by drill holes up to a depth of 1500 m for Platreef and 3300 m for Merensky and UG2.

15.7.3 Regional Setting

The BIC structure represents a huge saucer-shaped layered mafic/ultramafic igneous intrusion (2060 Ma age) forming a great geological basin that is divided into two prominent lobes: eastern and western, with a further northern extension (Fig. 15.13).

All three sections are remarkably similar. The rock types comprise ultramafic (peridotite, chromitite, and harzburgite) in the lower to mafic (gabbro, norite, and anorthosite) in the middle, and felsic phase (granite) in the top section (Table 15.4).

15.7.4 Genetic Model

The complex was formed by repeated injection of magma over a large timespan into a huge subvolcanic chamber. Cooling and differential crystallization was a slow process forming subhorizontal shallow level layers from the base of the chamber. The chamber covers an areal extent of +65,000 km^2 as preserved today. These processes were repeated reaching ~9 km thickness by the intermittent replenishment and addition of existing and new magma, producing a repetition of the mineral layering. Some individual layers or groups of layers can be traced for hundreds of kilometers. This layered sequence, the Rustenburg Layered Suite, comprises five principal zones: Marginal, Lower, Critical, Main, and Upper Zones. The intrusive in general dips to the center of the complex. BIC consists of four compartments: the western, eastern, northern, and southern limbs, in order of economic importance.

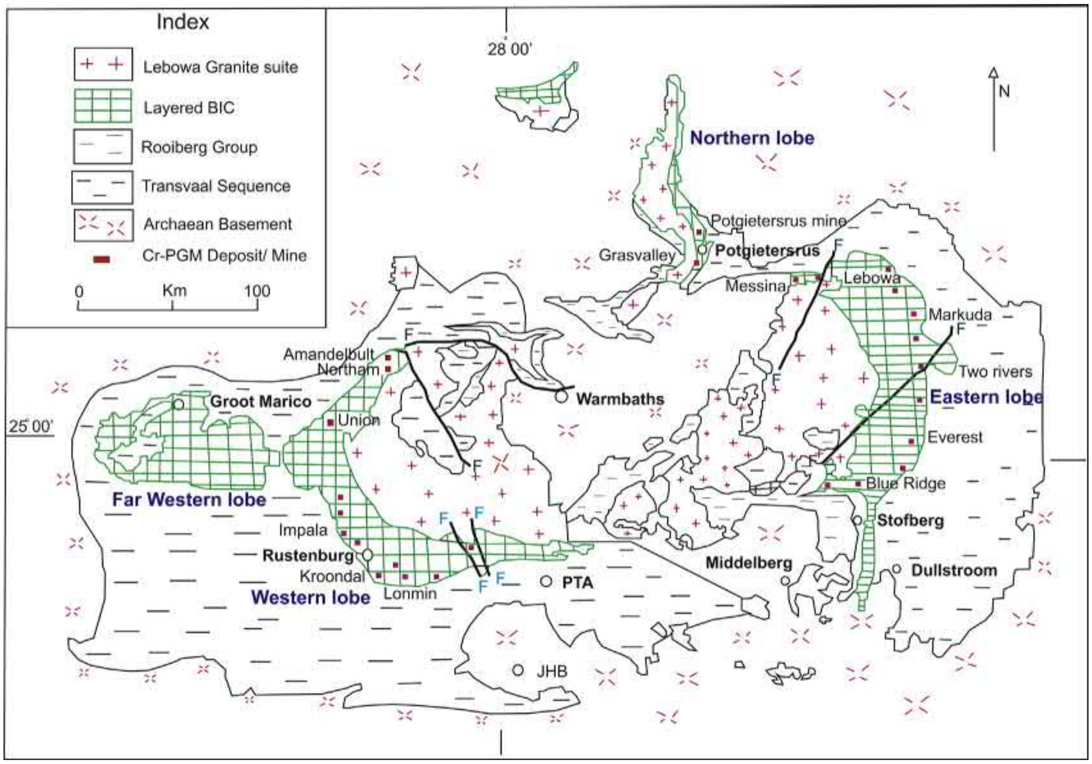

FIGURE 15.13 Schematic surface geological map of Bushveld Igneous Complex (BIC), South Africa, showing various limbs/structures and chromite-platinum-group metal (Cr—PGM) deposits/mines. *Haldar, S.K., 2013. Mineral Exploration — Principles and Applications. Elsevier Publication, p. 374.*

TABLE 15.4 Generalized Geological Succession at Bushveld Igneous Complex

Formation	Period	Rock Type
Lebowa Granite Suite	1790 ± 114 to 1604 ± 70 Ma	Younger sedimentary cover and granite intrusion
Rustenburg Layered Intrusive Suite, host rock	Proterozoic	Mafic and felsic intrusive rocks: norite-gabbro-pyroxinite-harzburgite-chromitite, granite
Rooiberg Group	Early Proterozoic	Volcanic flows and pyroclastics
Transvaal Supergroup	Late Archean to Early Proterozoic	Metasediments: shale and quartzite
Basement	Archean	Granite and gneiss

15.7.5 Mineralization

There are more than 20 chromitite horizons of varying thickness enriched in PGE and Fe—Ni—Cu sulfides. The three major, distinct, and rich orebodies are Merensky Reef, UG2, and Platreef. The former two reefs can be traced over 300 km in two separate arcs, and the latter extends over 30 km. Grade and thickness continue for kilometres in strike, and are negligible in down-dip. Some layers consist of +90% chromite, making the rare rock type as **chromitite**.

UG2 occurs in both the west and east lobe. The layer has sharp lower and top contacts with thicknesses ranging between 40 and 120 cm. UG2 is usually underlain by a coarse-grained feldspathic pyroxenite and rarely by anorthosite. It contains massive chromite grading between 60% and 90% Cr_2O_3 and 4.5—8.0 g/t Pt.

The Merensky Reef occurs in the east and west lobe with thicknesses between 30 and 90 cm. The reef rests on anorthosite and is overlain by pegmatitic feldspathic pyroxenite. The host rock is norite with extensive chromitite and sulfide layers or zones containing ore. The Merensky Reef contains 3.5 and 9.5 g/t Pt in pyrrhotite, pentlandite, and pyrite.

Platreef is located close to Thabazimbi-Murchison Lineament in the northern lobe with thicknesses between 50 and 400 m. It is formed as a result of the interaction between a new gabbroic parental magma of the Main Zone and a suite of sulfur-bearing sediments and preexisting Lower Zone cumulates. The chromiferous ore is rich in Fe—Ni—Cu sulfide and PGE.

15.7.6 Size and Grade

BIC contains +75% of the world's platinum resources from some of the richest chromite and PGE orebodies. The single lode, UG-2 chromitite unit contributes 58% of resources. Some layers contain 90% chromite making rare rock type chromitite.

The chromite reserve and resource are estimated at 11,550 Mt grading between 40% and 50% Cr_2O_3, 2.87 g/t Pt, and 1.80 g/t Pd with 5.67 g/t PGEs (Naldrett, 2004). Merensky Reef stands at 4210 Mt grading between 4.4 and 6.9 g/t PGE over the mining width. The Merensky Reef contains 3.5 and 9.5 g/t Pt in pyrrhotite, pentlandite, and pyrite (Naldrett, 2004). Merensky and UG-2 reefs contain ~90% of the world's PGE resources of 9952 Mt at 3.05 g/t Pt and 1.76 g/t Pd. Platreef has been estimated at 1597 Mt grading 1.77 g/t Pt, 2.01 g/t Pd, 0.41% Ni, and 40%−50% Cr_2O_3.

The deposits have been extensively drilled and depth continuity has been established up to 1500 m for Platreef and 3300 m for Merensky and UG-2.

BIC will continue the single-handed supply of global demand for platinum, palladium, and chromium metals with its enormous reserves and resources.

15.8 SUDBURY, CANADA: THE LARGEST NICKEL-PLATINUM-COPPER DEPOSIT IN THE WORLD

Canada ranks first in exploration expenditure in the world. It stands within the top five in the production of Ni, Zn, PGE, Au, Mo, Cu, Co, Pb, and Cd. The metallogenic provinces include Proterozoic magmatic Ni−Cu−PGE (refer to Fig. 1.2R) deposits in Sudbury region (1646 Mt premining) and Neoarchean intrusive Pd deposits in Lac des Iles (64 Mt) near Thompson. Canada was the leading producer of nickel ore at 255 Mt during 2016 with a world share of 11.30%; the country's current resource is 2900 Mt (U.S. Geological Survey, 2017). The Canadian mining industry is equipped with knowledge-based high technology and supported by more than 2200 mining-related companies.

15.8.1 Location and Discovery

Sudbury Basin also known as Sudbury Structure, Sudbury Nickel Irruptive, or Sudbury Igneous Complex (SIC) (46°27′50″N, 81°10′29″W) is a major geologic structure in the city of Greater Sudbury, Ontario, Canada. Sudbury Basin (200 km diameter) is the second-largest known impact crater on Earth after Vredefort (250−300 km diameter, 2023 ± 4 Ma impact age) in South Africa. The former is known for having the largest resources of nickel-copper-cobalt + PGE for many centuries. The latter is at the preliminary search stage for gold and uranium. The Sudbury Structure is the remnant of a deformed multiring impact basin, and hosts a vast amount of Ni−Cu−PGE sulfide mineralization (Doreen, 2008). Melting effect impact at Sudbury Basin can be traced up to 15 km depth from the surface.

Alexander Murray of the Geological Survey of Canada first reported the presence of sulfide minerals in 1856 at the present-day site of Murray Mine. Yet, the discovery of this significant Ni−Cu−PGE resource could be documented only by a blacksmith in 1883 during construction of the first transcontinental Canadian Pacific Railway. The identification of Ni−Cu metals resulted in a prospecting and staking rush. PGE realization came much later. Falconbridge had been mining nickel-copper ores in the Sudbury area since 1929. Xstrata acquired the Sudbury Mine through its acquisition of Falconbridge in 2006. The International Nickel Company (Inco) is the major mining company in Sudbury.

15.8.2 Regional Setting

Sudbury Mining District is represented by five different geologic environments ranging between Archean and Paleozoic. SIC is structurally placed between Archaean Levack granite-gneiss of Superior Province in the north and east, Paleoproterozoic metasedimentary and metavolcanic Huronian Supergroup rocks of Southern Province, and the Whitewater Group of the sedimentary package in the central part (Table 15.5). The Huronian Supergroup rocks are deposited in an intercontinental rift basin environment.

The main rock units of SIC range from an outer ring of norite through a transition zone of gabbro to an inner zone of granophyre. SIC represents a prominent elliptical multilayer ring structure (Fig. 15.14). The outer rims are

TABLE 15.5 Stratigraphic Succession of Sudbury Mining District

Stratigraphy	Formation	Rock Type
Palaeozoic	—	Limestone and dolomite
Mesoproterozoic	—	High-grade metamorphic rocks
Paleoproterozoic (1840 ± 21 Ma)	Sudbury	Granophyres
	Igneous	Quartz-rich gabbro
	Complex/ structure	Norite Ni−Cu
		Sublayer norite and gabbro Cu−PGE

Continued

TABLE 15.5 Stratigraphic Succession of Sudbury Mining District—cont'd

Stratigraphy	Formation	Rock Type
Paleoproterozoic (2500–1600 Ma)	Whitewater Group	Chelmsford formation
		Onwatin formation Zn–Cu–V–Cd–Ag–Ni
		Onaping formation Zn–Cu–Pb–Ag
	Huronian Supergroup	Murray granite, gabbro-anorthosite
		Quartzite
		Greywacke and volcanic rocks
Archean (+2500 Ma)	Levack basement	Granite gneiss, felsic plutons, metavolcanic, metasediments

popularly known as North and South Range. The North, East, and South Ranges are scattered with more than 100 deposits and +150 occurrences. There are over 80 producing and abandoned Ni–Cu–PGE mines. More than 11 Cu–Ni–PGE projects are in advance stages of exploration.

