THE NATURE OF
DIAMONDS

EDITED BY

GEORGE E. HARLOW

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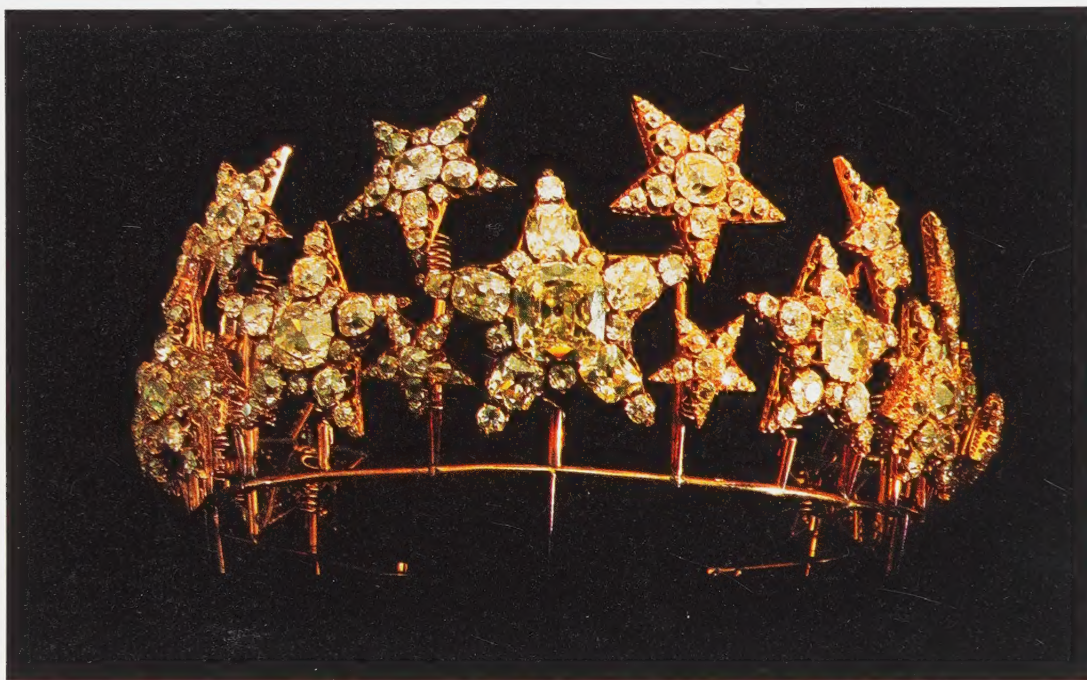

$29.95

The Nature of Diamonds

This diamond diadem with stars was commissioned by Queen Maria Pia of Portugal (1847–1911) and completed by Estevão de Sousa in 1866. The 25 stars are individually mounted en tremblant so the effect of sunlight on the bobbing stars would have been dazzling when the queen wore the tiara in daylight. (Manuel Silveira Ramos/PH3/courtesy of Palacio Nacional da Ajuda/Instituto Português do Património, Arquitectó, e Arqueológico, Lisbon.)

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of Diamonds

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Foreword

Diamond glitters and cuts. As a symbol and a tool, diamond, a peerless gem, bridges culture and nature and connects romantic ethereality with raw practical utility. This volume and the special exhibition created by the American Museum of Natural History which it accompanies remind us of the linkage between the stone's symbolic and scientific value and impel us to seek out and divine the underlying correlation between the two.

Intriguingly, the dual application and meaning of diamond is mirrored in the contrast between its origins and its physical presence. This story of transformation is the story of Earth's processes – encompassing vast periods of time, great depth beneath the planet's surface, and enormous energy. The metamorphosis of simple, pure native carbon from a base black substance like coal to a colorless, clear thing of beauty is just one of the Janus-like pairs diamond embraces. Brought to the surface of the Earth's crust by the capricious forces of ancient volcanic eruptions, diamond gains its industrial worth by virtue of being the hardest natural substance in the world. At the same time, diamond opposes its scientific practicality with its function as a sign of fluctuating social meaning. In culture, diamond's value is contingent not upon any absolute scale but upon the meaning that various cultures and individuals ascribe to it – a mythic talisman of power and purity, a symbol of regal structure, a token of everlasting love.

Demonstrating the power of nature to transform, the power of science to apply, and the power of culture to surround human interactions with ritual and to imbue natural elements with monetary value, the study of diamond joins the fields of mineralogy, geology, astronomy, material science, anthropology, art, history, literature, and even economics. This literal and figurative multifaceted character testifies to the broad-reaching importance of the Museum's investigation of the subject. In this inquiry and all of its endeavors, the

Museum brings the deep strengths of its collections, of more than 30 million cultural artifacts and specimens, and its scientific staff of over 200 to the study and interpretation of the natural world and its inhabitants.

It is the task of an expert cutter to transform the rough, transparent, adamantine diamond into a brilliant object capable of fulfilling technological or social functions. If we at the American Museum of Natural History have done our job properly, we have applied the tools of scholarship and the resources of collections to reveal the clarity and true color of this remarkable substance.

For their efforts in illuminating The Nature of Diamonds, I would like to thank the curator of the exhibition, George E. Harlow, the exhibition department, and Dean of Science Craig Morris. On behalf of the entire Museum, I would like to thank the many individuals and institutions around the world whose generous loan of diamonds and other objects make the accompanying exhibition sparkle and enlighten. Finally, for its important support of this exhibition, I am pleased to extend the deep appreciation of the Museum to the Diamond Information Center for De Beers.

Ellen V. Futter
President, American Museum of Natural History

List of Contributors

George E. Harlow, Ph.D., is curator of gems and minerals and a scientist in the Department of Earth and Planetary Sciences at the American Museum of Natural History, as well as the curator of the Museum exhibit "The Nature of Diamonds." The author of numerous journal articles and reviews, Harlow has also written *Gems and Crystals* and *Minerals and Gems*. A frequent lecturer and teacher, Harlow has been curator for other major Museum exhibitions.

Alan T. Collins, Ph.D., reader in experimental physics and head of the department at King's College, London, has done extensive research on the physical properties of diamond and has published more than 150 papers. A fellow of the Institute of Physics, he serves in editorial capacities on *Gems and Gemology, Diamond and Related Materials,* and the *Journal of Gemmology.*

Emmanuel Fritsch, Ph.D., is professor of physics at the University of Nantes, France, and previously worked at the Gemological Institute of America. Winner of the Prix Jean Rose in 1995 for his contributions to gemology, he has published extensively, including several prize-winning articles.

Melissa B. Kirkley, Ph.D., is principal geologist at BHP Minerals Canada, Ltd., Diamond Exploration, and has done postdoctoral research on kimberlites. Her many publications include numerous scientific papers for both journals and books.

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Diana Scarisbrick is a member of the Royal Society of Jewelry Historians and the author of *Rings* and a history of English jewelry. She writes widely on the history of jewelry and has served as curator of several exhibits in Cambridge and Oxford.

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Benjamin Zucker, a dealer in gems and president of a precious stones company, has written *How to Buy and Sell Gems* and *Gems and Jewels: A Connoisseur's Guide* and lectured at the Smithsonian Institution and Gemological Institute of America.

ACKNOWLEDGEMENTS

Introduction

I WAS HAPPY TO BE returning from Europe in June of 1996, having spent the month traveling around the Continent visiting various institutions well endowed with diamonds: the Grünes Gewölbe (Green Vault) in Dresden, the treasury at the Rosenborg Castle in Copenhagen, the diamond district in Antwerp, and the French crown jewels and several centuries of diamondiferous portraits in the Louvre. The experience was rewarding, but I was ready for a rest when I got back to New York in time for Independence Day. However, I was not finished with diamonds that day. The big foreign news was Boris Yeltsin's remarkable comeback in the Russian election for president. On "The News Hour," Jim Lehrer was interviewing experts on the details and significance of that event. Eating my hamburger, a cultural must for the Fourth of July, I listened as Leon Aaron, a Yeltsin biographer, spoke of the lethargic Russian president's resurrection from the crisis of his election campaign and ultimate triumph: "Under the pressure of the campaign, the graphite of his persona turned into diamond," Aaron commented. Upon hearing that rich metaphor, I almost dropped my burger. Not only did Aaron have an excellent grasp of his metaphor, but I thought he must have known I was listening.

Humans are products of the Earth and have devised language to describe their home and its qualities. Words can convey rich concepts, but there are only a few words referring to earthly materials that command immediate attention and entail superlative connotations, striking deep into the psyche. The original four "elements" of the ancient Greeks – earth, air, fire, and water – have great importance for us even today, and those terms have evolved to take on diverse meanings. Earth, the mother, terra firma, home planet, is really rock and soil – the hard stuff – all hard stuff originally. Of those four terms, "fire" is the one most loaded with meanings, but it is not substance; it is a transient phenomenon, too much like ourselves. Diamond, often described in terms of

"fire," is a substance whose very name evokes transcendent meanings. Not really known by the ancient Greeks, but named by them for Western civilization, "diamond" carries extraordinary meaning and significance – indomitable (from the Greeks), noble, pure, brilliant, hard, and valuable, connoting character and even shape. The only substance of comparable wonder known to the ancients was gold, the Sun's presence on Earth. What is it about diamond that enables mere mention of the word to conjure a broad range of vivid images and feelings?

"Diamond" indeed has many dimensions to its real and perceived meanings. Diamond is a mineral, a crystalline substance, the natural, transparent form of pure carbon. Diamond is the peerless gem that symbolizes purity and strength and, now, commitment to never-ending love – as we hear in "A diamond is forever." Diamond is *adamas*, the Greek word defining its property of indomitability – the hardest substance, used to cut or abrade all others, and the only substance that can scratch another diamond. "Diamond" is a shape, the outline of a crystal of the mineral in its most distinctive form, a description that we apply broadly to such diverse objects as playing cards and the focal point of America's pastime, baseball. Diamond is "ice," one of the most compact forms of wealth, a reliable and portable fortune. Diamond is "fire," the gem that refracts light into the rainbow, flashing out brilliant color better than any other gem. Diamond is that Indian gem that was reserved for royalty and aristocracy for over a thousand years, only recently becoming available to ordinary people. Diamond is your 75th wedding anniversary – far past your golden 50th – a milestone not reached by many. Diamond is strategic and high-tech: the ultimate cutting tool in an automated industrial society, an infrared window used in guiding heat-seeking missiles, a metal-like conductor of heat but nonmetallic electrical insulator for use in electronics, and a super-material for some of the toughest technological applications. Diamond is carbon, the same carbon that is one of the elements that you and I and all life forms are made from; some diamonds are, in fact, recrystallized organic substance – recycled life. Diamond is exotic, most commonly formed in the interior of the Earth and shot to the surface by volcanoes. In this guise, diamonds are also our "space missions" to inner Earth, bringing forth small samples of the Earth's mantle rocks pristinely in diamond's protective embrace for geoscientists to study. Diamond is indeed multifaceted, just as in its brilliant gem form.

The rich tapestry of stories found in diamond and provided by diamond, and diamonds, is the focus of this book. A comprehensive discussion of all the topics related to diamonds would require a thick encyclopedia, so the intent in *The Nature of Diamonds* is to provide a well-illustrated overview. Likewise, because the range of topics is exceedingly diverse, I have asked colleagues who are experts in their fields to assist with the project: specialists in diamonds, as well as academics whose analysis can place the subject in a broader context.

The book is organized in three sections. It opens with a scientific approach

to diamonds, starting with the mineralogy and physical and chemical properties. The second chapter discusses the sources of color in diamonds, an exciting new field that has experienced phenomenal growth in recent years, as explored here by Emmanuel Fritsch, a leading expert on the subject, now at the Gemological Laboratory of the University of Nantes in France, and for many years a research scientist at the Gemological Institute of America, in California. The third chapter treats the natural occurrences and origins of diamonds, also showing how diamonds have informed us about the Earth and its processes; that geological overview is presented by Melissa Kirkley, who earned her doctorate from the center for diamond study at the University of Cape Town and has had considerable experience in exploring for diamond occurrences with BHP Minerals. For Chapter 4, Alfred A. Levinson, former professor of geochemistry at the University of Calgary in Alberta, with a considerable list of publications on the geological provenance and history of gem resources, reviews the worldwide sources of diamonds and provides a short social and economic history of this dazzling gem. Between Chapters 4 and 5 we present a photographic portfolio of some of the world's great diamonds.

The next section of the book addresses the roles of diamonds in history and culture. In Chapter 5, we turn to the history of diamonds, from their Indian origins through the range of ancient perceptions, significations, symbolisms, and mythology and on into the European Renaissance. I have brought my own interests to bear on the subject, presenting some perspectives that are not well heralded or remembered; it is part of my museum approach to the subject. The chapter also includes a modest historical overview of diamond cuts, the actual shapes of faceted diamonds, as presented in the section written by my good friend, gem expert, and author, Benjamin Zucker. Next we turn to diamond's place in regal and aristocratic ornamentation for roughly six centuries. Written by the eminent jewelry historian Diana Scarisbrick, a scholar from England, Chapter 6 includes her work on diamond love and marriage rings. After Chapter 7 is a photographic portfolio featuring diamond treasures of Russia.

Chapter 7 muses on the literary value of diamonds at the end of the Victorian era, the finale of the mystical and aristocratic age of diamonds. The author, Carole Slade, is a Columbia University professor and scholar in comparative literature and is imbued with diamonds, mostly conceptually, as my chief adviser and partner in life (indeed, my wife). In Chapter 8, Janet Zapata records the transformation of diamond during the twentieth century into everyone's gem, with a review of the developing influence of the United States on the appetites and styles for diamond jewelry. A prominent jewelry historian, Zapata was my co-curator for "Tiffany: 150 Years of Gems and Jewelry" at the American Museum of Natural History. The story of diamonds would not be complete without mention of the romance between the glittering rocks and the movies. Maura Spiegel, a Columbia University professor, brings her scholar-

ship, feminist sensitivity, and knowledge of movies to an examination of image, gender perspectives, and culture in the silver screen's rendition of diamonds in Chapter 9. The section concludes with a brief overview (Chapter 10) of the coincidence of the new diamond abundance and American wealth and ambition, as well as the evolution of the marketing miracle that rejuvenated the demand and romance for diamonds.

The last chapters of the book examine the processes connected with finding and using diamonds, from extraction to technological applications. As a geoscientist and aficionado of technology and diamond's endurance, I describe in Chapter 11 the processes that take diamonds from the Earth to finished products, ranging from round brilliants to wire saws and diamond scalpels. Next, Chapter 12 provides an overview of the gemologist's role in diamonds as gems and presents the methods of identification and authentication of fully natural diamonds and the criteria for evaluating the quality of a faceted gem. The authors, Jim Shigley and Tom Moses, both work in the research department of the Gemological Institute of America and have a wealth of experience and knowledge. The book concludes with a chapter on the history of diamond-synthesis experimentation and an examination of the growing potential for high-tech applications for diamond in our sophisticated material culture (Chapter 13). Alan Collins, chairman of the Physics Department at King's College, London, and a world authority on the physics related to diamond, provides a clear presentation of these topics.

This book parallels and stems from an exhibition by the same name that, as Curator of Minerals and Gems at the American Museum of Natural History, I had long envisioned and, with the help of many, brought to fruition in 1997. My interest in diamonds was spawned, as for most of us, through my upbringing and our social culture, seeing "glitterati" wearing dazzling rocks in magazines, the movies, and television – watching George Reeves' television Superman transform coal into diamond in his bare hands with the aid of his x-ray vision. Going through college and graduate school as a mineralogist and geoscientist moved me into another realm of diamond, the "type" adamantine mineral and messenger from deep within the Earth. As a scientist at the Museum, I have studied mineral inclusions in natural diamonds and worked with real experts in the geoscience of diamonds; as a curator, I also get to see diamonds and meet those in the diamond industry.

Like those whom I have encountered, I am fascinated by diamonds and their vast context. I expected that most people would find an exhibition and book exciting and engrossing. We have tried to make the sources of our information as accessible as possible, with many additional notes and citations. We hope that your reading of *The Nature of Diamonds* will be rewarding.

George E. Harlow

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What Is Diamond?

GEORGE E. HARLOW

Figure 1. A Nomarski differential interference contrast photograph of etched trigons on the surface of a natural diamond. The trigon is 0.27 mm wide. (John I. Koivula/courtesy of Gemological Institute of America.)

"DIAMOND" IS A BRILLIANT, flashing gem, the symbol of portable wealth, the essential component in an engagement ring, the description of a common shape, and a supremely hard material with many extraordinary properties that make it useful in scientific and industrial applications. To understand what is behind all those attributes, it will be necessary to look closer at just what diamond is. I will start from the perspective of the mineralogist and then move on to look at the chemistry and physics of diamond (Figure 1) to provide greater depth of understanding.

