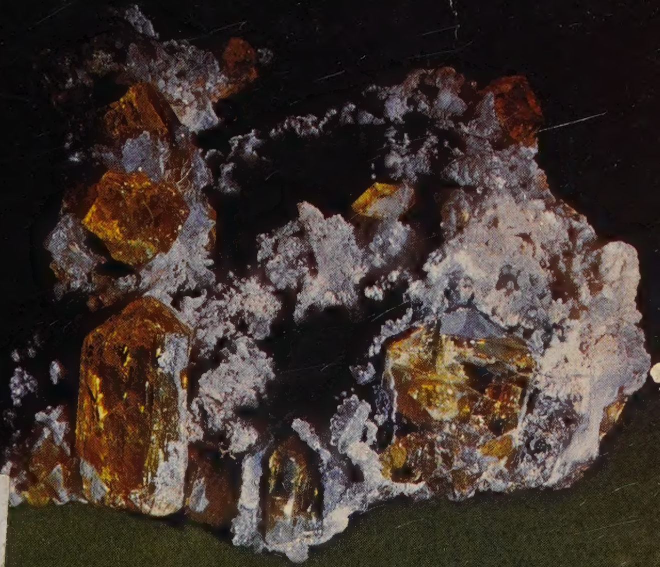
Beginner's Guide to
Minerals

Michael O'Donoghue



A Newnes Technical Book

Left to right: brazilianite, quartz, garnet, beryl (aquamarine), tourmaline, chrysoberyl, beryl (emerald)

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Preface

Many people are familiar with minerals as gemstones and as ingredients in rocks, but few understand how they can be recognized, classified and collected. Of the 2500 established species, many are powdery encrustations and relatively few occur as fine large crystals. This book discusses only those well-formed crystals, although the classification and identification techniques applied to them apply equally to species distinguishable only under the electron microscope.

I have written this book to fire the imagination of both potential and actual students of minerals, who may be encouraged to collect; I have explained physical and chemical properties and pointed out features which assist in field recognition. Since even the best-quality photographs cannot do justice to the finest mineral specimens, the reader will find that visits to museum collections are an ideal accompaniment to this book. In this way, a whole new natural world can open its doors to the enquiring mind.

Thanks are due to the Van Nostrand Reinhold Company for permission to reproduce Figures 2.2, 2.3, 3.1–3.4, 3.6–3.10 and 5.3, which originally appeared in *Prospecting for Gems and Minerals* by John Sinkankas.

M. O'D.

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Introduction

Rocks occurring at the earth's surface are composed of aggregates of minerals, which are mostly in a fine-grained form. Relatively few minerals occur as large, well-shaped crystals. Minerals are produced by a variety of processes. Many have remained unaltered in the earth's crust for millions of years while others are now developing, perhaps as a result of heat or stress at depths of several kilometres, but in other cases at the surface where water or gases of volcanic origin are cooling.

It is not easy to define the term 'mineral'. However, it can be said that a mineral is naturally occurring, usually inorganic, and may be either a chemical compound or an element.

Early studies

Scholars in classical times took an interest in minerals. Both Aristotle (384–322 BC) and Theophrastus (about 370–287 BC) mention previous work. Aristotle mentions minerals in his *Meteorologica*, and Theophrastus wrote *Concerning Minerals*, thought to be the earliest single work devoted to the study. Many people know the *Natural History* of the elder Pliny which includes four books on minerals; this was written in about 50–60 AD.

After the Roman era there is a gap in scientific writing until the Middle Ages, when the more fanciful aspects of the natural world seemed to occupy the minds of the writers.

These writers mixed observation with superstition, and attributed magical or curative powers to minerals, probably according to their appearance or rarity. A good example of this type of study is the *Natural History* of Albertus Magnus in the post-Roman era. From this time come the 'lapidaries', books about the magical properties of stones. Later, however, more serious study began and the *De Natura Fossilium* of Georg Bauer (Georgius Agricola) contains material in which minerals are placed in a type of classification based on colour and weight. De Boodt's *Gemmarum et Lapidum Historia* (dated 1609) is more in keeping with modern thought, and some of his observations are still significant.

Readers visiting a mineralogical display in a major museum will notice that the specimens are not arranged by size or colour. There is another arrangement which is not apparent until a mineralogical textbook is consulted; it is *chemical*, in which elements and the various kinds of compounds are grouped together (e.g. oxides, sulphides, silicates etc.). One of the pioneers of this type of arrangement (foreshadowed by Werner) was James Dwight Dana (1813–1895). His *System of Mineralogy* was first published in 1837 and the present revision is still in progress. A mineral collection or 'cabinet' will almost always be in 'Dana order' in which elements come first. Some collectors are 'Dana collectors' – they work through *System of Mineralogy* and try to obtain as many examples of the species quoted as they can.

Publications

The literature of mineralogy is not so extensive that it need deter the student from pursuing it; though there are many general books on minerals, most say the same things and it is sufficient to have one reliable one which can be consulted when necessary. The basic reference tools can always be found in a large library, but it is far better to have one's own books.

I have already mentioned Dana's *System of Mineralogy*; this is at present in three volumes. So far the silicates have not been covered, so there will be at least one other volume if and when production is recommenced. The *System* is the authoritative descriptive mineralogy and entries give all details known about any particular species. The beginner will not need it but it is surprising how quickly the time arrives at which it becomes a necessity. A much simpler plain list of minerals with their chemical composition is Michael Fleischer's *Glossary of Mineral Species* (latest edition 1980). This is regularly re-issued and between issues additions and deletions are published in the excellent journal *Mineralogical Record. Chemical Index of Minerals*, in which species are arranged by chemical families (as in major museum displays), is published by the British Museum (Natural History) and at present consists of one main volume with two supplementaries. One useful feature of this work is the table of pronunciation! Those who would like a more up-to-date Dana with pictures should try to get or at least consult *Encyclopedia of Minerals* by Roberts, Rapp and Weber. Published first in 1974, a second edition is promised. This large (and expensive) book lists all known minerals alphabetically instead of in the chemical order followed by Dana; each entry gives the major features of the species, and also gives references to the major paper or book in which the species is described.

There are many smaller books, some of which are very good; the *Hamlyn Guide to Minerals, Rocks and Fossils* is a very useful field guide. *Encyclopedia of Minerals and Gemstones* by the present writer combines a wealth of coloured photographs of minerals with chapters on identification and much material on the gem minerals, including details of how to polish them.

So far we have discussed only non-teaching mineralogical books; there are also some textbooks which the student should have. Probably the classic is *Manual of Mineralogy* (by J. D. Dana originally, but now brought up to date in a nineteenth edition). *Rutley's Mineralogy* (revised over many editions by H. H. Read) is an old standby, though a little old-fashioned. For rather more advanced students *Modern Mineralogy* by Keith Frye is highly recommended.

After some study of minerals has been undertaken, serious students will want (and need) to subscribe to a mineralogical journal. Without any doubt the one with which to begin in *Mineralogical Record* (PO Box 35565, Tucson, Arizona, USA). This has been in existence since the early 1970s, and has resolutely dealt with serious mineral study with emphasis on important localities and species. This is carried out on the level of the educated amateur and does not attempt the in-depth investigation of species seen in papers submitted to *Mineralogical Magazine* and *American Mineralogist*. The standard is very high and editorial control exacting. This goes to produce a quite superb journal. *Mineralogical Magazine* is sent to members of the Mineralogical Society as part of the membership entitlements, and this happens too with *American Mineralogist*. While both journals are the accepted vehicle for new discoveries and carry the most authoritative reports, it is probably better at this stage to be able to consult them in a library rather then subscribe yourself. Even serious mineralogists do not expect to understand all the papers in every issue!

For those with an interest in gem minerals, the magazine *Gems* covers the field in a serious and fairly elementary way; there are running series on identification, localities and faceting. Here again strict editorial control excludes the trivial.

The journal *Mineralogical Abstracts* is published jointly by the Mineralogical Society and the Mineralogical Society of America. It appears quarterly and is less expensive if you join one or other of the societies. Each issue is divided into a number of sections covering such topics as experimental mineralogy, gemstones, geochemistry, lunar studies and topographical mineralogy. Probably this is the section of greatest interest to readers of this book since it abstracts papers in periodicals published in other countries as well as in the UK and USA, with the result that a good deal of detail on foreign deposits can be found. Since the journal is entirely in English the reader gets a free translation service. It is perhaps pressing the point to suggest that the reader joins the society merely for the purpose of obtaining *Mineralogical Abstracts*; sets can be found in the larger university libraries and in the Science Reference Library of the British Library in London. No formality is needed to consult material in the Science Reference Library as almost all the books and journals there are on open access, and adequate photocopying and other facilities are provided.

It should be stressed that *Mineralogical Abstracts* does not abstract from popular journals, nor does it cover applied mineralogy apart from gemstones.

2

Collecting and conservation

Collecting

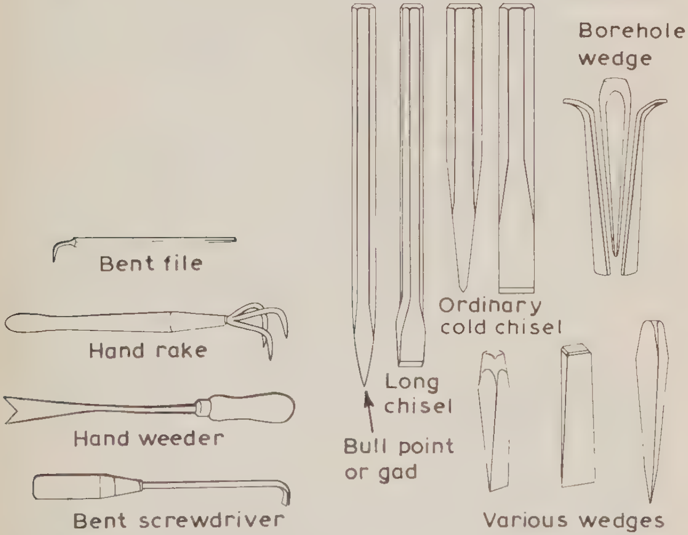
The beginner is best advised to join a mineral club and to gain experience of collecting through organised field trips. There is a great deal of observation to be done in the field, and amateurs frequently come across new locations for a particular species just as they do in botany and other sciences. It is very important for a person who has not done any field work to get the 'feel' of it – to find out, for example, that a mineral which is being sought occurs in very small crystals and in association with other, perhaps more obvious, species. Experience will soon show how little of a given area needs to be searched. Some associations of species are possible, others not.

Information about localities may be obtained from some of the publications already described. The Institute of Geological Science can sometimes give assistance regarding reports on mines. Research in the library of the Geological Museum, South Kensington, can be fruitful.

Unless you have contacts, it is often difficult to obtain permission to enter mines that are still in operation. However, if you are lucky enough to obtain assistance from a mine manager or managing director of a mining company, show that you appreciate the trouble he is going to. He has a job to do and is giving up time to do you a favour. Confirm arrangements in writing and make every effort to keep appointments – there will probably be no second chance.

Show an intelligent interest in the minerals and mining operations rather than simply a greedy expectation of getting your hands on some nice specimens.

Assuming that the required permission is obtained, you should arrive at the mine on time and with the necessary equipment (*Figure 2.1* gives examples). You will certainly need a safety helmet; indeed, no mine will let you on their property without one. Stout boots and a hammer will be needed, with containers for specimens. You should also bring a powerful torch. Do not assume that the mine management will kit you out.



(a) (b)

Figure 2.1. Common mineral-collecting tools. (a) Tools for cleaning out cavities and pockets. The hand rake is useful for digging in dumps, while the hand weeder can serve as both a chipping and prying tool in close quarters when working out specimens in a pocket. (b) Tools for splitting rock. Most are used as in everyday use. The borehole wedge is used in drilled holes to split rock. The side pieces or 'feathers' are inserted in the holes, followed by the tapered pin or 'plug'. Repeated blows on the pin exert enormous pressure on the rock (courtesy Van Nostrand Reinhold Company)

If your visit is to a closed and deserted mine, or even to dumps above ground, you will need a companion. For the sake of safety, and to prevent the worry of relatives, let someone at home know where you are and when you are expected to return. Failure to do this may result in your death and certainly a good deal of worry for others. If you have ever been in this position, ask yourself why you find it necessary to risk life and happiness just to possess mineral specimens; and be honest in your answer.

As with an operating mine, find out all you can about it before your visit; if you can locate the original company, try to get diagrams of the underground layout and find out what was being mined and in which parts of the mine any deep holes may be known to occur. If you can find retired miners with experience of that particular mine, make an appointment to visit them and do not forget to reward them appropriately, especially if they take you into the mine – they themselves may not be adequately insured.

First aid kits are vital, and a rope (about 100 ft) may also be essential. Eyes should be protected by safety glasses and hands by industrial gloves. A pad for the knees saves a lot of discomfort. An ample supply of food and drink should be taken for the collecting trip. Camera equipment will be mentioned in the section on mineral photography, but here we should remember that flash bulbs of some sort will be needed. When not in use all photographic equipment should be packed away in sealed bags since mines contain a lot of dust.

When, with your maps, you have entered the mine, it is best to concentrate on particular areas at a time rather than wander about. If there are ladders, watch out for their condition, and also step carefully since a layer of dust may cover water. Try to locate the main veins of the mineral which was being mined. When you have done so, it is a good plan to clear away the inevitable debris which may cover material containing good crystals. Since work will at one time have been carried out in this area, check that the surrounding rock (sides and roof) is not about to engulf you. Then look for specimens. Any sign of movement or dust clouds which have not been caused by yourself (e.g. moving pieces of loose rock) must be taken as a danger signal.

When crystals are found, the technique of removing them from the rock is important since many are firmly fixed to the extent that damage may be caused by impatience. In such cases the rule is to leave rather than damage, but if you can take some of the surrounding rock ('matrix') then do so, and try to remove the crystals carefully outside or at home.

The use of explosives is outside the scope of this book and they should in any case rarely be needed by serious mineral collectors.

Having said all this, I should say that I know there is a condition which seizes the most careful collector on entry to

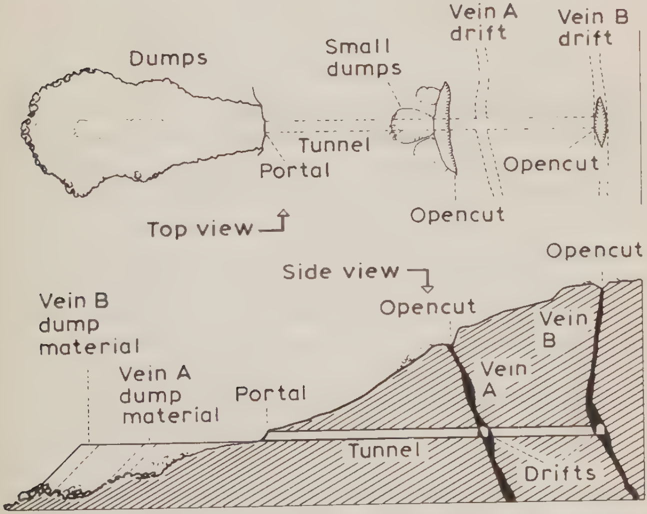


Figure 2.2. Mineral specimens cannot be found in every part of a dump. Here the tunnel to the two ore veins passes through barren rock, and is therefore without interest except in the two fan-shaped layers containing material extracted from drifts along the corresponding veins. On the other hand, the small dumps associated with open-cuts near the top of the hill may contain much interesting material (courtesy Van Nostrand Reinhold Company)

the collecting area of whatever kind. It is almost impossible to remember the rules of safety when there is a prospect of rare and attractive minerals in the area. There is an automatic abandonment of careful thought which has to be allowed for, and all one can do is bear it in mind. Going on expeditions with a club in which there are experienced collectors is by far the best way to collect underground.

Collecting on dumps has dangers though they are different ones. Many dumps are high and are made up of large boulders, often as big as a car. The things to avoid are sending boulders down on to the heads of people below, and getting a foot or leg trapped between boulders. Test the stability of each boulder before any weight is placed on it.

Mineral specimens cannot be found in every part of a dump. *Figure 2.2* shows why.

Conserving and showing mineral specimens

While in many cases the best treatment you can give a specimen is to leave it alone, there is no doubt that some form of cleaning often improves the look of a specimen enormously. Care of your specimen begins even before you have removed it from its parent rock – this should be done with great skill and patience. Many minerals are found in rock which is very hard to chip away – and such action would in any case almost certainly damage the crystals that you want. In such cases it is better to take away some part of the rock with you and leave the crystals *in situ*. Most minerals, though hard, are brittle; so once away from the mine, wrap up each individual one in paper so that specimens are not able to jostle together. If they do, small crystals may snap off their matrix and faces may be damaged, and where cleavage is a property you will have a simple demonstration! Boxes used by greengrocers to display fruit are excellent carriers.

Many specimens will have a coating of soil which can be removed with a piece of soft wood acting as a probe. It is advisable not to use metal for this task. When very small specimens are sought, sieve the material over a bowl rather than over the sink, the ultimate destination of many fine specimens. Be particularly careful when trying to remove matrix (the part of the find you do not want); with fragile minerals at least some of the matrix needs to be left in place. A press (there are a number of different kinds) will help to apply pressure without using sudden blows. Needles make good probes: mount them point inwards to a handle. Chisels of various sizes and grinding equipment are always useful.

Where one mineral is coated by another, the coating may need to be removed. Mica (found on minerals located in biotite schists, for example) can be removed with a stiff brush; calcite can be at least partly removed if advantage is taken of its cleavage. What will not cleave away can be removed with dilute hydrochloric acid, as long as this does not damage the underlying mineral.

Ultrasonic cleaners are best avoided, especially when the mineral is at all brittle. The blue transparent variety of zoisite (the gem variety called 'tanzanite'), for example, has very often been spoiled when placed in an ultrasonic cleaner. If, on the other hand, you know that a particular specimen will not react unfavourably, use water as the cleaning liquid and add a few drops of detergent to it.

Remember that many minerals are water-soluble (see list on p. 13). It may be possible to use alcohol as the cleaning agent in these cases, but do not place it near an open flame. Acetone (CH_3COCH_3), with which similar precautions should be taken, is sometimes useful. A specimen that has been cleaned in water may be dried by immersion in alcohol.

Chemical cleaners

Where chemical methods have to be resorted to for cleaning of specimens, great care needs to be taken. For example, hydrofluoric acid (HF) will remove feldspar coatings from beryl and tourmaline crystals, but it is an exceptionally dangerous acid and any work done with it must be carried out by experienced workers using a fume cupboard or, failing that, in the open air with the wind blowing away from you. HF should be kept in a place where no one else can get at it, especially children; it must be kept in polyethylene containers since metals and some plastics are attacked by it; do not pour it from one container to another. If it touches the skin at all, wash immediately with large flowing quantities of water. Do not inhale the fumes. Call a doctor if either of these accidents occur, no matter how minor they may seem. If you are an experienced worker, cover the part of the specimen that you wish to preserve with beeswax and apply the acid to the rest. Do not leave the specimen in the acid as this will eventually etch crystal faces. The beeswax will dissolve with acetone after cleaning is complete. Washing after treatment should take several hours to ensure all acid is removed. Used HF can be neutralised with calcite and then washed away with large quantities of water.

A slightly less dangerous acid for the cleaning of silicates is ammonium bifluoride (NH_4HF_2). This will react with warm water to form HF, so much care still needs to be taken. Protect surfaces not needing treatment. Sodium cyanide is used to clean gold, silver and copper; again this is a dangerous substance and should be used in a fume cupboard or out of doors with the wind blowing away from you.

Other well-known acids – hydrochloric, nitric and sulphuric – are not usually needed in their concentrated form, but when it is necessary to dilute them remember that acid must always be added to the water, never the other way round. A steady stream of the acid should be poured into the water – this is most important in the case of sulphuric acid. Hydrochloric acid is useful for cleaning carbonates since it will dissolve the commonly-found calcite coating. A dilute solution of about 5–10% is about right. Keep in a plastic or glass container, never in metal; keep an eye on the plastic ones too, since some allow acid to percolate through the sides. Sulphuric acid may attack hydrous minerals, taking the water from them. Nitric acid mixed with hydrochloric acid in the proportion of one part to three will dissolve gold. This mixture is known as aqua regia. Two parts of nitric acid added to nine parts of hydrochloric acid will dissolve platinum. All of these acids, mixed or separate, are dangerous if handled without due care.

Iron stains found frequently on minerals are composed of limonite. They can be removed with oxalic acid, $(COOH)_2 2H_2O$. This is also a dangerous acid and should not be inhaled; the powder form is the most dangerous. Acetic acid, also dangerous, may be used for dissolving encrusted calcite.

The following classification may be found useful:

Water-soluble. Nitrates; some hydroxides; chlorides, except those of lead, silver and mercury; carbonates of ammonium, potassium and sodium; borates that contain water of crystallization; most sulphates, except those of barium, lead or calcium; phosphates of ammonium, potassium and sodium; some of the arsenates.

Soluble in acids. Metals (e.g. gold and platinum in aqua regia); sulphides; some oxides; hydroxides; fluorides; carbonates; borates; silicates (most silicates dissolve with difficulty in boiling HF but the zeolite group are soluble in hydrochloric acid); sulphates; phosphates; arsenates; vanadates; molybdenates; nitrates.

Cleaning common minerals

Here are some of the minerals you are likely to meet, with some hints on how they may best be cleaned:

Albite feldspar. Often found with iron staining, which can be removed with oxalic or hydrochloric acid. Black stains from organic matter can be removed with sulphuric acid.

Blende. Ensure that calcite encrustations are removed quickly before crystal faces are damaged or dulled. Hydrochloric acid preferred.

Fluorite. The calcite coating should be removed with hydrochloric acid.

Garnets. Many of these are found in mica schists; the mica should be removed with a stiff brush or a needle. Iron staining removable with oxalic acid. The demantoid variety, especially that from Italy, is found in byssolite, a fibrous material which can easily be picked away.

Gold. Remove iron staining with any available acid. Quartz encrustations can be removed with HF.

Gypsum. Any clay sticking to the crystals can be washed off with water.

Halite. Should be cleaned with alcohol, never with water.

Malachite. This should be washed with distilled water to which a little ammonia has been added. It should then be soaked in clean water and finally immersed in acetone. Do not use this treatment for azurmalachite.

Marcasite. This iron sulphide decomposes easily and then smells of sulphur. Wash in warm distilled water, then add some ammonia. Rinse in clean water and soak in acetone to dry.

Mica group. These minerals are made up of leaves like the pages in a book. The individual leaves can be separated with water. Acids can be used for cleaning.

Microcline feldspar (amazonite). Iron stains can be removed with oxalic acid; hematite coating with warm concentrated hydrochloric acid.

Orpiment. When encrusted with calcite is best treated with acetic acid.

Prehnite. If hydrochloric acid is used quickly it will remove encrustations before rendering the surfaces powdery. Iron stains among the fibres of the mineral cannot be removed.

Proustite. This mineral undergoes surface alteration when exposed to light; the alteration product can be removed by rubbing followed by ultrasonic cleaning.

Pyrite. Iron stains should be removed with oxalic acid, quartz coating with HF.

Quartz. Iron stains removed with oxalic acid, calcite with hydrochloric acid. If immersed in warm cleaning agents, avoid too rapid cooling.

Rutile. Silicate encrustations removed with HF.

Silver. Remove the black tarnish with a solution of sodium or potassium cyanide, then wash with distilled water. Keep away from specimens which contain sulphur.

Spodumene. Encrustations of clay minerals can be removed with HF.

Topaz. Remove iron stains with oxalic acid, clays with HF.

Tourmaline. Clay minerals should be removed with HF, but carry out cleaning quickly to avoid dulling faces.

Turquoise. Clean with distilled water; keep clear of any greasy materials as turquoise is porous.

Vanadinite. Calcite encrustation should be removed with organic acids.

Willemite. Do not use acids; pick off any encrustations.

Storage

Mineral specimens should be stored away from dust, too strong a light and each other. Extremes of temperature should be avoided, so a cabinet backing on to a radiator or facing a window, for instance, is not in the happiest position. Some minerals are heat-sensitive; sulphur is a good example which may even crack if held too long in the hand. Some minerals take up moisture from the air and so should be kept in sealed jars; examples include sylvine, ulexite and halite. Others tend to dry out; these include torbernite, autunite and some varieties of opal. It is a sad fact that many fine opals develop a fine network of cracks or crazing some time after they have been mined. Not all do, however, and there is no way of telling beforehand. No known method of preventing this has yet been successful. Minerals prone to tarnish, such as silver, should be kept away from any source of sulphur; this includes atmospheric pollution as well as nearby pyrite.

Some minerals should not be exposed to bright sunlight, which may cause alteration and crumbling (as is the case with realgar and vivianite). Some gemstones, if artificially coloured by heating or irradiation, may fade or discolour in bright sunlight.

Labelling

When your specimens have been collected and cleaned, it is time to label them. This should be done on a temporary basis as soon as they are collected since all mineralogists know how easy it is to pick up a specimen and then look for another or take a lunch break, forgetting to put down where the first specimen was found and what other minerals were with it. Any later is too late. A list of your findings should be made on the spot and if photographs can be taken, so much the better. On returning home, you should immediately make a complete record of the trip and specimens collected. Each specimen should be put in some kind of container that can be labelled. Failing this the specimen itself should be carefully marked with a number or name. A number is probably better since it can be an inventory number too.

When all testing is complete and a satisfactory identification made, all details of the specimen should be recorded in the inventory. Even if you do not think that your collection has any great monetary value it will have some, and in any case its scientific interest may be considerable – especially if you have been visiting localities where not much collecting has been done previously. Details that should be recorded are:

- reference number;
- name of specimen, with details of tests carried out if these are significant;
- place of find and associated minerals (map reference where possible);
- size in millimetres;
- notes of unusual features (colour, crystal form and habit, inclusions);
- reference to the literature – preferably to a journal;
- date of find;
- estimated value.

Exchanging minerals

In the nature of things, many or most specimens in a collection won't have been self-collected, and in these case price paid or specimen received in exchange should also be recorded in the inventory. Most collectors maintain friendly contact with other collectors, with whom they exchange specimens. Usually each participant in the exchange has some speciality to offer the other; for example, a British collector might be able to offer Cornish minerals or fluorites from Cumbria to a collector from New Jersey who specialises in some of the zeolites found there. Although value for value is sometimes adhered to, this is not always easy in practice and most collectors are very generous. Most mineral journals easily available to the amateur carry a section in which would-be exchangers are listed with the materials they have to offer.