15.8.3 Exploration

The initial economic recognition of the Sudbury Mining District started with the discovery of large Cu–Ni sulfide resources. Exploration and mining program for new deposits continued in the region to identify poly-metallic Ni-Cu-PGE reserves and resources. Current exploration expenditures are mainly focused on the footwall-hosted Cu–Ni–PGE systems containing high Cu and PGE grades. This was rewarded by the discovery of new deposits like Victor and Levack Footwall. New exploration models for low-sulfide, high-PGE, polymetallic deposit styles of mineralization are being refined for both North and South Ranges. Base metal (zinc-lead) deposits are

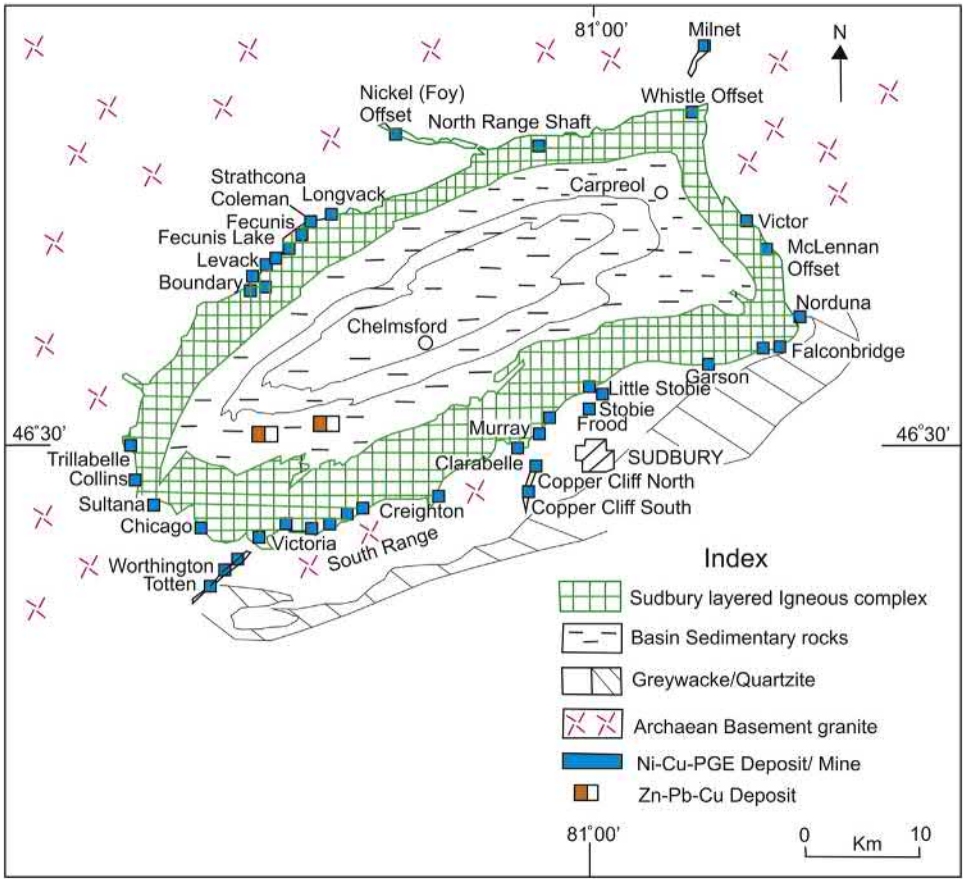

FIGURE 15.14 Simplified geologic map of the Sudbury Igneous Complex showing Ni–Cu–PGE and Zn–Pb–Cu deposits/mines. Sudbury Camp is ranked as the principal base and PGE metal mining district of Canada. *Haldar, S.K., 2013. Mineral Exploration – Principles and Applications. Elsevier Publication, p. 374.*

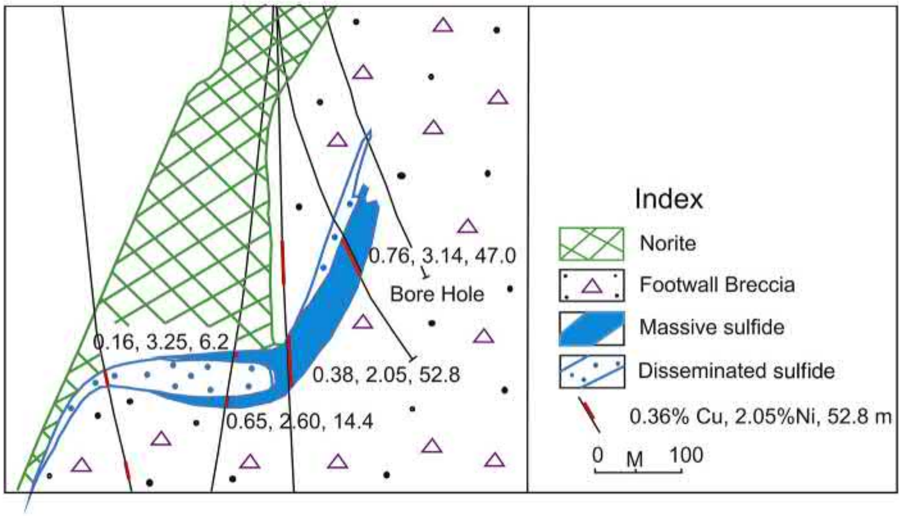

FIGURE 15.15 Geological cross-section of Victor mine, Sudbury Igneous Complex (SIC), showing orientation deep-drilling program.

regularly discovered in Sudbury Camp by evolving models and deep drilling techniques.

The knowledge-based 3D exploration modeling application of borehole electromagnetic geophysics and interpretation resulted in the identification of deep-seated targets. The multiple wedge orientation to perform number of deep drilling (+2000 m deep) from single collar point is cost effective, and paid dividend to success stories in past. Borehole geophysical surveys in old and new holes have been credited to the discovery of Victor contact Ni—Cu—PGE (1970—80), Fraser—Morgan and McCreedy East-153 zone (1990s), Kelly Lake Ni—Cu—PGE in Copper Cliff Offset (1995), Totten Depth Ni—Cu—PGE (1997), Ni Rim South (2001), Podolsky (2002), and Levack Footwall in 2005.

New exploration models for low-sulfide, high-PGE polymetallic deposit styles of mineralization are refined for both North and South Ranges. New discoveries are frequently being made in Sudbury Camp by evolving advanced techniques of deep directional drilling from a common collar at reduced cost and time (Fig. 15.15).

15.8.4 Mineralization

Mineralization is classified into three types: (1) contact, (2) offset, and (3) breccias. All contain Ni—Cu—PGE.

Contact deposits are typically located at the interface between SIC and Archean or Paleoproterozoic basement rocks (e.g., Murray Mine and Creighton Mine, South Range). Massive pyrrhotite-rich Ni—Cu—PGE sulfides are placed within the contact megabreccia zone. The basal igneous sublayer norite ± mafic/ultramafic inclusion hosts disseminated sulfides.

Offset-type deposits are hosted within radial or concentric quartz diorite offset dykes that may extend more than 30 km from the parent source of SIC. Economic mineralizations are found at Kelly Lake deposit on the Copper Cliff Offset dyke, South Range, Nickel Offset dyke at North Range, Totten deposit on the Worthington Offset dyke, Ni—PGE mineralization on the Trill Offset dyke, and Milnet deposit at the Whistle Offset dyke (Fig. 15.16). PGE—Cu—Ni content increases at distances from SIC. Massive and vein-type sulfides typically occur in steeply plunging orebodies along the length of the offsets. The deposits are dominated by pyrrhotite with less abundance of pentlandite and chalcopyrite.

FIGURE 15.16 The nickel bearing massive pyrrhotite, and patches (black irregular boundary) of pentlandite {(Fe, Ni)$_8$S$_9$} are inter grown from the Trill "offset inclusion quartz dyke" associated with the Sudbury Complex, Canada. The other nickel mineral millerite (NiS) occurs as micro level inters grown type. *Credit: Tom Evans.*

Breccia-type deposits are primarily Cu−Ni mineralization within fractured country rocks at the base of SIC. Sudbury breccia consists of fragments of ultramafic inclusions and norite in a quart-feldspar matrix. The sulfides are disseminated and massive stringers within footwall breccias and disseminations within overlying sublayer norite. Strathcona Cu-rich ore at North Range is located in fractures up to 100 m away from the basal contact.

15.8.5 Genetic Model

The Sudbury structure is postulated to be formed as the result of a meteorite impact (1840 ± 21 Ma) that produced a 150−280 km multiring crater, containing a 2−5 km thick sheet of andesitic melt. The immiscible sulfide liquid collected into topographic lows, where it was differentiated into Ni−PGE-dominated contact deposits by crystallization of a monosulfide solid solution. Residual sulfide liquid migrated into the footwall to form a variety of vein- and disseminated-type deposit that underwent remobilization of metals. The footwall of SIC and older basement rocks is extensively brecciated, deformed, and metamorphosed due to the impact. These breccias hosted the remobilized high-grade Ni−Cu−PGE mineralization. The period of mineralization and ore-forming process related to cooling of SIC can be over one hundred to one million years. Many deposits in the South Range have been modified by deformation. The whole episode marked Sudbury as the principal base and PGE metal mining district of Canada, Fig. 15.17.

FIGURE 15.17 Sperrylite crystal on weathered chalcopyrite mat from the Broken Hammer Ni−Cu−PGE Deposit, Wallbridge Mine, Sudbury Camp at North Range, Ontario. The crystal is approximately 8 mm across. The host rock is quartz diorite Offset Dike. *Courtesy: Dr Tom Evans.*

15.8.6 Size and Grade

Total mineral resources are estimated at +1500 Mt at 1% Ni, 1% Cu, and 1 g/t Pd + Pt. The figure includes past production, reserves, and resources (Doreen, 2008). The district also hosts significant polymetallic resources comprising U−Ni−Cu−PGE−Au and Zn−Pb−Cu deposits.

McCreed east produces +400,000 tpa of high-grade ore. The other deposits, Kelly Lake, Totten Depth, Ni Rim South (2.17% Ni, 6.45% Cu, and 15.40 g/t Pt + Pd + Au), Podolsky (13.8% Cu, 1.0% Ni, and 8.2 g/t Pt + Pd + Au), and Morrison, are either in production or being evaluated for production-planning purposes.

The 21st century has so far been notable for mineral exploration, active mining claims, and new discoveries with a marked shift in exploration focus to high-grade Cu−Ni−PGE deposits. The potential for Ni−Cu−PGE discoveries in the Sudbury structure is considered significant, both at near surface and at depth. There have been unprecedented exploration expenditures and activities over the past few years by both junior and established mining companies. Recent exploration success by major (Inco, Falconbridge), mid-sized (FNX), and junior (Wallbridge) exploration companies enhanced outstanding resource potential with considerable smelting and refining infrastructure.

15.9 JINCHUAN ULTRAMAFIC INTRUSION, CHINA: SINGLE LARGEST NI−CU−PGE SULFIDE DEPOSIT IN THE WORLD

The People's Republic of China is one of the fastest-growing economies in the world. China has abundant nickel and cobalt resources, and is the largest nickel producer in Asia having more than 120 nickel-copper ± PGE deposits/mines. Jinchuan group produces the maximum share. Chinese mines produced 90 Mt of nickel ore during 2016, 4% of world share at a resource base of 2500 Mt (U.S. Geological Survey, 2017).

15.9.1 Location and Discovery

Jinchuan (38°28′N, 102°10′E) is the single largest Ni−Cu−PGE sulfide deposit in the world, and stands third with a 515 Mt reserve base after Sudbury (1648 Mt) in Canada and Noril'sk (1309 Mt) in Russia. The deposit is located in Jinchuan District, Gansu Province, Northwest China. The Yongchang nickel deposit was discovered in 1958 at the foot of Longshou Mountain in the middle Hexi Corridor, and was renamed Jinchuan Non-ferrous Metals Corporation in 1961. Jinchuan Group Limited was formally established in 2001 with the development of large mining/beneficiation/smelting/refining and an industrial city complex.