Diamond is a mineral composed of carbon. It differs from other minerals composed of carbon (the well-known graphite and the rare lonsdaleite) in terms of the internal arrangement of its carbon atoms – its crystal structure. It is the crystal structure that determines the fundamental properties of any mineral. To illustrate how structural differences can produce significantly different minerals from the same atoms, we will be comparing diamond and graphite on several levels. Many crystalline substances can be synthesized in the laboratory, but only those that are discovered in nature and have been produced by inorganic processes can be called minerals. A *crystal* is a solid body formed of chemical elements or compounds; it has a regularly repeating internal arrangement of its atoms and often has external plane faces. Each mineral, or any crystalline substance, for that matter, has a distinctive submicroscopic-size unit, or building block. The units are stacked in billions of repetitions, each unit or building block oriented in the same way, filling the internal space of the structure to form a visible, tangible solid – the crystal (Figure 2). Unlike organisms that grow from within, a crystal grows by the addition of layers of atoms to its external surfaces; the necessary atoms are extracted from some growing medium, which can be a solid, liquid, or vapor. When the conditions in the medium are such that the crystal can grow unimpeded, the crystal will grow
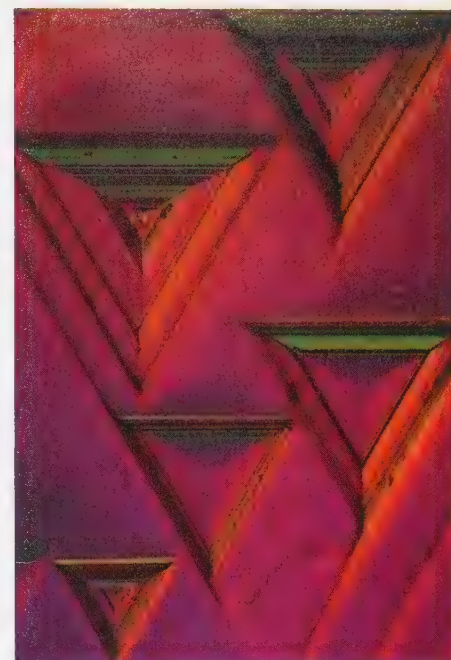
Figure 2. Diamond structure showing the tetrahedral arrangement of carbon atoms (blue spheres) forming the mineral's atom-scale building block containing 8 atoms. The unit cell is outlined in red. It appears that there are 18 atoms, but 8 at the corners are shared by 7 other cells, and 6 on the faces are each shared by another cell; so 4 are inside the cell. 6/2 = 3 are on faces, and 8/8 = 1 are at corners: 4 + 3 + 1 = 8. (Created by G. E. Harlow using Atoms © software.)
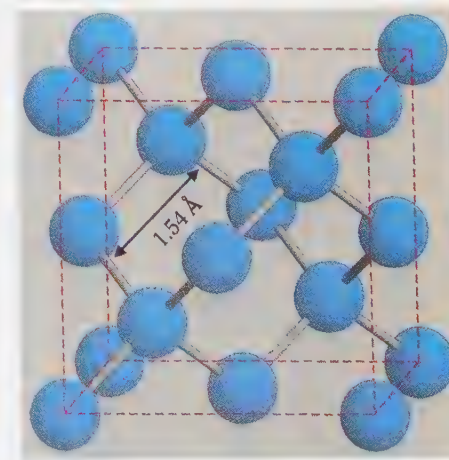
with the flat *crystal faces* characteristic of the objects we recognize as natural crystals (Figure 3). However, if there is an impediment to growth, such as insufficient space, the crystal probably will grow without flat faces and will form an irregular shape defined by the space in which it grows. With or without flat faces, the body is still a crystal. Destructive processes can reduce the crystal to a rounded object, which happens to many diamonds; nonetheless, that, too, is still a crystal. The building blocks or units for crystals are finite, with relatively small numbers of atoms, and so the chemical compositions of crystals will be restricted to simple numerical combinations of elements. Such combinations can be described using a small cardinal number (a positive integer, 1, 2, 3, etc.) for each fundamental constituent atom. Thus quartz, with one silicon atom and two oxygen atoms, is SiO_2 (the subscript 1 being omitted). In the case of both diamond and graphite there is only one element and one number, and the chemical formula is C_1, or simply C, pure carbon. Theoretically, diamond is a pure mineral, but usually there are trace chemical impurities, as discussed later. So diamond and graphite are two different forms of crystalline carbon, but that is where the similarity ends, for otherwise they are as dramatically dissimilar as day and night. It is the arrangements of their car-

Figure 3. The octahedral diamond crystal shown (above) is approximately 8 mm wide, and the "ball and stick" model (below) of the diamond structure shows the atoms 1 cm apart and the bond arrangement that produces octahedral cleavage in diamond. If the model were expanded to show all the atoms in the real crystal, it would stretch for 519 km (325 miles), roughly the distance from New York City to Niagara Falls, N.Y., as shown on the map (right).
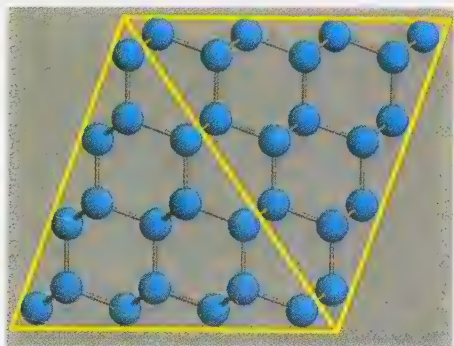
bon atoms, their crystal structures, and the ways in which their carbon atoms are connected to one another that dramatically differentiate these two carbon minerals. A little more information on carbon is needed to clarify their differences.

Carbon has an atomic number of 6, meaning that each carbon atom has 6 protons and 6 electrons. The positively charged protons in the nucleus of an atom hold the electrons in their orbits around the nucleus, and the electrons carry out the interactions between atoms that give all substances their unique properties, their chemistry. In the carbon atom, four of the electrons follow orbits that allow them to be chemically interactive; they are called the valence electrons.[1] As revealed by quantum chemistry and the periodic properties of chemical elements, the "shells" of orbits for elements in the second row of the periodic table are ideally balanced with 2 or 10 electrons. Carbon atoms prefer the latter state, forming configurations with other atoms that fill in the four empty places, or orbital vacancies, at least on an averaged basis. It is the geometry in which the carbons are arranged and the mechanism by which they occupy the vacancies in the valence orbits that distinguish diamond from graphite.

In a diamond, each carbon atom is surrounded by four neighboring carbons, forming a tetrahedral-shaped unit, a repeating geometry that creates a highly symmetrical and uniform framework (Figure 1). Between any two adjacent carbon atoms there is an electron-pair bond to which each carbon contributes one of its valence electrons. Because every carbon is bonded to four surrounding carbons, each carbon atom is surrounded by eight valence electrons.[2] The sharing of electrons between adjacent carbons provides a strong linkage, known as a shared-electron bond or *covalent bond* – the strongest form of attachment in chemical substances. The combined network arrangement of balanced powerful bonds endows diamond with its "indomitable" properties. By contrast, in graphite, each carbon is surrounded by three nearest carbon neighbors in a flat sheet. Each carbon shares a single electron with each of its three neighbors, but the remaining electron does not adopt a stable "double bond" with any single carbon, but rather is considered to "hop" in a time-averaged way among the three adjacent neighbors; thus the six-member carbon rings oscillate or resonate between single and double shared-electron bonds.[3] The individual sheets are very strong and give graphite some properties similar to those of diamond, such as a high melting temperature. To form a solid, the individual sheets of graphite must be stacked (Figure 4), but as there are no orbital electrons remaining that could form bonds to connect the layers, there are no strong chemical bonds between the sheets. There are only residual electrical charges between the sheets that provide a weak force of attachment between the layers.[4] One manifestation of this weakness of the attraction between carbon sheets is that the separation between them is more than twice the distance between adjacent carbon atoms within a sheet. Another is that

Figure 4. The graphite structure consists of sheets of six-member rings of carbon atoms (top), with a long distance and no strong connections between adjacent sheets (bottom). The parallelepiped in red represents the unit cell of graphite. (Created by G. E. Harlow using Atoms © software.)
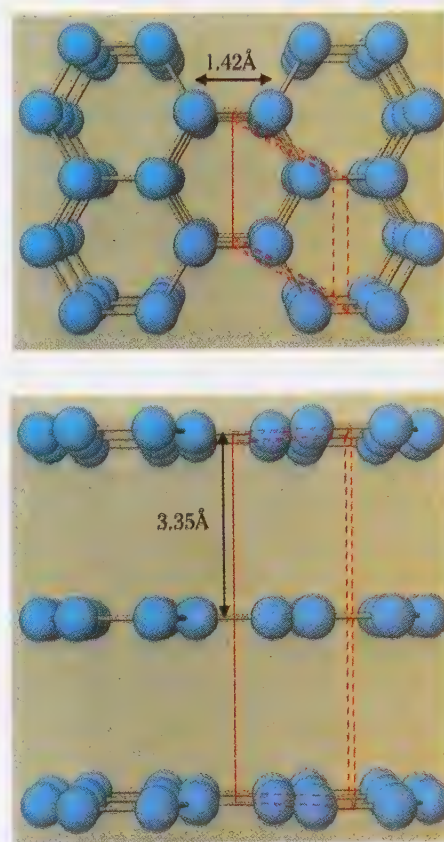
graphite is soft and slippery, because the layers easily slide over one another and are readily separated. Graphite is so slippery that it makes an excellent lubricant.

The repeating structural unit, called the *unit cell*, in diamond consists of eight atoms (Figure 2). The fundamental block that encompasses these atoms forms a cube; all the sides look identical, as do the edges. The cubic form and the highly symmetrical arrangement of atoms in diamond embody the *cubic* crystal system.[5] Diamond crystals, if they are true individual crystals, must have the basic form and shape, or "crystal habit," consistent with the geometry of the basic unit. The crystal habit most often associated with diamond is the octahedron (Figure 5), an eight-faced form in which all the flat surfaces or

Figure 5. The photograph shows octahedron (left), etched octahedron (center), cube (top middle right), intergrown dodecahedron (bottom middle right), etched macle (upper right), and flat macle (lower right). The idealized drawings below show some of these basic habits of diamond: from left to right they are an octahedron, a cube, a cubo-octahedron (combined) form, a macle twin, and a dodecahedron. (Harold and Erica Van Pelt/courtesy of American Museum of Natural History.)
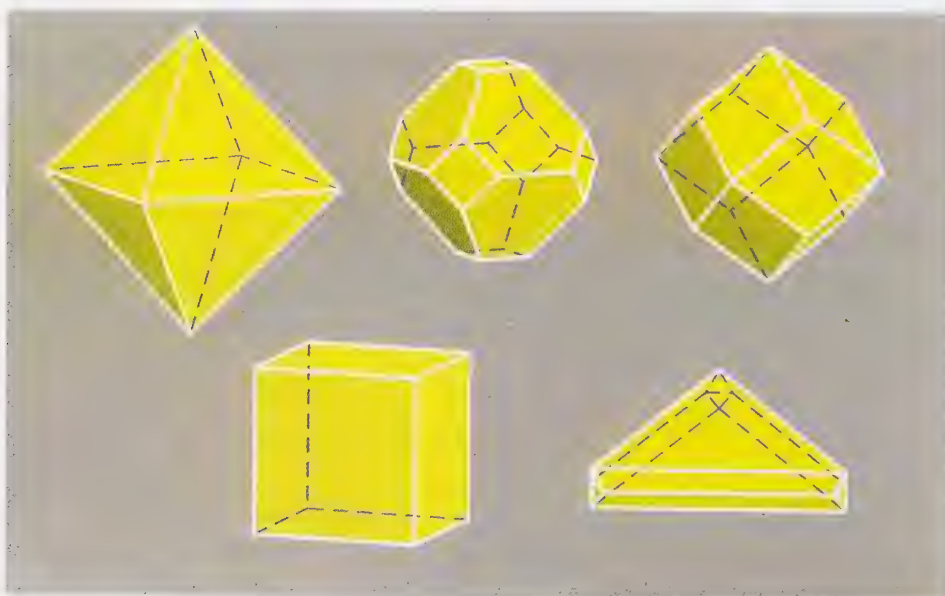
faces are equilateral triangles of the same size, and the angles formed by adjacent edges are identical at 70.53°. The octahedron has an outline that has come to be called the "diamond shape," and that shape is synonymous with this form of the mineral. Real crystals do not have totally flat faces. In Figure 3, triangular growth features called *trigons* can be seen on the octahedral faces of the diamond. The trigons shown here point in the direction opposite to that of the face, indicating that they are indentations; however, raised extensions, pointing in the same direction as the crystal face, can also occur. Both positive and negative trigons are believed to result from etching or dissolution, but positive trigons could be a natural result of growth on the crystal face.[6]

There are many other shapes that diamond crystals can take, particularly the cube, the rhombic dodecahedron (a 12-sided form of crystal more common in garnets), and the trisoctahedron (an octahedron with the triangular face pulled out from a central point to yield three new faces). Combinations of the different forms are also possible (Figure 5), but the rounded faces seen on many natural diamonds are not the growth faces of a crystal, but rather dissolution surfaces, like the rounded surfaces on melting ice cubes. Sometimes crystals will grow in pairs or groups in which the parts will have been rotated or inverted relative to their normal adjacent orientations. These growth pairs are

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DIAMOND DATA

Composition:	C (carbon) (see the classification of diamond types)
Crystal system:	Cubic (class: hexoctahedral)
Space group:	$Fd\bar{3}m$; $a = 3.57$ angstroms (3.57 Å)
Common forms:	Octahedron {111}, cube {100}, dodecahedron {110}, rounded variations
Twins:	Spinel-law common (yielding "macle")
Hardness:	10 on the Mohs scale; Knoop hardness number 56–115 (GPa), 10,000 on the Brooks indenter scale; octahedral face hardest, cube face softest
Cleavage:	Excellent on (111)
Density:	3.51 grams per cubic centimeter (g/cm³) (or specific gravity = 3.51)
Appearance & luster:	Colorless to yellow or various other colors; adamantine
Refractive index:	2.4175 (yellow sodium light)
Dispersion:	0.044
Optical transmission:	Transparent over broad spectrum
Thermal conductivity:	5–25 watts per centimeter per degree Celsius ($W \cdot cm^{-1} \cdot °C^{-1}$)
Electrical conductivity:	0 to ~100 ohm-centimeters (Ω-cm) (resistivity at 300K)
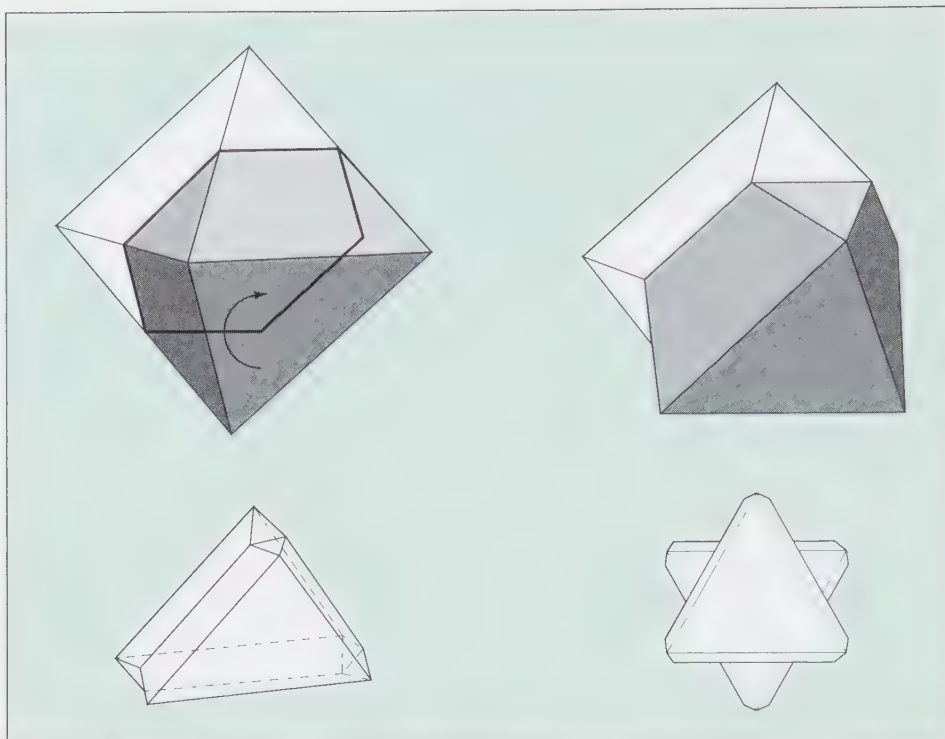
called *twins*, and the most common type in diamond is a triangular shape called a *macle*, which can be depicted by slicing an octahedron and rotating one of the halves 180° relative to the other (Figure 6). A particularly striking twin is the double macle in the shape of a Star of David (Magen David, Figure 6). By comparison, the hexagonal arrangement of carbon atoms in graphite produces hexagonal symmetry, and the crystals usually occur in the form of hexagonal plates.