In these circumstances, courtesy demands that certain rules are kept for the benefit of all. First, *all* letters received should be answered, even if you have nothing to offer in the field that your contact is interested in. Second, you should try to send good-quality material in return to match what you are sent. Do not send specimens of different minerals without first establishing that they are acceptable. Most important of all, see that your parcels are properly packed. This involves wrapping each specimen separately and enclosing the whole consignment in a strong container; many good types are on the market and individually-wrapped specimens in a box packed with polystyrene chips, all enclosed in a strong jiffy bag, should suffice to give the best measure of protection to anything sent through the mail. Unless you are sending valuable gem minerals there is no need to write out a full Customs declaration on the outside of your parcel. It is quite in order to state 'mineral specimens – no commercial value'. Where the specimens are gem material or are very valuable, it is better to ask the advice of the Customs before you send the material. Though there is not usually any duty to pay on uncut minerals, in some countries there may be a value added tax. It is obvious that it would be unfair to send someone a valuable consignment and to find later that they had had to pay some form of tax at their end. Final rule – if you write first, send first.

An exchange with a museum may be possible but museums require only rare minerals or specimens in excellent condition. Write to the curator before you turn up full of hope.

If you ever offer repaired specimens, the fact should be clearly stated. It is always permissible to repair a fine crystal group that has broken, especially if the broken-off pieces are lying where they fell in the mine. It is not permissible to stick crystals onto an impossible matrix even in the interests of display.

Buying from dealers

For those who want a particular species and are unable either to collect it for themselves or to exchange something else for it, buying is the only method possible. There are quite a lot of mineral dealers; most of them are in the United States though there are some good ones in other countries, notably in West Germany and the UK. Their advertisements appear regularly in such good-quality journals as *Mineralogical Record*, *Lapidary Journal*, *Lapis* and *Gems*. As in any other commercial field, the larger dealers with high reputations are the most likely to have what you want and to ask a fair price for it. There are some occasions, however, where a mineral dealer may be an amateur who just happens to live near a productive locality, and such people may have really good bargains. Most big dealers have price lists and it is not usually the practice to haggle over the price! If you have a piece you would like to sell, it is better to take it to one of the established firms who will have the best outlets for it.

Some 'rock shops' have mineral specimens as well as tumbled stones and jewellery findings; occasionally they may come up with something of interest, so if you have a local rock shop it does no harm to let them know the field in which you are interested. Rock shops are visited by travellers from other countries with material to dispose of, and it is always good if the dealer knows someone who will take some of it. In the end, though, it is constant correspondence and reading that gets the most interesting material.

Mineral photography

Many collectors will want to keep a record of the minerals in their collection, whether for inventory purposes, for pleasure, scientific study or to send to other collectors with whom exchanges are contemplated. Although it is not difficult to take a picture of a specimen, good pictures take some time and trouble. Background and lighting are quite as important as the type and sophistication of the camera used.

Where background is concerned the best thing to aim at is a contrast between background and specimen colour. Generally speaking, bright on bright is hard on the eyes, and too rough a background texture can also be trying. In the preparation of an earlier book I remember the difficulties encountered in the attempt to make a satisfactory background for a group of variously coloured gemstones. In the end balsa wood painted black was found to be a good solution. Some photographers like velvet, but with gemstones the near-impossibility of getting the velvet completely free from stray hairs and dust specks (which show up when so small a specimen as a gemstone is photographed) virtually rules it out. With mineral specimens (usually much larger than gemstones) the camera does not need to come so close and can ignore small specks. If in spite of all, you do use velvet (especially black), one way to get rid of specks is to rub adhesive tape over it, glue side down.

When the background is chosen the specimen needs to be placed in such a way that the background curves up behind it. This can be arranged by allowing the material to drape over books or a box. The edges should be kept down. One method used with some success is to place the specimen on a mirror, but of course this will only be successful when the back of the specimen can be shown. Faceted gemstones can be photographed in this way, however, and a number of books have employed this technique.

Most specimens do not have flat bottoms on which they can be rested; they need to be held in their best position by wax or some adhesive. Many collectors will be collecting specimens that are too small to be illustrated by normal photographic techniques; they may collect micromounts which need to be shown by the use of a microscope. At this stage it is worth pointing out that *photomacrography* is at magnifications from 1× to 50×, *photomicrography* is photography through a microscope, *microphotography* is the making of very small photographs such as microfilm or microdots, and *macrophotography* is the making of very large photographs.

All that is needed for photomicrography is a camera, microscope and an extension tube. But it is also possible using a tube to take pictures without the microscope. With a 50 mm lens and a tube of 3 feet in length, quite adequate pictures of 20× magnification can be secured. Cardboard lined with black velvet is made into a tube which will fit closely round the lens. To be in focus the lens must be about 2 inches from the specimen; this makes lighting a problem, but my leaving the shutter open and firing a flash at a number of places around the specimen a cumulative effect will be obtained. For the best depth of field *f*/16 is the appropriate stop. This will require quite a long exposure time, perhaps up to 16 seconds. Unless your photography is carried out in a vibration-free basement, even a sneeze may cause blur on the picture.

At the other end of the scale, pictures suitable for reproduction in high-quality journals can only be achieved by the use of macrophotography. However good your equipment and technique, really sharp edges and high resolution cannot be obtained with 35 mm apparatus. The view camera takes sheet film rather than rolls and is quite large compared with small 35 mm apparatus. But the lenses commonly used are relatively slow and some may be able to be stopped down as far as *f*/64 (the normal 35 mm camera lens usually stops down to *f*/22) so that a far greater depth of field is obtainable. Magnification can be up to 24× so that there is no need for microscopes or extension tubes. The size of the film is usually 4 × 5 inches but can be up to 16 × 20 inches or even more, according to the need. It has been worked out that as far as image quality is concerned, a sheet film image might be more than thirteen times better than a similar one using 35 mm.

The view camera can undertake movements which no other camera will perform. Lens board and film holder can be independently adjusted (this is impossible with a 35 mm camera); this allows pictures to be taken satisfactorily when the best surface of the specimen is at an awkward angle.

Admittedly, a view camera is not cheap, and most readers probably possess a single lens reflex camera (SLR) as these are so useful for general work. If you are going to use an SLR for close-up work, it is essential to have a removable lens facility; the best optical and mechanical systems are also advisable. If possible the mirror should be locked or otherwise fixed in the up position; if this is not done there is a chance that it will vibrate when an exposure is taken, causing slight blurring.

The choice of suitable lighting should take into consideration the nature of the specimen's surface, since a metallic lustre will reflect light back to the camera. Positioning of the lights is also a matter for some careful planning; many mineral photographers like to place their lamps so that light from them falls on to the specimen via some form of intermediate translucent substance such as plastic. This avoids unsightly highlights. Opinions differ about how good a translucent or transparent mineral specimen or gemstone should look. Some feel that using careful lighting to bring out the best colour is too much like outstripping nature; others like to see the piece in the best possible lighting conditions. Most photographers want their pictures to show a faithful record of their collection and are content with that; others want pictures to display at shows where an eye-catching presentation is needed.

3

Rocks and the minerals found in them

Rocks can be classified into three categories: igneous, sedimentary, and metamorphic. The collector should be able to identify the major rock types within each category. Many rock types are unlikely to yield good specimens of minerals and therefore the collector is most interested in the more productive types. Of the three categories, the metamorphic are the least productive of well-formed crystals (at least in UK) though the rocks are often interesting and attractive.

Igneous

Igneous rocks are formed from molten material that rises from below the crust. If the material reaches the earth's surface it may flow as lava, often issuing from a volcanic vent. It may be thrown into the air before settling to give *pyroclastic* rocks composed of volcanic ash lumps called volcanic bombs. The term *extrusive* is applied to igneous rocks which cool at the surface; they may cover extensive areas, as in the case of the Deccan in India. Cooling is rapid, so the rock is composed of small mineral crystals, often only visible under the microscope. Basalt and obsidian are igneous rocks forming in this way. Gas may form bubbles in lava, and these give rise to cavities called vesicles that may be infilled with minerals.

The molten material that does not reach the surface cools as masses within the crust; these are called *intrusions* and

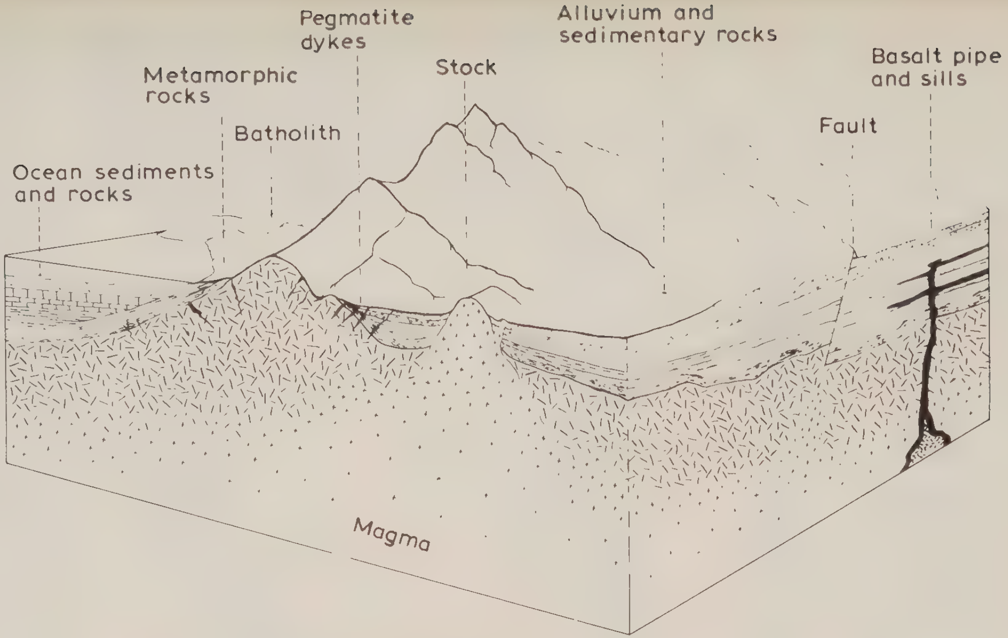


Figure 3.1. A section of the crust, with its three classes of rock. The upthrust portion of the magma, a batholith, forms the spine of the mountain chain. Eroded portions have settled into layers on both flanks to form sedimentary rocks near the surface and metamorphic rocks at greater depths (courtesy Van Nostrand Reinhold Company)

their rocks *intrusive*. *Batholiths* are large intrusions with deep roots; examples rise to the surface to give Dartmoor, Bodmin Moor and the Scilly Isles, all of which are joined at depth. *Stocks* are similar to batholiths but smaller. *Plugs* result from the cooling of rock in the feeder channels to volcanic vents. *Lopoliths* are large saucer-shaped intrusions. *Dykes* and *sills* are relatively small varieties of intrusion, the former cutting vertically and the latter horizontally through pre-existing rocks (*Figures 3.1, 3.2*). The rocks of the large or *major* intrusions have cooled slowly and are coarse-grained or *plutonic*. The rocks of the smaller or *minor* intrusions are composed of crystals of medium size, smaller than those of

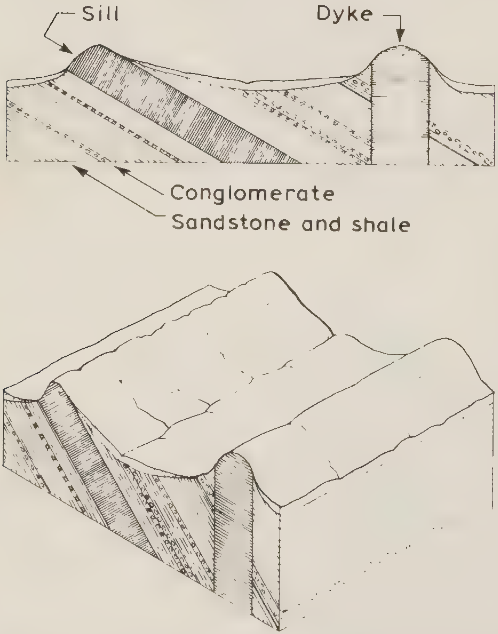


Figure 3.2. Basalt dyke and sill. Prominent cliffs and ridges often result from weathering or glaciation of these formations because basalt is usually more resistant than the softer sedimentary rocks (courtesy Van Nostrand Reinhold Company)

the plutonic rocks but larger than those of the extrusive rocks. Within slow-cooling magmas, crystals may become sorted so that concentration of a particular crystal occurs at a certain level (*Figure 3.3*).

Igneous rocks can be classified according to the size of the mineral crystals as indicated (fine-, medium- or coarse-grained) and according to the chemical composition. When

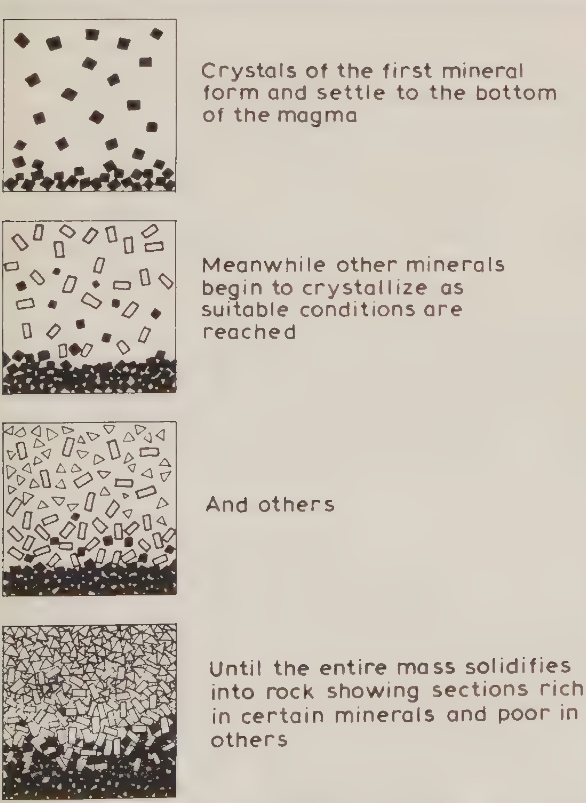


Figure 3.3. Schematic representation of magmatic concentration. Crystals forming at different times result in rocks of widely differing composition, although the original ingredients came from the same parent magma (courtesy Van Nostrand Reinhold Company)

an igneous rock is rich in SiO_2 (silica) it is termed *acidic*. The SiO_2 may occur as free quartz or be combined with varying proportions of elements to form minerals such as feldspars. An igneous rock with over 66 per cent SiO_2 is termed acidic; with 52–66 per cent it is intermediate; with 45–52 per cent, basic; and with under 45 per cent, ultrabasic.

The following table shows where some common igneous rocks fit into the classification based on SiO_2 content and grain size.

Classification of igneous rocks

	Acid	*Intermediate*	*Basic*	*Ultrabasic*
Fine grain	Rhyolite	Andesite	Basalt	(Rare)
Medium grain	Microgranite	Microdiorite	Dolerite	(Rare)
Coarse grain	Granite	Diorite	Gabbro	Serpentinites

The more acidic igneous rocks are light-coloured or *leucocratic*; the more basic ones are dark-coloured or *melanocratic*. The basic and ultrabasic rocks are rich in the ferromagnesian (also called *mafic*) minerals, in which iron oxides and/or magnesium oxide are present combined with SiO_2. Igneous rocks often contain one or more of the feldspars. These are: (1) potassium feldspars, also called orthoclase feldspars and including the varieties orthoclase (giving the group its name), sanidine and microcline. (2) The sodium-calcium feldspars, called the plagioclase feldspars, give a range of varieties according to the relative proportions of Na to Ca: albite, oligoclase, andesine, labradorite, bytownite and anorthite. The table opposite shows the mineral content of rocks in relation to their acidity (the term *accessory* means that the mineral occurs as a minor constituent).

Occasionally, an igneous rock may be composed of just one mineral; for example, dunite is composed entirely of olivine and anorthosite is composed entirely of feldspar.

Some igneous rocks have experienced slow cooling followed by rapid cooling with the outcome being large crystals or phenocrysts set in a fine-grained matrix. Some examples

Mineral content of rocks in relation to their acidity

Minerals		*Acid*	*Intermediate*	*Basic*	*Ultrabasic*
Free quartz		Essential usually over 10%	Accessory	Accessory	Absent
Orthoclase feldspar		Usually abundant	Only present in alkaline varieties		Absent
Plagioclase feldspar		Oligoclase albite	Andesine	Anorthite labradorite	Less than 10% anorthite labradorite
Mafic	Biotite	Common	Common	Accessory	Accessory
	Hornblende	Accessory	Common	Accessory	Accessory
	Monoclinic pyroxine	Very rare	Common	Common	Common
	Orthorhombic pyroxine	Very rare	Very rare	Common	Common
	Olivine	Very rare	Very rare	Common	Common
	Total Mafic %	20%	20–40%	40–70%	70%

of phenocrysts of interest to the collector include orthoclase in granite, olivine in basalt (particularly the peridot variety of olivine which is an important gemstone), sanidine in trachyte and quartz in rhyolite (a fine-grained rock with granitic composition).

Some ore deposits, including those of platinum, are found as segregations in large igneous intrusions, especially lopoliths. This results from early-formed heavy minerals sinking to low levels within the molten mass to give layers lower down, while higher levels are composed of later-crystallised, lighter minerals. Two important sources of minerals for the collector are pegmatites and hydrothermal mineral deposits.

Pegmatites

Pegmatites have large crystals and may contain relatively rare minerals (*Figure 3.4*). They are formed from the cooling of residual hot fluids that develop in a partially-cooled major igneous intrusion. The fluids are acid in composition and contain minerals that solidify at relatively low temperatures, and some water. They are able to penetrate cracks in the cooled part of the igneous mass and in the surrounding country rock. Cavities in pegmatites, called drusy cavities, are lined with crystals that grow from the walls towards the centre (*Figure 3.5*). This ensures that they do not collide during growth with other crystals and so can grow into ideal shapes. Pegmatite veins range in thickness from a few centimetres to many metres and can be up to 1 km in length.

In the large veins, individual crystals may range up to some tons in weight. This is especially characteristic of some beryls and spodumenes. Elements which become concentrated into pegmatites include boron, phosphorus, chlorine, fluorine, sulphur, beryllium and lithium. Common pegmatite minerals include quartz, feldspars and micas. When the pegmatite is granitic in composition, rarer minerals include chrysoberyl, beryl, topaz, tourmaline, spodumene, apatite and danburite; when the composition is rather less acidic (nepheline–syenite–pegmatite) the rarer minerals include aegirine, analcime, natrolite and chabazite.

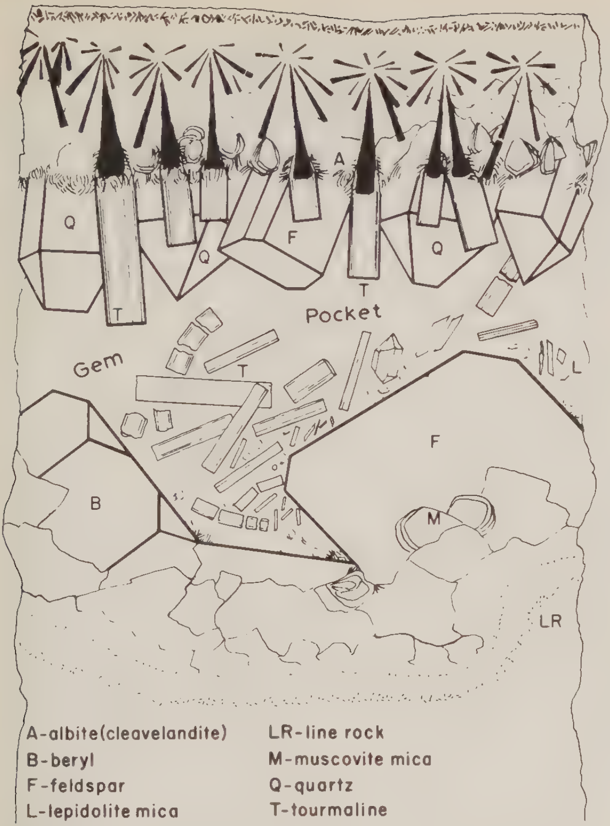


Figure 3.4. Cross-section of a gem-bearing pocket in the Himalaya pegmatite at Mesa Grande, San Diego County, California. Pockets of this type rarely exceed eight inches in depth, but extend considerably laterally and therefore provide vast quantities of desirable specimens (courtesy Van Nostrand Reinhold Company)

Hydrothermal mineral deposits

These are formed from volatile rich fluids that remain after the formation of pegmatites. The fluids are highly mobile and enter cracks in the rock to form veins (*Figure 3.6*). The minerals found are closely related to the temperature of

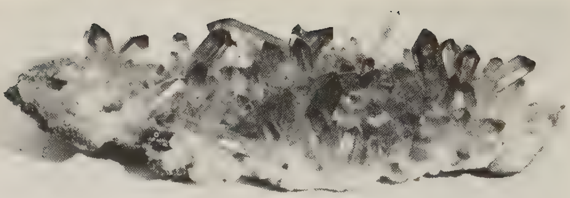


Figure 3.5. Crystals growing from part of a wall in a drusy cavity

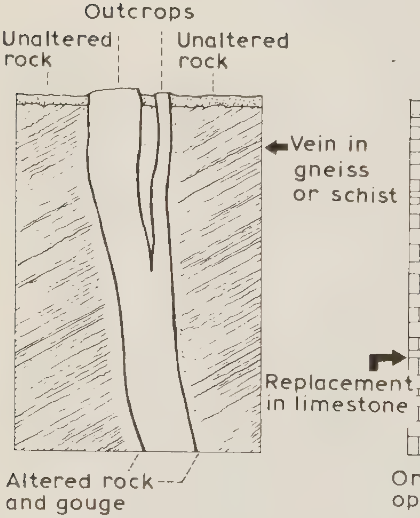


Figure 3.6. Two typical hydrothermal deposits. On the left is a sharp-bordered hydrothermal vein. Because of the resistance of gneiss and schist to chemical attack, only a thin zone of alteration, usually containing kaolin and sericite, separates the vein from country rock. In contrast, the ready solubility of limestone under similar conditions is shown on the right. Ore deposited well beyond the limits of the original fissure and small masses may be found many feet away from the main body. The boundaries of the ore body are extremely irregular (courtesy Van Nostrand Reinhold Company)

formation and the following terms are used to describe the different temperature ranges: 300–500°C, hypothermal; 200–300°C, mesothermal; and 50–200°C, epithermal. Gold as an element and silver, zinc and lead as ores occur in hydrothermal deposits and there are other minerals without economic importance ('gangue' minerals). The variety of minerals found include sulphides, silicates, oxides and arsenides. In hypothermal deposits the chief gangue mineral is quartz and this may be associated with gold, garnet, mica, cassiterite, apatite, topaz, tourmaline and others.

In mesothermal deposits the main gangue minerals are quartz, calcite, baryte, siderite and dolomite, and associated minerals include gold, galena, pyrite, sphalerite and bornite. In epithermal deposits the gangue minerals include quartz (sometimes in the form of opal) with fluorite, baryte etc., and ore minerals are pyrite, marcasite, silver, cinnabar and proustite. The three types grade into each other. Some veins contain only one mineral, others several. In the former case we find veins of galena in limestone; in the latter case as many as 30 minerals may be deposited in a sequence. This forms by the addition of layers until the space is full. The rocks flanking a vein may alter in colour due to the hydrothermal intrusion, and this is a feature to attract the eye of the mineralogist. Related to hydrothermal activity is metasomatic replacement where the country rock has minerals added to it from the fluid (*Figure 3.7*).

Minerals in areas of volcanic activity

In areas of volcanic activity, minerals can be seen growing on the edges of fumaroles where gases escape to the surface. Many minerals formed in this way are water-soluble, so that they do not last long; alternatively they may be overlaid and altered by further violent volcanic activity. Minerals containing sulphur are especially characteristic of these regions; chlorides, fluorides and sulphides are also found. The familiar geodes, a variety of amygdale (mineral aggregates deposited in lava-gas cavities), are found in areas of volcanic activity. They are composed of silica minerals, being lined with agate or completely filled with it; towards the centre

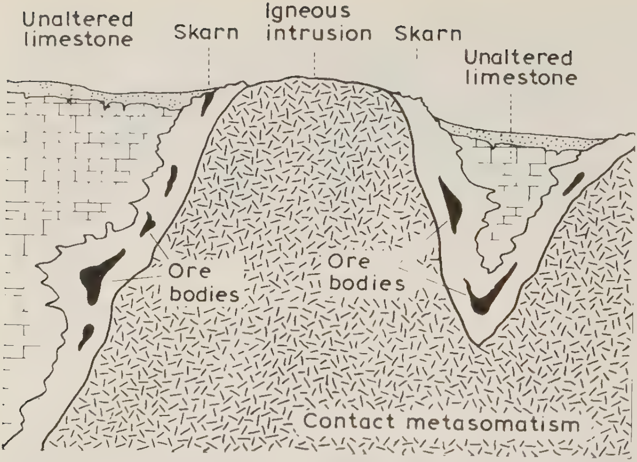


Figure 3.7. Effusions from the igneous intrusion have drastically altered the original limestone and formed a sheath of skarn rock surrounding the igneous mass. Small ore bodies have formed within the sheath. Outcrop surfaces are rough-textured due to widely-differing resistance of skarn minerals to weathering (courtesy Van Nostrand Reinhold Company)

crystals of amethyst may be found. Where water is trapped inside, the geode is known as an enhydro. Zeolite minerals are characteristic of amygdales. Around hot springs mineral deposits may be found. Calcite is often found here as well as a silica known as siliceous sinter. The range of minerals is not large since most of the minerals have been lost during the water's passage to the surface.

Sedimentary

These rocks are formed by the accumulation of sediment on the surface of the earth. The sediment is made up of fragments worn from pre-existing rocks, from chemical precipitates, or from the remains of organisms. Common types of sedimentary rock include sandstones, limestones and clays and classification is by chemical composition and grain size. The most frequently-found minerals in these rocks include quartz, calcite and gypsum. The finest-grained are termed argillaceous; the medium-grained, arenaceous; and the coarse-grained are rudaceous.

Most sedimentary rocks have a marine origin but others are formed in fluvial or terrestrial environments. After deposition, many sedimentary rocks become harder and lose some of their water. This process is called 'lithification'.