15.9.2 Geology

Jinchuan ultramafic intrusion of Proterozoic age occurs at the margin of the Sino-Korean massif. The magma was emplaced into late Archean metasedimentary rocks consisting of gneisses, chlorite-quartz schists, banded marbles, and migmatite. The intrusion extends over 6.3 km in a NW—SE-oriented lens, 20—525 m wide, at more than 1100 m of vertical depth. Jinchuan intrusions dip steeply to the southwest caused by extensive movement of regional thrust fault. The parental magma originated from high Mg basaltic composition, and the primary magma contained MgO up to 18.5 wt%. The intrusion consists of five ultramafic units that include lherzolite, dunite, plagioclase lherzolite, olivine websterite, and websterite in order of decreasing abundance. Dunite is sulfide bearing with 8%—30% Ni—Cu sulfides (Naldrett, 2004). The sequence of ultramafic units is subdivided into upper, lower, and transition layers:

The upper layer unit consists of dunite, lherzolite, and pyroxenite, and is largely free of mineralization or weakly disseminated sulfides at the base. The lower layer unit consists of coarse-grained dunites and lherzolite, and comprises oxidized No. 24 orebody Mineralization is primarily of disseminated, net-textured, and minor massive sulfides, forming the third largest orebody at Jinchuan.

The central part of the intrusion is characterized by a concentric distribution of rock types with a core of sulfide-bearing dunite enveloped by lherzolite. The intrusions and the deep-seated magma chambers comprise a complicated magma plumbing system. Normal faults played a significant role in the formation of the magma plumbing system and provided pathways for magmas (Song et al., 2011). A simplified geological map (Fig. 15.18) and generalized sequence of ultramafic intrusion and its preferred concentration of mineralization at Jinchuan intrusion are given in Fig. 15.19.

The super-large magmatic sulfide deposits occur in magmatic conduits as an open magma system providing a perfect environment for extensive concentration of immiscible sulfide melts along deep regional faults (Song et al., 2011). The deposit is divided into four segments by E—W to NE—SW-trending strike-slip faults displacing ultramafic body up to a kilometer in depth. Each segment represents a mine block and is referred to as Mine III (~500 m), Mine I (~1500 m), Mine II (~3000 m), and Mine IV (1100 m). Mines I and II intrusions are exposed to surface-hosting rich mineralization in dunite. Mines III and IV are covered by alluvium.

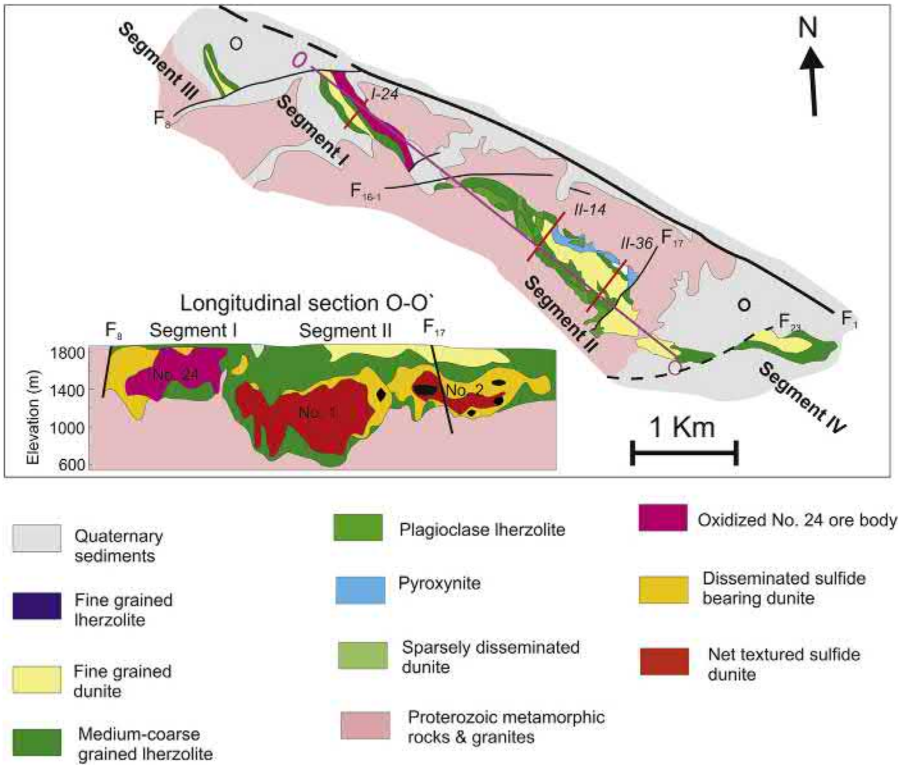

FIGURE 15.18 Geological map of Jinchuan ultramafic intrusion showing a super-large single Ni—Cu—PGE orebody extending over 6 km. *Song, X., Wang, Y., Chen, L., 2011. Magmatic Ni—Cu-(PGE) deposits in magma plumbing systems: Features, formation and exploration. Geosci. Front. 2(3), 375—384. Production and hosting by Elsevier.*

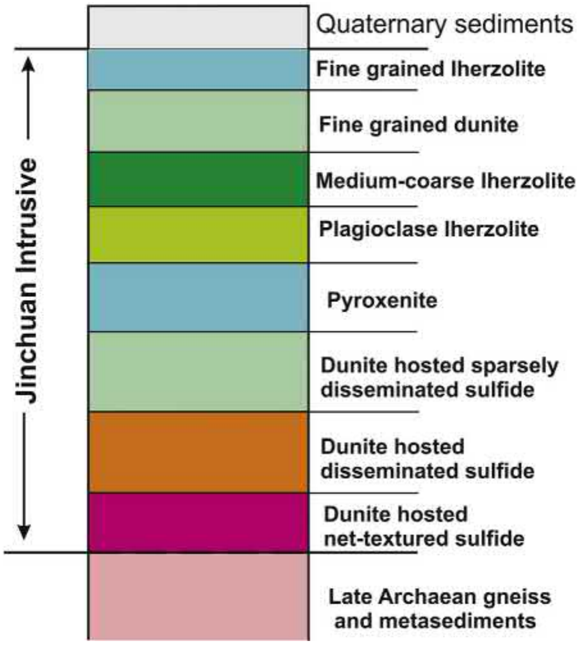

FIGURE 15.19 Stratigraphic sequence of ultramafic intrusion at Jinchuan Complex showing preferred concentration of sulfide mineralization in dunite host rock at basal layer. The individual unit discontinues in strike. *Haldar, S.K., 2016, Platinum–Nickel–Chromium Deposits: Geology, Exploration and Reserve Base, Elsevier Publication, p. 322.*

15.9.3 Exploration

The intrusive has been extensively drilled at regular interval cross-sections to delineate the host rock sequence and mineralization (Fig. 15.20).

15.9.4 Mineralization

The mineralization is rich in copper with an average Ni/Cu ratio of 1.76. The average PGE and gold concentration is moderately high at 1 g/t in sulfide ore (Naldrett, 2004). Sulfide orebodies occur in the middle and lower regions of the intrusion, with major orebodies of Mines I and II accounting for +90% of Ni–Cu reserves. Ore minerals include pyrrhotite, pentlandite, chalcopyrite, cubanite, mackinawite, and pyrite. Sulfide mineral is in abundance at the base. Nickel sulfides are dominant ores and occur as disseminated to net textured, with sulfide contents ranging between 1% and 40% by volume. The occurrence of massive sulfide ore is rare.

15.9.5 Reserve Base

The reserve base has been estimated at 515 Mt grading 1.18% Ni, 0.63% Cu, 0.019% Co, 0.13 g/t Pt, 0.10 g/t Pd,

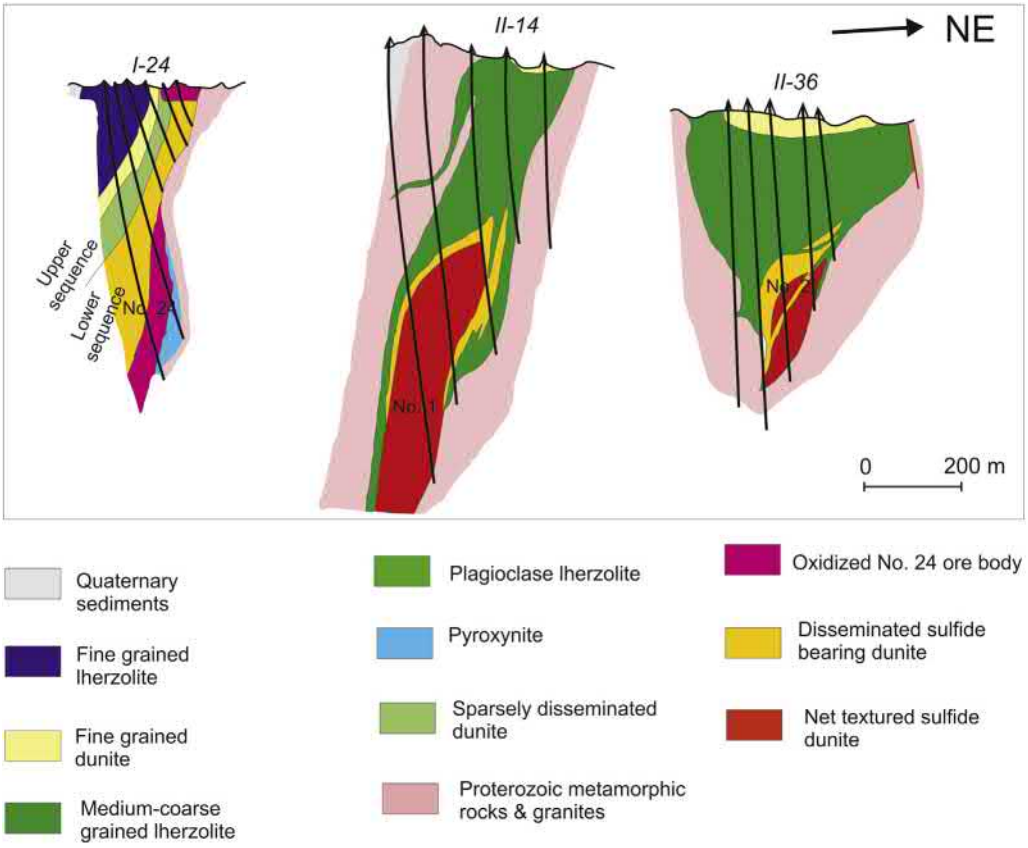

FIGURE 15.20 Geological sections of Jinchuan intrusion hosting Ni–Cu–(PGE) sulfide deposit. I-24, II-14, and II-36 are exploration section lines showing lithological succession, net texture, and disseminated and oxidized orebody. *Song, X., Wang, Y., Chen, L., 2011. Magmatic Ni–Cu-(PGE) deposits in magma plumbing systems: Features, formation and exploration. Geoscience Frontiers 2(3), 375–384. Production and hosting by Elsevier.*

0.005 g/t Rh, 0.010 g/t Ru, 0.010 g/t Ir, and 0.011 g/t Os, making a total PGE content of 0.26 g/t (Naldrett, 2004). Annual capacity of production includes 150,000 t of nickel, 600,000 t of copper, and 10,000 t of cobalt and PGE + gold.

15.10 RAMPURA-AGUCHA: THE SINGLE LARGEST AND RICHEST ZN—PB—AG DEPOSIT IN INDIA: GEOSTATISTICAL APPLICATIONS IN MINERAL EXPLORATION

Rampura-Agucha is the world's largest open pit zinc mine today with an annual ore production capacity of 6.0 Mt and matching beneficiation facility. The mine was commissioned in 1991. Rampura-Agucha is the single largest and richest known zinc-lead-silver orebody in India, comparable to world-class deposit, and the lowest-cost zinc producer globally.

15.10.1 Location and Discovery

The Rampura-Agucha deposit, (25°50′20″N, 74°44′47″E) is located 210 km southwest of the capital city Jaipur, and 230 km northeast of Udaipur city in Rajasthan, India (Fig. 15.21). It extends over a strike length of 1.6 km along NE—SW with steep dips (60—70 degrees) toward SE, and depth continues +1200 m from the surface.

Out of curiosity, Mr. T.C. Rampuria, a geologist at the state Department of Mines and Geology, Rajasthan, picked up a few pieces of colored, weathered rock samples (gossans) from a shallow depression of agricultural land during a routine inspection visit to a garnet quarry during August 1977. The samples indicated the presence of significant zinc and lead values. Repeated check analysis indicated similar values, and the world-class deposit was rediscovered by chance. Incidentally, the rich multimetal deposit of Neves Corvo was discovered in the same year as a unique geophysical success. Archaeometallurgical investigations in and around the Rampura-Agucha deposit unraveled the mysteries of mining and extraction practices for silver and lead metals by the ancients at around the fourth century BC.