HARDNESS AND CLEAVAGE

With the crystal structures of diamond and graphite in hand, their physical, optical, and chemical properties can be more readily understood. Diamond's signature physical property is its hardness: Diamond is the hardest known substance. This means that diamond is more resistant to scratching than anything else known, and diamond will scratch all other substances. Only a diamond can scratch another diamond. Various scales and measures of hardness have been developed. An old scale that is still commonly used is the Mohs scale. Developed by Austrian mineralogist Friedrich Mohs in 1822 to assess mineral hardness, it is a ranking of 10 minerals in which each higher-numbered mineral will scratch the lower-ranked ones. Thus, talc is the softest of the 10 minerals (graphite is only slightly harder), and diamond is the hard-

est. It is a convenient scale, but it is not truly indicative of diamond's extraordinary hardness, because the Mohs scale becomes dramatically nonlinear above 8. The increase in hardness from 8 to 9 is larger than the increases between the lower numbers, and the increase from 9 to 10 is dramatically larger. A plot of the Mohs hardnesses against another scale used to measure hardness, the Knoop scale, shows the nonlinearity (Figure 7): A nearly straight line shoots up from 9 to 10. (The Knoop scale is based on the pressure required to make a particular indentation in a substance's surface with a rhombohedrally shaped diamond indenter, and it is typically used for metals and other industrial materials, not gems.) The fact that diamond is the hardest even makes its hardness difficult to measure, because diamond must be used to assess its own hardness. Another aspect of hardness is that it is not the same on every surface nor in every direction on a single surface. For example, it is easier to grind an octahedron's corners off, fashioning a cube shape, than it is to grind parallel to the octahedron face. Indeed, the earliest gem-cut diamonds make it clear that the faceters were aware of that.

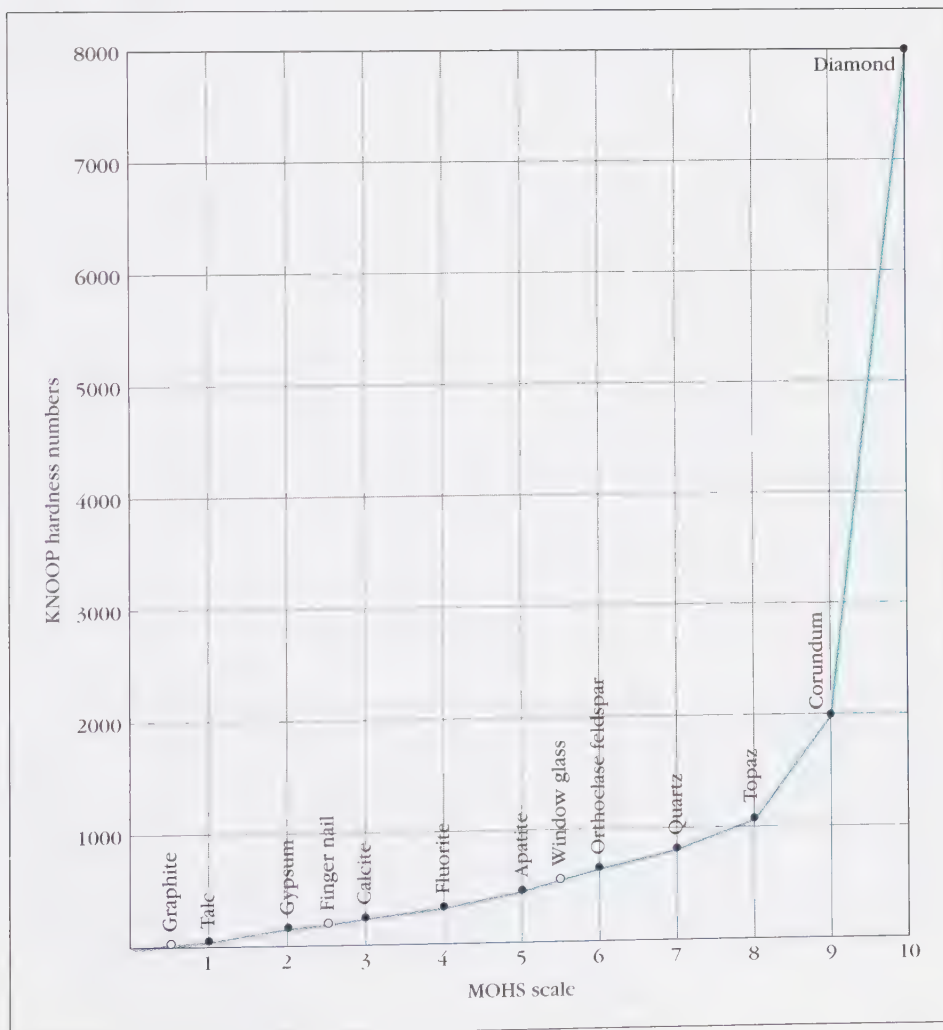| MOHS HARDNESS SCALE |
| --- |
| 1. Talc |
| 2. Gypsum |
| 3. Calcite |
| 4. Fluorite |
| 5. Apatite |
| 6. Feldspar |
| 7. Quartz |
| 8. Topaz |
| 9. Corundum |
| 10. Diamond |

Figure 7. Comparison of the Mohs scale of hardness and the Knoop indenter hardness scale shows the dramatically greater hardness of diamond, as compared with the nearly linearly related hardnesses of other minerals. (Adapted from Bruton, 1978.)
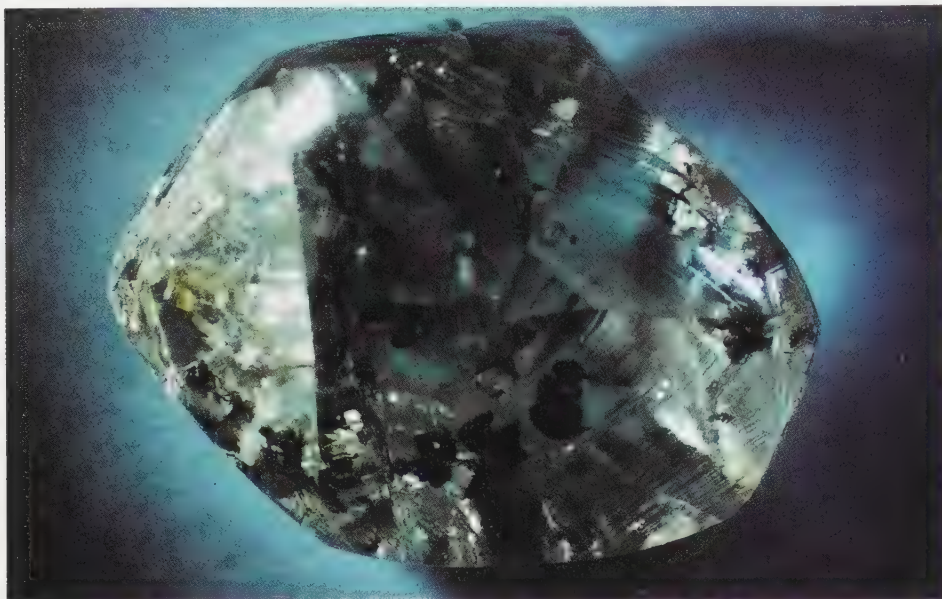
Figure 8. This rounded diamond crystal shows an internal flat crack (the vertical division between light and dark portions on the left) that follows the octahedral cleavage, the mineral's single weakness. The crystal is about 1 cm across. (George E. Harlow/courtesy of American Museum of Natural History.)

Hardness is a measure of durability, but not the only one. The way in which a material breaks provides a diagnostic property for its identification and is a significant factor in determining the material's ability to withstand wear and tear. First, there is the simple matter of durability – whether the material is fragile or tough. Some ornamental stones will break easily (opals are infamous for that), whereas others, such as jade, can handle severe abuse without cracking or breaking. Second, there is the question of directional weakness. Some materials will fracture irregularly because they have no particular direction of weakness. Quite a few will split very neatly, such as the mica minerals that yield perfect sheets (graphite will as well, but that is less frequently seen because of graphite's lack of large crystals and its softness). The mica splitting is called *perfect cleavage* – a neat splitting along a plane surface, whereas materials *fracture* along curved or irregular surfaces. Generally, minerals with good cleavage are less durable. Diamond has perfect cleavage in four directions. An octahedron can be fashioned from an irregular diamond crystal by appropriate cleaving. A cutter will take advantage of the cleavage planes when fashioning diamond gems because careful cleaving will yield desirable pieces quickly and efficiently (Figure 8). The octahedral shape results because these planar directions in the diamond crystal have singularly fewer bonds per unit area than the other directions; there is relative weakness across the octahedral face. This chink in the diamond's armor belies the ancient myth that a diamond would withstand the blow of an iron hammer. The average diamond in a ring will not cleave apart unless severely struck, but when worn for a lifetime, a diamond ring in hard service is likely to suffer some damage from cleavage. A large diamond in an earring or brooch is unlikely ever to suffer such a fate.

DENSITY AND OPTICS

A property of diamond that is very important but less heralded is its high density, 3.51 grams per cubic centimeter.[7] There is a general relationship to describe the fact that materials composed of elements that have low atomic numbers will have low densities and those with high atomic numbers will be

dense; this is mainly a matter of counting up the atomic weight, which is roughly proportional to the atomic number. Carbon, with a low atomic number (C is number 6 among the 92 naturally occurring elements), is a light element. The metals magnesium (atomic number 12) and aluminum (13) are light elements and are not dense, with densities of 1.74 and 2.70, respectively, whereas iron (26) and lead (82) are heavier elements, with densities of 7.9 and 11.4, respectively. Thus diamond is surprisingly dense, given its composition. For graphite, the other common form of carbon, the density is 2.20. Diamond is more than 50 percent more dense, meaning that its atoms are much more closely packed (which provides a hint about how and where diamonds are formed, as discussed in Chapter 3). Practically speaking, diamonds are more dense than most common minerals (for example, the density of quartz is 2.66) and will tend to be concentrated at the bottom of gravel deposits in streams or in beach sands along with other "heavies" such as gold (density = 19) and sapphire (density = 4.0). No wonder that diamonds often have been found by those searching for concentrations of gold in stream gravels (known as placer deposits).

Another direct consequence of diamond's density and stiff structure is the way it slows the velocity of light passing through it – its high *refractive index*. Although we are taught that the speed of light is about 186,000 miles per second, or about 300,000 kilometers per second (km/s), that is the case only in a vacuum, such as outer space. The transmission of light through air is slowed by about 50 miles per second, and in water its velocity slows to about 140,000 miles per second (225,000 km/s). The passage of light is slowed by its interactions with electrons in all substances. The more electrons per centimeter, the greater the delay in light's transmission and the reduction in its velocity. Refractive index generally correlates with density because it is correlated to the number of electrons in a specific volume. For example, in window glass (density about 2.5) the velocity of light is about 124,000 miles per second (200,000 km/s), whereas in leaded "crystal," the kind of glass used in chandeliers and decorative bowls, the lead content increases the density to as high as 4.5 and lowers the velocity of light to about 110,000 miles per second (176,000 km/s). In diamond, with its relatively high density, the electrons are packed together very densely and are tightly bound in the structure – a factor important in determining many of the properties of diamond – so that the velocity of light is reduced to about 77,000 miles per second (124,000 km/s), a stupendous decrease from its velocity in air, and near the maximum for any transparent substance.

Two important phenomena are determined by the variation in the velocity of light as it passes from one medium to another: light bending, or *refraction*, and light *reflection*, or *reflectance*. Because of the wave properties of light, its direction will be altered when it passes from one transparent substance to another that allows a different light velocity. All lenses function on the basis of this property. We are all familiar with this phenomenon when looking into

water, as into a swimming pool or even a glass of water: As you move from looking straight down into the water (at an angle of 90°) to an acute angle, objects in the water will appear to move toward you (e.g., a pole sticking out of the water will look bent) because the path of the light is being altered or bent. If you are under water looking up at a still surface, things will appear to be spread out farther than they really are, as if you are looking through a fish-eye lens; furthermore, at a certain critical angle and at shallower angles, the water surface will act as a mirror, reflecting light coming from below. What actually happens is that at the *critical angle* the light coming from an object in the water is bent parallel to the water surface, and then at even shallower angles to the surface the light is reflected back within the water. This *critical angle* is a measure of the difference between the velocity of light in water and that in air and is used to quantify the light-bending potential – the *refractive index*.[8] The refractive index of water is about 1.33, and that of a vacuum is 1.00. The higher the refractive index, the greater the reduction in velocity and the smaller the *critical angle* at which reflection, rather than transparency, will occur within the material of higher refractive index (Figure 9).

Reflectance, or the amount of light reflected by a transparent material, is also related to the difference in refractive indices between two materials (if air is one of the materials, the reflectance is essentially dependent only on the other material) and the angle of observation. The steeper the angle of incidence, the more reflective the surface; the higher the refractive index, the greater the reflectance. Typical window glass reflects about 4 percent of the light hitting it at 90°, but 17 percent of it is reflected if the angle is 30°; for diamond, the numbers are 17 percent and 27 percent, respectively. Thus our ability to see trans-

*Figure 9. These three light-ray drawings show how light is either refracted or reflected, depending on the angle of incidence of light exiting a diamond's flat surface into the air. The* critical angle, *which is 24.5° for diamond, is the limiting condition between refracted transmission and reflection of light. (Adapted from materials provided by the Gemmological Association and Gem Testing Laboratory of Great Britain.)*
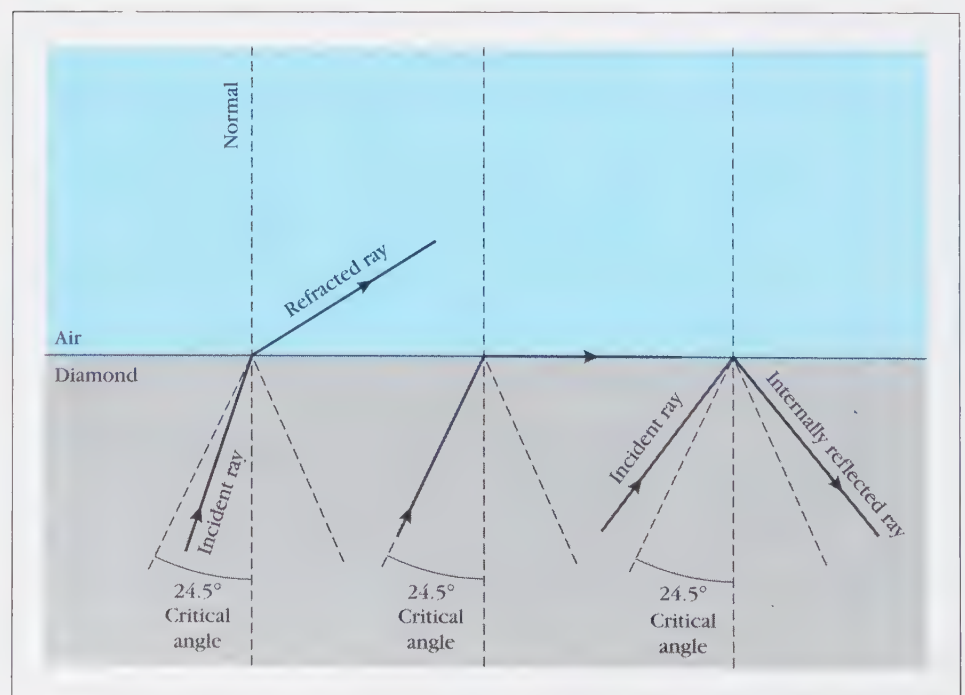
parent colorless objects depends on differences in refractive indices. A colorless drinking glass would be visibly undetectable if it did not bend and reflect light or if it had the same refractive index as air. Mineralogists classify this appearance in air as *luster*; glass and most rock-forming minerals have glassy or vitreous luster. Diamond, with its high refractive index, has *adamantine* luster; once again, diamond sets the standard, providing the definition of the maximal luster for a transparent material. Faceted diamonds are supremely brilliant and splendent because the refractive index of diamond exceeds those for most transparent materials. Its closest competitors are some synthetic materials created to imitate diamond (see Chapter 12). The cut, style, and proportions of the faceting as diamonds are turned into gems play critical roles in a diamond's glittering appearance, as also discussed in Chapter 12.