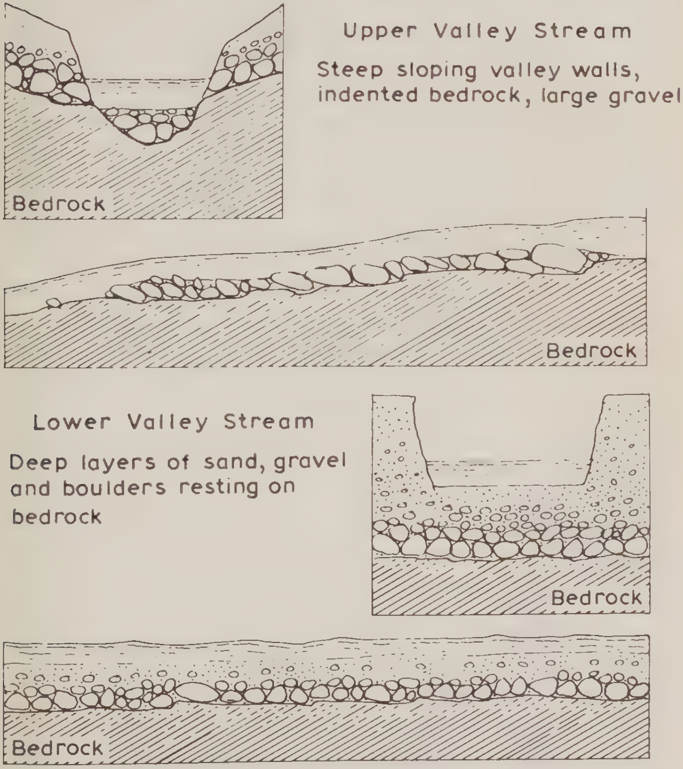


Figure 3.8. Typical stream beds can differ greatly, depending on how rapidly the bed of the valley drops. Lower valley stream beds tend to harbour more resting places for valuable minerals than do upper valley stream beds (courtesy Van Nostrand Reinhold Company)

Minerals may develop in the rocks at the time of deposition or during lithification. Sedimentary rocks occur in layers called 'strata'.

Sedimentary rocks that result from the erosion, transport and deposition of rock fragments are said to be mechanical in origin, and rocks in this category include sandstones, breccias and conglomerates. Minerals may become concentrated on stream beds because lighter or softer bed material is removed, leaving concentrations of hard, heavy minerals (*Figure 3.8*). Alluvial deposits are of mechanical origin (*Figure 3.9*), and various minerals including gold and diamond may

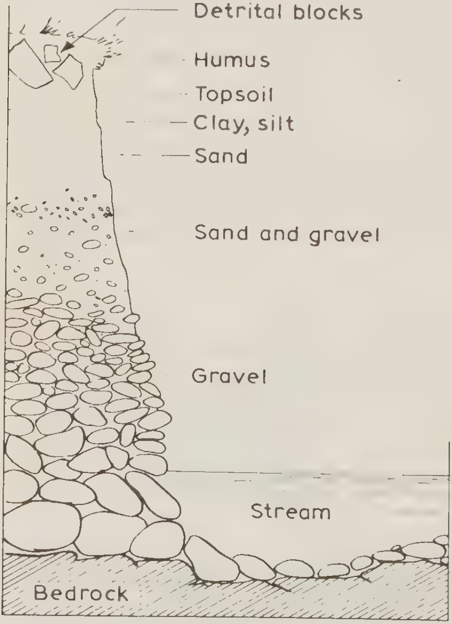


Figure 3.9. Typical alluvial deposit. At the base, the largest boulders rest upon bedrock. Above these are boulders of decreasing size; still further above, pebbles and sand form additional layers (courtesy Van Nostrand Reinhold Company)

be found in them. Within mechanically-formed sediments, concretions may be formed by the consolidation of the rock by concentrations of silica, iron oxides and carbonates. Crystals of strontium sulphate (celestine) may develop in this way. 'Sand crystals', so popular with some collectors, are formed in loose sediments; good examples are the 'desert roses' of gypsum crystals.

Among the sedimentary rocks with a chemical origin are magnesian limestones, rocks rich in chlorides, sulphates and nitrates, many calcium limestones and some ironstones. Evaporation of saline lakes, or enclosed arms of the sea, gives rise to salt deposits termed 'evaporites'. Most salt comes from this type of deposit, and resulting minerals include chlorides, sulphates and carbonates of calcium, sodium, potassium and magnesium. Gypsum, anhydrite, halite (rock salt) and other rarer minerals are characteristic of these deposits.

Non-marine evaporites are found in salt lakes and are rich in nitrate minerals, boron compounds and iodine. Some sedimentary rocks are rich in iron, and common iron ore minerals of sedimentary rocks are hematite and magnetite, with pyrite a little less abundant. Chert is a form of silica which also includes the varieties opal and chalcedony. The name 'flint' is applied to nodular masses of silica.

Some sedimentary rocks are rich in fossils and may even be dominantly composed of these, some limestones being examples. Fossils may be replaced by minerals such as pyrite so that their external appearance is preserved. Opal replaces shell or wood (this is called pseudomorphism since the opal takes on the form of the original organic substance). Jet is also formed in this way.

Secondary enrichment

This involves removal of compounds from a surface layer of rock, and their redeposition at lower levels. The surface layer is attacked by weathering and the minerals are decomposed into simpler compounds. Water, CO_2 or oxygen may react with minerals to create soluble compounds which can then be washed downward leaving insoluble silica, iron or aluminium oxides in an upper layer which is known as 'gossan' or 'iron hat'.

As the minerals are washed downwards, they move into less oxygen-rich and more saturated levels. Precipitation then occurs and there are layers rich in minerals (*Figure 3.10*).

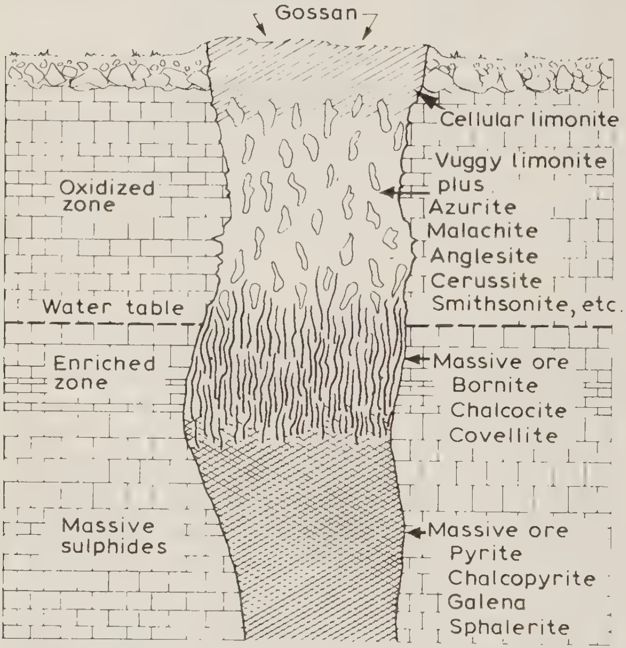


Figure 3.10. Structure of an oxidised copper-bearing vein, showing gossan, oxidised zone, the enriched zone and the unaltered massive sulphides which form the original vein material (courtesy Van Nostrand Reinhold Company)

In this way many of the metals which at first were found all through the oxidised zone become settled in the lower part only. This is the place to look for interesting carbonates, silicates, oxides and sulphides of copper, zinc etc. The copper minerals malachite and azurite, and smithsonite ($ZnCO_3$) and cerussite ($PbCO_3$) may be found.

Metamorphic

Metamorphic rocks are produced when existing igneous or sedimentary rocks are altered by the action of heat and/or pressure. New minerals may be developed, existing minerals may be crushed, and the changes may produce distinctive metamorphic structures in the rock.

Although many minerals typical of metamorphic rocks are also found in the igneous and sedimentary rock classes, some minerals are of metamorphic origin only. Unlike igneous minerals, minerals in metamorphic rocks do not grow in a largely liquid environment. This means that crystals compete with each other for space and rarely reach the full symmetry that they might be able to reach in a more accommodating environment. However, some minerals are able to grow larger and more perfectly-shaped crystals. Such crystals are called porphyroblasts (in igneous rocks, large crystals are phenocrysts). Garnet, andalusite and kyanite are characteristically found as porphyroblasts.

There are three types of metamorphism: dislocation, contact and regional.

Dislocation metamorphism occurs along zones of intense deformation such as thrust faults, and is produced by pressure, not heat. Rocks such as mylonite result, but well-developed crystals do not occur.

Contact metamorphism occurs around igneous intrusions where heat from the intruded magma, which is at a temperature of 700–1200°C, causes alterations in the surrounding rocks in a zone called a metamorphic aureole. Where there is addition of fluids from the intrusion into the aureole, changes produced are metasomatic. Rocks formed in this way include skarns which are rich in calcium, magnesium, and iron silicate minerals, and are found in altered limestones. Skarns may include iron-rich garnets (andradite) and the hedenbergite variety of pyroxene. Other silicates may include diopside, grossular garnet and wollastonite. Pyrite, magnetite and hematite are some of the metallic minerals sometimes associated with skarn deposits. Minerals that, in a volatile state, spread into the aureole from the intrusion may contain boron, fluorine, chlorine and water. Boron, for example, introduced into shales or slates, gives rise to rocks characterised by the presence of tourmaline (a boro-silicate). Impure limestones may react with boron volatiles to give datolite and axinite. Fluorine in the same type of rock may give lepidolite (one of the mica group) and fluor-apatite. Chlorine gives rise to the marialite member of the scapolite group.

Regional metamorphism occurs over an extensive area. It typically results from heat and pressure developed in a mountain-building (orogenic) zone.

Metamorphic grade

This refers to the extent to which metamorphism has caused changes in the rock. In the case of regional metamorphism

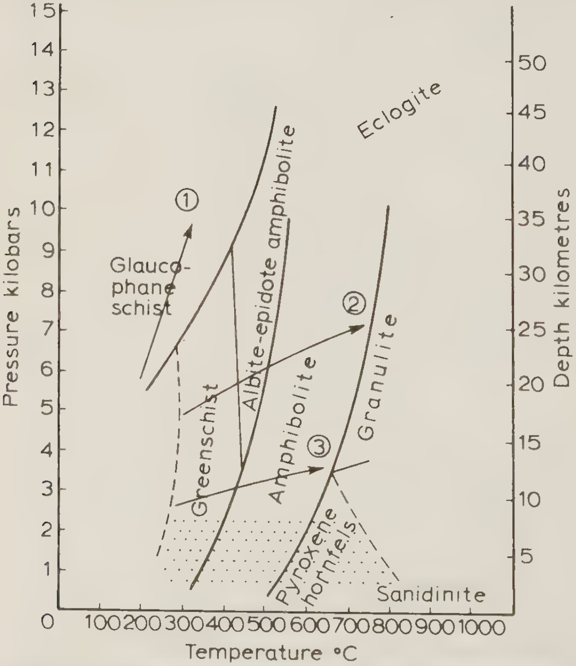


Figure 3.11. Estimated temperature and pressure ranges corresponding to Eskola's eight metamorphic facies

the same grade of metamorphism may be widespread, whereas in the case of contact metamorphism, heat decreases away from the intrusion. *Figure 3.11* shows the conditions under which different metamorphic rocks are produced.

Some examples of metamorphic rocks and their minerals

As metamorphism of fine-grained sedimentary rocks proceeds, shales, slates, phyllites and schists are formed. Along with these transformations of the rock, different mineral assemblages develop. Minerals occurring include chlorite, biotite, almandine garnet, staurolite, kyanite and sillimanite. Since these minerals are formed at different grades of metamorphism, their presence can be taken as a sign of the type of metamorphism involved, and for this reason they are known as index minerals. Other minerals that may occur in slates include andalusite, iolite, anatase and hypersthene.

The metamorphism of basic igneous rocks may give epidote, chlorite, sphene, albite, calcite and almandine garnet. Quartz sandstone is metamorphosed to quartzite. Pure limestones become marble, and metamorphosed impure limestones may, if Mg-free, give zoisite, idocrase, grossular garnet, diopside, scapolite, clinozoisite, sphene and wollastonite; but if Mg-rich (dolomite) may give serpentines, forsterite, spinel and the tremolite-actinolites. Igneous rocks rich in olivine are transformed into assemblages rich in serpentine minerals.

4

The composition and structure of minerals

Mineral chemistry

Most minerals are compounds. The atoms of the different elements may be held together by bonds of different types. Ionic, covalent and metallic bonds are the most important as far as minerals are concerned.

The *ionic bond* results from the coming together of charged ions with equal opposite charges, for example Na^+ and Cl^-. The extra electron (or electrons) in the outer shell of one atom fills the space in the outer shell of another.

In the *covalent bond*, two or more atoms close to each other share electrons of their outer shells so that each has the required number; and unlike ionic bonding, equal and opposite charges do not occur.

Metallic bonds occur where ions are closely packed together leaving the outer electrons to move about freely. This allows conductivity, both of electricity and of heat. The close-packed electrons pass on heat from one to another very quickly and so dissipate it with the result that the metal feels cool to the touch. Metallic bonding also permits malleability, the property of a metal allowing it to be beaten into sheets as with gold; and ductility, whereby it can be drawn into wires.

In many minerals, some atoms are strongly bonded to form sub-groups; the bonding of the sub-groups is covalent and they are called radicals or complex ions. In the important silicate group of minerals we find such radicals as SiO_4, which has a charge of minus 4. There is a tetrahedral arrangement of four oxygen atoms around a single atom of silicon (*Figure 4.1*). This radical may be bonded with a cation (a positively-charged ion) or cations with a valency of 4^+ to produce electrical balance. In the mineral forsterite, two Mg atoms, each with a valency of 2^+, combine with $(SiO_4)^{4-}$ to give $(Mg_2)^{4+}(SiO_4)^{4-}$.

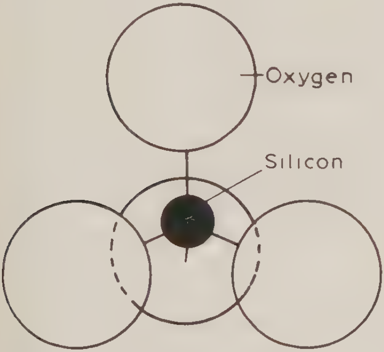


Figure 4.1. The SiO_4 tetrahedron has an O atom at each corner. The tetrahedron (and the octahedron below) is called a coordination polyhedron

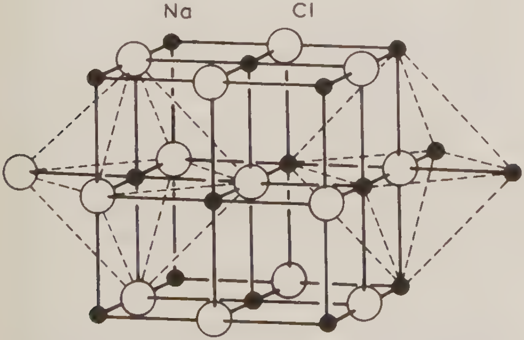


Figure 4.2. The structure of sodium chloride. The octahedral coordination of both sodium and chloride ions is shown by broken lines

Crystalline substances have their molecules arranged in a regular way, but amorphous substances do not. It is this regularity of arrangement that gives rise to well-shaped crystals. *Figures 4.2, 4.3* and *4.4* show the structure of some common ionically-bonded minerals.

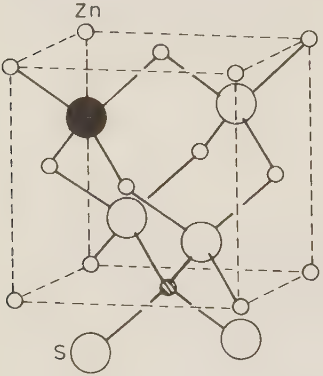


Figure 4.3. The structure of blende ZnS. Both zinc (shaded) and sulphur (dotted) atoms are in tetrahedral coordination

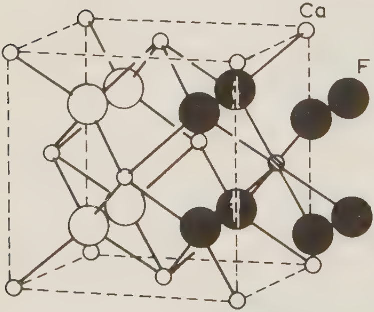


Figure 4.4. The structure of fluorite CaF_2. The Ca atom (shaded) has eight F nearest neighbours; each F atom has four Ca nearest neighbours arranged tetrahedrally about it

Polymorphism and isomorphism

Pressure compresses the electrons, thus giving a denser body. In some minerals with the same chemical composition there can be more than one structural variety; one example is silica (SiO_2) which at normal temperatures is quartz; when there is an increase of temperature to between 1470 and 1723°C the silica becomes cristobalite, a mineral found in volcanic lavas. Between 870 and 1470°C, silica is tridymite and there are still other varieties. This variation in structure without a change in chemical composition is called polymorphism, and the varieties are called polymorphs of silica. Probably better known are the two polymorphs of carbon, diamond and graphite.

The opposite of polymorphism, that is where there is a change in chemical composition while the structure remains the same, is called isomorphism. Isomorphous replacement means the substitution of one ion for another of similar size; a good example is the substitution of an ion of chromium for one of aluminium in corundum or beryl. Here the presence of chromium gives the red (ruby) and the green (emerald) respectively.

In some mineral families, a whole series of different compositions can exist with two end members which have definite chemical compositions, while intervening ones have parts of one composition and parts of the other. An example is the series forsterite-fayalite (peridot is a member of this series). Here forsterite is Mg_2SiO_4 and fayalite Fe_2SiO_4. The mineral family comprising these two end members is called olivine. If a mixture of these two end members were heated and cooled the result would be an olivine with both Mg and Fe in it. This is called a solid solution since it is as though one mineral has dissolved in the other. In this case all the intermediate members are known, though this is not always so; the series is sometimes called an isomorphous series. The formula of the olivine series is written $(Mg,Fe)_2SiO_4$; if we want to mention a particular intermediate mineral we could add subscripts to the symbols Mg and Fe to indicate what the actual proportions of magnesium and iron were.

Where there is an increase in temperature, there is a tendency for larger atoms to be incorporated into the structure. If this happens and the mineral then cools, the larger atoms get pushed out and the crystal reverses the solution process and forms two distinct species. These remain intimately mixed in grain size so that they are hard to distinguish. This process is called exsolution.

In some cases a mineral will ignore the law of electrical balance and just not have certain cations; the spaces left are known as vacancies and in some cases colour can be caused in this way.

The crystalline state

We all know what a crystal looks like. It has a 'special' (i.e. recognizable) shape, often with a sharp point or points and flat faces meeting in sharp edges. In practice, however, only some crystals look like this; others look completely shapeless and yet they too are crystals. If we examine a lump of artificial or natural glass, it may appear superficially to be very little different from a lump of rock crystal – yet it is completely different. In ancient times rock crystal was thought to be ice frozen so hard that it would never melt, and the Greek word for clear ice became transformed into our word crystal. (Ice is in fact crystalline.)

My definition of a crystal is a solid body with an internal atomic symmetry showing regularity over long range. This internal regularity may show itself on the outside of the body by creating flat surfaces and regular faces, but it may not. If no regular feature can be seen on the outside then tests must be made to discover whether the body has a regular internal atomic symmetry and what kind of symmetry it is.

The opposite of crystalline is amorphous (from another Greek word meaning shapeless). The amorphous state is defined as 'an X-ray amorphous material which exhibits the glass transition, this being defined as that phenomenon in which a solid amorphous phase exhibits with changing temperature a more or less sudden change in the derivative thermodynamic properties, such as heat capacity and expansion coefficient, from crystal-like to liquid-like values' (US Bureau of Standards). This appears to be a more complex group of substances than crystals! But in fact all that is being said is that glass (the 'X-ray amorphous material') has no long-range atomic order (shown by X-ray tests), and shows affinities with crystals at one temperature range, changing suddenly to a liquid-like state when that range is altered. Glass has been likened to a supercooled liquid, though this is not necessarily true of other amorphous substances.

In the amorphous state there is no long-range atomic order, and the lack of it can be shown by X-ray tests.

The well-formed crystals shown in mineral books and seen in museums have grown in very favourable conditions. Most crystals are hampered in their growth by other crystals competing for space, or by too rapid cooling.

The crystal needs a nucleus from which growth can be initiated. This may be another crystal or even a speck of dust. Without these, growth cannot begin until groups of atoms stay in contact long enough to become nuclei. This happens most often when the melt is cooling, and a reduction in melt temperature is often necessary before crystallization can start. When new feed material is constantly being added to the surface of the growing crystal, this surface at the same time makes itself as receptive as possible for the arrival of still more material. Sometimes growth takes place in 'steps' on the surface and, since a step has more surface area than the original plane (flat) surface, growth will take place more rapidly there than on the rest of the surface. This gives rise to an irregularity which in time spreads over the whole surface. Such an irregularity is called a screw dislocation, and gives rise to a growth spiral on the face of the crystal. This is one of the aspects of crystal growth that the grower has to contend with in his search for a perfect crystal. Although the growth spiral 'works its way out' so that on the surface it may appear only as a hump, the irregularity worms its way throughout the crystal and makes it unsuitable for optical or laser use – two areas in which perfect crystals are vital. Another accident of growth, less serious since it does not involve dislocations, occurs when a tiny new layer is built up on a growing face forming a step at its edge. Fresh material is deposited on this step, expanding it to cover the whole face. Growth is impeded until another such layer is formed.

So far we have thought of the growing crystals as containing atoms of the substance concerned and no others. But intruder atoms can push in to the structure if they are of similar size to those which are there by right. A good example is the replacement of some aluminium atoms in corundum (Al_2O_3) by chromium (Cr_2O_3). This gives the red of ruby, since chromium is a colour-giving substance in this context where aluminium is not. This replacement of one atom by another is called isomorphous replacement.

If we think of feed material being rapidly deposited on a particular face, it is clear that growth on this face takes place quite fast in a direction perpendicular to it. As more material is deposited the face becomes smaller, and is often lost altogether from the crystal if it develops into a point or edge. The final crystal consists of the faces that have grown at the slowest rate.

Hazards to normal growth

Many hazards affect normal growth. If, for example, the feed material is weakened in the vicinity of the growing crystal, that weakness is replenished by solution from further away; this is more likely to occur at edges and corners than at faces so that the edges and corners grow preferentially. This type of event can lead to hopper crystals or to dendritic (plant-like) growths. Another hazard is the presence of impurities (these can be very minute indeed); in 'ideal' growth conditions a crystal would be able to reject alien substances (unless they can enter the structure as we have seen with chromium in corundum). When they are not incorporated they accumulate ahead of a growing face, hindering the addition of new material and slowing its growth. Faces so affected may grow irregularly so that the crystal assumes a shape unlike its ideal one. Other impurities may be trapped as solid particles within the host crystal; they are called inclusions and form an important clue to the nature of some gemstones.

Some idea of how a particular crystal has grown may be deduced from an examination of the faces: a larger crystal may present a relatively rough appearance since it has had longer for things to happen to it, e.g. accidents may result in etching or grooving, both of which give clues to the crystal's identity. Sometimes one crystal may grow over another one and envelop it, as in the case of sceptre quartz where the original crystal terminations are capped by larger sections of the same shape; the reason for this is probably that the termination of the crystal is better able to obtain supplies of feed material than are the lower parts. In other cases one mineral may grow on certain faces of another one, e.g. hematite will settle on alternate faces of a quartz crystal. This is called selective encrustation and depends upon a crystallographic affinity between overgrowth and host.

Sometimes when the supply of feed material is interrupted and resumed several times in the course of a crystal's development, growth bands may be seen in the crystal; these are known as phantoms and can be seen most often in quartz. When the environment changes so that the crystal begins to dissolve rather than grow further, etch pits can develop which by their shape reflect the underlying symmetry of the crystal. In this way diamond shows trigons (triangular etch pits), and emerald shows hexagonal pits.

Habit

The shape of a crystal is a compromise between internal symmetry and growth environment, and the term habit is given to it. The habit is described by adjectives such as:

acicular – needle-like;
capillary – hair-like;
dendritic – plant-like;
columnar – like a pillar;
bladed – a set of blades;
tabular – flat;
wedge-shaped – as in a wedge.

Figure 4.5. Hematite, known as 'kidney ore', is reniform, or kidney-shaped

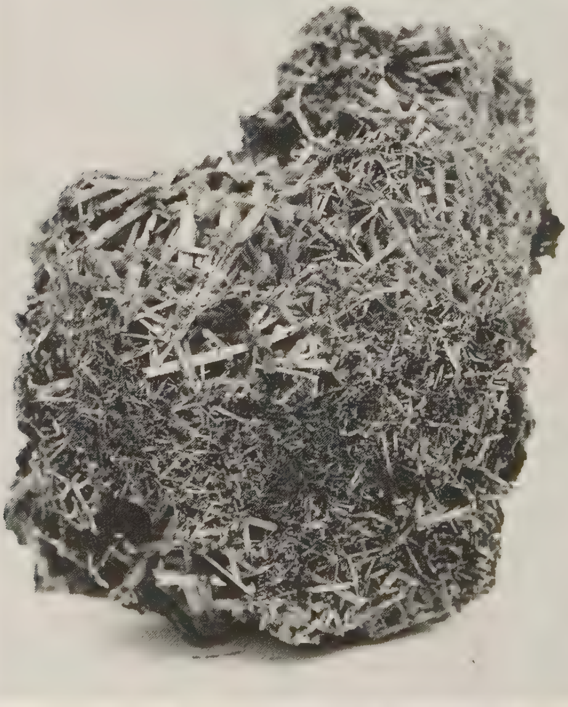


Figure 4.6. Crocoite, from Tasmania, is reticulated, i.e. forms a mesh

Some minerals do not occur as recognisable single crystals even under the highest possible magnification. They are instead made of many tiny crystals and the whole body resembles a mass; thus they are known as massive. The scientific name is crypto-crystalline because the individuals are hidden; the bodies often take on radiating or fan-like shapes which may have other distinguishing features. They may be:

botryoidal – like grapes;
reniform – shaped like a kidney (*Figure 4.5*);
mamillary – breast-shaped;
globular – spherical or nearly so;
reticulated – forming a mesh (*Figure 4.6*);
foliated – forming sheets which can easily be split;
fibrous – forming long fibres.