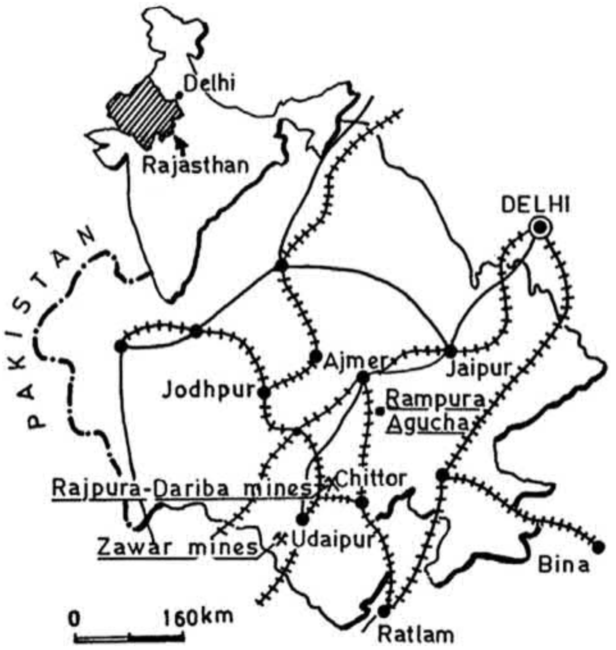

FIGURE 15.21 The world-class Rampura-Agucha deposit is located 210 km southwest of Jaipur and 230 km northeast of Udaipur, Rajasthan.

15.10.2 Regional Setting

Rampura-Agucha is a stratabound and stratiform, Paleoproterozoic (Roy and Purohit, 2018), sediment-hosted, high-grade zinc- lead-silver deposit. The stratigraphic sequence is grouped as:

1. Garnet-biotite-sillimanite gneiss (hanging wall)
2. Graphite-mica-sillimanite gneiss/schist (Zn—Pb—Ag ore)
3. Garnet-biotite-sillimanite gneiss (footwall)
4. Granite gneiss and mylonitic rocks (Archaean basement)

Garnet-biotite-sillimanite gneiss forms the predominant hanging wall unit in and around the deposit. The footwall section is composed of garnet-biotite gneisses with lenses of aplite and pegmatite. The host rock belongs to the Middle Aravalli Group of Paleoproterozoic age.

The major structural feature is interpreted as northerly plunging isoclinal synform with core occupied by the host rock. The rocks suffered three successive phases of deformation. The deposit occurs in highly metamorphosed Paleoproterozoic rocks conformable with surrounding Archaean gneisses by the presence of garnet and sillimanite, and lack of muscovite. Garnet has been altered to biotite indicating retrograde metamorphism. All mineral assemblages represent a high-grade metamorphic condition.

15.10.3 Mineralization

The single orebody is massive with sharp contact. The major opaque phases are sphalerite, pyrrhotite, pyrite, galena, and graphite with minor chalcopyrite, arsenopyrite, and tetrahedrite-tennantite.

15.10.4 Genetic Model

The high-grade metamorphism of upper amphibolite facies and strong deformation have obliterated all primary features. Carbon isotope study indicates the origin of abundant graphite content in ore as a biogenic derivation. A sulfur isotope study of sphalerite suggests that the orebody possibly recorded a profuse influx of metalliferous fluids in a proximal paleo-trough from which sulfides rapidly precipitated. It also incorporated relatively undiluted hydrothermal sulfur. This sulfur originated from a higher degree of inorganic reduction of seawater sulfate or basaltic sulfur from the abundant tholeitic sills in the footwall mineralization. Large carbonaceous constituents of graphite-mica-sillimanite schist host along with the strata-bound and stratiform nature of orebody suggest a sediment-hosted Zn—Pb—Ag (SEDEX)-type ore deposit. The model Pb age of the deposit is 1804 Ma.

15.10.5 Size and Grade

The reserves and resources of Rampura-Agucha Mine as of April 1, 2017 stand at 103.80 Mt at 14.00% Zn, 1.80% Pb, and 63 g/t Ag. The mine achieved 4.71 Mt of ore produced during the preceding year against an annual production capacity of 6.15 Mt due to interchanging between open pit and underground mining methods (source: Hindustan Zinc Limited Annual Report, 2017). About 60 Mt was produced until 2017 from a single open pit.

15.10.6 Mine Operation

The open pit mine is highly mechanized with a 34 m^3 excavator and 240-t dumpers for excavation of ore and waste.

Development and production from the underground operation have already begun to gradually replace open pit, which is expected to end by 2018—19, after ~30 years of life. The new operation is supported by a vertical shaft 950 m deep, two ventilation shafts, and two trackless decline/reams from the surface.

Processing facilities use rod and ball and a semi-autogenous grinding mill in combination, as well as froth flotation to produce zinc and lead concentrates. The concentrator is equipped with a process control system and multistream analyzer to facilitate effective quality control. Metal extraction is by in-house smelters. The tailing is disposed to an especially constructed on-site tailing dam with a layer of impervious soil at the bottom. Tailing water is settled, recovered, and recycled for industrial uses compliant with the zero discharge principle.

15.10.7 Geostatistical Applications in Mineral Exploration

Mineral exploration requires high investment, sustained cash inflow, and considerable time with inherent high risk. Exploration drilling is planned in a grid pattern to be conducted in sequence to facilitate midterm assessment of quality, quantity, and reliability of the estimates. Traditional procedures are unable to provide the degree of reliability/confidence limits. The application of mathematical models can quantify global precision and bring forth decision-making criteria at the end of each stage. These techniques evaluate sequential exploration data to optimize sampling for specific objectives. It helps in decision-making to continue or to keep the project in abeyance (Haldar, 2007). The standard available procedures are: theory of probability distribution, frequency, mean, variance, standard deviation, trend surface, semivariogram, and kriging. Drill samples share a major part of investment during exploration and justify critical analysis at every phase. The ongoing drilling program is modified accordingly. Statistical/geostatistical methods are equally appropriate during mine production and at the time of mine closure.

15.10.8 Exploration Scheme

Surface manifestations supporting economic mineral deposits at Rampura-Agucha are deciphered by weathered and gossanized cover rocks, malachite encrustation, mine debris and slag heaps on either side of a shallow depression, shaft and drive-like excavations reflecting ancient mining, and smelting activities in the area. M/s Hindustan Zinc Limited formulated a systematic exploration scheme (Fig. 1.4 and Table 15.6) guided by the surface signatures and results of the first borehole of the state Department of Mines and Geology, government of Rajasthan. The program was planned conceptually with a sequential evaluation model to achieve specified objectives.

The first three phases cover the upper 400 m depth followed by Phases 2, 3, and 4 for probing depth extensions of gossans and orebody (Fig. 15.22). The exploration program comprised 18,095 m of surface drilling in 133 boreholes, and was executed in a timeframe of 2 years (1980—82).

15.10.9 Database

The final exploration input, up to 400 m vertical depth, includes 24,900 m of surface drilling in 229 boreholes at 50 m × 50 m and 25 m × 25 m grid, 256 m of drilling in six underground boreholes, and 567 m of exploratory development (1980—82). The raw sample data, deviation survey, rock type, assay, and specific gravity are codified into database. The sample data is transformed into equal lengths of 1 m for general statistics and 5 m composites for geostatistical studies related to subblock-grade estimation using in-house and commercial software. The database is continuously updated with ongoing borehole assay input. An additional 24,000 m of drilling was completed during 2007—08 to explore and establish the continuity of ore up to 1200 m depth from the surface.

TABLE 15.6 Phased Exploration Scheme to Be Conducted in Sequence

Phase	Drill Interval (m × m)	Meters Drilled	No. of Boreholes	Objectives
1	200 × 50	2,948	18	Establish broad potential (25—30 Mt) over the strike length and laboratory-scale metallurgical tests
2	100 × 50	2,939	18	Firmly establish reserves, grade, and bench-scale metallurgical tests, preparation of detail project report (DPR), conceptual mine planning, and investment decision
3	50 × 50	6,011	36	Precision in estimates, database for detailed production planning, grade control, and pilot plant tests
4	Close space near surface, wide space at lower levels	6,197	61	Delineation of gossans, old workings, extension of orebody up to 300 m vertical depth from surface
	Total	18,095	133	2 years' time at (Rs) ₹ 12.5 million

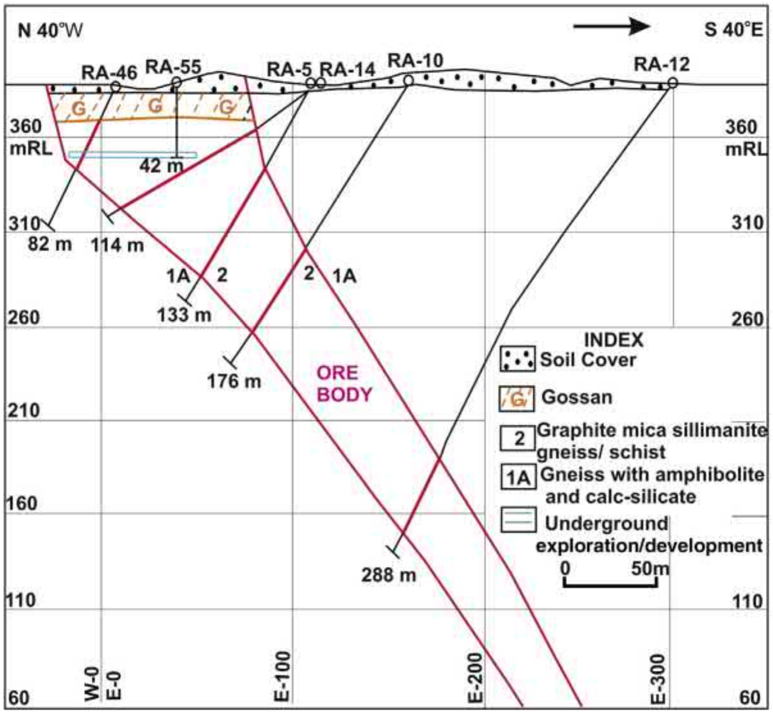

FIGURE 15.22 Drill section of Rampura-Agucha deposit probing depth extension of gossans and orebody (1982).

15.10.10 Quality Control and Quality Assurance

Quality control and quality assurance analyses are maintained following international protocol by the insertion of blanks and standards at regular intervals. Three statistical tests are conducted before accepting the sample data:

- Sample bias by testing the original half against the duplicate half of the diamond drill core (Fig. 15.23 and Table 15.7).
- Assaying bias by inserting duplicates, blanks, and standards at intervals of industry-accepted protocol (Table 15.7).
- Interlaboratory bias (home [India] and standard international laboratory [Canada]).

The results, scatter plot, and statistical analysis (Fig. 15.23 and Table 15.7) obtained indicate statistical significance with high accuracy. The exploration database is intrinsically reliable and accepted for estimation of reserves and resources.

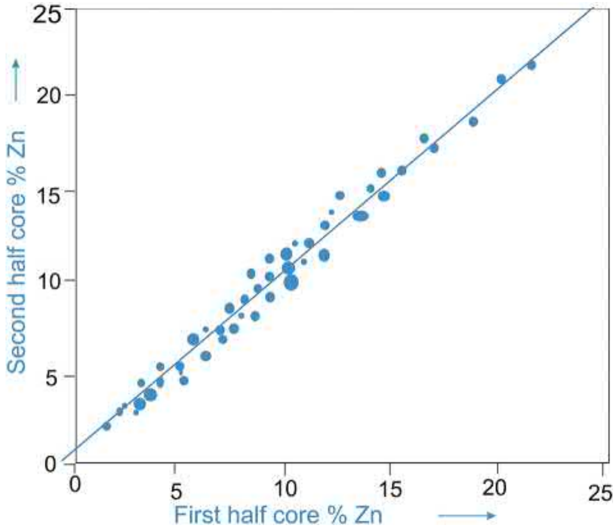

FIGURE 15.23 Scatter plot of original and duplicate half core sample values confirms significant statistical reproduction.