Two other optical properties of diamond must be mentioned: dispersion and transparency. The definition of *dispersion* will require the introduction of a few more concepts. For simplicity, the discussion of refraction treated that topic as if a material had only one refractive index for all colors or wavelengths of light, which is not the case. The light spectrum extends beyond our limited range of vision: from the low-energy, long-wavelength sensible heat of the infrared (inside red) range into the visible spectrum of ROY G BIV,[9] and then out beyond the visible region to the high energies and short wavelengths of ultraviolet (exceeding violet) light (see Figure 5 in Chapter 2). For any material, its refractive index and transparency will vary, depending on the wavelength of the light. Such variations lead to different wavelengths of light being bent different amounts when entering a colorless substance at an angle. The angular separation resulting from those differing amounts of bending permits the separation of the colors that make up white light, thus producing a rainbow from rain droplets and the color spectrum from a glass prism (Figure 10). Dispersion is a measure of those variations, and the *coefficient of dispersion* is equal to the difference in refractive-index values at two wavelengths of visible light: one blue-violet and the other red.[10] The value for diamond is 0.044, which is high but not extraordinary in the context of the refractive index of diamond being so great. Some minerals have higher coefficients of dispersion, such as cassiterite (0.071) and rutile (0.330), but typically they are strongly colored. Leaded glass used in crystal and "paste" (imitations of diamonds) can have dispersion coefficients greater than that of diamond, which is a reason for the use of crystal in chandeliers and in diamond imitations. The significant fact is that compared with the dispersion coefficients for gem minerals that can be colorless, that for diamond is high; for example, for quartz the value is 0.013, and for corundum (colorless sapphire) the value is 0.018. Consequently, colorless diamonds, when properly shaped or cut, will reveal a strong separation of the colors glinting out of the gem; that is the hallmark of a "brilliant." The proportioning of a stone is a balance between two goals: achieving angles inside the stone that will internally reflect light coming in from the top, and

Figure 10. The angle of refraction of light entering a transparent substance is dependent on the wavelength. High-dispersion materials such as diamond have large variations in their refractive indices which permit a large angular separation of light into the colors of the rainbow.
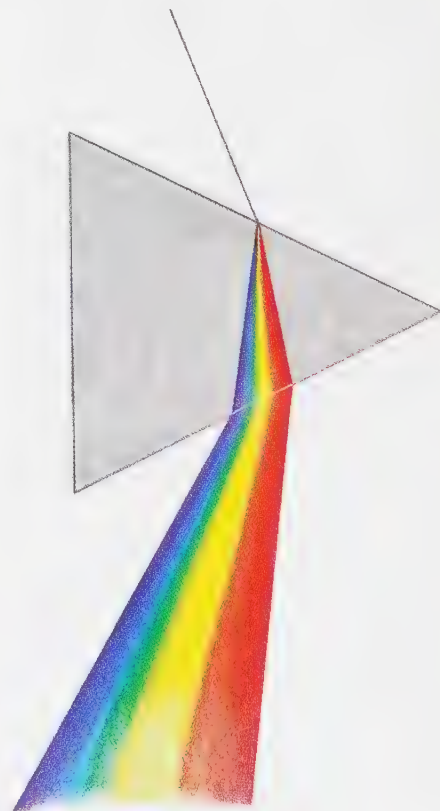
providing refraction angles and light paths that will permit the separation of colors. There is never a perfect solution that can achieve the maximum in both effects simultaneously – only compromises such as are produced in the modern brilliant cuts. The geometry of acceptable cutting is shown in Figure 11.

The second optical property in which diamond excels is *transparency*. Not to be confused with *clarity*, which has to do with freedom from flaws and inclusions (one of the "four Cs" dealt with in Chapter 12), transparency is an inherent property of a material: the measure of light transmitted by a transparent material. Window glass is transparent to light in the visible spectrum, whereas iron is opaque. Diamond is completely transparent to broad segments of the electromagnetic spectrum, which makes it a useful material for industrial, technological, and scientific applications. Beginning with the long wavelengths of the electromagnetic spectrum, diamond, like most electrical insulators, is transparent to radiowaves and microwaves and continues to be transparent into the infrared region except for a few strong characteristic bands of absorption. Most substances are fairly opaque to many parts of the infrared because their constituent atoms and molecules are excited into strong vibrations. Those interactions absorb the light energy, resulting in opacity for the wavelengths that are absorbed. Diamond's structural simplicity and strong bonding minimize that effect (the specifics and relationships are examined in

Figure 11. (a) The angles of a faceted diamond must be proportioned to its refractive index so that light entering the top (crown) will reflect internally and exit the crown. (b) This cut is too shallow, and light will exit the bottom (pavilion). (c) This cut is too deep, and light will exit the sides. (d) Proper proportioning will also permit dispersion to display "fire" from a diamond.
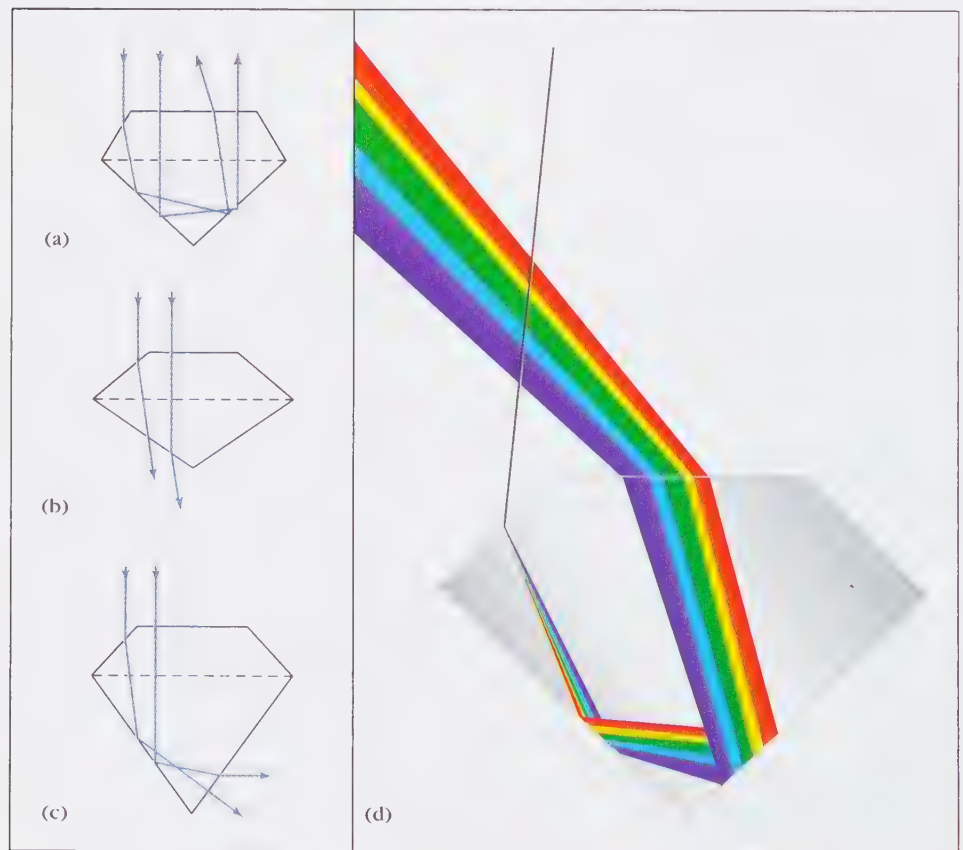
detail in Chapter 2). Colorless stones are, by definition, fully transparent to the visible wavelengths and remain so well into the ultraviolet range, where eventually the electrons become excited to high energy states and opacity occurs (see Chapter 13). A few rare natural diamonds of type II are transparent over more of the ultraviolet range. At higher energies, diamond's light-element composition makes it highly transparent to x-rays and γ-rays, and almost all materials are transparent to cosmic rays. Thus diamond, tough and transparent, makes an excellent window for looking at a host of phenomena that can be detected or probed with electromagnetic radiation. Diamond is a high-technology material that will find its way into more and more applications as we find better ways of growing and fashioning it.

Color in diamonds and other colorful phenomena, such as fluorescence, are so interesting and diverse that the entire next chapter is devoted to them.

ELECTRICAL CONDUCTIVITY AND THERMAL CONDUCTIVITY

There are a few differences between graphite and diamond that are truly dramatic: appearance, electrical conductivity, and thermal conductivity. The differences are largely due to the distinctive behaviors of the electrons in their structures. Graphite is opaque, gray-black, and nearly metallic in luster, whereas diamond is transparent. Graphite behaves somewhat like a metal because of the single electron in each carbon atom that does not form a stable strong bond; that electron migrates among the three strong bonds and can be easily moved through the structure. That electron mobility gives graphite the attributes of broad-spectrum optical opacity, metallic luster, and good electrical conductivity. In diamond, none of the electrons can be easily released from their oriented covalent bonds, and thus diamond is nonmetallic and a nonconductor of electricity – an insulator. There are a few exceptions in which some diamonds can be semiconductors, a topic discussed in Chapter 13. As for the other form of conductivity, thermal conductivity, diamond is more true to its superlative nature: Diamond has phenomenal thermal conductivity, the capacity to conduct heat. Usually, good thermal conductors are also good electrical conductors, such as the metal copper. At room temperature, diamond is four times as thermally conductive as copper, but diamond is not electrically conductive. What is going on to give diamond such thermal conductivity? Heat is caused by atoms in vibration, so in a very hot solid the atoms are really bouncing around – not going anywhere, but rattling in their structural cage. The energy that produces heat, whether from a chemical reaction or because of radiance from the sun, does so by stimulating atoms into vibration. A good conductor of heat must be efficient in transmitting vibrational energy through

its assemblage of atoms. There are two mechanisms for transmitting this energy in a solid: by moving energized electrons, and by transferring the vibrations or vibrational energy. The phenomenon of moving electrons is equivalent to that of conducting electricity – hence the dual conductivity rule that describes conduction in metals. The transfer of vibrational energy requires a rigid structure and a minimum of impediments or weak links in the vibrational handshaking. Thus the criteria for a good gem and a good vibrational conductor are the same: hardness and freedom from flaws. The rigidity of the diamond structure and its relative freedom from structural flaws permit the vibrational energy to be transmitted efficiently. The more nearly perfect the diamond and its freedom from defects, inclusions, and substituted atoms, the better its thermal conductivity, because there are fewer obstacles to disperse or impede the transmission of the vibrations.

Diamond's high thermal conductivity can be used to detect imitations. Diamonds are called "ice" because they feel cold when touched to the lips. When you touch a gem diamond to your lips, your lips are warm (at your body temperature), but the gem is cooler (at room temperature). As lips are very sensitive to changes in temperature, the diamond absorbs the heat from them and makes them feel cold. No other gems or any diamond imitations have diamond's "iciness," because they do not have its high thermal conductivity. There are electronic devices, about the size of a large pen, that can measure thermal conductivity more accurately – so accurately that they can distinguish between a diamond and a piece of metal.[11] On the practical side, a material that is a good conductor of heat, but not of electricity, is very useful, particularly in the world of electronics. Such high-tech applications of diamonds are discussed in Chapter 13.

SURFACE PROPERTIES

By this point it perhaps will not be surprising that there is yet another property of diamond that is unusual for a mineral: Diamonds love grease. In the world of wetness there are two opposite liquids: water and oil. Molecules of water tend to adhere to, or "wet," surfaces that resemble themselves – substances full of oxygen to which the hydrogen atoms in water can link, just as they link to the oxygens in adjacent water molecules to hold water together. Oils and greases are hydrocarbons, and although we all know how easy it is to get anything greasy, hydrocarbons adhere better to some surfaces than to others. The surfaces to which greases will most readily adhere do not contain "offending" oxygen atoms nor have surface-adherent water molecules – surfaces such as those of metals, plastics, and, of course, diamond, which is pure

carbon. (Things are not quite that simple, but the approximation is fairly accurate.[12]) The converse is also true: Water will not wet the surface of a wax, as seen when water forms droplets that roll off a freshly waxed automobile. Water also will not wet the surface of a diamond, but it will wet most minerals in rocks (Figure 12). That characteristic of diamonds was first recognized in 1896 by an employee of De Beers Consolidated Mines, which immediately took advantage of that property to separate diamonds from the other minerals scooped up in the mining operation, using a grease table. Washed gravel containing diamonds was flushed with water over a sloping surface covered with a mixture of wax and grease. The diamonds stuck to the mixture, while the wetted waste minerals were washed away. On the other hand, the diamonds we wear as jewelry also love grease and oil. All too quickly our diamonds acquire a greasy film that requires removal with ammonia or a detergent.
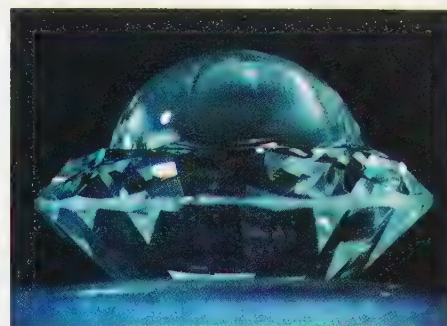

Figure 12. The surface of the drop of water sitting on top of this faceted diamond makes a very steep angle, almost 70°, with the flat diamond face. This manifestation of diamond's aversion to being wet by water is similar to the behavior of water drops on a freshly waxed automobile. (George E. Harlow/courtesy of American Museum of Natural History.)

SPECIAL NAMES

There are a few forms of diamond that have special names.

Boart

Boart, or bort, is bottom-grade diamond destined for use as industrial abrasive. Boart usually consists of small, irregular, imperfectly crystallized diamonds or massive aggregates that can be clear, yellow-green, dark, or opaque, but it can include large flawed black diamonds, which will be crushed to a uniform small size, sometimes referred to as crushing boart or mine boart for the larger poor-quality diamonds. The name may have been derived from a Middle French term meaning "bastard."

Carbonado

Carbonado is a diamond rock of very fine grain size – a natural aggregate of microscopic crystals of diamond, graphite, and amorphous (noncrystalline) carbon, with or without other accessory minerals. Carbonados occur as ball-like structures and were originally found in Brazil, but they have sometimes been associated with more recent finds in central Africa. The material is of uncertain origin, but it strongly resembles some quickly crystallized versions of synthetic diamonds that are used for polishing compound. Recent investigations have suggested that some carbonados may have resulted from asteroid impacts in ancient carbonaceous sand deposits, but that interpretation is not yet widely accepted (Figure 13).

Figure 13. This 136-gram carbonado, probably from Bangui, Central African Republic, is a natural polycrystalline form of diamond, something like a microcrystalline rock. The high luster is typical for a carbonado. (Denis Finnin/courtesy of American Museum of Natural History.)
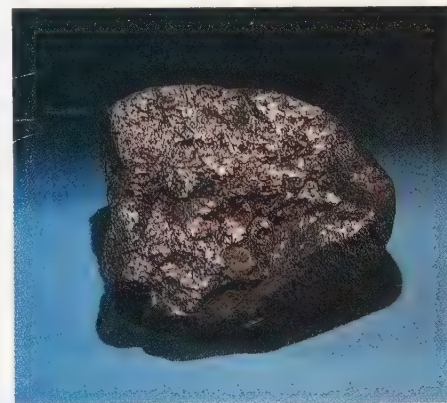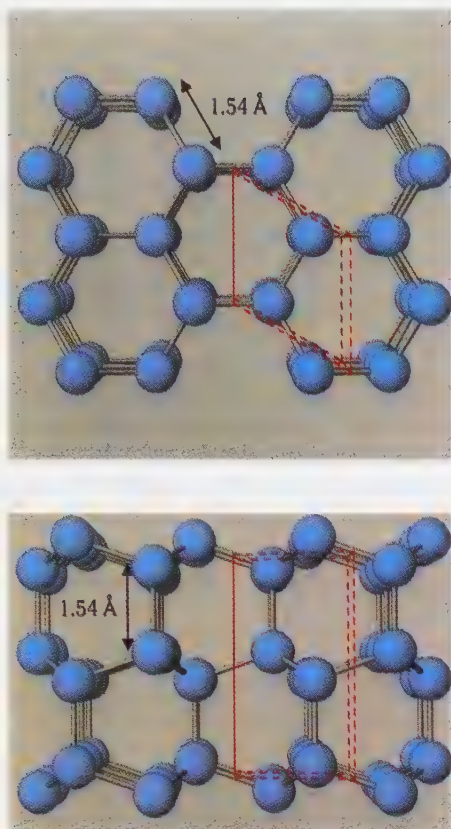
Figure 14. The structure of lonsdaleite looks like a cross between the structures of graphite and diamond, because in one orientation the sheet-like layering of hexagonal rings is seen (top), but in a perpendicular view the linkages of each carbon to four adjacent carbons are visible (bottom). (Created by G. E. Harlow using Atoms © software.)

Lonsdaleite

Lonsdaleite is not a variety of diamond but rather a different carbon mineral that is very similar to diamond. In lonsdaleite there is a repeating network of carbon atoms bonded to four neighbors, but the tetrahedral clusters all point in the same direction, rather than alternating back and forth (Figure 14). Thus lonsdaleite has hexagonal symmetry rather than cubic symmetry. Lonsdaleite appears to be less stable than diamond, but it is not found with diamonds that come from deep within the earth. It is found mostly in objects that were subjected to catastrophic shock, such as meteorites. Thus lonsdaleite is believed to be a *metastable phase*: There appears to be no set of pressure and temperature conditions in which it will be permanently stable; rather, it forms as a more easily attained configuration from a rapid change in conditions. Lonsdaleite has been referred to as type III diamond.