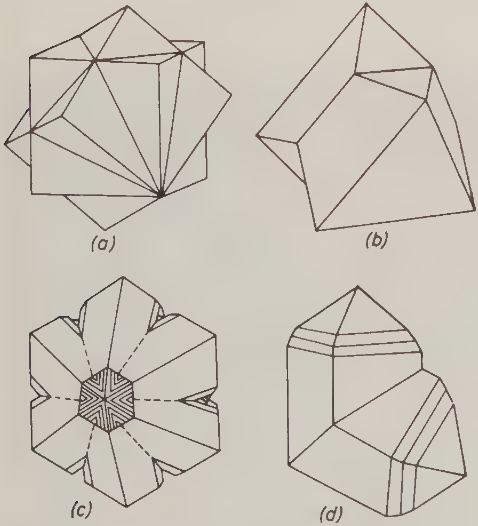


Figure 4.7. Some examples of twin crystals: (a) interpenetrant twin of fluorite, (b) contact twin of spinel, (c) pseudo-hexagonal trilling of three rhombic crystals of alexandrite, (d) geniculate twin of zircon

Twinning

Some crystals are twinned (*Figures 4.7* and *4.8* show some examples), and some mineral species occur as twins almost exclusively, as in some of the feldspars. Some twin individuals form mirror-images of each other, others penetrate one another as in fluorite. Twinned crystals can be recognised by re-entrant angles. Lamellar twinning, seen in some ruby and plagioclase feldspars, refers to the presence of many close-packed thin crystals like the pages of a book.

Alteration of crystals over long periods may cause them to take on different chemical composition and structure while retaining their external shape. This is called pseudomorphism (false form); quartz likes to do this, but probably the best example is opal which can replace wood or shell so that the final appearance is of a twig or shell made of opal (opal is not a crystalline substance but the example is a particularly attractive one).

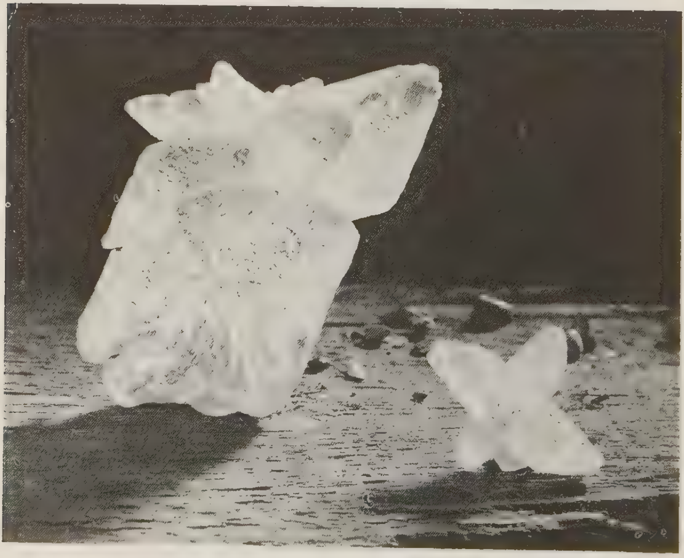


Figure 4.8. Twinning in selenite (gypsum) crystals

Cleavage

When a mineral splits into two with smooth surfaces left behind, it is said to have cleaved. Cleavage takes place along planes where there is a weakness in the structure resulting from the nature of the bonding. Diamond has four directions, each parallel to the faces of the octahedron; blende has six, parallel to the faces of the rhombic dodecahedron; and topaz has one, parallel to the basal pinacoid.

When a cleavage is described, reference should be made to both the direction and quality (whether it is easy to start and what kind of surface is left behind). Quality is described as ranging from perfect to fair. Some minerals may not show cleavage but will nonetheless break in a plane of weakness. These planes usually arise from twinning or from pressure. Good examples are the parting of corundum along lamellar twinning planes, or the octahedral parting shown by magnetite.

Cleavage is often parallel to a crystal face (*Figures 4.9* and *4.10*).

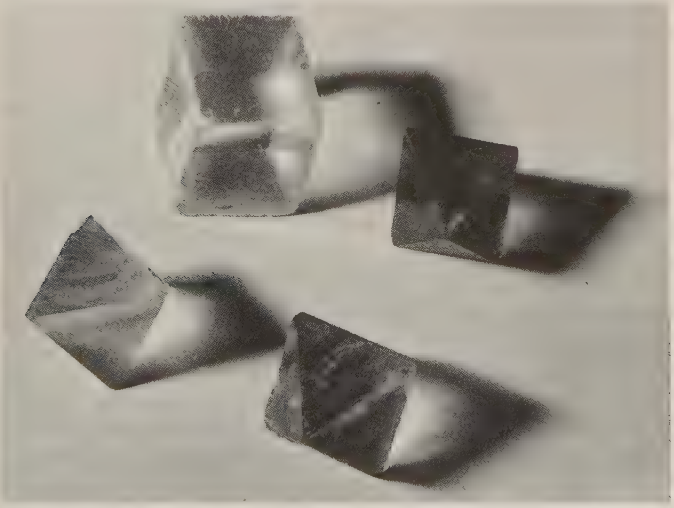


Figure 4.9. Cleavage forms. Top left is calcite, which is rhombohedral; the remaining three are fluorite, and are octahedral

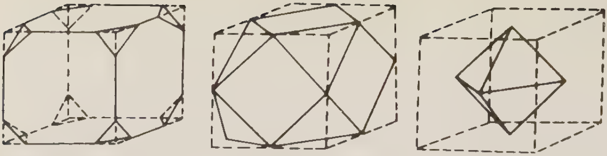


Figure 4.10. Cleavage directions of fluorite. This shows how an octahedral form can be cleaved out of a cube crystal

Parting should be distinguished from cleavage and occurs where there is twinning, as in corundum. Where a crystal breaks, as distinct from cleaving, it is said to fracture.

Lustre

The effect shown by the reflection of light from the surface of a mineral is called its lustre. Metallic crystals have the highest lustre – called metallic – and many of these look black because they reflect incident light so efficiently. Examples are pyrite and galena. Those minerals whose lustre is not metallic are classed as vitreous (glassy). Most minerals of gem quality have a vitreous lustre. A pearly lustre is shown on cleavage faces; sulphur is said to have a resinous lustre; and fibrous minerals such as some serpentines have a silky lustre. Diamond is a special case: its great reflective powers give it an unmistakable brilliance, and this kind of lustre is called adamantine. Some other minerals, particularly the transparent lead minerals cerussite and anglesite, have a lustre approaching adamantine.

Streak

This term is given to the colour left when the mineral is drawn across a surface of unglazed porcelain, known as a streat plate. The colour does not necessarily correspond to the colour of the mineral. The table opposite gives the streak of some minerals which are listed in two groupings according to the type of lustre.

The colour shown in the streak of a mineral is usually invariable even though there may be colour varieties. Since the streak plate has a hardness of about 7, only specimens of that hardness or lower can be tested this way. Hematite, which looks black, gives a red streak and the test is useful for iron oxides in general. Most silicates and carbonates give a white streak and so are not easily identified by this method.

Streaks of various minerals

Metallic lustre	Silver: arsenic, silver
	Grey: platinum
	Golden-yellow: gold
	Red: copper
Non-metallic lustre	Grey: bornite, chalcocite, galena, stibnite, marcasite, arsenopyrite, bournonite, graphite
	Brown: blende, rutile
	Black: magnetite
	Red-reddish-brown: cuprite, hematite, pyrargyrite, proustite
	Yellow: autunite, torbernite
	Green: malachite, vivianite, torbernite
	Blue: azurite, lazurite
	Purple: vivianite

Electrical properties

The presence of electrical properties distinguishes crystals from glasses though not all crystals show these properties. Tourmaline shows pyroelectricity, the ability to develop an electrical potential on heating; cut stones of tourmaline in a shop window, under the heat of display lighting, will attract dust particles. Piezoelectricity, the development of an electric charge on the application of pressure or the reverse, a slight change in mass when an electric charge is applied, is the basis of the use of quartz crystals in watches and a vast number of electronic devices.

The structure of crystals

One of the first things you need to know about crystals is that, for any given species, the angles between corresponding faces – the interfacial angles – have a constant value (*Figure 4.11*). This was discovered by Romé de l'Isle in the Law of the Constancy of Angles postulated in 1772–82. Before this, Steno had discovered that when a quartz crystal was cut into cross-sections certain shapes were obtained which, when compared with sections taken from a number of other quartz crystals, showed that the interfacial angles were the same in every case. The angle between crystal faces can be shown by drawing a line perpendicular to each of two adjoining faces and measuring the angle between the lines. A contact goniometer, even one made from a ruler and a protractor, will quickly prove this law.

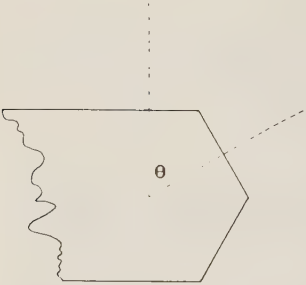


Figure 4.11. Interfacial angles are measured from the perpendiculars of the two faces and not the angle made by the two faces. The interfacial angle is θ in the illustration

In the eighteenth century the Abbé Hauy found out that all crystals were made up of minute but identical building blocks – it is said that his accidental dropping of a calcite specimen and his observation that it broke into small rhombohedra (bodies with flat parallel-sided faces) led to this discovery. We now know that this is not quite correct, since it is not a solid body which is endlessly repeated to form a crystal but rather a three-dimensional atomic pattern (called a unit cell). This was not proved until 1912, when Max von Laue passed an X-ray beam through a crystal and found that it split into several beams. This effect was ascribed to diffraction. Diffraction can be seen if a single spot of light is viewed through a fine mesh (an umbrella will do admirably). Several spots of light can be seen surrounding the one corresponding to the lamp; these arise by light rays diffracted by the threads of the mesh. The fineness of the mesh governs the distance between the main spot and its subsidiaries: a fine mesh causes the spots to be more widely spaced than a coarse mesh. Closely-spaced atoms in a crystal diffract X-rays at larger angles than do more loosely-spaced ones. When the beams are recorded photographically, the distances between the spots allow scientists to compute the position of the atoms.

Crystallographic symmetry

We all have some idea of the meaning of symmetry. The four arms or sails of a windmill look just the same whether the first or the fourth arm is hanging down – in other words it possesses fourfold symmetry. If you rotate a cube, looking down on one of its faces from above, four identical positions will occur during a 360° rotation, and this also is fourfold symmetry.

A brick, rotated in the same way and observed from the end, produces only two identical positions during the 360° rotation and so has twofold symmetry (*Figure 4.12*). In these instances we have used an axis of symmetry. If it is possible to divide a crystal into two parts, each being a mirror image of

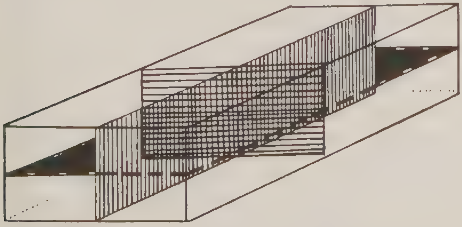


Figure 4.12. The planes of symmetry in a brick. This is the basic form of the orthorhombic system

the other, the dividing plane is called a plane of symmetry. A centre of symmetry has like faces and edges on opposite sides of it, and so will be at the mid-point of any straight line passing through the crystal (*Figure 4.13*).

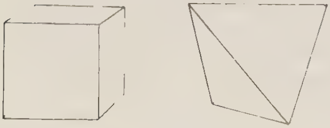


Figure 4.13. The crystal on the left has a centre of symmetry, but the tetrahedron on the right, having different terminations at bottom and top, does not

Crystal systems

From the symmetry present in a crystal, the crystallographer can place it in one of the 32 classes of the six crystal systems. Each system has distinctive crystallographic axes.

In the *cubic* crystal system all the crystallographic axes are equal in length and intersect at right angles; this system has the highest degree of symmetry. In the *triclinic* system, which has the least degree of symmetry, none of the axes are equal, nor do they meet at right angles. A good introduction to the study of the crystal systems is to consider the basic shapes peculiar to one or other system. For example, the cube immediately springs to mind; by cutting off the corners, a body resembling two pyramids (the Egyptian kind) arranged base-to-base is obtained. Each face of this body is an equilateral triangle and the body is known as an octahedron. In some minerals these shapes can be combined (how this happens is not always completely understood), and the resulting shape is known as the crystal's habit. The individual shape (cube, octahedron) is known as the crystal form (*Figure 4.14*). It may be easier to think of the form as the shape dictated by the crystal's genetic code, and the habit as the form modified by conditions of growth.

Some forms are complete in themselves; the cube and the octahedron do not need any other forms to make a complete body or to enclose space completely; but if we think of an oblong such as a brick we can see that there are variations needed to complete the shape. These are called open forms;

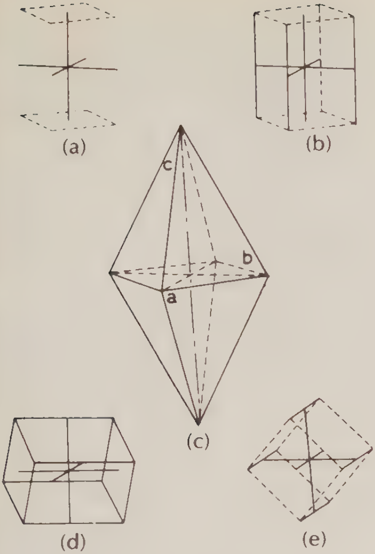


Figure 4.14. The forms of crystals: (a) basal pinacoid, (b) the prism, (c) the pyramid; (d) and (e) are dome forms

the cube is a closed form. The most common of the open forms is called the *prism* and can be defined as faces meeting in parallel edges. The familiar glass prism is an elongated triangle but the faces still meet in parallel edges. The *pinacoid* form is a pair of parallel faces and needs a centre of symmetry or a single plane of reflection symmetry to exist.

We can now make a closer examination of the crystal systems and the commoner forms associated with each of them.

In the *cubic* system (*Figure 4.15*) the highest class has nine planes and 13 axes of symmetry, and there are 15 possible forms; we have already met the cube and octahedron but there are other quite common ones, including the rhombic dodecahedron with 12 faces, each of which resembles a playing-card diamond; and the icositetrahedron with 24

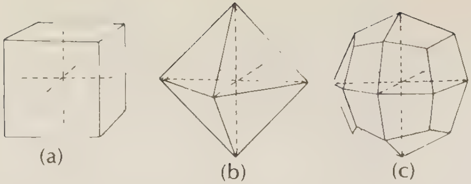


Figure 4.15. The crystallographic axes in a cube and examples of cubic crystals: (a) cube, (b) octahedron (diamond), and (c) icositetrahedron (garnet)

faces, each of which is also four-sided. Pyrite and galena form cubes; diamond and spinel commonly form octahedra and the rhombic dodecahedron is shown by some of the garnets, others of which show the icositetrahedron; combinations of the last two forms are also common in garnet. The tetrahedron, in which there are four faces each forming an equilateral triangle, is shown by the mineral tetrahedrite. Cleavage often gives a clue to the form; in diamond the cleavage is octahedral as it is in fluorite; in zinc blende it follows the dodecahedral form and is therefore sixfold.

With a descent from the high symmetry of the cubic system we come to the *tetragonal* (*Figure 4.16*), which has three crystallographic axes which are mutually perpendicular and two of which are of equal length; the third is either longer or shorter. It might be easier to think of a cube elongated in one direction if one wants to imagine a common tetragonal form.

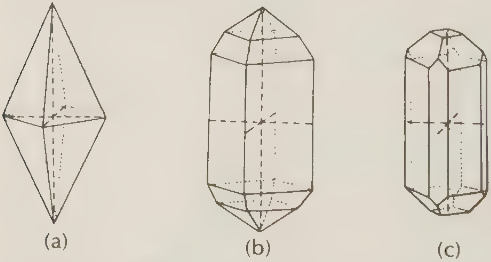


Figure 4.16. The crystallographic axes of the tetragonal system and examples of crystals of the system: (a) bipyramidal, (b) zircon, and (c) idocrase

The equivalent of the octahedron is still two pyramids joined base to base but the height does not equal either of the central dimensions. This form is called the bipyramid (the name octahedron being reserved for the 'cubic bipyramid'). The prism is also a common form and may complete space by pyramidal terminations. By definition the pyramid form will intersect all the crystallographic aces. Zircon is a tetragonal mineral and is found (though not commonly) as prisms capped by pyramids.

Relatively few important minerals are members of the tetragonal system, but the *orthorhombic* system comprises many well-known species (*Figure 4.17*). The system can be thought of as a brick as far as the crystallographic axes are concerned; the three meet at right angles but are unequal in length. In this system the prism, pinacoid and pyramid forms are joined by the dome, which intersects the vertical crystal axis and one of the lateral axes but which is parallel to the third. The bipyramid is a possible closed form, but most orthorhombic minerals combine two or more forms. Topaz, peridot, baryte and chrysoberyl are members of the orthorhombic system.

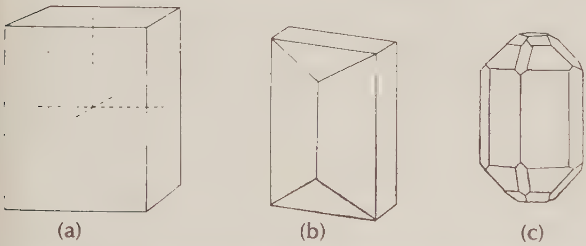


Figure 4.17. The crystallographic axes of the orthorhombic system and examples of crystals of this system: (a) fundamental form with axes, (b) staurolite crystal, and (c) topaz crystal

More minerals crystallise in the *monoclinic* system (*Figure 4.18*) than in any other. Here all the crystallographic axes are unequal; one is at right angles to the plane containing the other two which are not at right angles to each other. Prism and pinacoid forms are customary. The two important silicate

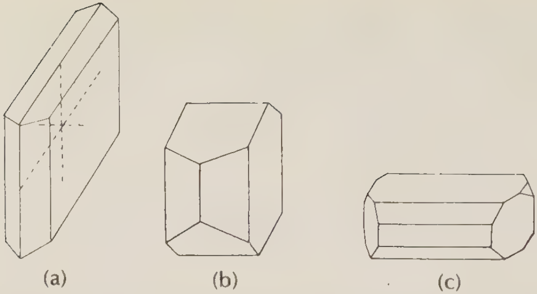

(a) (b) (c)

Figure 4.18. The crystallographic axes and examples of crystals of the monoclinic system: (a) gypsum (selenite) crystal with axes, (b) orthoclase feldspar crystal, and (c) epidote crystal

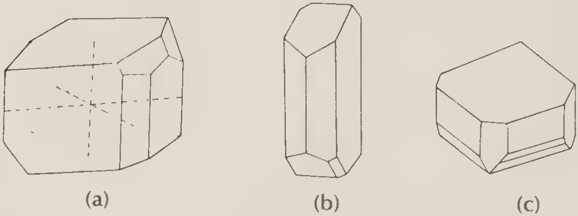

(a) (b) (c)

Figure 4.19. The crystallographic axes and examples of crystals of the triclinic system: (a) axinite crystal with axes, (b) albite feldspar crystal, and (c) rhodonite crystal

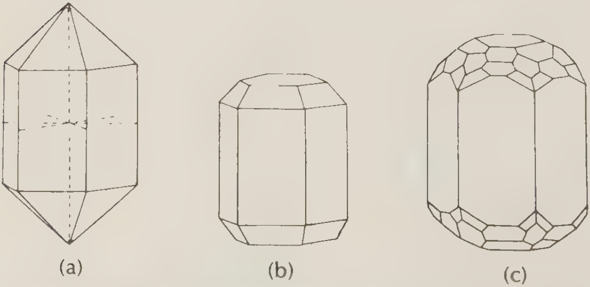

(a) (b) (c)

Figure 4.20. The crystallographic axes and examples of crystals of the hexagonal system: (a) crystal with axes, (b) apatite crystal, and (c) beryl crystal

families, pyroxenes and amphiboles, crystallise in the monoclinic system; in the pyroxenes the cleavage directions are separated by an angle of nearly 90 degrees; in the amphiboles the angle is about 124 degrees. Mica minerals are found as plates or 'books', whereas gypsum forms long prisms or tabular (flat) plates.

The *triclinic* system has the lowest symmetry of all the crystal systems. Here the axes are unequal and there are no right angles. The only form is the pinacoid; crystals show a platy or wedge-shaped habit (*Figure 4.19*).

In the *hexagonal* system there are four crystallographic axes; in the elongated regular hexagon one can readily see the vertical axis of sixfold symmetry with three lateral and equal axes at right angles to it (*Figure 4.20*). The angle between the lateral axes is 120 degrees; in the *trigonal*, or *rhombohedral*, class (which some crystallographers have made into a separate system on its own) of this system (*Figure 4.21*) there is a basic threefold rather than a sixfold symmetry – in tourmaline, for example, one can see the rounded triangular cross-section quite easily. Quartz and corundum also belong to the trigonal class. In the hexagonal system proper, beryl and apatite are important members. Common forms of the hexagonal and trigonal systems are the prism, pinacoid and pyramid.

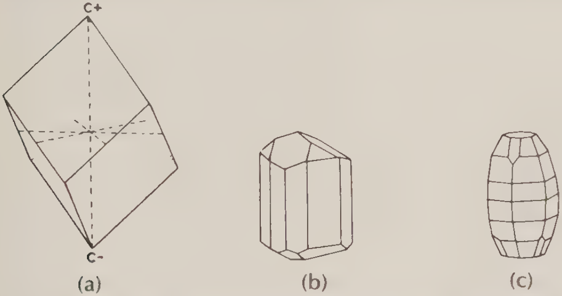


Figure 4.21. The crystal axes and some common forms of the trigonal system: (a) rhombohedron with axes, (b) tourmaline crystal, and (c) corundum crystal

5

Crystals and light

The velocity of light decreases slightly when passing through a transparent mineral or a transparent amorphous body. The velocity of light in space compared with that in the crystal is called the refractive index of the crystal and is always a number greater than 1. The slower the velocity of the light, the larger will be the index of refraction and the more the bending of the light ray on entering the transparent medium. This bending can easily be seen by placing an upright object in a bath of water and observing its apparent deviation from the upright.

Simple laws of refraction state that the angle of incidence (*i*) and the angle of refraction (*r*) (see *Figure 5.1*) are in a definite ratio to each other.

The laws of reflection state that the angle of incidence is equal to the angle of reflection, and that the incident ray (I), the reflected ray (R) and the normal to the point of incidence (N) lie in the same plane. This can also be seen in *Figure 5.1.*

Snell's law states that where the index of refraction is *n* and the angles of incidence and refraction *i* and *r* respectively, then *n* equals sin *i*/sin *r*. When the incident light falls normally (*n*) (at right angles to) the surface of the transparent medium (in this case water), it passes through with no refraction. If one were to look up while below the surface of water it would only be possible to see above the surface at angles less than 48.5 degrees from the vertical. At angles greater than this the interface between water and air would be totally reflective and appear dark. When the angle of incidence approaches 90 degrees, sin *i* approaches 1 and sin *r* equals 1/*n*. This is the critical angle, and light reaching the interface at an angle greater than the critical angle will be reflected back into the first medium. According to Snell's law, the greater the refractive index the smaller the critical angle.

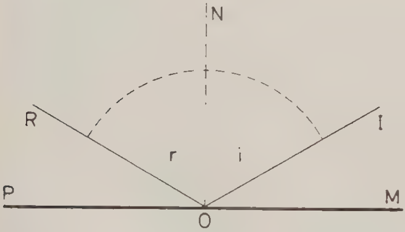


Figure 5.1. A simple illustration of the laws of reflection. The angle ION is the angle of incidence (i) and the angle NOR is the angle of reflection (r); the two are equal

The critical angle is of great importance to the lapidary since the facets of a cut gemstone are total reflecting surfaces; light enters the stone through an upper facet and is internally reflected, passing out through one of the upper facets.

In crystals belonging to all systems other than the cubic, the incident light is not only refracted on entering the transparent medium but is split into two rays, each of which travel through the medium at different velocities. This is called double refraction or birefringence. Certain minerals commonly show a high degree of birefringence, and if a gemstone is cut from one of the crystals at the back facet edges appear to be doubled with a tramline effect, as seen in *Figure 5.2*. Included matter, too, is doubled with an apparent profusion of matter. Crystals which are birefringent are known as anisotropic. In all anisotropic crystals there is at least one direction in which single refraction occurs (optic axis); in crystals of the tetragonal and hexagonal systems (uniaxial crystals) this direction is single and always parallel to

Figure 5.2. The doubling of print as seen through a rhomb of Iceland spar

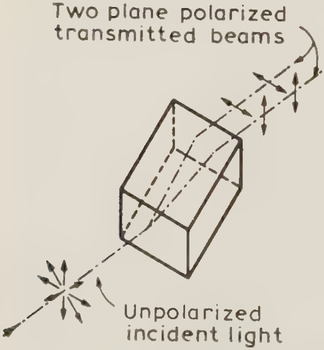


Figure 5.3. Double refraction and polarisation

the main (vertical) crystal axis. In crystals of the orthorhombic, monoclinic and triclinic systems (biaxial crystals) there are two such directions with no particular relationship to any crystallographic direction; this is known as double refraction (*Figure 5.3*).

In anisotropic crystals each of the two refracted rays is plane polarised. In unpolarised light, components of the ray vibrate in all directions at right angles to the direction of travel (like the spokes on an axle where the axle is the direction of travel). When the ray is polarised only one vibration direction can exist; in each of the two refracted rays in an anisotropic crystal the polarisation directions are at right angles to each other. More will be said about the uses of this property in the section on mineral testing.

Colour in minerals

The colour of a mineral is one of its most obvious features. Provided that we are looking at the specimen in white light, we can make the apparently paradoxical point that the mineral has no colour itself, since the colour it presents to the observer is present in the light. White light is made up of all the spectrum colours – red, orange, yellow, green, blue, indigo and violet – and the specimen absorbs some of these colours, leaving the remaining unabsorbed ones to combine to give the residual colour that we see. When there is no absorption the mineral shows no colour.

When a different colour is seen with a different direction of viewing, the effect is called pleochroism, and is due to differential selective absorption. Some minerals show a maximum of three different colours (they need to be turned to see them all), others show two. The mineral iolite shows three colours and tourmaline two. Naturally, the effect can only be seen with transparent minerals.