TABLE 15.7 Results of Quality Control/Quality Assurance Check Studies Between Two Halves of Drill Core, Repetitive Analysis in the Same Laboratory, and Other Standard Laboratories

Parameters	Original Versus Duplicate Half Core	Random Repeat Including Blanks and Standards	Interlaboratory (India/Canada)
No. of samples	123	990	46
Average of 1st set (% Zn)	10.99	11.04	10.27
Average of 2nd set (% Zn)	11.11	11.04	10.15
F value	1.02	1.00	1.13
Paired t value	0.66	0.09	0.35
Correlation coefficient (r)	0.97	0.97	0.97

15.10.11 General Statistical Applications

Histograms of 8570 drill core samples at 1 m lengths for zinc, lead, and iron have been plotted for distribution pattern, and revealed distinct bimodal, positively skewed, and normal distribution for zinc, lead, and iron, respectively. The samples are composited to 5 m (1181 numbers) for mine subblock estimation, and also represent a similar distribution pattern. The 1 m samples are utilized for estimation of deposit grade and confidence limits applying a normal statistical mode. The probability plot of the cumulative distribution of zinc and logarithmic probability of lead were attempted for comparison. Summary statistics using various methods are shown in Table 15.8. The global average grades and confidence limits have been accepted as estimated by normal statistical procedures.

TABLE 15.8 Summary Statistics of Estimates for Zinc-Lead and Iron by Normal, Probability, and Lognormal Procedure

Estimation Method	Zinc	Lead	Iron
No. of 1 m drill core samples	8570	8570	8570
Arithmetic			
Mean grade %	13.48 ± 0.17	1.93 ± 0.03	8.20 ± 0.07
Variance	63.20	3.26	10.42
Normal Probability			
Mean grade %	13.20 ± 0.15	–	8.20 ± 0.08
Variance	51.84	–	14.44
Logarithmic Probability			
Mean grade %	–	1.65 ± 0.02	–
Variance	–	0.62	–

15.10.12 Isograde Maps

Isograde maps along the composite longitudinal vertical section indicate identical disposition of primary metals, broad geological domains, and correlation imprint within each envelop. Zinc (Fig. 15.24), lead, and silver metals each increase toward the north, while iron and mineralized width decrease. The periodicity, and north plunging predominance of high and low (peaks and troughs) are repetitive between 200 and 300 m intervals along strike. Zinc and lead have a fairly good affinity (r = 0.75) in the north half of the orebody. Silver has a close association with either lead or occurs independently.

15.10.13 Semivariogram

3D semivariograms of 5 m composite assay values for zinc, lead, and iron are computed along and across the strike, plunge, and vertical depth of orebody on different options of step tolerance and angular regularization. The experimental semivariograms and the fitted spherical model for zinc and spatial variability parameters along four directions are given in Table 15.9.

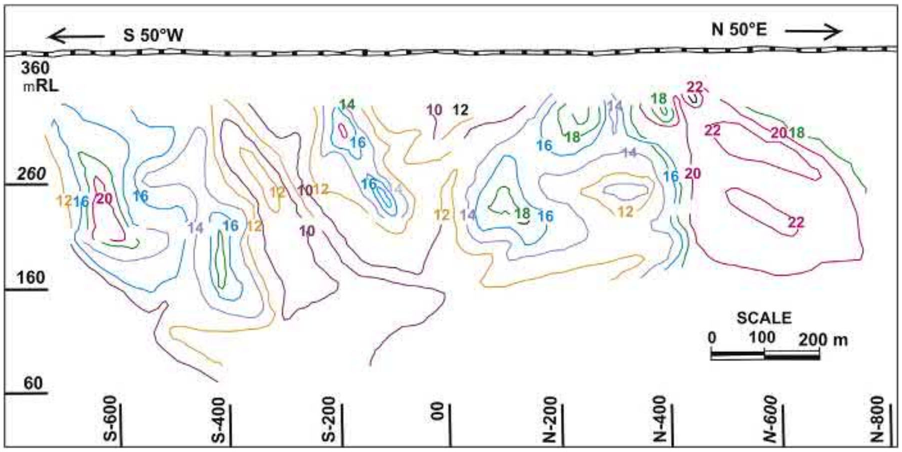

FIGURE 15.24 Isograde map of zinc indicates repetitive high and low metal concentration and periodicity along the longitudinal direction of the orebody.

TABLE 15.9 Global Semivariogram Parameters for Zinc

Parameters	Strike	Down the Hole	Plunge	Down Dip
Step interval (m)	25	5	25	25
Angular regularization	45°	45°	45°	45°
Population variance	57.92	57.92	57.92	57.92
Random variability	14.00	7.10	38.00	7.10
Structured variability	43.92	50.82	19.92	50.82
Range (m)	115	35	100	90

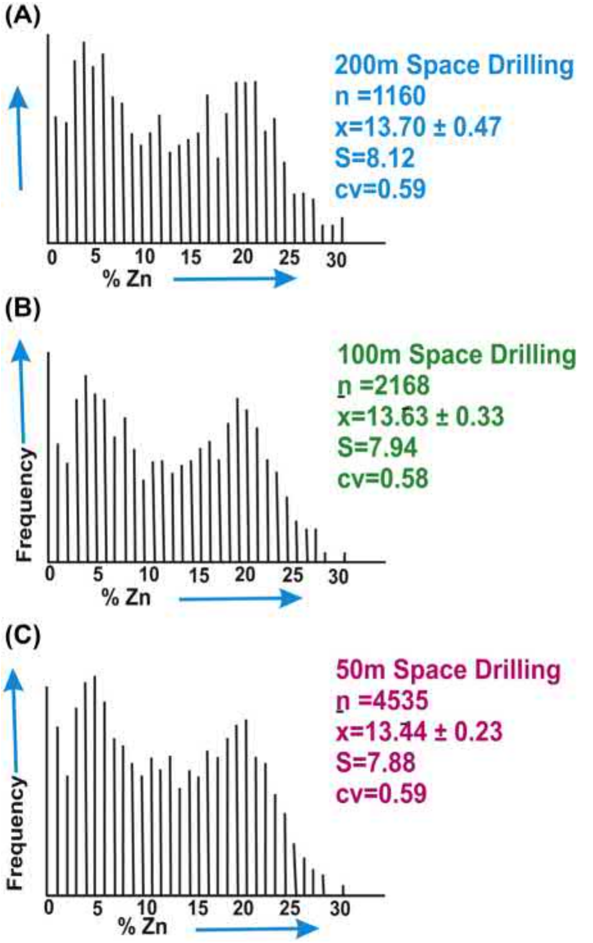

FIGURE 15.25 One meter Zn frequency distribution plot and statistical parameters of upper 400 m vertical depth: (A) 200 m × 50 m, (B) 100 m × 50 m, and (C) 50 m × 50 m grid.

15.10.14 Sequential Evaluation Model

The outcome of 1 m drill core samples from an upper 400 m vertical height analyzed by sequential evaluation models at the end of Phase 1 (200 m × 50 m), Phase 2 (100 m × 50 m), and Phase 3 (50 m × 50 m) was assessed by (1) frequency, (2) probability, and (3) semivariogram.

15.10.14.1 Frequency Model

The 1 m samples at optimum cut-off were analyzed employing statistical techniques at the end of each exploration phase. The zinc frequency plot represents a bimodal distribution with two modes around 5% and 20% Zn. It is evident from the frequency plot (Fig. 15.25A–C) that the pattern of population distribution is identical in three phases of drilling.

Percentage variation over mean grade has changed from ±3.43% at 200 m × 50 m to ±1.71% at 50 m × 50 m interval drilling at the 95% probability level. The percentage variation in tonnage confidence has improved from 18% to 9%, respectively. The comparative statistics are summarized in Table 15.10.

Grade precision is marginal with sequential drilling, and has given confidence to global estimation. Tonnage confidence has improved in progressive drilling and is adequate at 100 m × 50 m interval drilling for investment decision.

15.10.14.2 *Probability Model*

The probability model can be used to test the adequacy of sampling within the space of mean and standard deviation of the sample population under the study area. The mean assay and mineralized width, corresponding standard deviation, and their confidence limits are computed (Table 15.11).

TABLE 15.10 Grade-Tonnage Parameters at the End of Each Phase of Exploration

	Borehole Spacing		
	200 m × 50 m	100 m × 50 m	50 m × 50 m
No. of boreholes	18	36	72
Meters drilled	2,948	5,887	11,898
No. of 1 m samples	1,160	2,168	4,535
Mean grade % Zn	13.70	13.63	13.44
Standard deviation	8.12	7.94	7.88
Confidence limit at 95% level	±0.47	±0.33	±0.23
% variation	±3.43	±2.42	±1.71
Tonnage in million tonnes	24.78	24.42	25.22
Confidence limit at 95% level	±4.57	±3.53	±2.29
% variation	±18.4	±14.5	±9.0

TABLE 15.11 Mean and Standard Space (Probability Model) for Zinc, Mineralized Width, and Tonnage at the Completion of Three Phases of an Exploration Program

	Mean	$\overline{X}$ Limits at 95% Level		Standard	Standard Limits at 95% Level	
No. of Boreholes	$\overline{X}$	Lower	Upper	S or σ	Lower	Upper
Zinc Grade (%)						
18	13.70	13.22	14.16	8.12	7.79	8.45
36	13.63	13.30	13.96	7.94	7.70	8.18
72	13.44	13.21	13.67	7.88	7.72	8.04
Mineralized Width (Meters)						
18	61.22	50.52	71.92	23.16	15.59	30.73
36	59.76	51.65	67.87	24.82	19.09	30.55
72	61.51	55.98	67.04	23.96	20.05	27.87
Tonnage in Upper 100 m (Mt)						
18	24.78	20.27	29.29	23.16	15.59	30.73
36	24.42	20.89	27.95	24.82	19.09	30.55
72	25.22	22.93	27.51	23.96	20.05	27.87

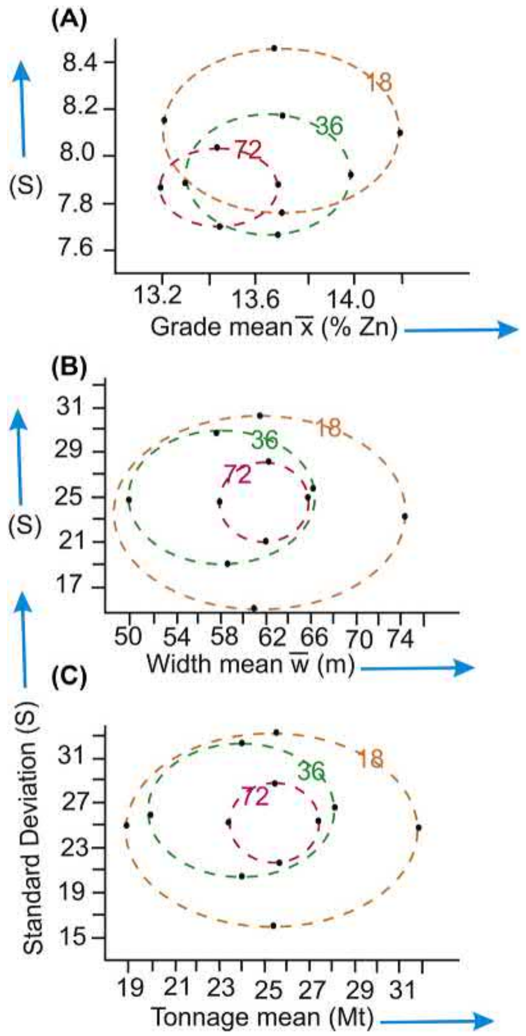

FIGURE 15.26 Probability areas representing results of sequential drill analysis: (A) zinc, (B) width, and (c) tonnage with increased sample.

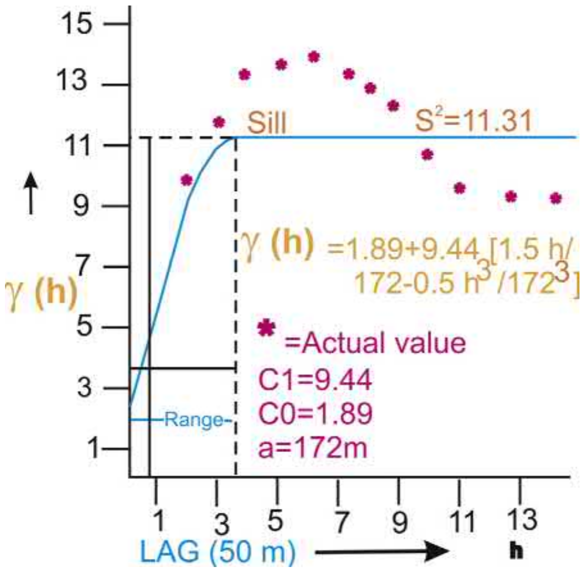

FIGURE 15.27 Global semivariogram of zinc along the strike showing unexplained variance and influence of samples.