TYPES OF DIAMONDS

For most of this discussion, diamonds have been described in idealized terms as being pure carbon, without impurities, and always as individual crystals. But in fact, nitrogen is an impurity found in most diamonds. Boron is much less common, but when it replaces individual carbon atoms, that changes a diamond's electrical conductivity and color. A classification of dia-

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SIMPLIFIED CLASSIFICATION OF DIAMOND TYPES

	Type I	Type II
Natural abundance:[a]	Ia: ~98%	IIa: ~2%
	Ib: ~0.1%	IIb: extremely rare
Nitrogen content (ppm):[b]	Ia: ~10–3,000	IIa: <10
	Ib: ~25–50	IIb: none (<0.1)
N distribution:	Ia: as small aggregates	
	Ib: individual substituted atoms	
Other constituents:		IIb: boron
Color:	Ia: see Chapter 2	IIa: usually colorless
		IIb: blue
Infrared signature:	Bands: 10,000–7,100 nm	
Ultraviolet signature:	Ia: opaque below 300 nm	Opaque below 230 nm
Special qualities:		IIb: semiconductor

[a]For larger diamonds (>0.1 carat); type II more common among microdiamonds.
[b]Parts per million (number of *N* atoms per million C atoms).

mond types was published in 1934, based on the variations in the physical properties of diamonds. The classification was eventually expanded to take account of impurities and substitutions of other elements, and it has subsequently been further refined and improved.[13] Type I and type II diamonds are differentiated on the basis of the presence of nitrogen inclusions, as revealed by infrared spectroscopy. Type I diamonds contain nitrogen, and type II diamonds do not. The limit of detection was about 10–20 nitrogen atoms per million carbons in the 1970s, and it is now about 1 part per million for a diamond a few millimeters thick. A further subdivision of type II diamonds is based on the nature of the aggregation of the nitrogen atoms. If there is a high nitrogen concentration, and if the diamond has been at a high temperature for a geologically long period of time (probably millions of years), nitrogen atoms tend to cluster as groups, defining type Ia diamonds, which are the ones most commonly recovered in mining. Synthetic diamonds, which can contain abundant nitrogen because of air contamination during the synthesis process, are at a high temperature for only a short time and do not form as type Ia diamonds. Type Ib diamonds usually contain less nitrogen, and in that situation the nitrogen atoms randomly replace carbons and do not form clusters.

These categories of diamond types are based on spectroscopic measurements, as reinforced by high-magnification imaging using electron microscopes. Such close observations often show that a single diamond can have portions that are of different types. This is possible because diamonds grow by adding layers of atoms to their surfaces, much as layers are added to a candle when it is dipped into melted wax. As a diamond crystal adds new layers of carbon, it incorporates impurities in amounts determined by the composition of its geological matrix. Thus if its surrounding conditions change, its impurity content may change as well, perhaps yielding a diamond with zones of different types. Such a diamond holds a partial record of the changes in its growth environment, information that is important for both natural and synthetic diamonds. The variabilities of features in natural diamonds (subtle colors, inclusions, trace-element variations, morphology of zoning) are distinctive, allowing them to be differentiated from synthetics and giving each an individual character.

NOTES

1 The electronic configuration of carbon is $2s^2 2p^2$; technically, that places all four $2p$ electrons in the valence shell.

2 The orbits are considered to hybridize into a form known as sp^3, which happens to have tetrahedral geometry. Thus the atomic geometry and orbital geometry are optimum for interacting, maximizing the stability of the diamond structure.

3 There is no stable fixed configuration for the distribution of these single (σ) and double (π)

bonds; consequently it is surmised that there is a time resonance in the bonding that gives each bond an average of $1\frac{1}{3}$ shared electrons.

[4] These are often referred to as van der Waals forces, named after the physicist who described these weak interactions.

[5] Delving into the six crystal systems, Bravais lattices, etc., is beyond the scope of this book; the interested reader should refer to an introductory text on crystallography or mineralogy.

[6] See Wilks and Wilks (1995), p. 123.

[7] Alternatively, density can be expressed as the ratio between the mass of a volume of the mineral and the mass of an equivalent volume of pure water at 4°C (39°F) and 1 atmosphere of pressure; that will yield the number 3.51 (a ratio of 1 : 3.51, a dimensionless quantity), called the *specific gravity* of diamond.

[8] Two equations apply here: The general relationship is that the refractive index = c/c_m, where c and c_m are the velocities of light in a vacuum and in a material, respectively. The critical angle is observed at the interface as the light moves from the material with a higher index (*optically dense*) to the material of lower index (*optically rare*) and is measured from the normal to the interface. It varies according to Snell's law: sin(critical angle) = 1/(refractive index).

[9] The acronym for the colors of the visible spectrum: red, orange, yellow, green, blue, indigo, and violet.

[10] The wavelengths are for the G and B Fraunhofer lines of sunlight, at 430.8 and 686.7 nanometers (nm), at which diamond's refractive indices are 2.4512 and 2.4075, respectively, which gives a coefficient of dispersion of 0.0437. Sometimes dispersion is referenced to other Fraunhofer lines, such as F and C, at 486.1 and 656.3 nm, at which diamond's refractive indices are 2.43554 and 2.40990 (dispersion coefficient 0.02564).

[11] The probes actually measure "thermal inertia," a property related to thermal conductivity and heat capacity (Hoover, 1983).

[12] The reaction to a surface is labeled either "hydrophilic" (a surface with affinity for water, readily forming hydrogen bonds) or "hydrophobic" (a surface that will not form hydrogen bonds). Water molecules attach by forming hydrogen bonds with other molecules or substances.

[13] See Robertson, Fox, and Martin (1934) and Fritsch and Scarratt (1992).

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2

The Nature of Color
in Diamonds

EMMANUEL FRITSCH

DIAMOND: A RARE BRILLIANT, colorless crystalline form of pure carbon.* That is the popular image of the best-known gem in our collective consciousness. We think of a valuable stone with many facets and beautiful "fire," so limpid and colorless it is "of the purest water," as experts used to say. But historical sources clearly show that since at least Roman times, people have also treasured diamonds that were colored. The Mogul rulers of India, Louis XIV of France, the Russian czars, and English monarchs have all cherished these curious colored gems. Today, most people think of diamonds as colorless almost by definition, and so colored diamonds are at first a little baffling. Yet diamonds can be found in virtually all the colors of the rainbow (Figure 1). Those with a strong enough tint are called "fancy colored diamonds" or simply "fancies."

Any colored diamond is a truly rare gem. Although significant statistics are not available, specialists estimate that there is one fancy colored diamond for every ten thousand near-colorless ones. This rarity explains in part why such remarkable gems were for centuries the expensive and exclusive toys of rulers and royalty. It also helps to explain why the general public has virtually no knowledge of them.

If this book had been written in 1980, the subject of colored diamonds probably would have been considered too anecdotal for inclusion. Colored diamonds are just beginning to come into fashion, to create their own market, after years of being considered as curiosities. It can be argued that the new colored-diamond era began in October 1987, when a 0.95-carat red diamond was

Figure 1. This suite of colored diamonds from the Aurora Collection shows that almost all the colors of the rainbow have been found in these rare gems. The largest stone is 2.3 carats. (Harold and Erica Van Pelt/courtesy of American Museum of Natural History and Aurora Gems.)

Figure 2. The auctioning of this extremely rare 0.95 carat fancy purplish red diamond provided a historic boost to worldwide interest in colored diamonds. It reportedly was purchased for nearly $1 million (U.S.) by a Swiss dealer representing the sultan of Brunei. The sultan is reputed to own perhaps the largest collection of colored diamonds in the world. (Tino Hammid/courtesy of Gemological Institute of America.)

auctioned for nearly $1 million (U.S.) in New York (Figure 2). The trade and a discriminating public were astonished and realized that colored diamonds were not just intriguing oddities of nature but could be worth good money.

As commercial interest grew, more colored diamonds were sent for expert evaluation at gemological laboratories, and a better understanding of color in diamonds began to develop. The increasing interest in colored diamonds probably has not yet reached a plateau. A symbol of the growing importance of colored diamonds is that the world's largest faceted diamond is no longer colorless, but yellow (Figure 3). It is the Golden Jubilee, unveiled in 1995, and at 545.67 carats it tops the perfectly colorless 530.2-carat Cullinan I.

This chapter will explore the topic of colored diamonds and how the color comes into existence. We will first see why ordinary objects appear colored. Then we will descend to the atomic scale to see what makes a material colored. We will explain how scientists use complex laboratory equipment to induce brilliant tints in otherwise colorless or weakly colored diamonds. Finally, we will review all the colors one can find in diamond, their origins, their relative rarity, and some of their more unusual characteristics.

WHAT MAKES A MATERIAL COLORED?

Most people are familiar with the fact that light from the sun can be separated into the colors of the rainbow using a glass prism (Figure 4). Sunlight, or "white light," is a combination of the colors of the spectrum, whose additive impression is white. This is true

Figure 3. Since 1995, the Golden Jubilee, at 545.67 carats, has been recognized as the world's largest faceted diamond. It has been offered to the king of Thailand by a group of Thai businessmen to celebrate the king's 50 years as monarch and only awaits fund raising to permit the gift to occur. This yellow stone symbolizes the rising importance of colored diamonds in the world jewelry market. (Courtesy of De Beers.)
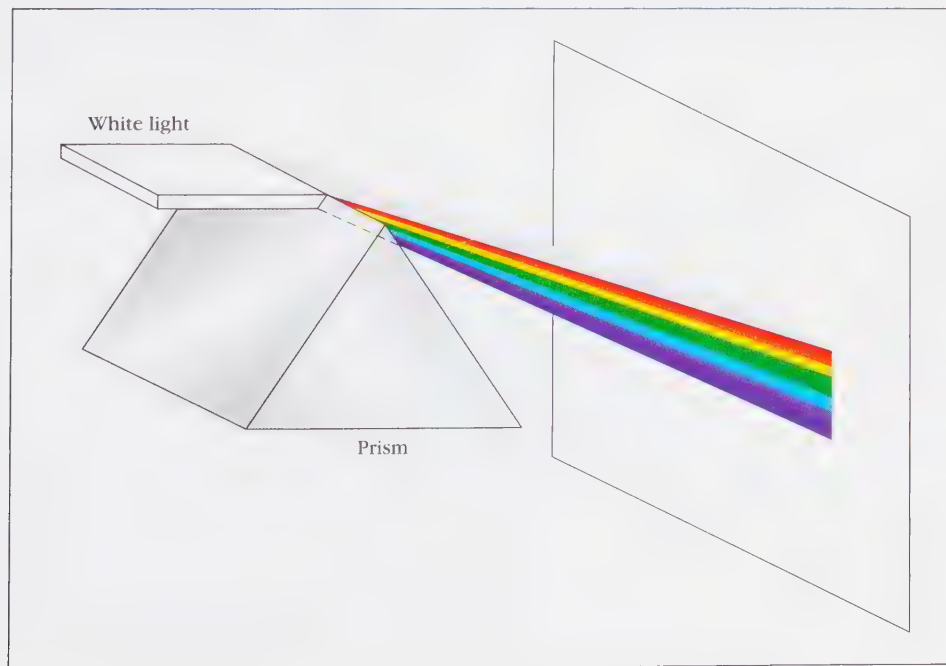
Figure 4. "White light," such as sunlight, can be refracted and decomposed by a prism into all the colors of the rainbow.
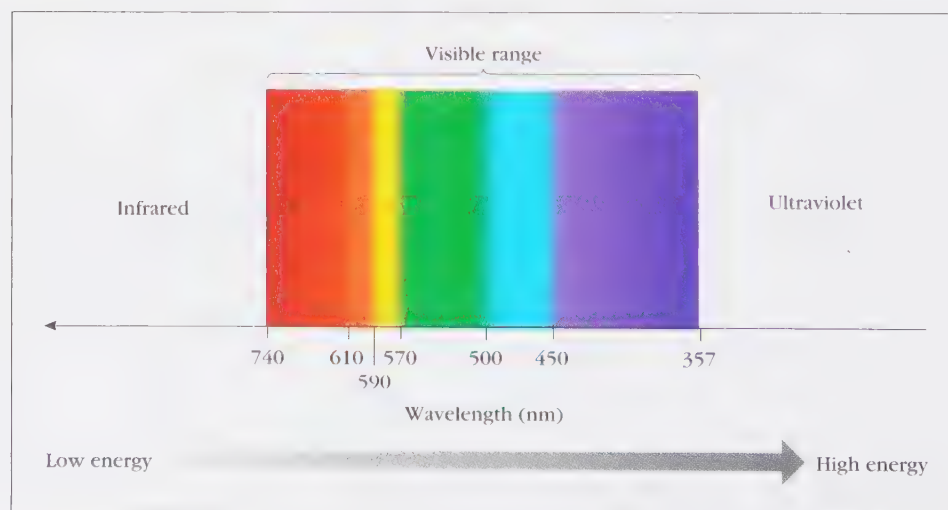

White light

Prism

for many light sources, not just the sun. We call the range of colors into which sunlight can be separated the "visible spectrum."

When visible light and all the other frequencies of electromagnetic radiation that make up the total electromagnetic spectrum came to be understood to have wave properties, it became clear that the phenomenon of color was associated with variations in energy, frequency, and wavelength, all related by a fundamental equation. (The relationship of energy and wavelength, or frequency, is given by Planck's radiation relationship that the energy change is equal to a constant (h – Planck's constant) times the frequency ν [$\Delta E = h\nu$], which is also equivalent to the constant divided by the wavelength λ [$\Delta E = h/\lambda$].) Each wavelength represents a particular color, as shown in Figure 5. The unit most often used to measure wavelength is the nanometer (one-billionth of a meter, 10^{-9} m), although there are many other units that can be used. Moreover, one wavelength does not represent just blue, but a particular hue of blue. For example, the blue at 490 nanometers (nm) is a royal or cobalt blue, whereas that at 500 nm is a teal blue.

When we see color in any material, such as a fancy colored diamond, that means that the light coming from the object has been modified by the object. One or more of the colors present in the original "white light" have somehow been eliminated, and therefore the light coming out is a combination of the remaining colors. For example, if a diamond absorbs those wavelengths that represent purple and blue, then the light coming out of that diamond will be a combination of green, yellow, orange, and red, which we will perceive as yellow; we will see a yellow diamond (Figure 6). Generally, if an object absorbs mostly light of one color, then it will appear to have the complementary color: A tomato absorbs mostly green light, and thus it appears red to our eyes.

Why are most diamonds almost colorless, but some are yellow and a few pink? What gives a diamond its color? When a diamond modifies light, it is generally because it absorbs a portion of the visible spectrum. Many types of chemical elements, compounds, and structures can cause light absorption in a

Figure 5. To understand color in diamonds, one must remember that light is a form of energy. In this representation of the visible spectrum, low energy is to the left, and high energy is to the right. Each color of the rainbow corresponds to a particular energy that is equivalent to a particular wavelength, measured in nanometers.
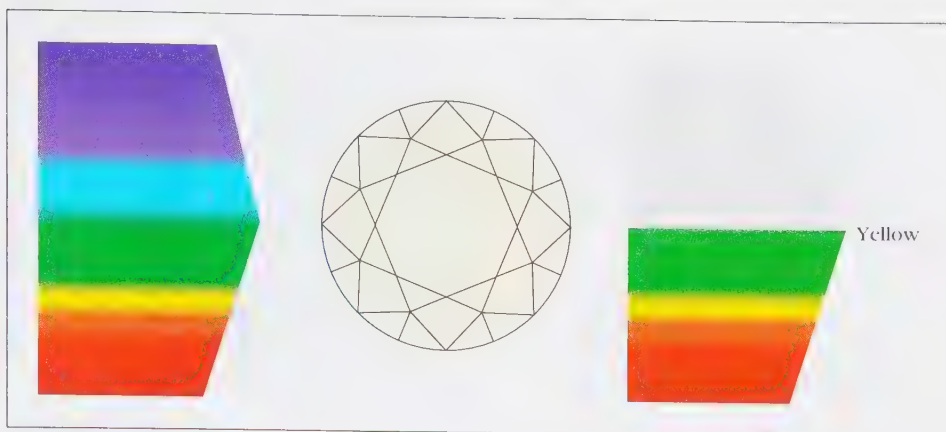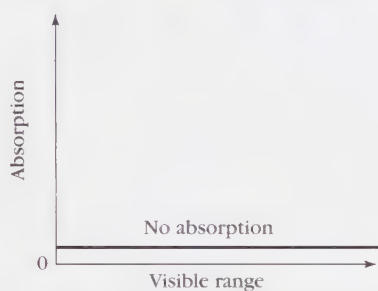
material. For example, many gems are colored by minor impurities of atoms of the transition-element metals of the periodic table. Ruby and emerald are colored by chromium, whereas amethyst, peridot, and red garnet are colored by iron. Diamond is an exception, because its colors are not related to metal impurities. Instead, the colors in diamonds often are related to nitrogen, which is an unusual impurity in other gems, but color can also be due to defects within a diamond's crystal structure. Whereas the agent for color in one gem may cause a similar color in another, none of the causes of color in diamond can be transposed directly to other gems.
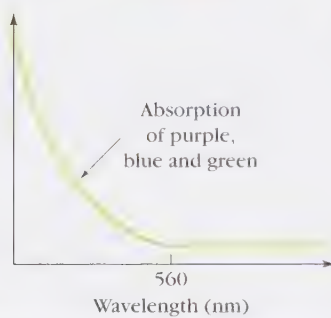
Color is due to the absorption of some wavelengths of visible light. We will first discuss this process in general terms and later cover the specific absorptions that induce particular colors. To understand the origin of color in diamonds, we must remember that light is a form of energy. If the light energy is sufficient to move some electrons in diamond from one particular energy level to another, light absorption will occur. In a pure and perfect diamond, the electrons are all shared among carbon atoms in bonds at comparable energies. The energies of electrons are diagrammed in Figure 7, showing the two permissible energy states. The bonded electrons are in the valence band, and the excited electrons can go into the conduction band. The gap between the bands represents the energy "kick" required to move an electron between the two permissible states. The difference in energy between these two bands is much greater than the energy found in visible light. Hence, for a pure perfect diamond, no visible light is absorbed, and such a diamond is colorless. However, such a stone is very rare; most "colorless" diamonds we see in jewelry are actually very slightly colored, though not enough to be seen by untrained eyes.