Colour in some minerals is caused by the presence of an element acting as an impurity; elements 22–29 on the periodic table (the transition elements) are titanium, vanadium, chromium, manganese, iron, cobalt, nickel and copper. The presence of one of these elements in a mineral (sometimes two act together) causes selective absorption of wavelengths from white light, and consequently shows residual colour to the observer. The red of ruby and the green of emerald are both due to differing amounts of chromium. Minerals in which the colouring element is adventitious are called allochromatic; those in which it is an essential part of the chemical composition are called idiochromatic. Examples of allochromatic minerals are the ruby variety of corundum and the emerald variety of beryl; idiochromatic minerals include malachite and rhodochrosite, coloured by copper and manganese respectively.

In many minerals colour occurs without any of the transition elements being present. There are several ways in which a mineral can gain colour and at least one of them is linked with structure defects. Not every crystal is as perfect as it may seem from the outside (and this is rare enough). In fact almost all crystals incorporate some kind of defect. One kind of defect involves the trapping of an electron; another the presence of an extra electron in a position where one would not normally be expected. A hole is the place from which an electron is missing.

One of the best-known examples is the cause of the deep-blue colour seen in some varieties of fluorite; here there is an 'F-centre' (the F standing for the German 'farbe', colour). It is possible for one of the fluorine ions (charged atoms) to be missing from its place and, to preserve the electrical neutrality of the crystal, an electron can fill up the hole. It is spoken of as 'trapped' in that position from which it can only escape under certain circumstances. When light is absorbed the electron moves to a different energy level and colour (sometimes fluorescence) is seen. In smoky quartz there is a hole colour centre. Aluminium ions replace silicon ions (aluminium counting as an impurity since the composition of quartz is SiO_2). Electrical neutrality is provided by sodium or hydrogen ions. If the crystal with this impurity is subjected to bombardment by X-rays or gamma rays, one of a pair of electrons is shifted from its position on an oxygen ion leaving the other member of the pair and causing a hole colour centre. Light is absorbed to give colour.

In the amethyst variety of quartz, iron impurity gives the violet colour on irradiation (heating will restore the crystal to the original yellow or green colour which was altered by the irradiation).

All the causes of colour we have seen so far are linked with a concept called crystal field theory, details of which are outside the scope of this book. In a concept known as molecular orbital theory, we think of electrons in orbit round two or more ions in an ionic-type structure. In the case of blue sapphire, ions of titanium and iron act together by 'swopping' charges. Iron is divalent in sapphire and titanium tetravalent; the swopping makes both ions trivalent as here: $Fe^{2+} + Ti^{4+} \rightarrow Fe^{3+} + Ti^{3+}$.

The reverse process is also possible. The swopping of electrons involves the expenditure of energy so that light can be absorbed. It is believed that many minerals with a blue or black colour owe their colour to this process. In the case of the blue mineral lazulite (one of the component minerals of lapis lazuli), groups of sulphur ions are held together by electrons in orbit around the group. These electrons can be raised to excited states with absorption of light and consequent colour. In graphite, which is black, certain electrons are able to travel round the whole crystal in the direction of the sheets of carbon which are arranged on top of one another. This causes so much light absorption that no colour is seen.

So far we have looked at causes of colour due to electrons on an ion, at a defect or on ionic or atomic groups. Where the electrons causing colour belong to the whole crystal rather than to a small part of it, the concept is known as 'band theory' and is linked particularly to the metallic minerals such as silver, gold and copper. It is also linked to the cause of colour in the substances known as semiconductors (these conduct electricity in certain circumstances only). In the metallic minerals like silver, the metal atoms allow their outer electrons to join a roving band of electrons which move through the crystal from atom to atom; this is how electricity is conducted. This results in a vast concentration of electrons which are efficient reflectors of light, giving the mineral the characteristic metallic lustre. Some absorption also occurs and most of the absorbed light is re-emitted at once. There are slight differences in reflectivity which cause the differences in colour; for example the yellow metals such as gold have more absorption at the blue end of the spectrum.

In semiconducting minerals there can be a range of colour from black (as in the lead sulphide galena) to colourless (as in diamond). Between these extremes only red-orange and yellow are found (cinnabar is red, greenockite orange). In these materials there is an energy gap in which no electrons can be present.

Only light which has an energy higher than that of the band gap can be absorbed, since at lower energies there is no destination for the electrons. Where the band gap energy is small, absorption is possible at all visible energies and the colour is grey or black. These minerals are narrow band gap semiconductors. Where the energy of the band gap is larger, absorption is possible in the ultra-violet region only, so that the mineral is colourless; these are wide band gap semiconductors. Diamond is an example of this type. Where the energy of the band gap is such that only blue and violet energies of light are absorbed the resulting mineral colour is red to orange or yellow (complementary colours to the violets and blues). In the case of the deep red mineral proustite, all but the red component of visible light is absorbed.

Where there is a wide band gap in a semiconductor (as in diamond), there can be no absorption in the visible. Nor can there be any electrical conductivity unless some impurity is present. When there is some impurity, such as nitrogen in diamond, extra electrons may be provided so that when nitrogen replaces a carbon atom there is one more electron present. These extra electrons, called donors, form small groups or individual atoms with the result that light of certain energies can be absorbed. When this absorbed light is in the blue or violet region, the crystal shows the complementary colour of yellow; this is how yellow diamonds get their colour. More nitrogen gives a dark green. When there is so much nitrogen that it forms large clusters, donors are no longer provided and the crystal remains colourless. In the case of boron (the cause of colour in some blue diamonds), there is one fewer electron than in carbon so that a level giving one hole for each boron atom is given.

So far we have looked at the cause of colour in crystals which involve a single colour only. Many crystals show a play of colour similar to that displayed by opal (though opal, as it happens, is not crystalline). In the case of opal the play of colour is caused by diffraction from an array of spheroids of cristobalite, a high-temperature modification of silica. Provided that the spheroids are regularly stacked, and so have regular voids between them, diffraction can take place. The size of the spheroids is also critical – for blue-green light, for example, the size should be about 500 nm.

Other minerals show colour caused by interference. This can be seen in oil patches on water and arises from the difference in speed of two components of a ray of white light entering a thin film. Part of the light is reflected from the surface of the film while another part travels into the film and is reflected from the undersurface. This second component has lost ground to the first since it has travelled a longer distance, and the waves of which it is composed are partly in step and partly out of step. Where they are in step (in phase) reinforcement of the light takes place; where they are out of phase, extinction (loss of light) occurs. The alternate bands of colour and darkness follow a specific order. In minerals interference takes place at cracks and cleavages within or at the surface of the crystal, and also in minerals which are subject to tarnish (bornite, often called peacock ore).

Many gem varieties of minerals can have their colour changed by a variety of treatments. Heating can alter the colour of zircon from reddish-brown to colourless, blue or golden-yellow; green aquamarine is changed to blue; smokey quartz is made colourless. Where a change in valency occurs on heating, or where water is driven off, colour may be altered as in tiger's-eye where the golden-yellow alters to red. Colour centres mentioned above can be created in a crystal by gamma-ray irradiation; they can in some cases be destroyed by heating. Irradiation of diamond, producing colour centres, turns the stone green or black. This colour can be altered to yellow by heating.

Where reflected light is affected by some kind of subsurface structure the effect is known as sheen. Here the light is scattered from inclusions or from close twinning. When the centres of scattering are large no change in the colour occurs, but there can be colour when the centres are small. The green colour and sheen of aventurine quartz are caused by inclusions of the green fuchsite mica which contains chromium; similarly inclusions of iron oxide cause an orange to brown effect in the sunstone variety of feldspar. The name aventurescence is sometimes used for this effect. The name adularescence is used for the shimmer seen in moonstone (another variety of feldspar). This can be a blue colour and is usually said to be due to a layered intermixture of orthoclase and albite feldspars in intimate twinning. It is possible, however, that scattering from very minute particles is equally involved. A variety of synthetic spinel is made in which particles scatter light at the blue end of the spectrum, and this is so similar an effect to that seen in moonstone that it is very likely that the same process is involved.

The cat's-eye effect (chatoyancy) is due to the reflection of light from needles or hollow tubes arranged in parallel bundles. Gemstones in which this effect is seen include chrysoberyl and quartz. Inclusions of rutile needles arranged at right angles to the vertical axis of such crystals as corundum or rose quartz give a star effect (asterism). Usually the star has six rays, though some stones show four.

The flashes of spectrum colour seen in a brilliant-cut diamond observed in white light are due to dispersion. This refers to the breaking-up of white light into its component spectrum colours on passing through a prism (in this case formed by the angles of the cut stone). Some coloured minerals also have a high degree of dispersion, but in these cases the body colour lessens the effect. The term 'fire', used by jewellers and in the gemstone trade, refers to dispersion.

6

Mineral testing

What happens when an apparently new mineral species is discovered? (This is not a rare occurrence since approximately fifty new species are accredited each year.) First, 'field' tests are conducted, in which the colour, lustre, apparent symmetry, signs of cleavage and approximate specific gravity are noted. Careful note should be taken in the field of the mode of occurrence of the unknown – what other minerals are found with it and what geological formation it belongs to. Even the most advanced collectors may find several 'unknowns' at the same time, most of them turning out to be quite well-known species whose characteristics and names have temporarily disappeared from the mind! Naturally everything should be written down at once, and if a photograph can be taken, so much the better. A knowledge of mineral chemistry is important too, since deposits consisting largely of one element will contain minerals with that element prominent.

Once back from the field, the next step is to consult the literature (which is mentioned elsewhere). Geological survey reports for the area in question should be looked at first.

X-ray analysis, though beyond the scope of the amateur, is an important technique giving information about the elements present and the spacing of the atoms. It needs experience to interpret, because a number of minerals can give rise to similar patterns. Various methods of chemical analysis can be used on the specimen. It may be that the mineral, or one closely allied to it, has been made in the laboratory, in which case it will be mentioned in some of the chemical literature. If both chemical and X-ray sources prove unavailing then there is a strong possibility that the mineral is new. If this is indeed the case and a careful search of the literature has revealed no report describing the species, it now has to be described for posterity. First it has to be analysed chemically and the proportion of the various elements calculated. A prototype formula can be worked out at this stage, the final one being left until the exact composition can be arrived at. X-rays are again brought into service, for the determination of the crystal system, class and group of the new material and such work can be difficult, some aspects requiring computer back-up for final determinations.

Optical properties (colour, transparency, refractive index, birefringence, optic sign etc.) can only be measured on a specimen of some size (or on a man-made counterpart). If there are several specimens of the same material, any differences in measurements should be recorded; this also applies to the other tests. Specific gravity should be determined – this is not easy with very small crystals – and should agree with the calculated SG plotted against refractive index on a straight line graph.

When the properties and composition of the mineral have been determined, you should compile a note on the occurrence. All minerals found with the specimen should be noted as well as their position relative to the newcomer; the nature of the surrounding rock should be established. The next stage is to give the mineral a name. This remains the prerogative of the senior author of the descriptive paper. The name should be easily distinguished in sound and spelling from any other existing mineral names; the convention is that it ends in '-ite'.

The data and the proposed name is now submitted to the International Mineralogical Association Commission on New Minerals and Mineral Names; this body examines the data and votes on whether the case for a new species is established. It is always possible that the investigation will discredit some apparently securely-established species in its search for the true status of the unknown. Once the IMA has agreed the status it is the prerogative of the senior investigator to become the senior (i.e. first-named) author of the standard descriptive paper on the mineral; this paper will appear in *Mineralogical Magazine* or the *American Mineralogist*, and will in time be abstracted in *Mineralogical Abstracts*.

Naturally the above is a simplification of the process by which an unknown mineral takes its place in the established list, and many of the tests are outside the scope of this book, as they are unavailable to the amateur. But beginning in the field, there are a great number of observations that the collector can make, and simple physical and optical tests are quite easily performed with care and time at home. The immediate recording of locality data can be done by anyone and, in many cases, information supplied by amateurs has helped professional staff in museums and the like to gain some idea of the identity of material submitted to them.

Recording the information

When a specimen is collected, the first observation should be written down in a way that afterwards should become your standard. This way random jottings are not needed, and it avoids any gaps in information normally taken but momentarily forgotten on a particular instance. The record should therefore always begin with the same properties; what they are and the order in which they are taken depends on you, but the order should always remain the same. Here is one possibility.

Location: place, including country, county or state, nearby town or village, name of mine, Ordnance Survey references added afterwards where possible. Nature of area – is it in a mine? Is the mine surface or underground, working or abandoned? What is the country rock and are there any signs of rock alteration? What other minerals can you see? Is the one under discussion close to them, touching them, intermingled with them? Does it occur in a cavity or as an incrustation on some other mineral? Was it found loose?

What is the height of the place where it was found, relative to the rest of the area? (It might, for example, be found at the foot of a quarry wall or be in the bed of an existing or former stream.)

Before you pick up the specimen take a photograph of it *in situ* if at all possible. Then examine the specimen. What colour is it? Before deciding this, wash off any dirt (but only in cases where delicate crystals will not be damaged in so doing). If it is transparent or translucent, see whether there is a change of colour with direction of viewing. Test the streak by drawing the specimen (again, not the terminations of crystals) across the streak plate and record what is seen. Although many minerals give a white streak, some minerals which appear black are really a very dark red and will show this in their streak or powder. A rough idea of the specific gravity can be obtained by 'hefting' the specimen – lifting it in the hand and getting some idea of its weight compared with its mass. Metallic minerals will always feel heavy. Any brightness of surface should be noted; this is called the lustre of the mineral and will be better seen on reaching home. Similarly, rainbow colours seen on bright surfaces indicate incipient cleavage and tell you a lot about the crystal structure of the specimen.

If it is possible to record some details of any apparent crystal faces, it is a good idea to do so as soon as the specimen is recovered: you do not know how fragile it will turn out to be, and inadequate packing for the journey home has spoilt many fine crystals. If it really is necessary to ascertain the hardness of the specimen, a set of hardness pencils may be used in the field; but they are just as easily used at home.

On arrival at home, the specimen should first be cleaned (methods of cleaning and conservation are described in Chapter 2). The cleaning process will show up a number of features which may have been obscured by dirt: the crystal form may become apparent; twinning may be seen; signs of cleavage and of transparency may show. It is not easy to suggest what test to use first, since to some extent it depends on the state of the specimen.

Specific gravity test

The specific gravity (SG) of a substance is its weight compared with the weight of an equal volume of pure water at 4°C. It can be expressed as $A/A - W \times C$ where A is the weight in air and W the weight in water; C is a constant and if the liquid used for the determination is water, C equals 1. If some other liquid is used then C is the SG of that liquid. A simple apparatus comprises the chemical balance, which is first used to weigh the specimen in the usual way; then the specimen is held totally immersed in distilled water by means of a counterweighted wire cage suspended from one of the balance arms (*Figure 6.1*). Care must be taken to eliminate air bubbles by brushing, and surface tension (which is quite strong in water, enough to hinder the balance movement and give unacceptable results where great accuracy is needed) by the addition of a few drops of a liquid such as toluene, or by the use of toluene completely (remember to change the value of C in this case – the SG of toluene is 0.88). System error lurks in all work of this kind, and can range from the specimen falling out of the cage (this method is unsuitable for very small and very large pieces) to simple miscalculation.

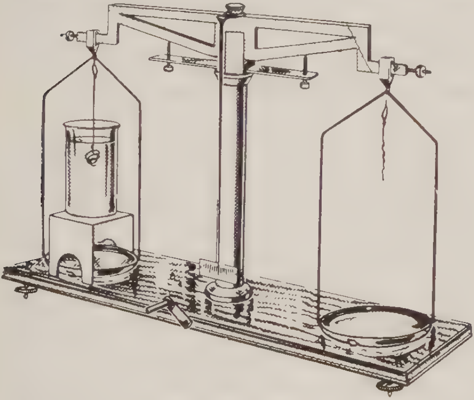


Figure 6.1. Chemical balance set up for hydrostatic weighing

Naturally, if the piece is a mixture of minerals your result will not be very useful; SG determinations work best with the purer minerals such as gem materials. Porous minerals will absorb the liquid and so invalidate your results.

Any specimen which cannot be accommodated by the method described (which is known as the hydrostatic method) must be immersed in a series of liquids in which it will either float, sink or remain suspended when pushed below the surface. In this last, the match between the SG of specimen and liquid is closest and all we need to know is the SG of the liquid.

A home-made balance for SG determinations consists of a ruler pivoted about one-third of its distance and balanced horizontally so that the end can move up and down in a slot on which the balance point is marked. The specimen is contained in a wire cage and the non-indicating end of the ruler has some heavy object suspended from it as a counterweight.

Operation of the home-made balance involves placing the counterweight in such a position that the specimen is balanced half-way along the scale. Note the distance from the pivot. Balance the specimen in water (bubble-free and with a drop of detergent added to minimise surface tension) and then move the immersed specimen to a different position and take another reading. The two readings are D_a and D_w (D representing distance). The readings here are in inverse proportion to the weight of the specimen in air and water. Apply the formula $D_w/D_w - D_a$ to find the specific gravity.

SG is numerically equal to the mineral's density in grams per cubic centimetre. The table opposite gives the mean values, in ascending order, of the SGs of some significant minerals.

Hardness test

Hardness tests should be carried out with care because specimens are easily damaged. The standard table of hardness is that devised by Friedrich Mohs; it consists of a list of

Specific gravity of various minerals

Ulexite	1.9
Opal	2.1
Sulphur	2.0
Stilbite	2.1
Graphite	2.1
Halite	2.1
Natrolite	2.2
Sodalite	2.2
Gypsum	2.3
Apophyllite	2.3
Wavellite	2.4
Serpentine	2.5–2.6
Microcline	2.5–2.6
Orthoclase	2.5–2.6
Scapolite	2.7
Turquoise	2.6–2.9
Albite	2.6
Plagioclase	2.6–2.7
Quartz	2.6
Oligoclase	2.6
Beryl	2.6–2.9
Vivianite	2.6–2.7
Calcite	2.7
Prehnite	2.8–2.9
Tremolite	2.9–3.1
Nephrite	3.0
Tourmaline	3.0–3.3
Hornblende	3.0–3.4
Apatite	3.1–3.2
Andalusite	3.1–3.2
Actinolite	3.1–3.3
Fluorite	3.1
Axinite	3.2–3.3
Olivine	3.2–4.3
Torbernite	3.2
Jadeite	3.3
Diopside	3.2–3.3
Epidote	3.4–3.6
Diamond	3.5
Topaz	3.5
Spinel	3.6
Grossular	3.6
Malachite	3.6–4.0
Chrysoberyl	3.7
Siderite	3.8–3.9
Blende	3.9–4.1
Zircon	3.9–4.7
Almandine	3.9–4.3
Celestine	3.9
Corundum	3.9–4.0
Smithsonite	4.0–4.5
Rutile	4.2
Baryte	4.5
Pyrolusite	4.4–5.0
Stibnite	4.6
Marcasite	4.8
Pyrite	5.0
Bornite	5.0
Hematite	5.3
Bournonite	5.8
Scheelite	5.9–6.1
Arsenopyrite	6.0
Cuprite	6.1
Anglesite	6.3
Cerussite	6.5
Cassiterite	6.8–7.1
Pyromorphite	7.0
Galena	7.5
Bismuth	9.7
Silver	10–11
Platinum	14–19
Gold	15–19

minerals arranged in order of hardness and with a numeration 1–10, with diamond as the hardest known substance at 10. It runs as follows:

1 Talc
2 Gypsum
3 Calcite
4 Fluorite
5 Apatite
6 Feldspar
7 Quartz
8 Topaz
9 Corundum
10 Diamond

Note that the difference in hardness between each successive number is not the same; each mineral will scratch the ones with lower numbers. Quartz at 7 is in a significant position since much airborne dust is silica. This means that material of a lower hardness will be abraded by dust over a period (this applies most significantly to some of the gem minerals). Intermediate places on the scale have been assigned to one or two convenient sources of abrasion; the finger nail has a hardness of about 2.5 and a penknife blade 5.5. Some minerals vary in hardness with direction (kyanite is 4 along the crystal and 7 across it). In general the oxides and silicates are harder than sulphates and carbonates, halides and phosphates.

The hardness test is carried out by scratching the specimen, preferably while observing with a microscope or lens, with a piece of known hardness mounted in a wooden holder (a hardness pencil). The dust raised by the scratch should be blown away and the indentation, which should be only a few millimetres in length, carefully examined. Some minerals may merely mark the specimen rather than scratch it. Always use a fresh surface for testing since surfaces long exposed may have suffered alteration; cleavage surfaces can often be obtained and used or a small face can be ground on the specimen.

Some minerals may be scratched easily yet are hard to break or crush. This property of toughness is called the tenacity of the mineral, which varies; a brittle mineral is easily broken or powdered and a malleable one beaten into thin sheets (gold is the best example). Ductile minerals can be drawn into wire (gold again), and sectile ones peeled with a blade (like sharpening a pencil). Elastic minerals will bend and resume their original shape while flexible ones will also bend but not return to their first state. Some examples are: sectile – gypsum; brittle – calcite; and flexible – selenite.

If during the application of one of these tests your specimen does break, you can console yourself by observing the nature of the fracture. The commonest type is called conchoidal and resembles the whorls of a conch shell. Glass shows this very markedly, and other minerals to a lesser extent. Splintery or hackly fractures leave sharp edges and fibrous is another type, needing no elaboration.

Hardness

1	Talc
1–2	Graphite, vivianite
1.5–2.5	Torbernite, galena, pyromorphite, halite
2.0–2.5	Copper, gold, silver, chalcocite, anglesite, bournonite, biotite, muscovite
3	Bornite, cerussite
3.0–3.5	Calcite, celestine
3–4	Tetrahedrite, chalcopyrite, blende, rhodochrosite, dolomite, malachite, cuprite, mimetite, wavellite, pyromorphite, variscite
4–4.5	Platinum
4.5–5	Turquoise, hemimorphite, scheelite, vivianite, apatite, dioptase, analcime
5.0–5.5	Goethite, lazurite, monazite
5.5–6.0	Uraninite, actinolite, tremolite, datolite, opal
6	Orthoclase, sodalite, diopside, rhodonite, olivine
6.0–6.5	Pyrite, marcasite, rutile
6.5–7.0	Cassiterite, zircon, hematite, jadeite, nephrite, andradite, prehnite, axinite
7	Quartz, epidote, clinozoisite
7.0–7.5	Pyrope, spessartine, tourmaline, almandine
7.5–8.0	Phenakite, beryl
8.0–8.5	Spinel, topaz, chrysoberyl
9	Corundum
10	Diamond

Refractive index

It is not easily possible to determine the velocity of light in a large clear crystal, but it is possible to measure the critical angle by means of an instrument known as a refractometer. Mineral specimens commonly are small and need to be viewed in a suitable liquid of known refractive index. If a piece of ice is immersed in water there is scarcely any difference in the refractive indices and the ice is difficult to see. This principle is used over a whole range of minerals and liquids, and a large number of immersion liquids will be kept in the laboratory for this kind of determination.

Both refractive index and separation of isotropic from anisotropic crystals can be carried out by the utility instrument called the polarising microscope. For refractive index measurements to be carried out, any microscope needs a calibrated fine adjustment or some other means of measurement; all polarising microscopes have this, however. When the specimen is immersed in a liquid of known refractive index, the raising of the microscope tube shows a bright line passing into the medium (specimen or liquid) of a higher refractive index. Lowering the tube reverses the process. This method, which is especially suitable for small mineral grains, is called the Becke line effect. If the refractive index of a faceted gemstone or transparent crystal needs to be taken, it is possible to take readings with the polarising microscope in the following way: the microscope is focused first through the stone or crystal, reading from the surface first and then to the cover slide on which the specimen is resting. A scratch on the surface and one on the slide should be looked for to assist focusing. Then a reading is taken directly to the surface of the slide, not passing through the specimen. The first reading is the apparent depth, which due to refraction appears less than the real depth – the second reading. Real depth/apparent depth gives the refractive index of the specimen.

The polarising microscope also provides polarised light; between the light source and the stage is a piece of polaroid material which allows light vibrating in one direction only to pass. Somewhere below the ocular (eyepiece) is another piece of polaroid which allows light to pass which is vibrating in a direction at right angles to that passed by the first piece of polaroid. This first piece is called the polariser, and the second the analyser. When an isotropic mineral is placed between these two (on the stage) no light reaches the eye-piece since the polarised light which has passed through the polariser remains unaltered in its vibration direction. All isotropic minerals and amorphous substances, such as opal and glass, remain dark even when turned through 360 degrees.

Interference colours

In the case of anisotropic minerals where the ray is split into two, each is plane polarised in respect of the other. When placed between crossed polars, the mineral will become dark and light alternately four times during a complete revolution. The two rays into which the incident ray has been split on entering the crystal vibrate at right angles to each other and travel at different velocities. One ray is called the fast ray and the other the slow ray. If an anisotropic specimen with parallel sides is examined between crossed polars, the two rays will interfere with each other since light has travelled through with two different velocities. Where white light is used, colours will be seen due to this interference. Where there would be darkness and light if monochromatic light were used, depending upon whether the one ray was a whole number of wavelengths behind the other (extinction) or fractional numbers (enhancement), we get colours from the enhancement; and instead of extinction and darkness we find the complementary colour to the one which would have been eliminated from the spectrum. This set of colours is known as interference colours.

There are different orders of interference colours, depending upon the path difference of the wavelengths by 1, 2, 3 and so on. These orders are called first order, second order and third order. Since interference colours arise from birefringence, thickness of the specimen and its orientation, a continuous change in the direction of the light will give a continuous change of interference colours. For any given orientation, the more birefringent and the thicker the specimen is, the higher order of interference colours it will show. If a specimen is of uniform thickness as a cleavage section might be then it will show a single colour.

Colours of known amounts can be obtained with a specimen by the use of one or other of the accessory plates. These include the quartz wedge, gypsum plate and mica plate. In all types the fast ray or vibration direction of the lower refractive index is parallel to the long side of the wedge or plate. The gypsum plate is a cleaved section of a gypsum crystal of such a thickness that it will give a uniform red in white light (first order red). The mica plate is also a cleavage section and gives for yellow light a path difference of ¼ wavelength. It is sometimes for this reason known as the quarter waveplate.

The quartz wedge is elongated and wedge-shaped, with the vibration direction of the fast ray parallel to its length and that of the slow ray across its length. As the wedge is introduced into the optical train it becomes slowly thicker and thus increases the path difference of the rays passing through it, giving a succession of interference colours. The greater the angle of the wedge, the greater the orders shown by each part of the length. If the quartz wedge is viewed in monochromatic light, it is seen to be crossed by alternating dark and light bands: dark when the path difference is a whole number of wavelengths and light where it is not a whole number.