These limits, around their respective means, when plotted on an x-y coordinate system (assay, width, and tonnage on the x-axis and their respective standard deviations on the y-axis) would delimit an area statistically defined as the grade-tonnage space in which the true population mean and standard deviation are expected to exist (Fig. 15.26A–C). The probability area approximates an elliptical configuration defining a region of 90% probability indicating that the point representing the true population mean and standard deviation for the deposit would plot within this region. The size of probability region reduces with increase in samples. Such progressive probability regions for cumulative confidence limits of the mean and standard deviation would indicate improvement in the estimate of average grade, width, and tonnage. Reduction in probability area with an increase in drilling is indicative of improvement in precision. It is evident that after completion of Phase 2 drilling, the project does not warrant any further improvement for investment decision.

15.10.14.3 Semivariogram Model

The statistical models enumerated earlier are based on the firm assumption of continuity of ore between holes. A geostatistical semivariogram model of grade and width on mineralized intersections along different directions can confirm this continuity or otherwise. The global semivariograms along the strike for zinc composite grades (Fig. 15.27) are fitted to the spherical model. The semivariograms show moderate unexplained variance ($C_0 = 1.89$) and range of sample influence ($a = 172$ m) for estimation.

Similarly, the global semivariogram along the strike for mineralized widths (Fig. 15.28) is fitted to the spherical model. The semivariogram depicts no nugget effect ($C_0 = 0$) and a high range of sample influence ($a = 555$ m) for estimation.

15.10.15 Estimation Variance and Optimization of Drill Hole Spacing

Grade and tonnage precision with increasing number of drill hole samples using the semivariogram model is depicted in Table 15.12 (refer to Chapter 9 for estimation procedure).

The number of boreholes in the x-axis and corresponding precisions in the y-axis at respective drill intervals from Table 15.12 are plotted in Fig. 15.29. The curve becomes flat and stable after drilling at 100 m × 50 m intervals. It clearly

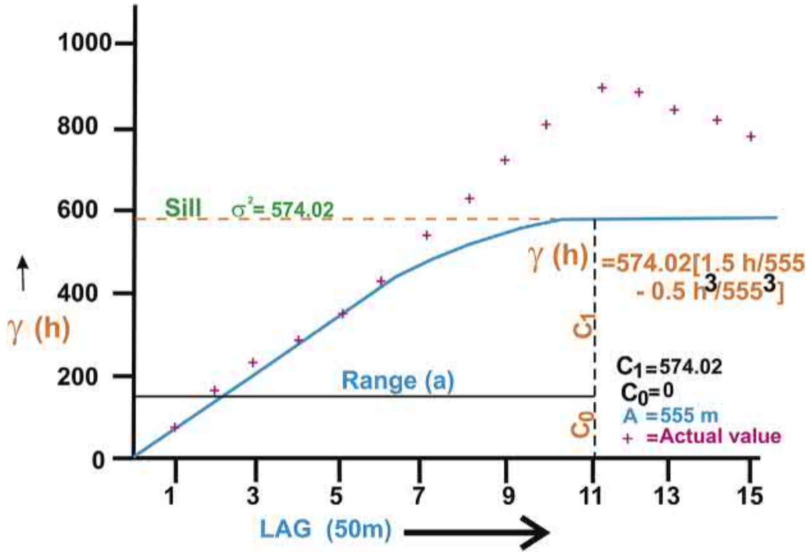

FIGURE 15.28 Global semivariogram of mineralized width along the strike showing no nugget effect and long range of sample influence.

TABLE 15.12 Errors of Estimation at Different Drill Hole Spacings

Drilling Grid						
Strike "h"	Depth "L"	No. of Boreholes	Estimation Variance σ^2e	Standard Deviation σe	Confidence Limit (±)	% Variation Around Mean
Zn Grade						
200 m × 200 m		7	3.54	1.88	1.39	10.37
200 m × 100 m		14	4.15	2.03	1.07	7.95
100 m × 100 m		24	2.83	1.68	0.67	5.00
100 m × 50 m		36	3.09	1.76	0.57	4.20
50 m × 100 m		48	2.15	1.47	0.42	3.10
50 m × 50 m		72	2.30	1.51	0.35	2.60
Mineralized Width						
200 m × 200 m		7	30.42	5.51	4.08	6.67
200 m × 100 m		14	45.92	6.78	3.54	5.79
100 m × 100 m		24	16.07	4.01	1.60	2.68
100 m × 50 m		36	20.09	4.48	1.46	2.45
50 m × 100 m		48	6.31	2.51	0.71	1.16
50 m × 50 m		72	9.18	3.03	0.70	1.13

suggests that further drilling marginally improves the confidence. Additional drilling beyond this stage is necessary for precise mine planning and dilution control.

The exploration data at the end of each phase are processed using statistical and geostatistical models for precision and adequacy to achieve specific objectives. Rampura-Agucha exploration data processed by frequency, probability, and semivariogram models indicate that drilling at 100 m × 50 m space provides adequate confidence for a definitive feasibility report leading to investment decision. Additional drilling at 50 m × 50 m will endorse mine design and subblock grade estimation control.

The chance rediscovery of the single largest zinc-lead-silver orebody on the surface at Rampura-Agucha created a position in the world map for the cheapest mine production cost and largest production of 6 Mt of ore from a single source. India has been elevated from zinc metal importer to exporter of zinc concentrate and metal.

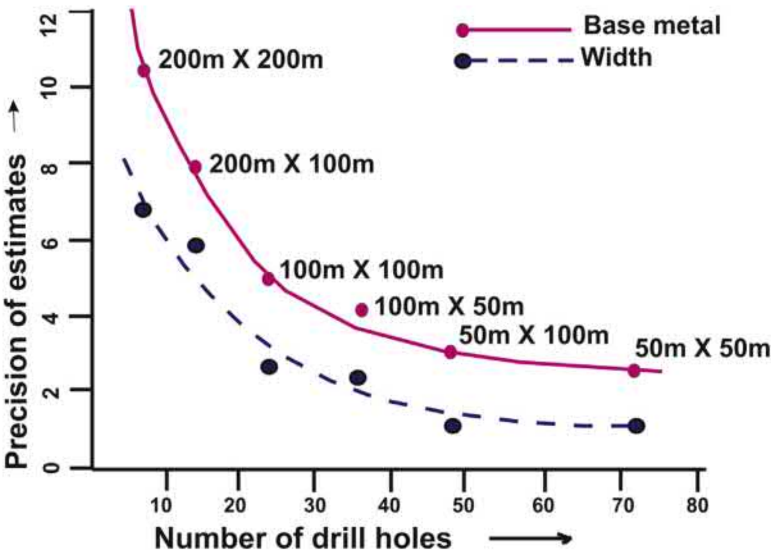

FIGURE 15.29 Precision of estimation versus drill hole spacing that indicates the adequacy of sampling leading to investment decision.

15.11 JHAMARKOTRA, INDIA: DISCOVERY OF THE LARGEST STROMATOLITIC ROCK PHOSPHATE DEPOSIT BY GEOLOGICAL MODELING AND EXPLORATION TO ENVIRONMENT MANAGEMENT PRACTICES: A HOLISTIC APPROACH

Phosphorus (P) or phosphate (P_2O_5) is indispensable as an important plant nutrient for the growth of agricultural productivity using single superphosphate (SSP), and phosphoric acid as fertilizer, chemicals, and medicinal uses. Rock phosphate is not an effective substitute nor can it be recycled. It occurs as igneous deposits (inorganic) of fluorapatite (CaF), $Ca_4(PO_4)_3$, with 42% P_2O_5 and chlorapatite, $(CaCl)Ca_4(PO_4)_3$, with 41% P_2O_5. Another type is sedimentary (organic) rock phosphate or phosphorite with 14%—34% P_2O_5.

Fertilizer resources and production play a pivotal role in the economic growth of agriculture-based countries. The top phosphate reserves and annual production of various countries in 2016 are: China (3.1 Bt reserves and 138 Mt production), Morocco and Western Sahara (50 Bt reserves), United States (1.1 Bt reserves and 27.8 Mt production), Russia (1.3 Bt reserves and 11.6 Mt production), Jordan (1.2 Bt reserves and 8.3 Mt production), Brazil (6.5 Mt production), and Egypt (1.2 Bt reserves and 5.5 Mt production). Other potential countries are Saudi Arabia, Peru, Israel, Tunisia, and Vietnam.

India meets about 35%—40% of the requirement of raw material for phosphate fertilizer through indigenous sources. The rest is imported in the form of rock phosphate, phosphoric acid, and direct fertilizers. Indian phosphate deposits are situated at Udaipur, Mussoorie, Lalitpur, Hirapur, and Jhabua.

15.11.1 Location and Discovery

The Jhamarkotra deposit (24°28′N, 73°52′E) is the largest rock phosphate-bearing stromatolite colony in the world. Jhamarkotra is one of the largest and fully mechanized open pit mines and contributes 98% of production in India. It is located 26 km southeast of Udaipur city.

GSI mapped the area during the 1950s as a limestone bed showing typical elephant skin color and crocodile skin texture. GSI missed the phosphate belt hidden in Archean host rocks of +2000 million years old. Prof. R.P. Sheldon, a noted phosphate authority at the US Geological Survey, conceived and postulated a knowledge-based model that was unconceivable at the time. The proposal of the existence of stromatolitic phosphates of 1300—2000 Ma around Udaipur came as a complete surprise. Thereafter GSI discovered Kanpur and Maton deposits during 1968 (adjacent to Jhamarkotra village) on a routine geochemical survey for phosphate in the mid-1960s. The state Department of Mines and Geology, Rajasthan, was rewarded with the discovery of the Jhamarkotra rock phosphate deposit on June 30, 1968 while searching for the elephant skin-colored and crocodile skin-textured stomatolitic phosphorite (Fig. 15.30). The deposit is the oldest (2000 Ma) and largest, and is of outstanding commercial significance (richest) having more than 80% proven reserves in India.

FIGURE 15.30 Profuse growth of stromatolite colony with elephant skin color and crocodile skin texture on the surface at Jhamarkotra is an outstanding exploration field guide.

Within a year of discovery (1969–70), 82,000 t of high-grade ore (HGO) were mined. From 1968, surface outcropping and the acute necessity of phosphate prevailing at the time resulted in the unconventional, primitive, pick-axe mining operation of HGO concurrently with exploration, following an "earning while learning" ideology.

15.11.2 Regional Settings

The regional settings of the Jhamarkotra deposit belong to the Lower Aravalli age (Early Proterozoic) and are:

Post-Aravalli granite.
Greywacke
Arkose and conglomerate
Basal quartzite and volcanics.
Banded gneissic complex.

15.11.3 Host Rocks

The host rock is stromatolitic, blue green, algae-rich dolomite-limestone in a closed basin environment. Polyphase folding, faulting, deformation, weathering, and leaching have resulted in an enriched HGO.

15.11.4 Mineralization

The stratified phosphate horizon is sandwiched between dolomite-carbonate sediments and represents a columnar biogenic sedimentary structure called stromatolite (refer to Fig. 1.23). The columnar interspace is made of dolomite.

15.11.5 Genetic Model

The stramatolitic phosphate-bearing bed in Jhamarkotra represents a thick pile of sedimentary package formed under a shallow epicontinental sea of Lower Aravalli age. The origin is linked to the metabolic activity of a certain primitive lifeform.