For a diamond to manifest color, some impurity or defect must locally create an energy level or state for an electron between the two broad bands. This state will induce color only if it corresponds to an energy difference (either from the valence band to it, or from it to the conduction band) that is found in the visible spectrum. Then that energy of light can excite an electron to make the energy transition; in a real sense, light is the fuel helping electrons to "jump" to states of higher energy.
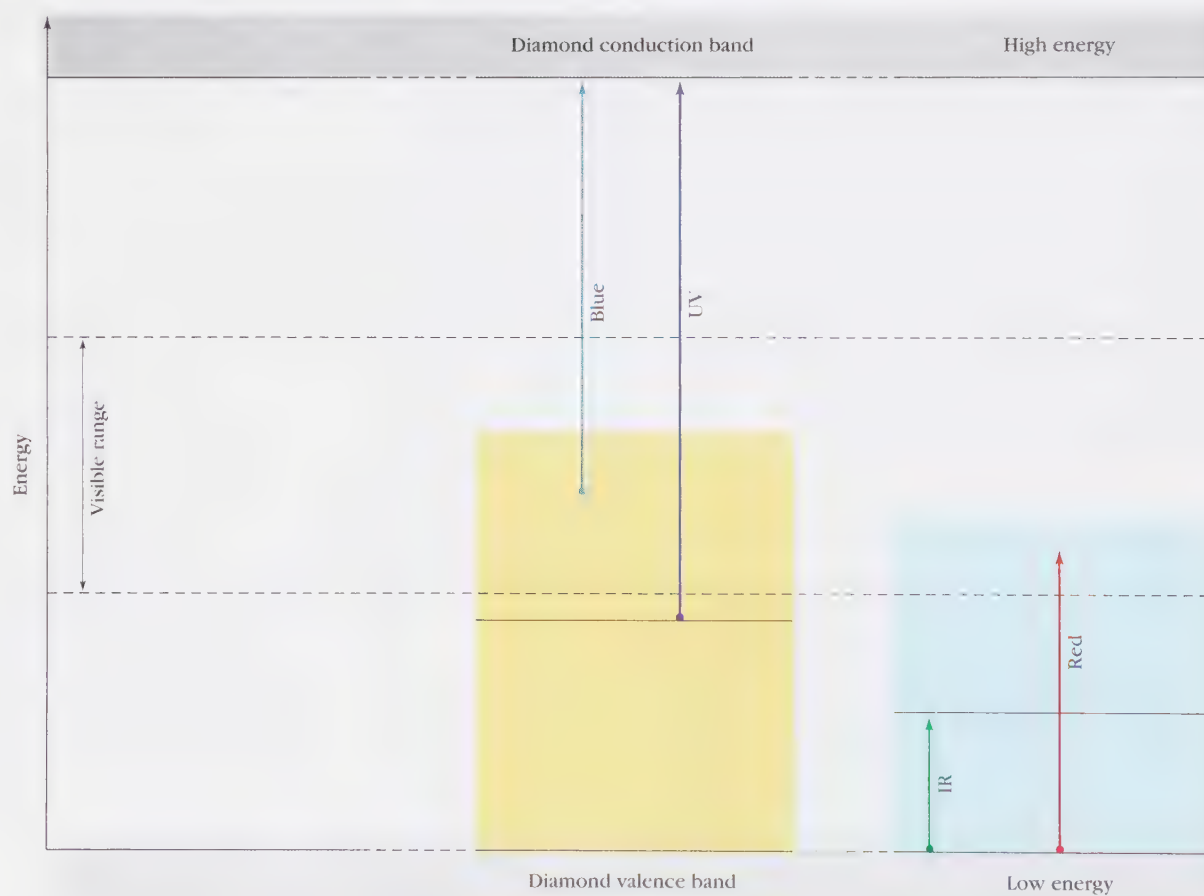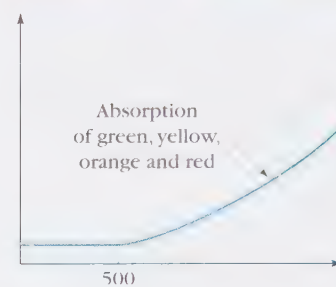
Colorless diamond

"Canary" yellow diamond

Blue diamond

Absorption

No absorption

0

Visible range

Absorption
of purple,
blue and green

560

Wavelength (nm)

Absorption
of green, yellow,
orange and red

500

Diamond conduction band

High energy

Blue

UV

Energy

Visible range

Red

IR

Diamond valence band

Low energy

If a diamond has nitrogen atoms dispersed in its structure, they can provide sites for creation of such a higher state (Figure 7, center), and its energy range will be broad. Some electrons from this site will be able to jump to the conduction band using the energy provided by mostly violet and blue light. Therefore, energies equivalent to violet and some blue will be eliminated from the white light going through this gem. The resulting color will be a strong, intense yellow. Diamond specialists call such diamonds "canary" diamonds because of the similarity between their yellow and that of the plumage of the famous singing bird. If the diamond contains some boron, then a different broad energy band will be created (Figure 7, right). This band will be centered at an energy slightly lower than that of red (infrared) and will extend into the visible range. Electrons from this site will be "fueled" by the red light (with minor amounts of orange, yellow, and green light), which will be subtracted from the white light, resulting in a blue hue.

Just as a particular impurity can affect color, so can defects in the structure – mistakes in the arrangement, or missing atoms. These act as pseudoatoms and are called "color centers" or simply "centers." Many of these are actually combinations of a true structural defect and an impurity. A few well-characterized color centers have been recognized in real diamond structures. Perhaps the simplest one is the carbon vacancy (Figure 8), which is just a missing carbon atom. The neutral vacancy is called the GR (general radiation) center.

Many color centers incorporate nitrogen, which is the most common impurity in diamond. It can be found as an isolated impurity but also in a number of combinations, in groupings of two, three, or four atoms. These clusters are named the A aggregate, the N3 center, and the B aggregate, respectively. The N3 center is a color center. The other two do not absorb visible light by themselves, but participate in more complex color centers. Nitrogen is also found in extended planar defects called platelets, which combine large numbers of carbon and nitrogen atoms. The N3 center is formed by a triangle of three nitrogen atoms that are substituting for three carbon atoms and surround a common vacancy. The N3 name is not derived from the center's three nitrogen atoms (chemical symbol N), but refers to the third absorption in a series occurring only in natural (hence, N) gems. Another series of centers found in nitrogen-containing diamonds comprises the H centers, associated with heat-treated (hence, H) stones. Of greatest relevance to color are the H3 and H4 centers, which are formed when a vacancy gets trapped at an A or B aggregate, respectively. The N-V center is formed when an isolated nitrogen (N) atom is trapped at a vacancy (V).

A final important point is that color can be due to absorption of light by more than one mechanism; in particular, it is often the case that two or more color centers will be present simultaneously in a given diamond. The attribution and identification of the sources of color are potentially very complex.

Figure 7 (opposite). A pure, perfect diamond is colorless because visible light does not have sufficient energy to excite any of its valence-band electrons and be absorbed. However, the presence of nitrogen or boron impurities substituting for carbon in the structure can induce spectacular coloration. An isolated nitrogen atom will provoke absorption of violet, blue, and green, resulting in a yellow hue. An isolated boron atom will induce absorption of green, yellow, orange, and red, producing a blue tint. (Adapted from Gems & Gemology, *Gemological Institute of America.)*
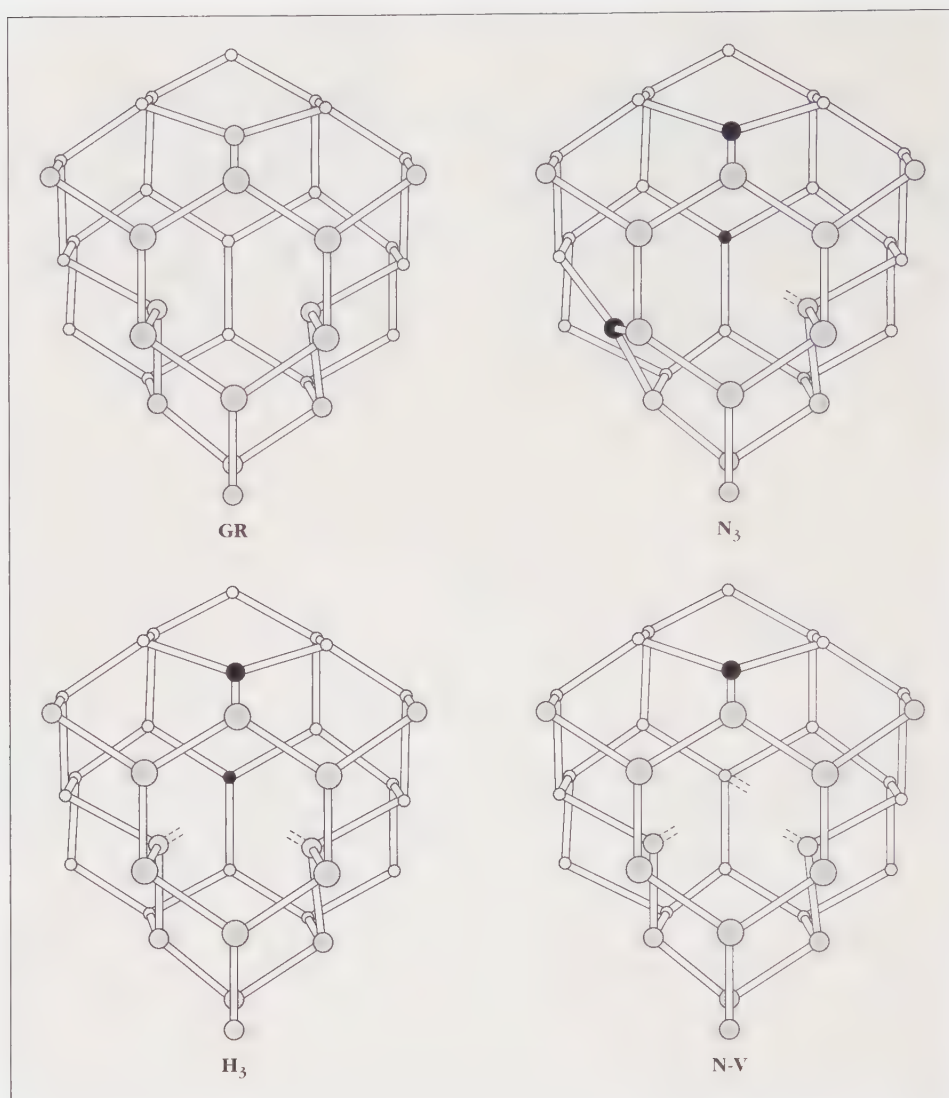
FLUORESCENCE AND PHOSPHORESCENCE

Although light absorption is the most common cause of color in diamond, it is not the only one. Another rare possibility is that fluorescence may contribute to the color. "Chartreuse" diamonds, also called (incorrectly) "green transmitters," are excellent examples; they should rather be called "green emitters." These otherwise yellow diamonds emit such a strong green light that in rare cases it dominates the color of the diamond. A historical example is an intense greenish yellow diamond of 2.15 carats: the diamond of Pedro II, emperor of Brazil. As its fluorescence is due to the H3 system absorbing in the blue, the green component of the color varies in intensity depending on the composition of the exciting light; thus, in blue-rich daylight the stone is greener than in blue-poor incandescent light (Figure 9).
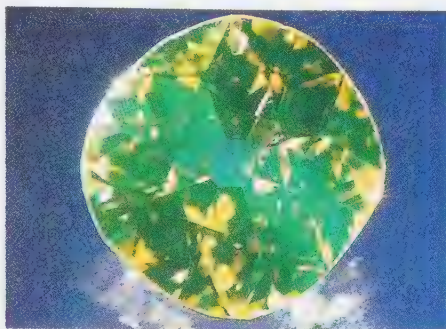
Figure 9. This 2.15-carat cushion-cut Brazilian diamond manifests its color change from yellowish brown in incandescent light to intense greenish yellow in fluorescent light. It was given by Pedro II (1825–91) to his niece. Pedro II ascended the throne of Brazil in 1831 and ruled until 1889. He was a scientist in his own right and was greatly interested in diamonds, mineral specimens, and geology. (Thomas Moses/courtesy of Benjamin Zucker.)

WHEN DIAMONDS "GLOW IN THE DARK"

Fluorescence and phosphorescence are two aspects of a more general phenomenon called *luminescence*, which is the emission of visible light by materials subjected to some kind of excitation. For gems, that excitation typically is exposure to ultraviolet radiation (the invisible light just "beyond" violet)[1] or even visible light. For example, approximately one-third of all gem diamonds will luminesce blue when placed under an ultraviolet lamp in a darkened room.

Luminescence is called *fluorescence* when the emission of light as perceived by the naked eye stops at the same time the excitation is taken away. For example, the blue fluorescence of the diamonds mentioned earlier is no longer visible as soon as the ultraviolet lamp is switched off. In some rare cases, however, the emission can still be visible, although progressively decreasing in intensity, after the ultraviolet light is turned off; that is the practical definition of phosphorescence for a gem.[2] *Phosphorescence* is the emission of light still visible with the naked eye after the excitation has been removed. When viewed in a darkened room, the fluorescence or phosphorescence caused by invisible ultraviolet light can be described as "glowing in the dark."

In a sense, fluorescence is the reverse of the process of absorption. During absorption, electrons take up energy from visible light to reach a higher-energy, "excited" state (Figure 10a). During fluorescence, electrons come back from those higher-energy states, releasing (emitting) that energy as visible light (Figure 10b).

So absorption (of the "exciting" radiation) is needed to see fluorescence. In general, not all the energy absorbed is returned as fluorescence (Figure 10c). Some is lost as heat; that is, a stone will gradually get warm under ultraviolet or visible light. For example, if a stone absorbs ultraviolet radiation, it may fluoresce light in the visible range (which corresponds to a small loss in energy). Alternatively, if the diamond is "excited" by visible light, it may absorb some high-energy violet and blue, but fluoresce only in the green, which represents a slightly lower energy. That is the case for the chartreuse diamonds or green transmitters.

The phenomena just described occur so fast that they appear instantaneous. When the excitation ceases, the emission ceases (fluorescence). For the emission to last several seconds after the excitation is turned off, there must be a storage mechanism for the higher energy of the electrons that is released rather slowly, producing continuing emission. That occurs when an appropriate third state exists for the electrons, intermediate in energy between the high-energy excited state and the low-energy ground state (Figure 10c). If that third state has adequate characteristics, it can act as a trap (see Figure 10, bottom), "holding" electrons coming down in energy from the excited state. Just a small input of energy, such as a small amount of heat, is enough to ease electrons over the trap, releasing them much more slowly to the ground state than in fluorescence. If that release is slow enough, it will be perceived as phosphorescence by the human eye. Other, more complicated schemes are possible to explain phosphorescence in diamonds. We have documented "chameleon" diamonds (a variety of green diamond) distinctly emitting for more than a quarter of an hour after a 1-minute exposure to a standard long-wave ultraviolet lamp.