Crystals where incident light is split into two refracted rays can be classified into two types. In one type there is one direction of single refraction, known as the optic axis, and these crystals (of the tetragonal, hexagonal and trigonal systems) are known as uniaxial. Uniaxial crystals have two refractive indices; one of them is invariable and the other moveable. The stationary index is known as omega (ω) and the moveable one as epsilon (ϵ). In biaxial crystals there are two optic axes and therefore three possible refractive indices, though on a refractometer, for example, only two can be seen at one time without moving the specimen. All these indices are variable (they are all extraordinary); they are given the designations alpha (α) for the lower arithmetical value of refractive index, gamma (γ) for the higher value and beta (β) for an intermediate value – not half way (except by chance) but usually nearer to one of the other values.

If a crystal section (or even a faceted gemstone) is examined between crossed polars, a position will be found in which interference colours become visible. The light needs to be convergent, and for this purpose it is useful to place a 10× lens between the specimen and the analyser – there are various devices to avoid the need of a third hand here – and while moving the specimen look for a characteristic figure. When looking along the optic axis of a uniaxial crystal, this figure (called the interference figure) takes the form of a black cross surmounting coloured concentric circles (*Figure 6.2*). The arms meet in the centre, except in the case of quartz where the centre is hollow. The interference figure of quartz is unique and therefore diagnostic; it can be seen very well when rock crystal beads are placed between crossed polars. There is no need to use a lens to obtain convergent light in this case, since the spheres act as their own lens.

Figure 6.2. Uniaxial

Figure 6.3. Biaxial

With biaxial crystals the characteristic figure can vary, but is basically elongated coloured bands with two black brushes superimposed on them back to back (*Figure 6.3*). In one position a cross figure may be obtained, but it can be distinguished from the similar figure obtainable from uniaxial crystals by the coloured bands forming two eye-like figures, one on each side of the black cross.

Fluorescence and phosphorescence

A number of minerals can be recognised by their characteristic fluorescence and phosphorescence. Fluorescence is simply the emission of energy by a substance when irradiated by energy of shorter wavelength. The energy emitted is in the form of visible light. Most minerals displaying fluorescence contain impurity ions known as activators. Exciters of luminescence include X-rays, cathode rays and, more familiar to the collector, long- and short-wave ultraviolet light.

Looking at the electromagnetic spectrum we see that violet light has a lower wavelength than red light; it has a higher energy and can be thought of as more powerful. Beyond the violet end of the visible spectrum is the region known as the ultraviolet, of still higher energy. X-rays are of higher energy still. If energy in the ultraviolet region irradiates certain minerals they emit radiations of a higher wavelength but lower energy, so that when ruby is subjected to long-wave ultraviolet rays, it glows red, a colour of lower energy. Since ruby is red anyway, a more striking example can be found in some diamonds which are an off-white shade (near to very pale yellow). Many of these stones glow a sky blue under ultraviolet light. In the case of the calcium tungstate scheelite (colourless in daylight), short wave ultraviolet light will produce a bright blue fluorescence.

Ultraviolet light is produced quite simply by a high-pressure mercury discharge lamp in a quartz tube and fitted with a filter which allows some visible (violet) light to pass but which also permits the passage of a powerful line at 365 nm in the near ultraviolet; this line stimulates the fluorescence. A low-pressure quartz mercury lamp fitted with a filter allowing the passage of a line at 253.7 nm acts as a source of short-wave ultraviolet light. This filter, too, allows some visible light to pass, and it should be added at this point that it is inadvisable to allow any of the radiation to strike the eyes – especially short-wave radiation, as long-term damage may be caused and short-term irritation certainly will be.

Before examining some examples of fluorescent minerals, here is a simple method of detecting the presence of chromium, particularly in gemstones such as ruby (or supposed ruby). The specimen is illuminated by light which has passed through a blue filter, such as a flask of copper sulphate. The specimen thus illuminated is observed through a red filter. Since any red colour seen cannot have emanated anywhere but in the specimen (blue light having no red component), it must be the result of fluorescence. This phenomenon was first observed by G. G. Stokes in 1852, and is known as crossed filters.

Phosphorescence is the emission of radiation after the exciting medium has been removed. Thus some minerals will continue to glow after the ultraviolet lamp has been switched off, and some species glow for quite a long time. This effect, like all those connected with light, is best observed in a darkened room. Willemite will glow for many minutes after short-wave irradiation.

Since both forms of ultraviolet sources involve the transmission of some visible blue or violet light, it is possible to mistake the reflection of this visible light for true fluorescence, especially when examining a pale or colourless specimen. If in doubt about the effect seen, place a piece of ordinary glass between lamp and specimen – this is with short-wave light only – and see if the glow persists; if so, the effect seen is reflection of visible light only, since the short-wave energy will not pass through the glass.

Many authorities recommend the purchase of a short-wave lamp if there has to be a choice between that and a long-wave lamp. Many models on sale today incorporate both types. It is interesting to note that short-wave radiation often causes some response from minerals which are usually inert to long-wave.

Some minerals show a particular colour in long-wave ultraviolet light and a different one in short-wave. This is seen in some man-made minerals but also in some natural ones such as tugtupite which glows a salmon pink in long-wave and a deep crimson in short-wave. In this case a third interesting phenomenon is found, in that the material fades slightly in daylight but the colour (pink to red) can be restored by irradiation. A calcite from Terlingua, Texas is reported as glowing a momentary pink when the short-wave lamp is switched on; this colour is replaced by a blue fluorescence which eventually swamps the pink. This blue glow can be continued as a phosphorescence of outstanding brightness.

Some localities seem particularly well-endowed with fluorescent minerals; one of the most celebrated localities is Franklin, New Jersey, where calcite, willemite and a variety of other minerals are found together. Spheres cut from the rock in which these minerals are embedded look quite a dull brown by daylight, but under ultraviolet light appear most spectacular with a variety of glowing colours. Rotating spheres of this kind make a good show display. Remember that if a particular specimen does not fluoresce it does not necessarily mean that your identification is wrong. Though most examples of a mineral may fluoresce, any particular one may not; fluorescence is rarely diagnostic but is a useful secondary test. Naturally, in dark mine conditions a lightweight ultraviolet lamp powered by a battery is most useful.

Fluorescence in ultra-violet light

Whitish	Long wave: colemanite, aragonite Short wave: anglesite, scheelite
Red	Long wave: corundum (ruby), red spinel Short wave: calcite, red spinel
Orange	Long wave: corundum (yellow Sri Lanka material), diamond, sodalite (in patches)
Yellow	Long wave: anglesite, diamond, apatite, zircon Short wave: opal, zircon
Greenish-yellow	Long wave: autunite, adamite Short wave: similar
Green	Long wave: adamite, autunite Short wave: opal, some chalcedony
Blue	Long wave: diamond, fluorite, witherite Short wave: fluorite, diamond, scheelite
Violet	Long wave: fluorite Short wave: fluorite

Phosphorescence

White	Gypsum, opal
Pink	Calcite, some diopside
Orange	Blende
Bluish-white	Celestine, zircon
Pale blue	Diamond, cerussite
Blue/violet	Fluorite

Chemical testing

The chemical testing of minerals can get very complicated, but simple tests can be carried out without danger and with some chance of success. Naturally the larger the specimen the better chance of identification; no one wants to risk a few precious grains. Both wet and dry chemical tests can be carried out, but probably the flame and blowpipe are the easiest to use and to interpret.

Use of the blowpipe is common amongst prospectors since it can identify several of the more important ores. It is simply a tube through which the user blows to obtain a hot flame, the tube being so shaped to assist the operator. The tube is placed in a flame rich in carbon; gas from a Bunsen burner is excellent but a candle flame will do. With the Bunsen burner the air hole should be closed to ensure a luminous flame. It is not always easy to master the technique of the blowpipe, simple though it may appear. The flame produced has to be continuous and this needs the operator to supply a constant stream of air. This is done by collecting air in the mouth (puffing the cheeks out); breathing in through the nose ensures steadiness of supply, and the tongue is used to block the passage of too much air from the lungs.

The hottest part of the blowpipe flame may reach temperatures up to 1500°C and the ease of fusion of a mineral at such heat gives some idea of its identity. A small piece is held in the flame (the hottest part lies just outside the part you can see) and the type and speed of melting noted. Some minerals melt completely but in other cases only edges melt; the degree to which they are affected is known as their fusibility. Whereas quartz is virtually infusible in the blowpipe flame, stibnite fuses easily in a candle flame.

The blowpipe can be used to make a reducing flame, i.e. one with no oxygen in it. The opposite of reduction is oxidation, the adding of oxygen to a substance. Part of the blowpipe flame contains carbon monoxide; this has a power to remove oxygen from substances so that CO_2 will be formed. If a piece of ferric oxide, Fe_2O_3 is placed in that part of the flame it will be reduced to ferrous oxide, FeO. To accomplish the oxidation of a substance it must be placed so that the flame can heat it but not contact it. In this way pyrite, FeS_2 may be converted to ferric oxide Fe_2O_3 and sulphur dioxide SO_2.

Charcoal blocks may be used to obtain metals from their ores and to collect oxides. They can be heated and the mineral, in powder form, placed in a small hollow in the block. To assist the reaction a flux may be used in some cases, mixed with the mineral in the proportion 2 flux to 1 of mineral. Some metals will be reduced on the block even when the blowpipe proves ineffectual. Silver forms a bright white globule with no coating; a reducing mixture is used. Since other metals form similar globules the apparent silver is dissolved in nitric acid to which hydrochloric acid is then added, upon which a white silver chloride precipitate is formed. Lead forms a grey fusible globule which is bright in the reducing flame, and iridescent in the oxidising flame. Hot incandescent charcoal will reduce the lead. Dissolve in nitric acid; add sulphuric acid to the clear solution thus formed. White lead sulphate precipitate will be obtained.

A mineral can be powdered and placed in an open glass tube which is then, while inclined, heated in a Bunsen flame. The flame is first allowed to play on the upper part of the tube and then on that part of the tube just above the mineral. A current of air will be formed through the tube and the mineral may oxidise. Some oxides will escape as gas while others will condense on the walls of the tube as sublimates. Sulphur comes out of this test particularly well; sulphur dioxide escapes from the tube and this gas has a characteristic smell. It will change blue litmus paper to red when the moistened paper is placed at the upper end of the tube.

The closed-tube test is intended to show the behaviour of a mineral when heated without oxygen. The powdered specimen is placed in the tube and heated by a Bunsen flame. Minerals containing water of crystallisation (particularly the zeolite family of silicates) will give off water on the cold upper part of the tube. Sulphur or sulphides with a high sulphur content will glow red when hot and turn yellow when cooled.

The colour imparted to a flame by a mineral held in it will give some idea of the elements contained in the specimen. Strontium will turn the flame crimson, as will lithium; copper will turn it emerald-green, when obtained from copper oxide; otherwise copper will give blue. Any copper mineral will give a blue flame if it is moistened with hydrochloric acid first. Sodium colours the flame a bright yellow, and the very smallest amount of this element in a specimen is sufficient to give this colour. Boron gives a yellow-green (most boron-containing minerals should first be broken down by sulphuric acid). Barium also gives a yellow-green. The best way to carry out the flame test is to place the specimen in the Bunsen flame on a piece of platinum wire. The persistence of the sodium flame can be masked by placing a piece of blue glass in front of the flame. This will mask the yellow and allow the other colour to be seen. Even when a specimen contains no sodium, traces of sodium on it (e.g. from dust) may colour the flame yellow.

Some elements can be dissolved in fluxes to give colour to the fused mass. Borax is one of the most commonly-used fluxes. The flux is first fused on a platinum wire and the mineral then mixed with it in powdered form. The bead is then re-heated to allow satisfactory solution. Identification is by colour of the bead. Oxides of chromium give a yellowish colour in an oxidising flame and an emerald green in a reducing flame where borax is the flux. If the flux used is phosphorus salt the flame is emerald green in both cases. Manganese gives a reddish violet in the oxidising flame, and is colourless in the reducing flame using a borax flux. With the phosphorus salt flux the colours are violet and colourless. With uranium, taking the type of flame and the flux in the same order the colours are yellow, pale green, greenish-yellow and emerald green. With cobalt the colours are blue in all cases.

Dry chemical analysis commonly involves the following reagents: borax and phosphorus salt as already described; cupric oxide which makes a good flame test for chlorine; potassium iodide and sulphur equally as a test for bismuth, lead and other metals. This is often called the bismuth flux. Metallic zinc or tin is used for reduction tests in solution of hydrochloric acid.

The wet chemical analyses usually involve hydrochloric acid to dissolve minerals. Nitric acid and sulphuric acid are used in concentrated and dilute forms respectively. Note that an acid is diluted by pouring it into water, *never* the other way round as very dangerous spattering will result. Ammonium oxalate is used as a test for calcium and sodium phosphate in an aqueous (watery) solution as a test for magnesium. Ammonium molybdate is used to test for phosphates, silver nitrate for chlorine, dimethylglyoxime for nickel and hydrogen peroxide for titanium.

7

Mineral descriptions

The descriptions of minerals which follow are arranged in chemical rather than alphabetical order. This is the traditional method of arranging a mineral collection or cabinet and all major collections are in fact arranged this way. Entries begin with elements and their alloys and then proceed to oxides, sulphates, silicates and so on. Since many of the important minerals are members of mineral families, they are placed with the families, which are themselves introduced by brief descriptions. The listing in general follows that of the *Chemical Index of Minerals* published by the Department of Mineralogy of the British Museum (Natural History).

For each mineral the important constants are given, together with features to help identification, notes on cleaning where relevant, and some of the more important localities. The same order is followed for each entry; those wishing to find a specimen by referring to one or other of its properties will be able to do so by using the identification tables which follow this section.

Since the best method of conserving a specimen is often to leave it alone, details of treatment are only provided when some specific action is needed. If the specimen does need to be cleaned, distilled water is usually the best thing to use; to avoid repetition this should be assumed to be the recommended treatment unless some other action is stated. In some cases the chemical composition of a mineral may be uncertain. When this is the case the composition is given in words rather than as a formula. Hardness is referred in all cases to Mohs' scale; specific gravity is given as grams per cubic centimetre, gm/cm^3. Locality spellings follow the usage of the Universal Postal Union.

ELEMENTS

Copper, Cu

Cubic; cubes or rhombdodecahedra less common than dendritic or filiform shapes.

Colour: copper-red with brown tarnish; streak copper-red; metallic lustre.

Ductile and malleable; hardness 2.5–3.0; SG 8.9

Occurs in basaltic lavas, sandstones and conglomerates; found in veins and beds with chalcopyrite, cuprite, malachite etc.

Localities: Cornwall, UK, crystals; Turnisk, USSR, dendritic; Keweenaw, Michigan and Bisbee, Arizona, USA are major economic deposits.

Remove black copper oxide with a solution of one part by weight sodium hydroxide, three parts potassium sodium tartrate and 20 parts distilled water.

See *Figure 7.1.*

Silver, Ag

Cubic; dendritic wires or scales, crystals rare.

Colour: silver, tarnishing to black; streak silver white; metallic lustre.

Ductile and malleable with hackly fracture; hardness 2.5–3.0; SG 10.1–11.1.

Occurs in hydrothermal veins, probably formed by the action of hot water on silver sulphides; disseminated in various metallic sulphides.

Localities: Kongsberg, Norway (fine specimens); Pribram, Czechoslovakia; Charnarcillo, Atacama, Chile; Keweenaw, Michigan and Butte, Montana, USA.

Remove tarnish with sodium cyanide or electrolytically; keep away from all forms of sulphur.

See *Figure 7.2.*

Figure 7.1. Native copper from Keweenaw, Michigan, USA

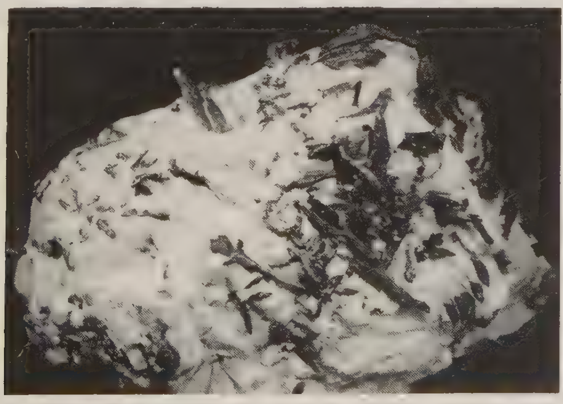


Figure 7.2. Silver in calcite

Gold, Au

Cubic; crystals rare but are octahedra, cubes or rhombdodecahedra; more commonly found as grains, dendrites or nuggets; twinning common.

Colour: golden yellow, lighter with high silver content; streak golden yellow; metallic lustre.

Ductile and highly malleable; hardness 2.5–3.0; SG 19.3 (pure gold), 15.6–19.3 (alloyed).

Occurs in various types of rock, also in sea water. Auriferous quartz found in hydrothermal veins is a major source of gold. Alluvial deposits frequently prospected by 'panners'.

Localities: Witwatersrand, South Africa; Zimbabwe; Egypt; Ghana; parts of the UK, particularly Wales; USSR; Czechoslovakia; Australia and New Zealand; western states of the USA; Canada.

Remove quartz with strong hydrofluoric acid.

See *Figure 7.3.*

Figure 7.3. Gold nugget showing large octahedral crystal faces, from Grass Valley, California, USA

Mercury, Hg

Hexagonal; rare in metallic state, crystallising at 10°C. Usually found as fluid globules.

Colour: tin white; bright metallic lustre.

SG 13.6

Occurs as small isolated drops, though in regions of high volcanic activity it may form large fluid masses in cavities.

Localities: Idrija and Mount Avala, Yugoslavia; Landsberg, West Germany; California and Texas, USA.

Handle with care; highly poisonous.

Diamond, C

Cubic; octahedra, rhombdodecahedra, icositetrahedra; twinning frequent.

Cleavage: perfect octahedral.

Colour: white, yellow, pink, green, blue, brown, black; streak white; adamantine lustre; greasy feel.

Hardness: 10; SG 3.52; RI 2.42; dispersion 0.044; some stones may show anomalous birefringence.

Luminescence: varies but many off-white to yellow stones glow sky-blue.

Types:
- (1a) Contains nitrogen in platelet form. Most natural stones are this type;
- (1b) Nitrogen in dispersed form;
- (2a) No significant nitrogen;
- (2b) No nitrogen but some aluminium – all natural blues;
- (3) Meteoritic form with hexagonal structure named lonsdaleite.

Occurs in 'pipes' of kimberlite, a serpentinised olivine or alluvially with quartz, corundum, platinum, zircon etc.

Localities: many countries on the African continent, particularly South Africa; Brazil; USSR, particularly Siberia; Venezuela; India; Australia.

See *Figure 7.4*.

Lead, Pb

Cubic; thin plates and small globular masses.

Colour: grey.

Very malleable and somewhat ductile; hardness 1.5; SG 11.4.

Occurs rarely as the native metal, more commonly alloyed. Found in compact limestone and in gold placers.

Localities: Pajsberg, Sweden; Ural mountains, USSR; Mexico; New Jersey, USA.

Figure 7.4. Diamond crystals showing octahedral form and twinning

Bismuth, Bi

Hexagonal; massive form more common than crystals; may be granular or arborescent.

Cleavage: perfect.

Colour: silver-white, becoming reddish with tarnish; streak silver-white; metallic lustre.

Hardness 2.5; SG 9.8.

Occurs in veins of granite and gneiss; deposited hydrothermally. Often obtained from gold and silver smelting.

Localities: San Baldomero, Bolivia; East Germany; Australia; Devon and Cornwall, UK.

Sulphur, S

Orthorhombic though other variant forms are found due to different types of the mineral occurring: usually as acute pyramidal crystals. Tabular and massive forms also found.

Colour: bright yellow; streak white; resinous lustre.

Slightly sectile; hardness 1.5–2.5; SG 2.0–2.1; RI 1.958, 2.038, 2.245 with strong birefringence.

Occurs in regions of volcanic activity and in fumarolic gases; also formed by the decomposition of hydrogen sulphide in hot springs. Found in sedimentary rocks, usually with limestone or gypsum.

Localities: Girgenti, Sicily, produces the finest crystals; Japan; Iceland; Louisiana, USA.

Very sensitive to heat – even the warmth of the hand may cause it to crack. Do not expose to bright sunlight nor attempt to clean.

Iron, Fe

Native iron is rare, the element being found either in masses (terrestrial) forming a matrix in which silicate minerals are embedded, or as grains or scales (meteoritic).

Colour: grey to black; metallic lustre.

Hardness 4.5; SG 7.3–7.8; strongly magnetic.

Localities: in basalt at Disco Island, West Greenland. Kamacite, a form of meteoritic iron, is echoed terrestrially by awaruite, found in Awarua Bay, South Island, New Zealand. This contains 60% or more nickel.

Platinum, Pt

Cubic; commonly found as grains. Rare in native form, usually alloyed with iron, iridium, rhodium, palladium or osmium.

Colour: grey; streak steel-grey; metallic lustre.

Malleable and ductile; hardness 4.0–4.5; SG 14–19 (up to 22 in pure form).

Occurs in nuggets or grains found alluvially but emanating from weathered Pt-bearing rocks.

Localities: Ural mountains, USSR; Colombia; New South Wales; New Zealand; USA; Canada.

SULPHIDES AND SULPHATES

Sulphates and sulphides have the element sulphur in common. In the sulphate minerals is the complex anion $(SO_4)^{2-}$. Sulphates are found in sedimentary rocks and often in salt deposits which are formed from the precipitation of salt from highly saline water in lakes. The minerals gypsum and anhydrite are very common and both are formed from saline water. Baryte, $BaSO_4$ is found in veins in which it was deposited by hot water within the earth. This is a notably dense mineral, formerly known as 'heavy spar' though it is not particularly hard. Sulphide minerals have S^{2-} as the anion; they are formed in the absence of oxygen, a condition preventing the formation of sulphates. Likely places for the formation of sulphides includes levels below the water table; many ores of metal are sulphides.

Metal atoms and sulphur atoms are bonded into a variety of structures with the bonding being covalent more often than ionic. Hardness of sulphides is generally low but density is high. The common iron mineral pyrite, FeS_2 is probably the most collected sulphide.

SULPHIDES

Bornite, Cu_5FeS_4

Cubic, usually massive though some cubes and rhombdodecahedra are found.

Colour: reddish-brown but developing an iridescent tarnish of a mainly purple colour, giving rise to the name 'peacock ore'; streak pale grey to black; metallic lustre.

Hardness 3; SG 4.9–5.4.

Occurs in hydrothermal veins with chalcocite; may also occur in pegmatites and in igneous rocks.

Localities: fine crystals from the Redruth area of Cornwall; Montecatini, Tuscany, Italy; Androta, Malagasy Republic.

Chalcopyrite, $CuFeS_2$

Tetragonal, crystals resemble tetrahedra, massive forms and twinning common. Colour: brass-yellow with iridescent tarnish (sometimes called copper pyrite); streak greenish-black; metallic lustre.

Hardness 3.5–4.0; SG 4.1–4.3.

Occurs in igneous rocks and in hydrothermal veins with pyrite and blende.

Localities: St Agnes, Cornwall and Devon, UK; St Marie-aux-Mines, Alsace, France; Arizona and other states of the USA.

Blende, ZnS

Cubic, commonly forming tetrahedra, dodecahedra and cubes. Polysynthetic twinning common. Alternative name sphalerite.

Cleavage: perfect dodecahedral.

Colour: yellow, brown, black, red, colourless; streak brown to yellow; adamantine lustre.

Hardness 3.5–4.0; SG 3.9–4.1; RI 2.37–2.42; dispersion 0.156.

Occurs in area of contact metamorphism where sulphides are introduced into rocks; found in veins.

Localities: fine crystals, sometimes cut as gemstones, from Picos de Europa, Santander, Spain; St Agnes, Cornwall, UK; Missouri, USA.

Remove calcite encrustation with dilute hydrochloric acid.

Galena, PbS

Cubic, forming well-shaped crystals, usually cubes. Some skeletons and twins.

Cleavage: perfect.

Colour: grey; streak grey; metallic lustre.

Hardness 2.5–2.75; SG 7.4–7.6.

Occurs in beds and veins, formed by hydrothermal reaction; also from contact metamorphic deposits.

Localities: found with silver in Czechoslovakia; Freiburg and the Harz mountains, Germany; Truro and Liskeard, Cornwall, UK; Missouri, USA.

See *Figure 7.5*.

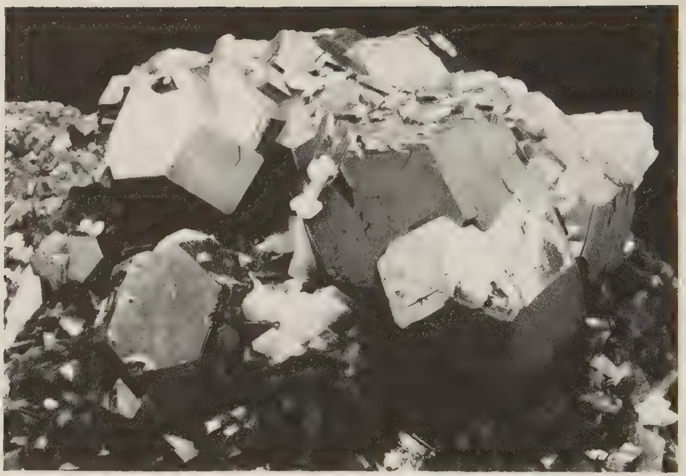


Figure 7.5. Galena

Stibnite, Sb_2S_3

Orthorhombic, prismatic crystals with vertical striations; massive forms or groups of columnar crystals also known.

Cleavage: perfect.

Colour: lead-grey; streak similar; metallic lustre, especially brilliant on broken surfaces.

Hardness 2; SG 4.52–4.62.

Occurs in veins with quartz or as beds in schists and in hot-spring deposits.

Localities: fine crystals from the Ichinokawa mines, Shikoku, Japan; Wolfsburg, Germany; economic deposits in Honan Province, China; Algeria; Mexico.

Pyrite, FeS_2

Cubic, as cubes striated on each face, the striations not following each other round the cube; also as pyritohedra.

Colour: resembles gold but looks more brassy; streak greenish-black; metallic lustre.

Hardness 6.0–6.5; SG 4.95–5.10.

Figure 7.6. Pyrite crystals from Elba and Spain

Occurs in a wide variety of rock types, sometimes associated with coal. Frequently mistaken for gold and known as 'fool's gold' on this account.

Localities: worldwide but fine crystals found in the St Gotthard region of Switzerland; pyritohedra on Elba.