15.11.6 Exploration

Progressive exploration between 1970 and 1980 by the state Department of Mines and Geology concurrently with mine development and production by Rajasthan State Mines and Minerals Limited included regional mapping of Jhamarkotra basin, plain table précised mapping of a 16 km long phosphate bed, 500 pits and trenches, 18,000 channel samples, and 60,000 m of diamond drilling in 600 boreholes at an interval of 100 m strike and 50 m inclined depth (Fig. 15.31). The exploration established a 16 km linear stretch of phosphate bed and outlined major reserves at "A" to "D" blocks. The surface elevation varies between

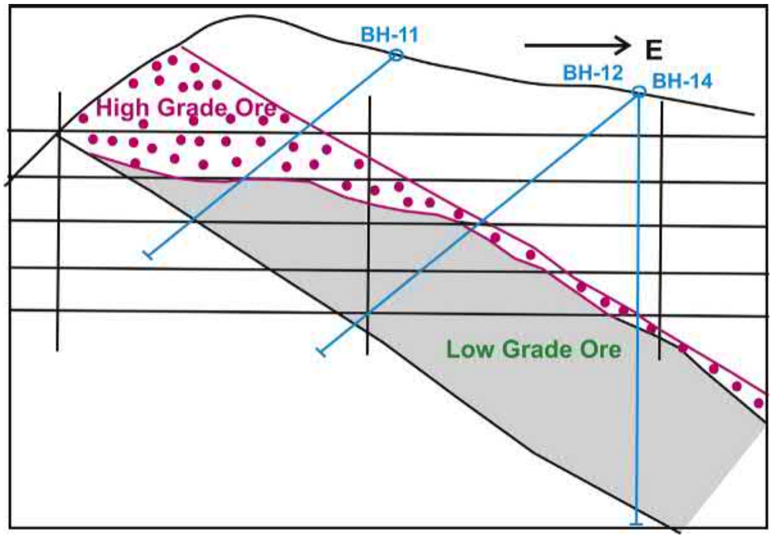

FIGURE 15.31 Standard cross-section showing the drilling pattern at Jhamarkotra rock phosphate deposit.

FIGURE 15.32 Robust crawler chain-mounted wagon drill in operation at Jhamarkotra rock phosphate mine, which drills at a 5−10 m bench height and is easy to move to hole sites.

600 and 200 mRL. The thickness of the phosphate bed varies between a few centimeters and 35 m with an average of 15 m.

15.11.7 Size and Grade

The D block with an extension of 1500 m shares the maximum reserve and grade. Mining activities are mainly in the D block. The A block is next in order. The other blocks (B, C, and E) have little resources with low grade.

HGO is represented by 16 Mt at 33% P_2O_5, 12% SiO_2, 1.6% MgO, and 2.6% R_2O_3. LGO is comprised of 36 Mt at 18% P_2O_5, 8% SiO_2, 10% MgO, and 2% R_2O_3 making a total of 52 Mt at 22% P_2O_5, 9% SiO_2, 7.5% MgO, and 2% R_2O_3 as of April 2008.

15.11.8 Mining

Conventional open pit mining, blending, and processing of HGO and LGO started from 1985. The pit slope at the footwall is between 32 and 50 degrees, and at the hanging wall it is between 42 and 50 degrees. The overall ore-to-overburden ration is 1:8.7. The mining machinery deployed are the jackhammer, crawler-mounted wagon (Fig. 15.32), infrared and reverse circulating drilling units, hydraulic front-end loader, and 50−90 t dumpers.

Cumulative ore handling between 1970 and 2008 was 26 Mt (HGO + LGO) of ore and 272 Mt of overburden making a total rock handling of 298 Mt at an ore-to-overburden ratio of 1:10.50. Annual production continues at about 2 Mt of HGO and LGO. The entire stretch of the open pit mine in D and A blocks has reached its bottom pit limit (Fig. 15.33) from 600 to 200 mRL.

FIGURE 15.33 Entire stretch of A and D block at Jhamarkotra phosphate deposit has been mined for a vertical height of 400 m, and has reached the ultimate open pit mine bottom. A group of geoscientists assembled on a mine visit.

15.11.9 Beneficiation

The beneficiation of low-grade rock phosphate includes crushing, grinding, and milling followed by the conventional froth flotation route. About 0.60 Mt of fine tailing fraction in slurry form are generated annually.

15.11.10 Environment Management

Environmental matters were conceived by management from the inception of the mine with a view to addressing them compassionately. Issues, as and when identified, were resolved by appropriate matching actions. The salient features were:

- Geomorphic and demographic aspects—land use
  +60 years of ultimate mine life will result in the formation of a huge serpentine gorge, 7 km long, 700 m across, elevation height between 600 and 320 mRL, and the formation of a few artificial massive waste mounds flanked by two micro-watershed regimes. The mine lease area of 1379 ha included 270 ha of de-reserved forest land. There were 12 surrounding villages occupying 30% of 6946 ha of land. The villages were populated by 7394 tribal inhabitants on a subsistence economy. Migration and rehabilitation were obligatory, as was social responsibility. This was taken care of by minimal displacement and disturbance to villages and villagers, even falling within the leasehold.
- Waste rocks disposal—overburden
  The classified forest area within the leasehold was de-reserved to accommodate 450 Mt of waste (173 million m^3) right on the edge of D block considering minimum haulage, maximum waste accommodation capacity with least horizontal spread, and the capacity to withstand the load. The boundary limits of the progressive dumping ground in the de-reserved forest area were demarcated by stone walls. Transportation was made by large dumpers and bulldozers. The stages of dumping were maintained by horizontal movement and vertical lift. The west dump areas did not affect the agricultural land or village premises. Reclaimed land was used for infrastructure development, beautification, parks, and playgrounds.
- Fines waste disposal—mine and beneficiation plant
  Handling of 0.60 Mt of fine wastes from mine and beneficiation plant annually was a matter of concern. Fixed sprinklers ensured effective dust suppression in the dumping and crushing areas. Mobile sprinklers were deployed along the haulage road to suppress dust emission. Beneficiation plant rejects in slurry form were filled to a tailing pond through a pipeline. The tailing pond was designed with zero water discharge, recovery, and recycling for industrial usage. An extensive plantation was made on an old tailing dam to arrest flying dust, particularly in summer months.
- Air
  The effect of relay blasting gas was minimized by explosives selection, evacuation of miners from blast areas, and waiting for dust to settle.
- Noise and vibration
  The effect of noise and vibration was minimized by proper selection of machinery and correction at manufacturer level.
- Effluent treatment from tailing ponds
  An acid water treatment plant was installed to recover from the tailing pond and used for industrial purposes.
- Water management plan
  A captive dam was constructed to arrest the flowing monsoon water from the Jhamri river catchment area, and stored in a reservoir. The water is drawn from intake wells and filtered. Potable water was supplied to the mine township, Jhamarkotra, and surrounding villages, and to Udaipur city. A garden and guesthouse were developed around the dam site for picnicking and social amusement.
- Afforestation
  The company made an ecofriendly gesture by planting neem (*Azadirachta indica*) saplings on level dumping ground as a backdrop to a raised waste dump. *Jatropha* (Euphorbiaceae family) was planted for fuel oil, along with other types of plant species that would flourish around the mine and road sites.
- Health care
  A fully equipped and free medical dispensary with senior doctors existed at the mine site to attend to routine health care issues of employees' families and local tribal villagers. The management established cardiothoracic and spiral CT scan units at Udaipur city Government Medical College and Hospital to treat as a priority employees' families and tribal villagers as and when referred by mine medical officers.
- Education
  The company set up a higher secondary school at the mine colony to spread education around the villages and organize computer awareness. An industrial training institute and vocational training center were established with hostel facilities for tribal students.
- Economy
  Direct and indirect employment, including discovery, exploration, mine development, and reaching full capacity production, significantly raised the living standards of all types of people. Other benefits to the nation were the payment of (Rs) ₹ 50 million to state coffers over 37 years for state developmental works and (Rs) ₹ 12 million per annum as royalties to the state government for infrastructure development, and many more.

FIGURE 15.34 Mother protects a child with warm comfort and utmost care. Similarly, the mining companies must treat the affected community with compassion.

The total management philosophy of care with compassion is reflected in Fig. 15.31, and mineral exploration continues the next day (Fig. 15.34).

The Jhamarkotra rock phosphate deposit is an ideal greenfield discovery of concept-based geological modeling in mineral exploration. The mine has taken care of many environmental issues with compassion and greatly contributed to agricultural growth of the country.

15.12 BASE METAL DISCOVERY TREND: THE LAST 50 YEARS IN INDIA

The second half of the 20th century was regarded as the golden age of mineral exploration—a time for major geoscientific breakthrough for base metal mineral discovery in India. The global development of mineral-based industries during the preceding 50–60 years experienced phenomenal growth, and for India it is no different. A number of Proterozoic stratiform, sediment-hosted, large copper-zinc-lead-silver deposits were discovered, and developed attributes and models of some major deposits in India, Australia, and Canada (Ross et al., 2004). For centuries, Indian mineral explorations had been historically focused mainly on coal, iron ore, manganese, and mica. A number of interesting events occurred in the 1940s—World War II ended and at last, a free new India was born. The emerging Republic of India visualized a new perspective and formulated 5-year plans in tune with the infrastructural development of the country as a whole. Over the years, the government incorporated various public sector undertakings, such as the Oil and Natural Gas Commission in 1956, the National Mineral Development Corporation in 1958, the Bharat Aluminium Company in 1965, Hindustan Zinc Limited in 1966, Hindustan Copper Limited in 1967, Uranium Corporation India Limited in 1967, Bharat Gold Mines Limited in 1972, and the Steel Authority of India Limited in 1973. These public sector undertakings were entrusted with the mission of exploration, development, and production of public consumable and marketable mineral base end products. This triggered extensive new searches for petroleum, coal, bauxite, gold, iron ore, zinc-lead, copper, uranium, and many others. Perhaps for the first time in Indian history the earliest recordings of Kautilya's *Arthashastra* were realized. Kautilya (Chanakya) was a scholar, teacher, and guardian of Emperor Chandragupta Maurya, the founder of the Mauryan Empire. This "treatise on economics" (327 BC) described an extensive search, and research was undertaken in mineral industries in ancient India. This topic focuses on the base metal (zinc-lead-copper) discovery trend rather than sampling a few significant, singular, giant-type deposits.

15.12.1 Significance of Investment Framework

The process of mineral discovery is more associated with high risk compared to any other investment opportunity. The minerals are indispensable and their discovery is essential for the growth of any nation. The fundamental shift in postindependence national character empowered the new generations looking for adventure in the mineral sector. The amount of investment and risks associated with discovery-type greenfield/brownfield and exploration stages such as reconnaissance, prospecting, and detailed exploration are the standard procedures in mineral search and development.

15.12.2 Reserves/Resources

After independence, continued efforts by various exploration agencies resulted in significant augmentation of Indian zinc-lead-silver-copper resources. In 1947 the known zinc-lead resource was a meager 0.5 Mt from Mochia Mines of Zawar Group, Rajasthan, with 175 tpd production capacity. Since then the resource has risen to 418 Mt by 2000 and further to 510 Mt in 2010 (Fig. 15.35). Ongoing exploration during 2010 and 2015 outlined an additional +100 Mt reserves and resources from working deposits. The Indian subcontinent is blessed with +95% zinc-lead-silver deposits in the northwestern Proterozoic sediments of Rajasthan (Haldar, 2007). The total reserves and resources base of producing/developing mines and deposits under detailed exploration as of March 31, 2015 stand at 313 Mt, containing 34.7 Mt of zinc-lead metal and 885 MOZ of silver.

Total in situ copper reserves and resources were estimated at ~10 Mt in 1947 with production of 310,000 t of ore at 2% Cu per annum from a single mine at Mosaboni, Singhbhum Group of deposits in Jharkhand. The reserves

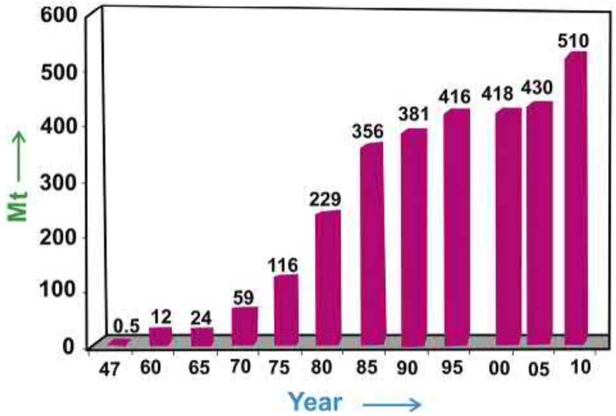

FIGURE 15.35 Reserves and resources buildup of Indian zinc-lead deposits over the last six decades.

and resources were increased to 1390 Mt in March 2005 by continued exploration: 370 Mt (26.5%) fall under "reserves" (Proved and Probable) and the balance of 1020 Mt (73.5%) are "resources" (Feasibility, Prefeasibility, Measured, Indicated, and Inferred). The largest resources of copper ore, to a tune of 668 Mt (47.9%), are in the state of Rajasthan followed by Madhya Pradesh with 404 Mt (29%) and Jharkhand with 226 Mt (16.2%).