It should be noted that as far as we know, phosphorescence does not participate in the coloration of diamonds. However, fluorescence might influence the perceived color of a colored diamond.[3]

Figure 10. Schematic representations of the processes of fluorescence and phosphorescence: (a) First, an electron is excited from its low-energy ground state to a higher energy state by an absorption of ultraviolet or visible radiation. (b) This electron can descend to the ground state by releasing the absorbed energy as visible light; this process is fluorescence. (c) In an alternative case, this electron can descend to an intermediate-energy state by releasing a small quantity of heat (infrared radiation). If the configuration of the intermediate state is appropriate to temporarily trap the electron, it can descend back to the ground state, releasing the energy of the transition as visible light. The latter process, illustrated below, requires more time than the one in (c), and the emission of light continues after the excitation shown in (a) has ceased; this is phosphorescence.
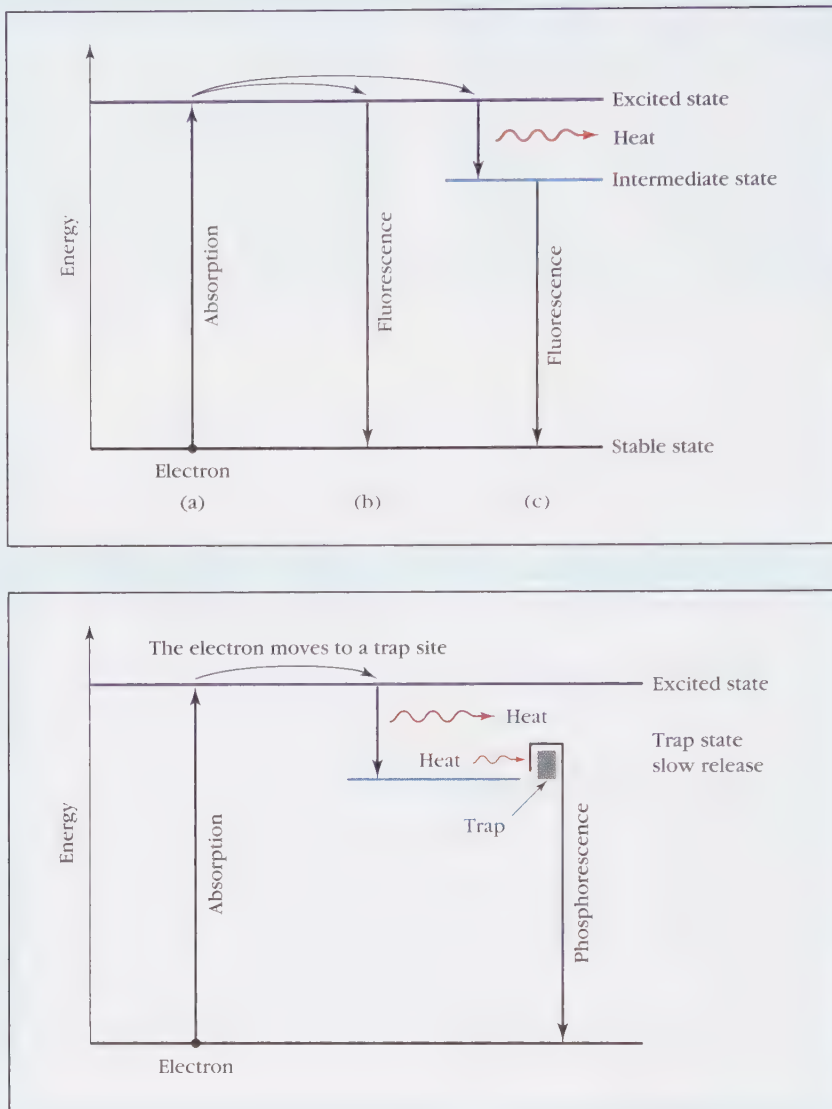
WHEN HUMANS TRY TO IMITATE NATURE

Because natural colored diamonds are so rare and valuable, many people have tried to reproduce them. The saga of laboratory-treated colored diamonds began a few years after radioactivity was discovered in 1896. The French scientist and Nobel Prize winner Antoine-Henri Becquerel (1852–1908), the discoverer of radioactivity, irradiated some diamonds to see if their color would change. Those now-green stones are kept at the Musée d'Histoire Naturelle in

Paris. Sir William Crookes (1832–1919), the British scientist who discovered the element thallium and invented a vacuum tube that bears his name, exposed diamonds to radiation to see what would happen. He noted that their color could turn to green. Nevertheless, it was not until after World War II and the development of atomic piles that commercial treatment of diamonds began. First popular with diamond treaters was the cyclotron, a large piece of equipment that accelerates electrons. Today, neutrons, electrons, and γ-rays are used commercially to modify the colors of diamonds and other gems. All those methods involve fairly large machines, and diamond treatment is conducted almost exclusively by companies or laboratories specializing in irradiation techniques.

We now know that irradiation can turn near-colorless diamonds green or blue, depending on the characteristics of the diamond being irradiated and on the radiation being used. Irradiation of some diamonds with electrons produces light-blue stones of a hue similar to a pale aquamarine, a color that is extremely rare for diamond in nature. Yellow, orange, and pink colors can be obtained by heating certain categories of diamonds after irradiation. The final color will depend on the properties of the starting material, the irradiation process, and the conditions of the heat treatment.

Some diamond colors can be reproduced; that is, the source of the color in the treated stone is the same as in its natural counterpart. Some other colors, however, can only be imitated by laboratory treatment. For example, most natural pink diamonds owe their striking color to a defect that cannot be reproduced by treatment. So treated pink diamonds can only imitate those natural stones.

There are also simpler methods to modify the colors of diamonds. In eighteenth-century jewelry, some diamonds were backed with colored foil. The underside of the diamond, the pavilion, was covered with a thin colored metallic sheet, something resembling pink aluminum foil. That trick could turn a faint yellow or brown diamond into a very desirable pink diamond. In addition, the diamond would seem more brilliant because of the metallic reflections. From the same bag of tricks, one can simply color a diamond with ink, pencil, or any other colored matter that will stick to the gem. Such a ruse became a big story in 1983: Before a presale viewing to be held at one of the major auction houses, a light-yellow, emerald-cut diamond of 10.88 carats was painted with pink fingernail polish and then "switched" for a far more valuable 9.58-carat natural color pink diamond, also an emerald cut. Luckily, the substitution was discovered in time by an expert gemologist who was intrigued by the strange character of the color.

Both the public and collectors continue to be absolutely fascinated with natural colored diamonds, although not with those diamonds modified in the laboratory.

COLOR IN DIAMONDS

The following sections will review the causes of color in natural and treated diamonds, beginning with the most common colors, extending to the rare ones, and finishing with black, gray, and white. The causes of color in diamond are summarized in Table 1.

Brown: The Most Common Color in Diamonds

Looking at the daily output of diamond mines worldwide, if color is seen, it is most often brown. Brown diamonds were among the earliest diamonds used in jewelry, as brown crystals were set in Roman rings between the first and third centuries C.E. However, historically, earthy, desaturated[4] colors were never big sellers in jewelry. Calling such gems "cognac" or "coffee" did not seem to help much. Customers preferred bright tones. For that reason, brown stones were largely ostracized from the glamorous world of rare colored diamonds. Only a very small number of enlightened connoisseurs have used them to make elegant, understated men's rings. As a matter of fact, brown diamonds, even if gemmy, often were not offered for sale at the prestigious De Beers showings, but were deemed "industrial" diamonds, with the larger crystals being turned into dies for wire manufacture. That situation has changed radically because of the large output of browns by the Argyle mine in Western Australia, otherwise famous for its pinks. In the mid-1980s, Australian marketers launched a campaign to elevate brown diamonds to glamour status. They marketed them under the trade names of "champagne" for the lighter gems and "cognac" for the darker stones (Figure 11). Properly romanticized, these gems have come back into the market with a vengeance. Fueled by a design competition and the development of a color-grading system of their own, champagne diamonds are now highly visible in medium-priced jewelry. As one journalist

Figure 11. Brown diamonds did not enjoy great popularity until the Argyle mine in Australia began producing large numbers of these stones. Australian marketers launched a vigorous campaign to promote these gems as "champagne" and "cognac" diamonds, and they are now commonly seen in jewelry. The stones range from 0.48 to 0.56 carats. (Maha DeMaggio/courtesy of Gemological Institute of America.)

TABLE 1

Diamond colors, natural and treated

Color	Nuance	Type	Cause	Name of center
Violet		Ia	hydrogen-related defects	
Blue		IIb	traces of boron	
		Ia & IIa	irradiation	GR1
	grayish	Ia	hydrogen-related defects	
		Ia & IIa	irradiation	GR1
Green		Ia & IIa	irradiation + brown or yellow component	
	yellowish	Ia	fluorescence	H3
	grayish	Ia	hydrogen-related defects	
	various shades	Ia	various unknown defects	
Treated green	bluish to yellowish	Ia	irradiation	GR1
Yellow		Ia	aggregate of 3 nitrogen atoms	N3
	grayish	Ia	hydrogen-related defects	
		Ib	isolated nitrogen	
Treated yellow		Ia	N3 + vacancies trapped at nitrogen aggregates	N3 + H3 and H4
Orange	brownish	Ia	N3 + vacancies trapped at nitrogen aggregates	N3 + H3, rarely H4
	yellowish orange to pure orange	Ia	unknown, nitrogen-related	"480-nm band"
Pink, red, purple		Ia & IIa	unknown center related to deformation	
	pale pink	IIa	vacancy trapped adjacent to isolated nitrogen	N-V
Treated pink-to-purple		Ib (often with Ia)	vacancy trapped adjacent to isolated nitrogen	N-V
Brown		All types	unknown center related to deformation	
Treated brown		Ia	various nitrogen-related defects	N3, H3, H4, others
Black		All types	mostly black inclusions	
Treated black		Ia	irradiation	GR1
Gray	often yellowish	Ia	hydrogen-related defects	
	often bluish	IIb	traces of boron (?)	
White		Ia	unknown inclusions	

Figure 12. The brown color is not homogeneously distributed but concentrated in brown lamellae called "brown graining" about 0.1 millimeter thick. (Courtesy of Gemological Institute of America.)

put it, "this successful marketing campaign truly turned trash into treasure."

There are various reasons for brown color in diamonds. Most diamonds are colored by brown "graining" (Figure 12). This poorly defined term refers to parallel lamellae of brown color in an otherwise near-colorless diamond crystal. These lamellae are very thin, only a few hundredths of a millimeter thick. Their precise origin is still a mystery, but they are generally attributed to permanent deformation of the diamond structure. The cause of the brown color imparted at the atomic level is still unknown. Less commonly, brown can be

caused by other color centers. For example, defects associated with hydrogen, the presence of isolated nitrogen atoms, and the "amber" color center are all known to induce brown in specific circumstances. Brown can also be mixed with many other colors. Many "fancies," particularly yellow, orange, and pink gems, show a brown component in their color. Recently, greenish brown stones, called "olive," have become more popular in jewelry. However, no diamond is treated to become brown on purpose, although some stones may turn brown after treatment. That result is considered undesirable and represents the combination of several different centers.

Yellow: Often Related to Nitrogen

Yellow is the second most commonly found color in diamond. At the end of the nineteenth century, yellow was encountered more often than would have been expected among diamonds discovered in the Cape Province of South Africa. That abundance of yellows contrasted with the primarily colorless gems from India and Brazil, the main diamond sources prior to the discoveries in Africa. Yellowish and yellow stones became known as Cape stones. Today, yellow diamonds are recognized from everywhere, although some mines produce more yellows than others, and the meaning of "Cape stones" has shifted to designate the defect responsible for the color, rather than the geographical provenance. Yellow color is caused by absorptions that gemologists call, not surprisingly, Cape lines, but scientists call N3 and N2 lines. These lines are due to the well-known N3 color center, formed by three atoms of nitrogen.

Most yellow colorations are related to nitrogen (Figure 13). As noted earlier, the isolated nitrogen causes strong absorption of violet and blue light, resulting in yellow color. Even for a low concentration of the impurity, the coloring power of this defect is strong, and the resulting color is saturated. Stones so colored are traditionally called canaries, and type Ib by scientists (see the definitions of diamond types in Chapter 1). The diamonds classified by gemological laboratories as "intense" or "vivid" yellows are almost exclusively of this type. As nature would have it, such exceptional stones are also the rarest of all yellow diamonds.

More common are the Cape diamonds. They contain much more nitrogen than type Ib stones, typically 10–100 times more, but the color is more subdued, perhaps a softer, golden yellow for a stone of the same size. They can reach the intense color grade, but only if they are large.

Other defects also can cause yellow color in diamonds. For example, brownish yellow in some cases has been attributed to hydrogen-related defects (Figure 3). Such stones, although not uncommon, are far from being as numerous as Cape yellow diamonds. We have even studied a pair of yellow diamonds that showed no evidence of nitrogen or hydrogen impurities – stones unique in our experience.

Figure 13. Three type Ia "Cape" yellow diamonds in the rear, with a colorless (E-color) 0.35-carat round brilliant to the left center and a type Ib "canary" round brilliant to the right of center. (Stephen Hofer.)
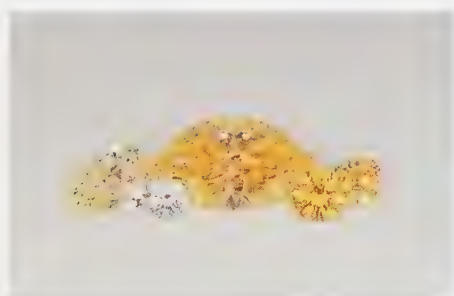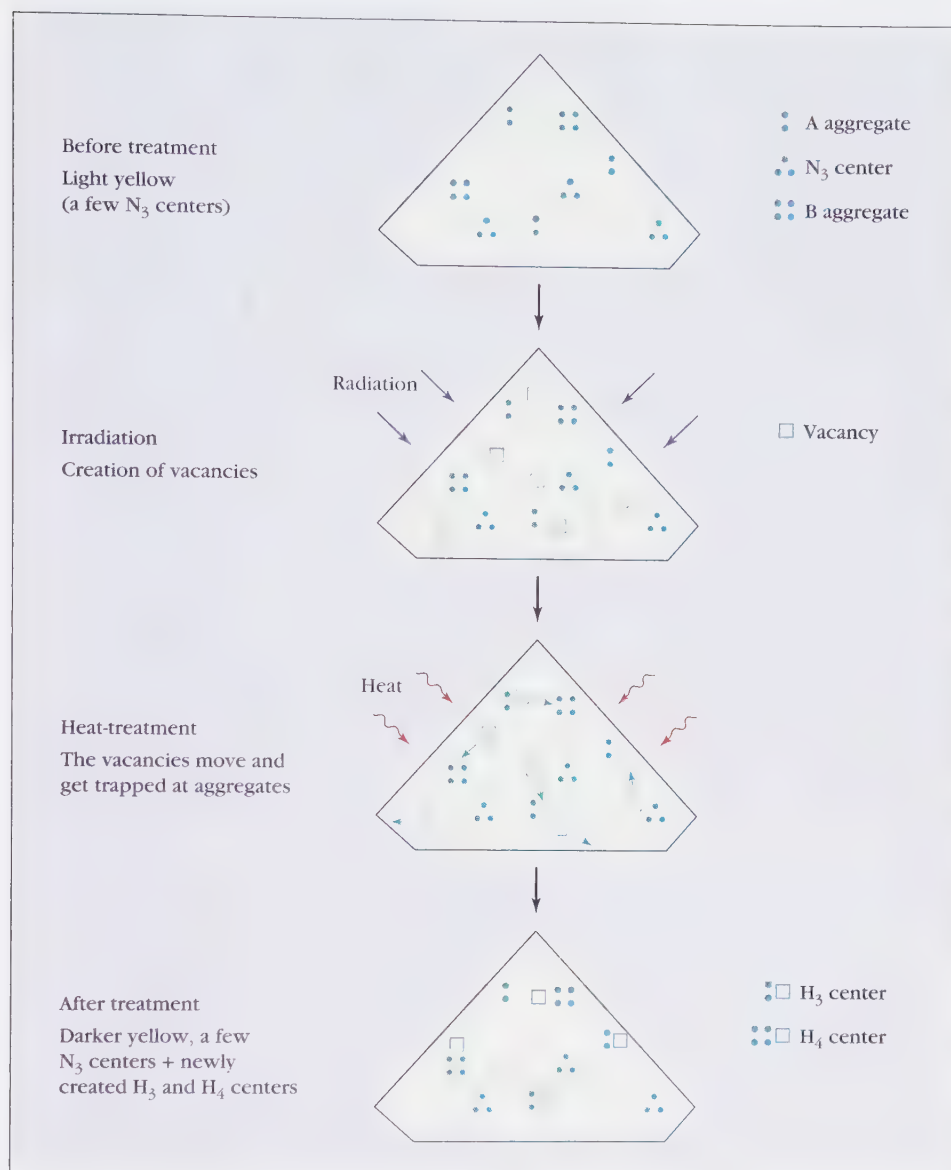
Figure 14. Schematic representation of the treatment to turn a light-yellow diamond into a darker yellow stone; the sizes of the symbols for the types of defects are not to scale.

Before treatment

Light yellow
(a few N_3 centers)

Irradiation
Creation of vacancies

Radiation

Heat

Heat-treatment

The vacancies move and
get trapped at aggregates

After treatment

Darker yellow, a few
N_3 centers + newly
created H_3 and H_4 centers

A aggregate

N_3 center

B aggregate

☐ Vacancy

☐ H_3 center

☐ H_4 center

Treated yellow diamonds never owe their color solely to Cape lines or to isolated nitrogen. The yellow color in a treated diamond is a sort of imitation of the corresponding natural color, as it is produced by a different mechanism. Treated stones usually start as Cape stones of a pale yellow color that are irradiated and then annealed (Figure 14). Irradiation creates vacancies, and annealing helps to move those vacancies around in the structure until they get trapped at A or B aggregates or disappear at the crystal's surface. The resulting defects are called H3 or H4, and they absorb blue light. Therefore, these newly created color centers considerably reinforce the originally weak yellow color, and as a result the treated gem becomes more marketable.