Remove iron stains with oxalic acid; do not keep in too dry an atmosphere.

See *Figure 7.6.*

Marcasite, FeS_2

Orthorhombic, usually tabular or pyramidal; massive, reniform and globular habits also common.

Colour: bronze-yellow (may deepen with exposure to light); streak greyish-black; metallic lustre.

Hardness 6.0–6.5; SG 4.85–4.90.

Occurs with galena, blende and calcite in replacement deposits in limestone.

The marcasite of the jeweller is pyrite.

Localities: Arizona, USA; spear-shaped crystals from Karlovy Vary (formerly Carlsbad), Czechoslovakia; chalk marl between Folkestone and Dover, Kent, UK.

Do not clean.

See *Figure 7.7.*

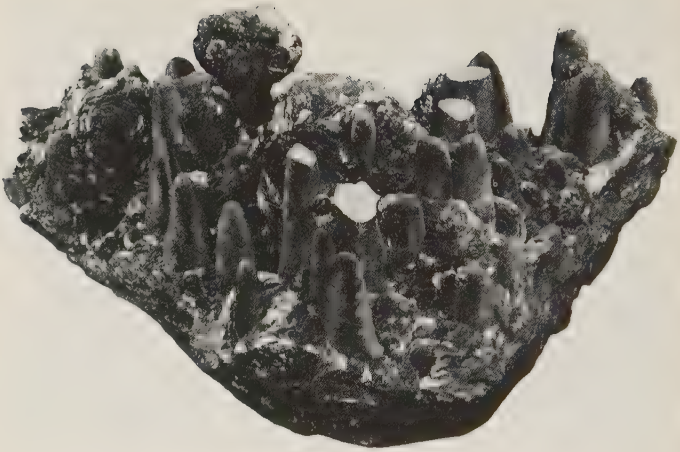


Figure 7.7. Marcasite from Arizona, USA

Arsenopyrite, FeAsS

Monoclinic, forming trillings or cross-shaped twins. Alternative name mispickel.

Colour: white to grey; streak greyish-black; metallic lustre.

Hardness 5.5–6.0; SG 5.9–6.2.

Occurs with gold and tin in pneumatolytic deposits; also with quartz in veins deposited by hot waters, and with silver ores.

Localities: silver mines at Freiburg, Germany; crystals from the Binnental, Switzerland, and Franconia, New Hampshire, USA.

Proustite, Ag_3AsS_3

Hexagonal, found as scalenohedral or acute rhombohedral crystals and massive forms are also known.

Cleavage: distinct.

Colour: deep scarlet; streak similar; adamantine lustre; suffers surface alteration on exposure to light.

Hardness 2.0–2.5; SG 5.57–5.64; RI 3.0–2.7.

Occurs in the upper portions of silver veins with galena and blende.

Proustite and pyrargyrite are known as ruby silver ores.
Localities: fine crystals from Ste Marie-aux Mines, Alsace, France; Jachymov, Czechoslovakia; Atacama, Chile.
Remove silvery surface coating by gentle wiping.

Bournonite, $CuPbSbS_3$
Orthorhombic, often forming twins resembling cog-wheels ('cog-wheel ore').
Colour: grey; streak grey; brilliant metallic lustre.
Hardness 2.5–3; SG 5.7–5.9.
Occurs in veins with galena and other sulpho-salts.
Localities: Neudorf, Harz mountains, Germany; Wheal Boys, Endellion, Cornwall, UK; western USA.

SULPHATES

Gypsum, $CaSO_4.2H_2O$
Monoclinic, tabular crystals, twinning common.
Cleavage perfect.
Colour: white, colourless, greenish, yellow or brownish; greenish fluorescence possible; vitreous lustre.
Hardness 2; SG 2.3.
Occurs in sedimentary deposits, saline lakes and volcanic deposits.
Localities: England; California and Colorado, USA; Chile; USSR.

Celestine, $SrSO_4$
Orthorhombic, tabular crystals or as nodules.
Cleavage: perfect.
Colour: white, light blue, yellow, brown; some specimens may fluoresce; vitreous lustre.
Hardness 3.0–3.5; SG 4.0.
Occurs in limestones and hydrothermal vein deposits.
Localities: Yate, Gloucestershire, UK; Mexico; Germany; Switzerland; USSR.

Baryte, $BaSO_4$
Orthorhombic, tabular crystals or aggregates.

Cleavage: perfect.

Colour: white, grey, colourless, brown; may fluoresce; vitreous lustre.

Hardness 3.0–3.5; SG 4.5.

Occurs in hydrothermal vein deposits, sedimentary rocks, cavities in igneous rocks or as a deposit from hot springs.

Localities: Cumbria and Derbyshire, UK; Romania; France; Germany.

See *Figure 7.8.*

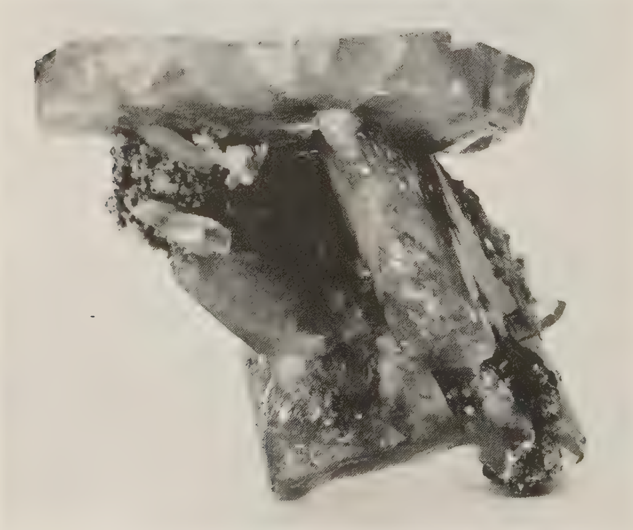


Figure 7.8. Baryte from Cumbria, UK

Anglesite, $PbSO_4$

Orthorhombic, tabular crystals or masses.

Colour: white, yellow, pale green or blue; streak colourless; vitreous lustre; yellow fluorescence possible.

Hardness 2.5–3.0; SG 6.4; RI 1.87, 1.89.

Occurs as a secondary mineral in lead deposits, formed by the oxidation of galena.

Localities: Matlock, Derbyshire and Leadhills, Lanarkshire, UK; Tsumeb, Namibia.

OXIDES

When the anion of a mineral is oxygen on its own it is called an oxide; it is a hydroxide when the anion is the group $(OH)^-$. In a number of minerals, cations of elements occur which are much smaller than the O^- anion and in these cases there is a close-packed structure; minerals with this structure are dense and hard. Corundum, Al_2O_3 (including ruby and sapphire) is an example. The iron ore hematite, Fe_2O_3 and the tin ore cassiterite, SnO_2 are important economic oxides. The spinel group of oxides can be given the general formula XY_2O_4, where X represents a divalent and Y a trivalent cation. Hydroxides are usually formed by the reaction of oxides with water and are often soft.

Cuprite, Cu_2O

Cubic, forming octahedra, dodecahedra and cubes; also massive.

Colour: dark red, streak brownish-red; adamantine lustre.

Hardness 3.5–4.0; SG 5.8–6.1.

Occurs by the alteration and oxidation of copper sulphide deposits.

Localities: USSR; Namibia (gem-quality crystals found at the Onganja mine); Cornwall, UK.

Keep out of strong light to avoid formation of surface film.

Chrysoberyl, $BeAl_2O_4$

Orthorhombic, characterised by pseudo-hexagonal twins ('trillings').

Colour: yellow-green; the variety alexandrite is green in daylight changing to dark red in tungsten light; and cat's eye (cymophane); vitreous lustre.

Hardness 8.5; SG 3.50–3.84; RI 1.747, 1.748, 1.757.

Occurs in granites, pegmatites and schists.

Localities: alexandrite from Brazil; Urals, USSR; Zimbabwe. Cymophane from Sri Lanka. Yellow-green from Brazil.

Periclase, MgO

Cubic, as cubes or octahedra.

Cleavage: distinct.
Colour: colourless.
Hardness 5.5; SG 3.56–3.58; RI 1.74.
Occurs in contact metamorphosed limestones.
Localities: Vesuvius, Italy; Nordmark, Varmland, Sweden.

Spinel, $MgAl_2O_4$
Cubic, usually as octahedra.
Colour: red, blue and various shades of these two colours; vitreous lustre.
Hardness 8; SG 3.58–3.60; RI 1.718.
Occurs in gem gravels or in limestone or dolomite.
Localities: Mogok, Burma; Sri Lanka.

Corundum, Al_2O_3
Hexagonal, forming tabular twins (the common habit of ruby) or bipyramids (characteristic of sapphire); ruby frequently shows lamellar twinning with associated parting.
Colour: red (ruby); blue (blue sapphire); many other colours all used as qualifying adjectives to sapphire.
Hardness 9; SG 3.99; RI 1.76–1.77.
Occurs as an accessory mineral in dolomites and limestones or in mica schists; from gem gravels.
Localities: finest ruby and blue sapphire from Burma; Sri Lanka; East Africa; Australia; Kampuchea; Thailand.

Quartz, SiO_2
Hexagonal, forming prisms capped by rhombohedra; twinning almost invariable though seen only by examination with instruments; piezoelectric; massive forms with a fine grain include the chalcedonies; pyroelectric.
Colour: rock crystal is colourless but amethyst (violet), citrine (yellow), smokey quartz (brown) and rose quartz (pink) are common; greens and blues less common.
Hardness 7; SG 2.65; RI 1.54–1.55.
Occurs in a variety of environments but fine crystals found in granite pegmatites.
Varieties of massive (crypto-crystalline) quartz include the chalcedonies; carnelian (reddish-orange); sard (light- to

reddish-brown); moss agate (grey or bluish with dendrites of iron compounds); agate, a variety of chalcedony in which bands of different colours occur; chrysoprase, coloured an apple green by nickel; bloodstone, dark green with red flecks; jasper, dark-reddish to yellow and fine-grained with iron oxide. Rutilated and tourmalinated rock crystal are known, the former being known as Venus's hair stone; cat's-eyes and star stones (rose quartz) are fairly common.

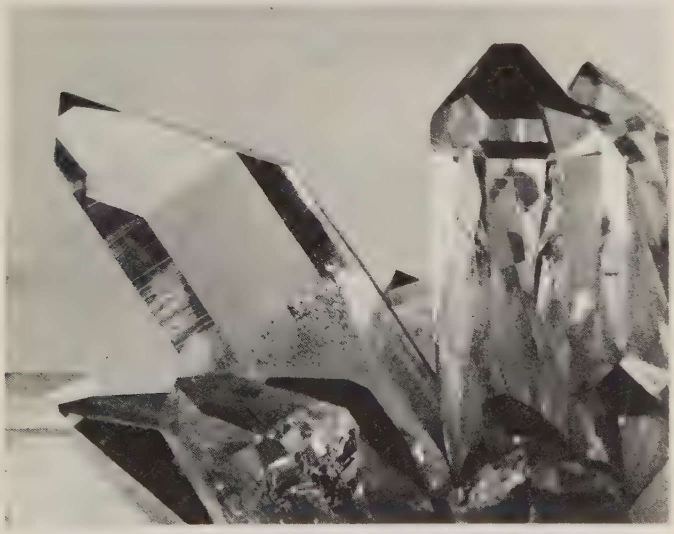


Figure 7.9. Quartz crystals showing prism and rhombohedron forms

Localities: worldwide though fine rock crystal is found in the St Gotthard area of central Switzerland; fine amethyst from Brazil and from the Ural mountains of the USSR; the variety tiger's eye (a crocidolite replaced by quartz and showing dark banding against a rich brown or yellow background) comes from South Africa.

See *Figure 7.9.*

Opal, SiO_2 *with a variable water content*

Amorphous, massive, stalactitic or replacing organic matter such as wood or shell (pseudomorphous).

Colour: precious opal shows a play of spectrum colour (due to diffraction from regularly stacked cristobalite spheroids) against a dark background (black opal) or a lighter one (white opal). Fire opal may show a play of colour but has a flame red to orange body colour. Common opal may be apple green from a nickel content. Water opal has a play of colour in a clear colourless body.

Hardness 5.5–6.5; SG 1.9–2.3; RI 1.45.

Occurs in seams in igneous rock where it is deposited by silica-bearing water at low temperatures; veins in sandstone.

Localities: precious opal from Australia; Brazil; Indonesia. Fire and water opal from Mexico; Czechoslovakia.

Rutile, TiO_2

Tetragonal, prismatic crystals capped by pyramids; geniculate (knee-shaped) twins found. Anatase and brookite are polymorphs, with rutile, of TiO_2.

Colour: dark reddish-brown to black; streak pale brown; adamantine lustre.

Hardness 6.0–6.5; SG 4.2–4.4; RI 2.62–2.90 (for synthetic rutile, used as a diamond simulant); DR 0.287; dispersion near 0.3.

Occurs in igneous rocks and in gneisses, schists and limestones; found as acicular crystals penetrating quartz.

Localities: Graz, Austria; St Gotthard area, Switzerland; rutilated quartz from Val Tavetsch, Switzerland.

Remove silica coating with hydrofluoric acid; iron stains with oxalic acid.

Cassiterite, SnO_2

Tetragonal, pyramidal or short prismatic crystals.

Colour: reddish-brown to black; streak white to grey; adamantine lustre.

Hardness 6–7; SG 6.8–7.1; RI 1.9–2.1; DR 0.096; dispersion 0.071.

Occurs in high-temperature hydrothermal veins and granite pegmatites; principal ore of tin. 'Wood tin' shows fibrous structure resembling wood.

Localities: Camborne and other areas of Cornwall, UK; pseudomorphs after feldspar at Wheal Cotes, Cornwall, UK; Bolivia; Namibia.

Magnetite, Fe_3O_4

Cubic, forming octahedra, rhombdodecahedra; fibrous masses; twinning common.

Colour: black; streak black; metallic lustre.

Hardness 5.5–6.5; SG 5.2; strongly magnetic.

Occurs in igneous rocks, contact and regionally metamorphosed rocks and in high-temperature veins.

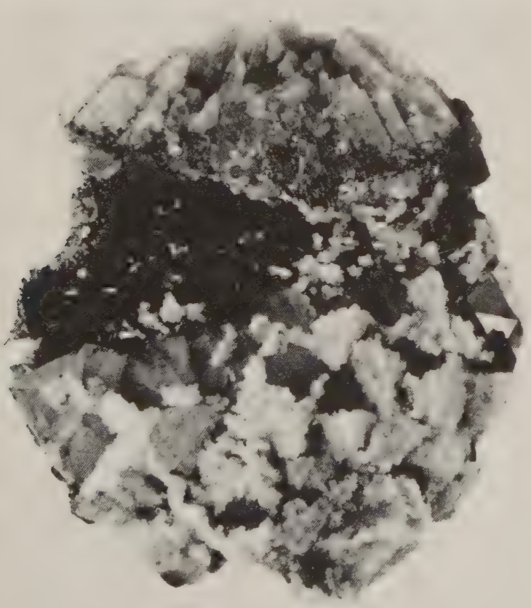


Figure 7.10. Hematite and quartz from Cleator Moor, Cumbria, UK

Localities: Norrbotten, northern Sweden; Ural mountains, USSR; Binnental, Switzerland; Port Henry, New York, USA.

Hematite, Fe_2O_3

Hexagonal, tabular or rhombohedral crystals; mamillary and botryoidal forms common.

Colour: grey to black; streak red to reddish-brown; metallic lustre.

Hardness 5–6; SG 4.9–5.3.

Occurs in igneous rocks and in hydrothermal veins; also in sedimentary rocks.

Localities: hematite, the most important ore of iron, is found widely throughout the world: Lake Superior area of USA; fine crystals in the St Gotthard area of Switzerland; Cleator Moor, Cumbria, UK.

Clean in dilute hydrochloric acid.

See *Figure 7.10*.

HALIDES

The halide group of minerals have either fluorine, chlorine, bromine or iodine as their anion; together these elements are known as halogens. The common bond is ionic and most halides show the high symmetry of the cubic crystal system. They are neither very hard nor dense; the best-known halide for the collector is fluorite, and halite (rock salt) is another important halide (whence the family name arises).

Halite, NaCl

Cubic, as cubes with concave faces; massive forms known as rock salt.

Cleavage: perfect.

Colour: no colour but shades of blue, yellow or red sometimes seen; streak white; vitreous lustre.

Hardness 2.5; SG 2.1–2.2; salty taste.

Occurs by the drying of brines or enclosed sea water.

Localities: worldwide, but fine crystals from Wieliczka, Poland.
Clean with alcohol.

Fluorite, CaF_2
Cubic, as cubes which by the operation of octahedral cleavage become octahedra; interpenetrant twinning common.
Cleavage: perfect octahedral.
Colour: pink, blue, green, purple, red, black, colourless; streak white; vitreous lustre; fluorescence (name for this phenomenon taken from the mineral) best under long-wave ultraviolet light.
Hardness: 4; SG 3.2; RI 1.43.
Occurs in mineral veins.
Localities: (in UK) lead veins of Northumberland; Cumbria and Durham; Derbyshire (massive banded purple variety known as Blue John). Pink octahedra from the St Gotthard area of Switzerland; Hardin County, Illinois, USA.
Remove calcite covering with HCl, iron stains with oxalic acid.

CARBONATES

Carbonates are composed of the anion $(CO_3)^{2-}$ and form an important mineral group. Since many marine organisms extract carbonate ions from salt water for use in their bony structure, the ages have seen an accumulation of sediments with a high carbon content. Limestones are rocks with such a high carbon content and the most important mineral in limestone rock is calcite, $CaCO_3$. The coordination polyhedron of the carbonate ion is a triangle, and for that reason many carbonate minerals show a basic threefold symmetry, being members of the trigonal class of the hexagonal system. This is not always the case, however; witherite, a carbonate of barium, is orthorhombic since the size of the barium cation is large. This forces the ions to pack in a different way, giving a fourfold coordination polyhedron. Calcium carbonate ($CaCO_3$) also has an orthorhombic form, the mineral aragonite. Here there is also a fourfold coordination polyhedron. Carbonates effervesce in acids and are usually soft.

Malachite, $Cu_2CO_3(OH)_2$

Monoclinic but almost invariably found as masses with botryoidal formation or as stalactites.

Cleavage: perfect.

Colour: bright to dark green, banded; streak pale green; vitreous lustre.

Hardness 3.5–4.0; SG 4; effervesces with HCl.

Occurs in the oxidation zone of copper deposits; found with azurite and a mixture of the two is known as azurmalachite.

Localities: Ural mountains, USSR; Zaire; Arizona, USA; Cornwall, UK.

Wash with distilled water. Add ammonia till a blue precipitate is formed, then add more water and allow to soak for one hour followed by soaking in distilled water. Remove water by soaking in wood alcohol and allowing to dry. Do not clean in this way if azurite is present.

Calcite, $CaCO_3$

Hexagonal. Crystals show a wide variety of forms, the commonest being the scalenohedron and rhombohedron; also found massive or stalactitic; twinning frequent.

Cleavage: perfect.

Colour: white or various shades of grey, yellow, red, black etc, these from impurities; streak whitish-grey; vitreous to pearly lustre.

Hardness 3; SG 2.7; RI 1.48–1.65 with a high birefringence and dispersion.

Occurs as the chief mineral in limestones and may also be found in pegmatites, in ore deposits and as stalactites and stalagmites.

Localities: world-wide with fine specimens from Cornwall, Durham and Cumbria, UK.

Aragonite, $CaCO_3$ *(dimorphous with calcite)*

Orthorhombic, acicular; twins and stalactitic forms common.

Cleavage: distinct.
Colour: white to yellowish; streak similar; vitreous lustre.
Hardness 3.5–4.0; SG 2.9.
Occurs in low-temperature deposits, particularly in limestone caves and near hot springs; also in ore deposits.
Localities: fine aggregates of acicular crystals from Cumbria, UK; wide occurrence.

Dolomite, $CaMg(CO_3)_2$
Hexagonal, rhombohedral crystals or massive.
Cleavage: perfect.
Colour: white, pink to pale brown; vitreous lustre.
Hardness 3.5–4.0; SG 2.8.
Occurs in hydrothermal vein deposits and in altered basic rocks with an Mg content.
Localities: Switzerland; Italy; New York and Iowa, USA.

Witherite, $BaCO_3$
Orthorhombic, crystals invariably twinned and forming pseudohexagonal dipyramids with massive forms also found.
Colour: white to grey, sometimes tinged with yellow or brown; blue phosphorescence after short-wave ultraviolet irradiation.
Hardness 3.0–3.5; SG 4.2.
Occurs in hydrothermal vein deposits.
Localities: fine crystals from Northumberland and Cumbria, UK; Illinois, USA.

Smithsonite, $ZnCO_3$
Hexagonal, rhombohedral crystals with curved faces; scalenohedra or as botryoidal masses.
Colour: white, apple green, bluish-green, deep pink to purple (from Co); streak white; vitreous to pearly lustre.
Hardness 4.0–4.5; SG 4.3–4.4.
Occurs in the oxidised zone of ore deposits.
Localities: fine blues from the Kelly mine, New Mexico, USA; Tsumeb, Namibia; Zambia.

Cerussite, $PbCO_3$

Orthorhombic, usually tabular or massive. Fine twins frequent.

Cleavage: distinct.

Colour: white to blue-green; streak colourless to white; submetallic lustre.

Hardness 3.0–3.5; SG 6.5.

Occurs in the oxidised zone of ore deposits.

Localities: Leadhills, Strathclyde; Tsumeb, Namibia; Broken Hill, New South Wales, Australia.

Rhodochrosite, $MnCO_3$

Hexagonal, usually massive but very fine scalenohedra from South Africa.

Cleavage: perfect.

Colour: pale pink to deep red; vitreous lustre.

Hardness 3.5–4.0; SG 3.7.

Occurs in hydrothermal ore deposits.

Localities: Hotazel and N'chwaning, Kuruman, South Africa; Catamarca Province, Argentina; Harz mountains, Germany.

Clean with dilute HCl.

SILICATES

Next to oxygen, silicon is the most abundant element in the earth's crust and combines with oxygen to form the silicate sub-group or complex anion $(SiO_4)^{4-}$ with a tetrahedral coordination. These tetrahedra can join together in several different ways, occurring on their own, as chains, double chains, rings, sheets, frameworks or pairs. Where there are independent silicate tetrahedra, the SiO_4 groups are tightly held by cations arranged around and about them. This is the case with olivine, which we have already met, and with the garnet family of minerals. Garnets look roughly spherical (though examination will show that many of them have the form of the rhombic dodecahedron, icositetrahedron or a combination of both forms); they are also quite hard and have a high specific gravity.

Pairs of SiO_4 tetrahedra are possible but less commonly found than some of the other types; ring silicates have a greater abundance, and show a number of groups touching to form a ring which can be repeated above and below to form a columnar crystal. This is seen in the important mineral beryl where there are six SiO_4 tetrahedra in rings which give a hexagonal shape to the crystal; the tetrahedra share oxygen atoms at the corners which touch so that the ratio of oxygen to silicon is three to one instead of four to one as in a single tetrahedron. Crystals of ring silicates are hard and have a moderately high specific gravity.

Pyroxenes and amphiboles are two important mineral groups within the silicate family; both are chain silicates in which the SiO_4 groups form chain-like structures bound together by other elements. In diopside the binders are calcium with an eightfold coordination and magnesium whose coordination is sixfold. The density can vary; if the mineral is rich in Mg it is low, and if it is rich in Fe or Mn it is high. Jadeite, one of the two distinct minerals that may officially be called 'jade', is a chain silicate and a member of the pyroxene group.

Where tetrahedra of SiO_2 are linked by three of their corners, as in the mineral family of the micas and many of the clay minerals, continuous layers bound together by cations are formed. The bonding between the sheets is much weaker than that obtaining inside them and the result is that there is a marked tendency for the layers to come apart like the pages of a book. This gives a greasiness which in the case of graphite (also having this type of structure though not, of course, a silicate) gives important lubricating powers. One of the mica group, muscovite, is important as an insulator, the thin sheets providing this property.

A firm three-dimensional structure is found in the framework silicates. Here the tetrahedra are linked at all four corners. In the mineral quartz all the cations are silicon (giving the formula SiO_2) and the framework is electrically balanced without any other cations being added. If another element replaces some of the silicon, other cations may be needed to give the required balance. This happens in some of the other silicates as in the feldspar group where up to half the silicon ions may be replaced by aluminium (Si^{4+} replaced by Al^{3+}). It is clear that in these cases another positive charge is needed, and in the feldspars this can be provided by Na^+ or K^+. A similar need arises in the zeolite group of silicates. The name aluminosilicates is used to group those minerals in which aluminium replaces some of the silicon. The bonding in framework silicates, partially covalent, gives a somewhat loosely-packed structure so that the minerals are hard but not particularly dense.

Olivine group

A complete series exists from forsterite (Mg_2SiO_4) to fayalite (Fe_2SiO_4).

Peridot, $(Mg,Fe)_2SiO_4$
Orthorhombic, prismatic crystals.
Cleavage: distinct.
Colour: green to brown; streak yellowish; vitreous lustre.
Hardness 6.5–7.0; SG 3.2–3.3; RI 1.65, 1.69; DR 0.038.
Occurs in igneous rocks such as basalt.
Localities: St John's Island (Zeberged), Red Sea; Burma; Arizona, USA; Norway; Eifel region of West Germany.

Garnet group

The general composition of the garnets follows $X_3Y_2Si_3O_{12}$, where X may be divalent Ca, Mg, Mn or Fe, and Y trivalent Al, Fe or Cr. Since there is some extensive atomic substitution in the group, the end members are described. See *Figure 7.11.*

Pyrope, $Mg_3Al_2Si_3O_{12}$
Cubic, dodecahedra, icositetrahedra or combinations; pebbles.