The status of all mineral deposits changes with exploration in and around the existing deposits, mine depletion, and new discoveries. Questions that frequently arise are:

1. What is the reserve and resource that should be reported for a mineral body?
2. Should it continue to reflect the initial discovery?
3. Should we assess the current state of the reserve after depletion?
4. Should we report the status quo after accounting for both depletion and new finds?

The author strongly advocates the last option. Other than the obvious benefits to local explorers and businesses alike from accurate reporting, this update will qualify the deposit for global comparison and merit-based ranking.

15.12.3 Reserve Adequacy

By and large, Indian zinc-lead deposits are comparatively richer in zinc with low lead content. Exclusive lead deposits are few such as Sargipalli in Orissa and Agnigundala in Andhra Pradesh. Reserve contribution was inadequate and both have already been phased out.

Hindustan Zinc Limited (Vedanta) is one of the world's top producers of zinc (0.879 Mt/a), silver (500 t), and lead (0.185 Mt/a) metals. Binani Zinc Limited produces another 30,000 t of zinc metal based on imported concentrate. These companies ensure India's significant self-sufficiency in zinc, and the country has become a leading net exporter of zinc metal.

Indian copper deposits are either narrow with low-grade orebody (Khetri Copper Belt), or low-angle and deep seated and do not support large-scale mechanization in underground mining (Singhbhum Copper Belt), or methods have changed from surface to underground such as at Malanjkhand, Madhya Pradesh. India depends primarily on the import of copper concentrate and metal.

15.12.4 Resource Requirement

Zinc is the fourth most widely used metal after iron, aluminum, and copper in the world. Due to its resistance to nonacidic atmospheric corrosion, zinc is instrumental in preventing the corrosion of steel and extending the life of buildings, vehicles, ships, steel goods, and structures, ranging from telecom towers to high-mast lighting. In a booming economy that encourages construction, the demand for zinc literally galvanizes a nation. Most of the zinc demand in the country (+70%) is in the construction sector. The current output of zinc-lead ore being mined is about 9 Mt/a at 7%−10% Zn + Pb, with silver as a by-product. This satisfies +100% of the national demand for zinc metal and exports of zinc concentrate and metal.

Copper metal production is constrained as it is heavily dependent on imported concentrate and metal. This is a good time to pause and remember that mineral resource is a nonrenewable asset, and that the gestation period between discovery and production takes 10−15 years. The question arises: What discovery rates would be required, at current rates of production, if the industry had to replace exhausted reserves with new grassroots discoveries? The regional exploration plans would need to maintain a rolling in situ reserve inventory of 100−190 Mt to maintain self-reliance on a long-term basis. If we fail to meet these numbers, we would be left with the alternatives of import of concentrate, metal, secondary generation, etc. The country is fast approaching a crisis state, which can only be overcome by moving toward new opportunities beyond state/national boundaries.

15.12.5 Discovery Trend

Zinc was probably extracted in India as early as the second century BCE. The reduction of zinc oxide using a condenser and oxygen-devoid container on an industrial scale took place at Zawar mine area, India, around the 13th century AD, after which the technology spread to China and other countries.

India has always been one of the primary copper metal producers in the world. There is ample evidence of ancient mining and smelting remains around the present zinc-lead-copper mining belts. Carbon dating of wooden implements

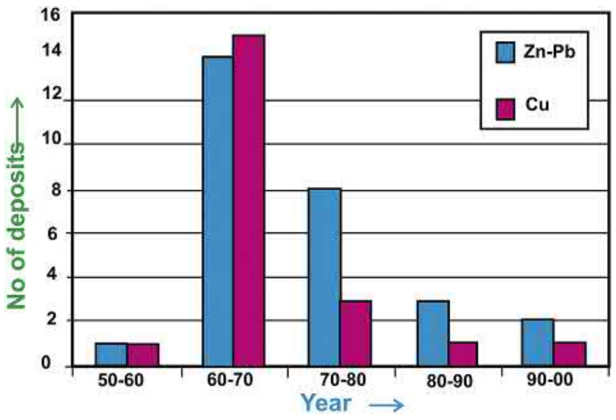

FIGURE 15.36 Number of Zn−Pb and Cu deposits discovered in the last 50 years. There have been no new discoveries since 2000 in India. Additional resources in the existing deposits have compensated for annual production.

recovered from the ancient workings indicates that these operations are +2100 years BP. Therefore all the "finds" of Zn−Pb−Ag−Cu deposits are, in a strict sense, "rediscoveries" of abandoned mining belts and may be termed brownfield discoveries. Barring a few hidden deposits at a depth of ~130 m from the surface at Rajpura-Dariba-Bethumni belt, most of these "rediscoveries" are by chance (Fig. 15.36). New investigations over the years have enhanced significant economic reserves in and around the known orebody, and cannot thus be termed "new" discoveries. The availability of existing infrastructures enhances the value of these reserves.

A quick scan of historical discovery trends reveals some interesting results. The overall records of mineral discoveries by number of deposits and associated reserve base created over last 60 years are respectively depicted in Fig. 15.37. The point to note is that the base metal discovery rates peaked during the 1960s and 1970s and declined thereafter. Overall, this major reserve enhancement should provide immediate (short/medium-run) mine development and production: ~100 Mt of Zn + Pb reserves have been added between 2008 and 2012 from existing mining projects.

Most of the Indian deposits are medium size, the exceptions being the three world-class large deposits: Malanjkhand copper (145 Mt at 1.35% Cu), Madhya Pradesh, discovered in 1970, the often-mentioned Rampura-Agucha zinc-lead-silver (+120 Mt at 13.90% Zn, 2.00% Pb, 9.50% Fe, and 63 g/t Ag), Rajasthan, discovered in 1977, and Sindesar-Khurd zinc-lead-silver (110 Mt at 5.8% Zn, 3.8% Pb, and 215 g/t Ag), adjacent to Rajpura-Dariba Mine, discovered in 1987. The first two deposits are large reserve, high-grade, open pit mines with a low cost of production. Thus these are significant for lowest payback period and high return on investment over a long mine life in the Indian mining sector. Sindesar-Khurd deposit is a deep-seated underground mining opportunity and will pay back quickly due to rich silver content. One other deposit worthy of mention is the Banawas Copper Block (18 Mt at 1.74% Cu), an extension of Khetri Copper Complex, discovered in the 1990s. The deposit is rich in metal content and amenable to underground mining. As we can see in these cases, the real voyage of discovery consists not in seeking new landscapes but in having new eyes.

15.12.6 A New Beginning

Even as technological development enables better and faster methods of mineral discovery, the world's nonrenewable mineral reserves are steadily depleting with progressively increasing rates of production and consumption. Economic growth, in the process, has assumed the softer name of revenue! Greenfield discoveries and expansion of

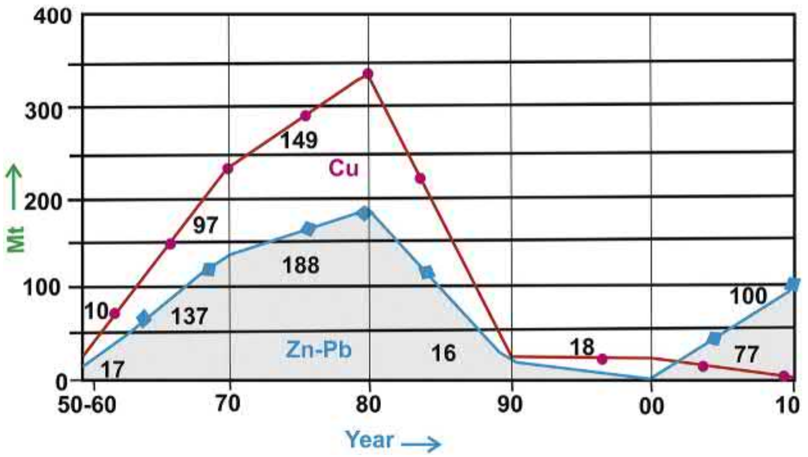

FIGURE 15.37 Resource buildup of copper and zinc-lead in each decade on account of new discoveries.

reserves in and around the existing operating blocks need to be intensified for “a tonne-to-two tonnes” substitution of the depleted ore. In India, surface orebodies have become particularly hard to find. Therefore traditional exploration techniques may no longer yield the required results. We need to take the plunge and target deep-seated, and hitherto hidden, deposits.

Future exploration will integrate several approaches and techniques in all the phases of discovery. Multidisciplinary approaches will utilize in-depth knowledge of regional and deposit geology, studies of structures like lineaments, faults, and fractures, which control the mineralization in an area, application of rock and soil geochemistry, and interpretation of high-resolution aeromagnetic (magnetic and electromagnetic) and gravity surveys with deep penetration capacity. These are the new roads that will lead us to the hidden metallic bodies.

Exploration projects would still need to be sequential and dynamic, with controlled objectives, schedules, and budgets for the intermediate phases of activity. The data collected and computed must be interpreted and evaluated at the end of each intermediate phase, with the subsequent phases being rescheduled as and when necessary. In the event that intermediate results do not meet the “go-no go” criteria, the project can be shelved until adequate resources are available for the next stage or the market price increases in between. Thus today’s explorer needs to wear the hard hat of the engineer, the stopwatch of the project manager, and the pocket protector of the statistical analyst. Many deposits such as the Neves Corvo copper-zinc-lead-tin orebodies in Portugal, the Cannington zinc-lead-silver orebodies in Australia, and Sindesar-Khurd zinc-lead-silver orebodies in India are the results of reinterpretation and application of new approaches to existing information.

15.12.7 Conclusions

The discovery rate of base metal deposits throughout the world rose during the 1960s and 1970s. It declined during the 1990s and no significant deposits have yet been reported in the 21st century. Indian base metal deposits are rediscoveries of ancient abandoned mining sites and extensions in the known belts. Most of the orebodies have cropped out at the surface, either unaltered or exposed as oxidized gossans. Traditional prospecting combined with geology, limited geophysics, and geochemistry gave rise to the discoveries in the recent past.

The chances of finding new copper, zinc, and lead deposits at shallow depths are remote in India, and for that matter anywhere in the world. Forthcoming discoveries will depend on modern exploration technologies applied to an integrated geological model. The international race to the moon and other planets, and in interplanetary space, is already initiated—this time with the stated objectives of mining the moon/outer space for resources as varied as rocket propellant, helium-3, and lunar metals! But that is another story…

The new environment of increasing risk-prone mineral discovery requires extraordinary creativity, innovation, technical skill, and perseverance coupled with commercial discipline to attain ultimate success. The incentives are global economic demand, driving continuously high trends in metal prices, technological necessity, and the primeval joy of unveiling the opening chapters of creation. These are the factors that motivate corporations to pioneer and unearth new deposits, and to upgrade the marginal low-grade deposits for production purposes. Mineral exploration and mining companies need fortitude, foresight, fortune, and fearlessness—and a fair share of humor to accept the challenges ahead (Fig. 15.38).

FIGURE 15.38 Last evening at Lennard Shelf Exploration Camp, North West Australia, 2010. The setting sun will rise the next morning with new resolutions, new aspirations, and new hopes for success and prosperity in mineral exploration. *By—the Author.*

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Dr. Swapan Haldar has over 50 years of professional and academic experience in oil and base-noble metal exploration and mining. His profession has often required visits to zinc, lead, gold, tin, chromium, nickel, and platinum mines and exploration camps in Australia-Tasmania, Canada, USA, Germany, Portugal, UK, France, Italy, Netherlands, Switzerland, Saudi Arabia, Egypt, Jordan, Israel, Bangladesh, and Nepal. Since 2003, Dr. Haldar has served as Emeritus Scientist of the Department of Applied Geology at Presidency University in Kolkata, and a guest lecturer at Calcutta University and the Indian Institute of Technology in Dhanbad. He has authored 40 journal publications and four books, including *Platinum-Nickel-Chromium Deposits: Geology, Exploration and Reserve Base* (Elsevier). Dr. Haldar has a unique professional blend of experience in the mineral industry combined with classroom teaching of postgraduate students and executives.

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ISBN 978-0-12-814022-2

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