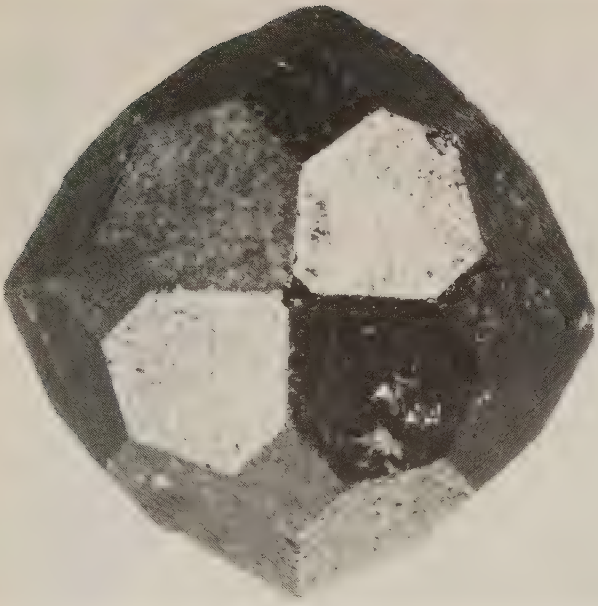


Figure 7.11. Garnet

Colour: pink to purple, bright red when Cr is present.
Hardness 7.0–7.5; SG 3.5–3.8; RI 1.73–1.75.
Occurs in peridotites or serpentines.
Localities: South Africa; Australia; Madras, India.

Almandine, $Fe_3Al_2Si_3O_{12}$
Cubic, dodecahedra, icositetrahedra or combinations.
Colour: deep red; streak white; resinous lustre.
Hardness 7.0–7.5; SG 4.1–4.3; RI 1.83.
Occurs in metamorphic rocks (schists, gneisses).
Localities: India; Sri Lanka; Tanzania; Idaho, USA (4-rayed star form).

Grossular, $Ca_3Al_2Si_3O_{12}$
Cubic, dodecahedra, icositetrahedra or combinations.

Colour: bright emerald green (with Cr or V content), yellow, red, orange, brown; streak white; resinous lustre.

Hardness 6.5–7.0; SG 3.4–3.6; RI 1.74.

Occurs in metamorphosed impure calcareous rocks or in schists.

Localities: Kenya (V-bearing variety, 'Tsavolite'); Transvaal, South Africa (the hydrogrossular variety of a jade-like green); Brazil; Sri Lanka (the orange-brown hessonite variety).

Andradite, $Ca_3Fe_2Si_3O_{12}$

Cubic, dodecahedra, icositetrahedra or combinations.

Colour: emerald green (with Cr) to black; vitreous or resinous lustre.

Hardness 6.5; SG 3.7–4.1; RI 1.89.

Occurs in chlorite schists and serpentinites; metamorphosed limestones.

Localities: Ural mountains, USSR (Cr green variety 'demantoid'); Ala Valley, Piedmont, Italy; California and New Jersey, USA.

Epidote group

These are silicates of calcium, aluminium and ferric iron with some replacement by ferrous iron and magnesium.

Zoisite, $Ca_2Al_3Si_3O_{12}(OH)$

Orthorhombic, striated prismatic crystals or masses.

Cleavage: perfect.

Colour: grey, pink (thulite), blue to purple ('tanzanite'), brown or green; vitreous lustre.

Hardness 6.5–7.0; SG 3.3; RI 1.68, 1.72.

Occurs in regionally metamorphosed rocks and metamorphosed impure limestones. 'Anyolite', a green variety with embedded ruby crystals, from East Africa.

Localities: Tanzania ('tanzanite'); Finland; California, USA.

Epidote, $Ca_2(Al,Fe)_3Si_3O_{12}OH$

Monoclinic, deeply striated prismatic crystals.

Figure 7.12. Epidote crystal from Knappenwand, Untersulzbachtal, Austria

Cleavage: perfect.

Colour: yellow to brownish-green to black; streak grey; vitreous lustre.

Hardness 6–7; SG 3.3–3.5; RI 1.74–1.78.

Occurs in regionally metamorphosed igneous and sedimentary rocks.

Localities: fine crystals from the Untersulzbachtal, Austria; USSR; Japan; Outukumpu, Finland; California, USA.

See *Figure 7.12.*

Pyroxene group

An important group of rock-forming minerals with the general formula $X_2Si_2O_6$ where X is usually Ca, Mg, Fe, Li, Ti, Al or Na. Orthopyroxenes are members of the orthorhombic crystal system and have little calcium; the clinopyroxenes are monoclinic and contain Ca, Na, Al, Fe^3 or Li. Pyroxenes have two cleavage directions intersecting at nearly 90 degrees.

Enstatite, $MgSiO_3$
Orthorhombic, usually massive; prismatic crystals found.
Cleavage: easy.
Colour: colourless, yellow, emerald-green (Cr), brown; streak grey; vitreous lustre.
Hardness 5–6; SG 3.2–3.4.
Occurs in basic igneous rocks.
Localities: Harz mountains, USSR and Eifel region of Germany; emerald-green chrome variety from Kimberley, South Africa; Colorado, USA.

Diopside, $MgCaSi_2O_6$
Monoclinic, short prismatic crystals or masses.
Cleavage: perfect.
Colour: colourless, grey, bright emerald green (Cr), red to brown; streak white or grey; vitreous lustre.
Hardness 5.5–6.5; SG 3.2–3.3; RI 1.66, 1.72.
Occurs in calcium-rich metamorphic rocks.
Localities: emerald-green chrome variety from Outukumpu, Finland; Ural mountains, USSR; Burma; California, USA.

Jadeite, $NaAlSi_2O_6$
Monoclinic but always found as boulders. One of the two minerals to which the name jade can apply (the other is nephrite).
Colour: translucent emerald green ('Imperial jade'), pale green, mauve, white, brown, yellow, grey; streak colourless; vitreous lustre.
Splintery fracture; hardness 6.5–7.0; SG 3.3; RI 1.66.
Occurs in serpentinites from olivine rock.
Localities: Burma; California, USA; New Zealand; Mexico.

Rhodonite, $MnSiO_3$
Triclinic, usually massive but tabular crystals known.
Cleavage: perfect.

Colour: pink to red with black veining; vitreous lustre.
Hardness 5.5–6.5; SG 3.5–3.7; RI 1.71, 1.75.
Occurs in manganese-bearing ore bodies.
Localities: Franklin, New Jersey, USA; Broken Hill, New South Wales, Australia; USSR.

Amphibole group

A group of silicates with the hydroxyl molecule (OH) characterised by extensive atomic substitution. Two cleavages intersect at 120 degrees.

Tremolite, $Ca_2Mg_5Si_8O_{22}(OH)_2$
Monoclinic, as long bladed crystals or fibrous aggregates; twinning common.
Colour: white, grey, pink, brown, pale green; vitreous lustre.
Hardness 5–6; SG 2.9–3.2
Occurs in contact and regionally metamorphosed dolomites.
Localities: Italy, Switzerland; California, USA; Ontario, Canada.

Actinolite, $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$
Monoclinic, fibrous aggregates; long bladed crystals.
Colour: green; vitreous lustre.
Hardness 5–6; SG 3.0–3.4.
Occurs in contact or regionally metamorphosed limestones.
Localities: the variety nephrite (with jadeite, the jade of commerce) from New Zealand; Alaska; British Columbia, Canada; Siberia, USSR. The fibrous variety byssolite from various places.

Mica group

Micas are members of the monoclinic crystal system and often form pseudohexagonal prisms with perfect basal cleavage. All contain (OH).

Muscovite, $KAl_3Si_3O_{10}(OH)_2$
Monoclinic, forming tabular crystals or massive, lamellar.
Cleavage: perfect.
Colour: white, grey, yellow, brown, red, violet; streak colourless; vitreous lustre.
Hardness 2.5–4.0; SG 2.7–2.8.
Occurs in granites, pegmatites, schists or in sediments.
Localities: widespread.

Biotite, $K(Mg,Fe)_3(Al,Fe)Si_3O_{10}(OH,F)_2$
Monoclinic, forming massive scaly aggregates.
Cleavage: perfect.
Colour: brown to green; streak colourless; vitreous or metallic lustre.
Hardness 2.5–3.0; SG 2.7–3.4.
Occurs in granites, pegmatites, schists and other rocks.
Localities: widespread.

Serpentine group

Usually monoclinic, the serpentines are fibrous or lamellar.

Talc, $Mg_3Si_4O_{10}(OH)_2$
Monoclinic, foliated or fibrous masses or thin tabular crystals.
Cleavage: perfect.
Colour: pale or dark green, white grey or brown; streak white; greasy lustre.
Hardness 1; SG 2.5–2.8.
Occurs by the hydrothermal alteration of ultrabasic rocks.
Localities: Lizard, Cornwall, UK; Transvaal, South Africa; California, USA.
Clean with dilute acid.

Feldspar group

The most abundant minerals in the Earth's crust, and found in many rock types. General composition may be written as X

$(Al,Si)_4O_8$ where X may be Ca, Na, K or Ba (though barium feldspars are rare). The remaining feldspars fall into three types: $KAlSi_3O_8$ (the orthoclase, sanidine, microcline group); $NaAlSi_3O_8$ (albite); and $CaAl_2Si_2O_8$ (anorthite). There is a complete series between the last two mentioned and also between the pure potassium and the pure sodium feldspars. The first series is known as the plagioclase series, the second as the alkali feldspar series. The plagioclase series is divided as follows: albite 100–90 per cent albite; oligoclase 90–70 per cent; andesine 70–50 per cent; labradorite 50–30 per cent; bytownite 30–10 per cent; anorthite 10–0 per cent.

Albite, $NaAlSi_3O_8$
Triclinic, tabular or platy crystals commonly twinned.
Cleavage: perfect.
Colour: white, colourless, bluish, brown or reddish; streak white; vitreous lustre.
Hardness 6.0–6.5; SG 2.6.
Occurs in pegmatites, granites etc.

Figure 7.13. Microline from Pike's Peak, Colorado, USA

Localities: very widespread; fine crystals from the St Gotthard region of Switzerland; Bourg d'Oisans, Isère, France; New Mexico and Arizona, USA.

Microcline, $KAlSi_3O_8$
Triclinic, short prismatic crystals.
Cleavage: perfect.
Colour: white, green with white bands; vitreous or pearly lustre.
Hardness 6.0–6.5; SG 2.5–2.6.
Occurs in granites and pegmatites, schists and hydrothermal veins.
Localities: Zimbabwe; Colorado, South Dakota and Virginia, USA; Brazil; Mexico.
See *Figure 7.13*.

Orthoclase, $KAlSi_3O_8$
Monoclinic, frequently twinned, also as lamellar masses.
Cleavage: perfect.
Colour: white, grey or yellowish; streak white; vitreous to pearly lustre.
Hardness 6.0–6.5; SG 2.5–2.6.
Occurs in igneous rocks including pegmatites; in crystalline schists, ore veins and sedimentary deposits.
Localities: Malagasy Republic (transparent yellow form); sanidine from the Eifel region of West Germany; Baveno, Italy (fine twinned crystals); Karlovy Vary (formerly Carlsbad), Czechoslovakia (fine twinned crystals); moonstone variety shows adularescence and is found in Sri Lanka, India and Burma.

Anorthite, $CaAl_2Si_2O_8$
Triclinic, short prismatic crystals or lamellar masses; twinning frequent.
Cleavage: perfect.
Colour: white to grey; streak white; vitreous lustre.
Hardness 6.0–6.5; SG 2.7.
Occurs in basic volcanic and plutonic rocks.
Localities: widespread.

Labradorite, $(Na,Ca)Al_{1-2}Si_{3-2}O_8$

Triclinic, usually massive or tabular crystals; twinning frequent.

Cleavage: perfect.

Colour: white or grey with play of spectrum colour from interference of light due to lamellar twinning.

Hardness 6.0–6.5; SG 2.6–2.7.

Occurs as a constituent of basic igneous and metamorphic rocks.

Localities: Labrador, Canada; Norway; California, USA.

Oligoclase, $(Na,Ca)Al_{1-2}Si_{3-2}O_8$

Triclinic, cleavable masses.

Cleavage: perfect.

Colour: grey, greenish, yellow to brown or reddish; sunstone has bright reflections from inclusions; streak white; vitreous lustre.

Hardness 6.0–6.5; SG 2.6.

Occurs in pegmatites, granites and syenites.

Localities: Norway; Canada; California, USA.

Sodalite, $Na_4Al_3Si_3O_{12}Cl$

Cubic, masses or dodecahedral crystals.

Cleavage: distinct.

Colour: dark blue with whitish streaks from calcite; streak colourless; vitreous lustre.

Hardness 5.5–6.0; SG 2.1–2.4.

Occurs in nepheline syenites.

Localities: USSR; Burma; Brazil; Ontario, Canada.

Zeolite group

Zeolites are aluminium silicates containing water of crystallisation which can be driven off by heating. Water is taken up again when the minerals are exposed to it in vapour form.

Natrolite, $Na_2Al_2Si_3O_{10}.2H_2O$

Orthorhombic, slender prismatic crystals vertically striated; fibrous masses.

Cleavage: perfect.
Colour: colourless, white, yellowish; vitreous lustre.
Hardness 5.0–5.5; SG 2.2.
Occurs in basaltic cavities or in nepheline syenites.
Localities: Mount St Hilaire, Quebec, Canada; Bishopton, Strathclyde, UK; Belfast, Northern Ireland.

Analcime, $NaAlSi_2O_6.H_2O$
Cubic, icositetrahedra or modified cubes; lamellar twinning common.
Colour: white, greenish, yellowish, pink; vitreous lustre.
Hardness 5.0–5.5; SG 2.2.
Occurs in basalts and other igneous rocks.
Localities: Isle of Skye, UK; widespread occurrence.

Stilbite, $NaCa_2Al_5Si_{13}O_{36}.14H_2O$
Monoclinic, cruciform penetration twins; aggregates.
Cleavage: perfect.
Colour: white, grey, orange, pink; streak colourless; vitreous lustre.
Hardness 3.5–4.0; SG 2.1–2.2.
Occurs in basaltic cavities and some hot spring deposits.
Localities: Isle of Skye, UK; Switzerland; California, USA.

Other silicates

Chrysocolla, $Cu_2H_2Si_2O_5(OH)_4$
Orthorhombic but found as microscopic acicular crystals in radiating groups or as aggregates; more often botryoidal.
Colour: blue to blue-green, brown to black; vitreous or earthy lustre.
Hardness 2–4; SG 2.0–2.4.
Occurs in the oxidation zone of copper deposits.
Localities: Liskeard, Cornwall and Roughten Gill, Cumbria, UK; Shaba, Zaire; Pennsylvania, USA.

Pectolite, $NaCa_2Si_3O_8OH$
Triclinic, aggregates of needle-shaped crystals forming globular masses.

Cleavage: perfect.
Colour: white; silky lustre.
Hardness 4.5–5.0; SG 2.7–2.8.
Occurs in cavities in basaltic rock.
Localities: Weardale, Durham and Ratho, Edinburgh, UK; Franklin, New Jersey, USA.

Hemimorphite, $Zn_4Si_2O_7(OH)_2.H_2O$
Orthorhombic, thin tabular vertically-striated crystals; as masses.
Cleavage: perfect.
Colour: white, colourless, pale blue-green; streak colourless; silky lustre.
Hardness 4.5–5.0; SG 3.4–3.5.
Occurs in the oxidised zone of ore deposits or in calcareous rocks or in pegmatites.
Localities: Roughten Gill, Cumbria, UK (fine green crystals and mamillary crusts); Mapimi, Durango, Mexico; California, USA.

Zircon, $ZrSiO_4$
Tetragonal, short prismatic crystals; metamict varieties may be in aggregates.
Colour: red, brown, green, yellow or colourless (blues arise from heating); adamantine lustre (metamict varieties have greasy lustre).
Hardness 7.5 (metamict 6.0); SG 4.6 (metamict 4.0); dispersion 0.038; RI 1.92–2.01.
Occurs in igneous rocks and some metamorphic rocks.
Localities: Thailand; Sri Lanka (metamict varieties always green to brown); Burma; Expailly-St-Marcel, France (red variety); Australia; Colorado, USA.

Beryl, $Be_3Al_2Si_6O_{18}$
Hexagonal, prismatic crystals.
Colour: emerald green (emerald); greenish-blue (aquamarine); pink (morganite); golden yellow (heliodor); colourless (goshenite); red (bixbite, but 'red beryl' less confusing and preferred); vitreous lustre.

Hardness 7–8; SG 2.6–2.9; RI 1.56, 1.59.

Occurs in granite pegmatites, biotite schists, pneumatolytic hydrothermal veins.

Localities: emerald from Colombia; USA; USSR; Zimbabwe; Brazil; India; Tanzania; South Africa. Aquamarine from Brazil and Malagasy Republic. Morganite from California, USA; Malagasy Republic. Heliodor from Namibia and Brazil. Red beryl from Utah, USA.

Euclase, $BeAlSiO_4OH$

Monoclinic, long prismatic crystals.

Cleavage: perfect.

Colour: blue, green, colourless; vitreous lustre.

Hardness 7.5; SG 3.0–3.1.

Occurs in granite pegmatites, mica schists.

Localities: Brazil; Ural Mountains, USSR; Tanzania.

Prehnite, $Ca_2Al_2Si_3O_{10}(OH)_2$

Orthorhombic, usually as granular masses; stalactitic and reniform masses.

Colour: pale or dark green, yellow or white; streak colourless.

Hardness 6.0–6.5; SG 2.9.

Occurs as a hydrothermal or secondary mineral in basic igneous rocks, or in granites or metamorphosed limestones.

Localities: several Scottish localities; Switzerland; France.

Staurolite, $(Fe,Mg)_2Al_9Si_4O_{22}(OH)_2$

Monoclinic, prismatic crystals with cruciform twinning.

Colour: dark reddish-brown; streak colourless or grey; resinous lustre.

Hardness 7.0–7.5; SG 3.6–3.8.

Occurs in mica schists.

Localities: Ticino, Switzerland; France; Massachusetts, USA.

Apophyllite, $KCa_4Si_8O_{20}(F,OH).8H_2O$

Tetragonal, as pseudocubic crystals.

Cleavage: perfect.

Colour: grey, pale yellow, pale green, reddish; streak white; vitreous lustre.
Hardness 4.5–5.0; SG 2.3–2.4.
Occurs in basalt cavities.
Localities: Isle of Skye, UK; Brazil; Mexico; India.

Topaz, $Al_2SiO_4(OH,F)_2$
Orthorhombic, prismatic crystals with well-developed terminations.
Cleavage: perfect.
Colour: reddish-brown, orange, yellow, pink, blue, colourless; streak colourless; vitreous lustre.

Figure 7.14. Topaz crystals

Hardness 8; SG 3.53; RI 1.62–1.64.
Occurs in pegmatites and quartz veins.
Localities: Brazil; Nigeria; Cornwall, UK; USSR; Burma.
See *Figure 7.14.*

Danburite, $CaB_2(SiO_4)_2$
Orthorhombic, prismatic crystals with rhombic cross-section.

Colour: yellow, gold, pale pink, brown, colourless; streak colourless; vitreous lustre.
Hardness 7; SG 3.0; RI 1.63, 1.64.
Occurs in dolomite with feldspar.
Localities: Danbury, Connecticut, USA; fine yellow from Mogok, Burma; Uri, Switzerland.

Axinite, $(Ca,Mn,Fe,Mg)_3Al_2BSi_4O_{15}(OH)$
Triclinic, distinctive wedge-shaped crystals.
Colour: clove brown; strongly pleochroic; streak colourless; vitreous lustre.
Hardness 6.5–7.0; SG 3.3; RI 1.68, 1.69.
Occurs in contact metamorphic areas with calcite and quartz.
Localities: Brazil.

Tourmaline,
$(Na,Ca)(Li,Mg,Fe^2,Al)_3(Al,Fe^3)_6B_3Si_6O_{27}(O,OH,F)_4$
Hexagonal, prismatic crystals with rounded triangular cross section, vertically striated.

Figure 7.15. Tourmaline. A well-formed group of black, vertically-striated crystals, from Brazil

Colour: red, blue, various shades of green, yellow, orange, brown, black, parti-coloured; vitreous lustre; strong pleochroism (light and dark of same colour).
Hardness 7; SG 3.0–3.1; RI 1.62, 1.64; DR 0.018.
Occurs in pegmatites and metamorphic rocks.
Localities: California, USA; Elba; Brazil; Mozambique; Malagasy Republic.
See Figure 7.15.

PHOSPHATES

Phosphates form a large and interesting mineral family since there is quite a large number of species. Many of them show attractive forms and colours, though economically the phosphate family is outstanding as a source of fertiliser. Phosphates are characterised by the presence of the phosphate anion $(PO_4)^{3-}$. This differs from the silicate anion in that the phosphate anion is trivalent instead of tetravalent. Since phosphorus itself is quinquivalent and oxygen is divalent, it is easy to see how the valency of the group arises. As in the silicates, the phosphate tetrahedra can form into pairs or rings (though not into the more complex structures). They can also occur separately. The most important family in the phosphate group is apatite; this is found in many igneous rocks and also in teeth and bone. Fossil bones are major phosphorus sources. Phosphates are not hard, nor are they notably dense.

Turquoise, $CuAl_6(PO_4)_4(OH)_8.4\text{–}5H_2O$
Triclinic, short prismatic crystals but these are very rare; usually found as masses or crusts.
Cleavage: perfect.
Colour: bright blue to greenish-blue; waxy lustre.
Hardness 5–6; SG 2.6–2.8.
Occurs by the action of surface waters on Al-bearing rocks.
Localities: Egypt; Iran (the finest gem material). Lynch, Virginia, USA (crystals).

Variscite, $AlPO_4.2H_2O$

Orthorhombic, usually masses or nodules, sometimes octahedra.

Colour: pale to emerald-green; waxy lustre.

Hardness 3.5–4.5; SG 2.6.

Occurs in aluminous rocks altered by phosphate-bearing waters.

Localities: Fairfield, Utah, USA; California, USA; Nevada, USA; Germany; Australia; Brazil.

Wavellite, $Al_3(OH)_3(PO_4)_2.5H_2O$

Orthorhombic, radiating aggregates of acicular crystals.

Cleavage: perfect.

Colour: green, white, yellow-green, brown, blue, colourless; vitreous lustre.

Hardness 3–4; SG 2.4.

Occurs in hydrothermal veins or phosphate rocks.

Localities: Arkansas, USA; Barnstaple, Devon, UK.

Torbernite, $Cu(UO_2)_2(PO_4)_2.8\text{–}12H_2O$

Tetragonal, tabular crystals or lamellar aggregates.

Cleavage: perfect.

Colour: emerald-green; streak pale green; vitreous lustre.

Hardness 2.0–2.5; SG 3.2.

Occurs in pegmatites.

Localities: Cornwall, UK; North Carolina, USA; East Germany.

Autunite, $Ca(UO_2)_2(PO_4)_2.10\text{–}12H_2O$

Tetragonal, tabular crystals or as crusts.

Cleavage: perfect.

Colour: bright yellow, pale or dark green; vitreous or dull lustre; bright fluorescence (yellow-green).

Hardness 2.0–2.5; SG 3.1.

Occurs by the alteration of uraninite in granite pegmatites.

Localities: St Austell and Redruth, Cornwall, UK; Australia; East Germany.

Vivianite, $Fe_3(PO_4)_2.8H_2O$
Monoclinic, flexible laminae.
Cleavage: perfect.
Colour: begins colourless, altering to dark green or blue, purple to black; streak colourless altering to brown or dark blue; pearly lustre.
Hardness 1.5; SG 2.7.
Occurs in metallic ore veins and as an alteration of phosphate minerals in pegmatites.
Localities: Poopo, Bolivia; St Agnes, Cornwall, UK; Cameroons.

Ludlamite, $Fe_3(PO_4)_2.4H_2O$
Monoclinic, tabular crystals or as masses.
Cleavage: perfect.
Colour: bright to apple green; vitreous lustre.
Hardness 3.5; SG 3.2.
Occurs in the oxidation zone of ore deposits.
Localities: Wheal Jane mine, Truro, Cornwall, UK; Hagendorf, Bavaria, West Germany.

Bayldonite, $(Pb,Cu)_3(AsO_4)_2(OH)_2$
Monoclinic, granular masses.
Colour: yellow to green; resinous lustre.
Hardness 4.5; SG 5.5.
Occurs in the oxidation zone of copper ore deposits.
Localities: St Day, Cornwall, UK; Tsumeb, Namibia.

Apatite, $Ca_5(PO_4)_3F$
Hexagonal, prismatic crystals.
Colour: yellow-green, blue, green, purple, brown, colourless; streak white; vitreous lustre.
Hardness 5; SG 3.1; RI 1.63–1.64.
Occurs in igneous rocks, pegmatites and in hydrothermal veins.
Localities: Durango, Mexico; Quebec and Ontario, Canada; Burma.

Pyromorphite, $Pb_5(PO_4)_3Cl$

Hexagonal, forming hexagonal crystals; reniform or globular masses common.

Colour: green, yellow or brown; streak white; adamantine lustre.

Hardness 3.5–4.0; SG 7.0.

Occurs in the oxidation zone of lead ores.

Localities: England and Scotland; Broken Hill, New South Wales, Australia; Burma.

Mimetite, $Pb_5(AsO_4)_3Cl$

Monoclinic, acicular crystals.

Colour: bright yellow, orange or colourless; vitreous lustre.

Hardness 3.5–4.0; SG 7.3.

Occurs in the oxidation zone of lead ore deposits.

Localities: Tsumeb, Namibia; Durango, Mexico; Leadhills, Scotland.

Vanadinite, $Pb_5(VO_4)_3Cl$

Hexagonal, prismatic crystals or globular masses.

Colour: bright red to orange; streak white or yellow; resinous lustre.

Hardness 3; SG 6.9.

Occurs in the oxidation zone of lead ore deposits.

Localities: Scotland; Mibladen, Morocco; Colorado, USA.

The groups described above are the most common ones. There are many minerals which do not belong to any of the groups so far encountered, and some can be mentioned briefly. The arsenates and vanadates, both classes providing attractive specimens, are linked closely with the phosphates in that the anionic units are tetrahedral groups in which the X of XO_4 can be arsenic (As) or vanadium (V). In the molybdates and tungstates there is also an XO_4 group in which X can be either molybdenum (Mo) or tungsten (W). The ideal tetrahedron suffers some distortion in these groups.

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This book provides a concise and readable introduction to anyone interested in the study and collection of minerals, regardless of their experience in the field.

Michael O'Donoghue has used his extensive knowledge of the subject to provide a mass of information in a compact volume. He starts with the practical business of collecting and conserving specimens, and then introduces the reader to the chemistry of minerals. Other topics covered include the structure of crystals, the nature of light, and igneous and metamorphic rocks. A detailed description is given of tests by which minerals are identified, and the commoner minerals are listed in identification tables for easy reference.

Whether you are a student or a practising collector, this book gives you all the vital information and more at your fingertips.

Front cover shows apatite crystals in matrix (Mexico).

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