Figure 15. Red and purple are among the rarest hues in diamonds, and pink is certainly one of the more attractive colors. Each of these colors is due in total or in part to a color center resulting from deformation. However, the atomic details of the center, and whether or not it incorporates an impurity, remain mysteries. These stones range between 0.50 and 0.95 carats. (Tino Hammid/courtesy of Gemological Institute of America.)

Figure 16. As with brown, pink is concentrated in lamellae in an otherwise near-colorless diamond crystal. This feature is called "pink graining" by gemologists. The image is 0.9 mm across. (John I. Koivula/courtesy of Gemological Institute of America.)
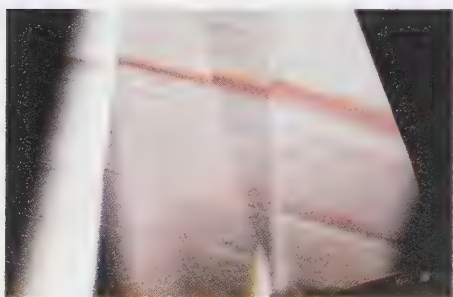
Pink, Red, and Purple: Beautiful Deformations

Some of the most fascinating colors in diamond are pink and its two close relatives, red and purple (Figure 15). Pink diamonds, such as the 185-carat Darya-i-noor, were cherished by the Mogul rulers of seventeenth-century India. More recently, pink diamonds have been discovered in small numbers around the world (e.g., Brazil, Indonesia, and Tanzania), but it is their regular production by the Argyle mine in northern Australia that has brought them to prominence in the colored-diamond market. Before the opening of the Argyle in 1985, there was no source of pink diamonds of sufficient reliability to allow the development of a structured market in them. Argyle sells its larger, most beautiful pink stones through a system of "tenders," silent auctions held annually in Switzerland.

Equally interesting are red diamonds. In terms of color science, "red" is a dark or intense pink. Prior to the auctioning of the famous 0.95-carat fancy purplish red in 1987, no more than two dozen red or reddish diamonds had ever been recorded. Most of them probably were dark red or even brownish and might not be called red by today's standards. Historically, the Triangulo Minero area in the state of Minas Gerais in Brazil and the Kapuas River in Borneo have had reputations as sources of red diamonds. Today, the Argyle mine puts out a very small number of stones deserving the extremely rare description "red." The prices of these stones at Argyle's tenders have never been disclosed.

Pure purple diamonds are even more rare. Only a few examples are known. However, the vast majority of diamonds commonly called pink are actually purplish pink.

Pink, red, and purple diamonds have been described as close relatives, and indeed they share many characteristics. First, their color is concentrated in parallel lamellae, also called pink "graining," in otherwise near-colorless crystals (Figure 16). Second, the most significant light absorption responsible for the color is the same for the three varieties: a broad absorption band centered at about 550 nm. That feature is most pronounced for red diamonds, which can best be described as dark or intense pink. The reason for that absorption band is still a topic of much debate and research, but it is generally believed to be related to deformation of the diamond structure. However, the exact details of the color center remain a mystery. In purple diamonds, in addition to that broad band, we have noticed another absorption, centered at about 390 nm and often partially hidden under the Cape lines, that seems to correlate with the purple hue. However, the source of this last feature is unknown.

Once it was thought that the pink color in South African diamonds was due to manganese inclusions, but eventually it was found that the stones were being contaminated by dust from nearby manganese mines. Recently, some attention has focused on the differences in the chemical compositions and structures of colorless and pink diamonds. However, all the research to date has

Figure 17. This magnificent piece of jewelry was assembled from diamonds produced from the Premier mine. It was presented by Sir Thomas Cullinan, the mine chairman, to his wife, Annie, soon after the Cullinan Diamond was discovered in 1905 (see "The World's Great Diamonds"). The central blue pendant diamond weighs 2.60 carats. (Harold and Erica Van Pelt/courtesy of S. H. Silver.)

been on the basis of global comparisons of the overall colorless and pink gems, rather than comparisons between the colorless matrix of a pink diamond and its pink lamellae. Thus, such data as have been reported may represent coincidences in features rather than actual correlations of compositional and color features.

The data on the origin of color in pink diamonds are similar to those for brown diamonds. Brown color is also concentrated in lamellae, and there is a continuum of diamond colors between brown and pink. I have observed one unusual diamond in which both pink and brown grainings were present, indicating that the centers responsible for the two colors probably were very close in structure. An understanding of such subtle differences might one day allow us to turn the abundant brown diamonds into attractive pink ones.

There is one notable class of pink diamonds in which the color is not due to absorption in the 550-nm broad band. They are sometimes referred to as Golconda pinks because some of the stones came from the Golconda area of India. These rare diamonds are always pale pink, even if they are large, with little or no purple component. Their color is due to the N-V center. Their nitrogen content is extremely low.

Treated pink diamonds are also colored by the N-V center. The starting materials for these are type Ib diamonds, which contain isolated nitrogen atoms. Irradiation creates vacancies, and controlled heating allows the vacancies to become trapped at the isolated nitrogen atoms. The resulting color is pink, but often with a strong purple component. This process has recently been applied to turn synthetic yellow (type Ib) diamonds into red ones.

Blue: Boron Brings on the Blues

Blue diamonds have been sources of wonder for centuries. When Jean-Baptiste Tavernier sold the 112-carat French Blue to Louis XIV in early 1669, Europe's attention was immediately drawn to the first famous blue diamond. More than three centuries later, the same stone, recut to 45 carats and now called the Hope, is probably the best-known gem in the United States and perhaps the world. Although the Hope is an Indian diamond, many natural blue diamonds have come from the Premier mine in South Africa. Sir Thomas Cullinan, once the mine owner, put together several blue and colorless stones from the mine as a necklace for his wife (Figure 17). Those unusual stones may have been what Sir Arthur Conan Doyle had in mind in "The Adventure of the Blue Carbuncle," although the identity of the carbuncle stone is a mystery that puzzles Sherlock Holmes aficionados to this day.[5] Blue diamonds have also been found in Brazil and Indonesia.

Most natural blue diamonds do not contain any nitrogen impurities that can be detected with infrared spectroscopy, and diamonds without detectable nitrogen, regardless of color, are classified as type II, but the blue ones contain

very small amounts of boron. The more boron, the deeper the blue. Referred to as type IIb diamonds, they also are semiconductors (see Chapters 1 and 13). That characteristic was highlighted in the novel *Congo* (and a 1995 movie), by Michael Crichton, in which scientists embarked on a perilous expedition to recover scarce electrically conductive diamonds. Blue diamonds rarely have the depth of color of a blue sapphire, and some show a hint of gray. As nitrogen is much more common and abundant than boron in diamonds, natural blue diamonds are quite rare.

Recent discoveries have slightly broadened the blue-diamond family to include two categories of nonconductive blue diamonds without boron, but with a fair content of nitrogen. First, in 1991 it was reported that natural irradiation could be a cause of blue color in a very small number of diamonds (Figure 18). Naturally occurring radiation may have the power to displace atoms and create a GR center, which would absorb red and orange light. If a stone were near-colorless before irradiation, then the creation of GR absorption could result in a nonconductive blue diamond. Although the color in such cases is often a pale, aquamarine-like blue, it can be surprisingly dark on occasions. Next, in 1992, some rare grayish blue diamonds from the Argyle mine in Australia were found to be nonconductive stones. They belong to a class of hydrogen-rich diamonds, and their color is caused by a complex series of absorptions believed to be due to color centers involving hydrogen.

Laboratory irradiation also can produce blue diamonds that do not contain boron. Starting with the light-brown diamonds for which there is little demand, irradiation with electrons from a linear accelerator can yield a blue stone. Most commercially treated blue diamonds are of the typical aquamarine blue color, and they are beginning to turn up in jewelry worldwide.
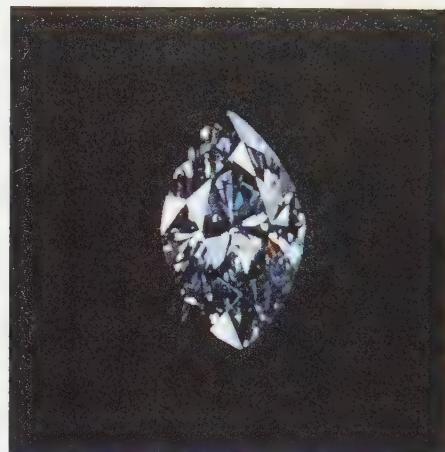

Figure 18. This marquise-cut blue diamond (0.39 carats) from the Argyle mine was colored by natural irradiation, a category of natural coloration recognized only in 1991. (Courtesy of Argyle Diamonds.)

Figure 19. The Dresden Green, 41 carats, is the only famous green diamond. Green diamonds usually have become colored by natural irradiation after ascending close to the Earth's surface. (Shane McClure/courtesy of Gemological Institute of America.)

Green: A Rare Color with Many Faces

Faceted natural green diamonds are rarities. The key word here is "faceted." There are many crystals that can be described as green diamonds, and indeed they are green, but their coloration is limited to a very thin superficial layer. Thus, when such a stone is faceted, the original "skin" of the diamond is removed, and the stone loses its green color. Natural green gems are so rare that only one, the 41-carat Dresden Green, has become famous (Figure 19). It is reputed to have come from India, but some experts now believe it to be of Brazilian origin.

Few green diamonds are mentioned in the historical records, and there are few in museums. A small cross that belonged to Marie Antoinette, wife of Louis XVI, reportedly contains some natural green diamonds. Since World War II and the development of commercial diamond treatments, green diamonds have been viewed with suspicion, because even leading gemologists have found it difficult to distinguish between natural green diamonds and their

treated counterparts. Only since the early 1990s has that difficulty been alleviated somewhat by the development of criteria having to do with the distribution of the green color, coupled with advanced testing in spectrometers that can span the spectrum from ultraviolet to infrared. As a consequence, natural green diamonds can still command fairly high prices. For example, a 1.28-carat bluish green diamond, accompanied by a report from a gemological laboratory stating that its color was natural, sold at a prominent auction house in 1992 for about $250,000 (U.S.).

Even though green diamonds are rare, they are sufficiently numerous that scientists have found that they can be subdivided into many categories. For those in the largest subgroup, the green color is due to natural irradiation. A GR center will absorb red and orange, leading to a blue color, but if the diamond has another absorption conferring it a yellow-to-brown color component, such as an N3 center or brown graining, then the consequence of natural irradiation will be a green tint. Sometimes irradiation itself seems to create another color center responsible for a brownish component. These facts explain why there is a continuum of colors between green and blue for diamonds colored by irradiation. It is rare to find such a stone with a highly saturated color; the green in radiation-colored diamonds is never a vivid emerald green, but more a slightly brownish, yellowish, or bluish green.

The origin of color in naturally irradiated green diamonds still is not fully understood, particularly in regard to the source of the radiation and the characteristics of the diamond prior to irradiation. That problem derives from the paucity of well-characterized natural green diamonds and the difficulty of gaining access to study the few that exist. It is believed that their irradiation took place after the diamonds had reached locations near the surface of the earth. Such radiation might have originated from radioactive minerals in the kimberlite in which the crystal was emplaced or from radioactive waters percolating through the kimberlite pipe.

Another spectacular variety of green diamond is called a "green transmitter" (Figure 20) or "chartreuse" diamond, presumably because of its color similarity to the French liqueur of the same name. The green in such cases is due to the overwhelming fluorescence, which hides the yellow body color of the stone. In fact, most green transmitters are only yellow or greenish yellow. Only a few exceptional stones deserve to be classified as green diamonds. The strange name "transmitter" comes from a test used by gemologists: When such a stone is placed in a small-aperture diaphragm and lit from underneath, one sees a cone of green light transmitted through the stone. In fact, that green light is emitted, not transmitted, and these stones should rather be called "green emitters." Because their color is due to emission, they are not only the greenest of all green diamonds but also the most vivid of all colored diamonds. Although one tends to associate fluorescence with exposure to ultraviolet radiation, in this case it is exposure to daylight that triggers the phenomenon. The defect

Figure 20. The green transmitter is a rare and spectacular type of green diamond. Such green fluorescence is so strong that it dominates the otherwise yellow body color of the stone. This stone weighs about 1 carat. The diamond of Pedro II in Figure 9 is also a green transmitter. (Courtesy of Gemological Institute of America.)
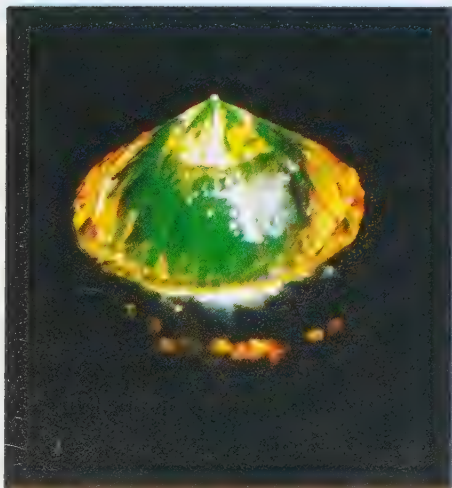
responsible for this behavior is the H3 center. It absorbs blue and violet and emits green (which is slightly lower in energy) if no other defect interferes with the fluorescence process.

Several other possible causes for the green color of diamonds have been identified by recent research. The first two have to do with hydrogen-rich diamonds. Very rarely, one of the complex absorptions found in the spectrum of grayish blue stones cited earlier can be overwhelmingly important. It is a broad absorption band centered at about 720 nm; it imparts a drab grayish green to diamond, and it is exceedingly rare. The second category of hydrogen-rich green diamonds comprises the chameleon diamonds, better known to collectors. These stones are called chameleons because, like the reptile of the same name, they can change color. They can go from their stable, generally grayish green color to a bright yellow (Figure 21) via two different processes. One way is to heat one of these stones in the flame of an alcohol lamp to temperatures of 200–300°C (390–570°F); the other is to leave such a stone in the dark for an extended period of time, at least for one night, and sometimes much longer. Within a few minutes after the gem is removed from the heat or darkness, it will change from an unstable bright yellow to its stable green. In 1995, the absorption responsible for that behavior was identified as an extremely broad band extending from about 550 nm deep into the infrared, and hence the green color. Although chameleon diamonds were rare until the early 1980s, more and more of these gems are being seen on the market. They remain curiosities for the collector, because once they are mounted, the spectacular color effect can no longer be easily demonstrated. The largest documented stone of that kind is the 22.28-carat, heart-shaped Green Chameleon.[6]

Finally, there are two series of absorptions that can each create a green color when they dominate the absorption spectrum of a diamond. These have been discovered so recently that the details have not been published. The first series is called the 725 triplet, although it entails many more absorptions than just a triplet; one of its peaks occurs at about 725 nm. The second is an amazingly complicated spectrum consisting of a series of sharp peaks that resemble the teeth in a caiman jaw, and therefore it is called the caiman-jaw spectrum. Thus far, such green diamonds are only laboratory curiosities.

Once again, laboratory irradiation can essentially replicate natural irradiation by inducing the GR center. It is therefore not surprising that green diamonds can be easily produced by exposing certain categories of starting material to the appropriate kinds of radiation. Treated green diamonds are believed to compose the majority of green diamonds found in the gem market today.

Orange: The Truly Rare Color

Red and green were long considered the two rarest colors in natural diamonds. However, red diamonds are now produced on a regular basis by the
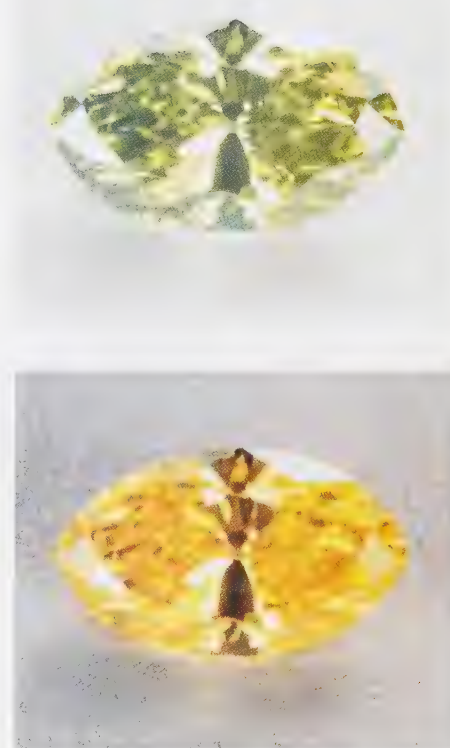

Figure 21. Chameleon diamonds can change from a grayish green color (top) to bright yellow (below) when they are heated over the flame of an alcohol lamp or are left in the dark for prolonged periods of time. The reason for this unusual behavior remains a mystery to science. This stone weighs 0.39 carats. (Robert Weldon/courtesy of Gemological Institute of America.)

Figure 22. A rare "apricot" orange diamond. (Tino Hammid/courtesy of Gemological Institute of America.)

Argyle mine in Australia, and small numbers of green diamonds can now be identified as being natural. Thus those colors may no longer be the two rarest. Instead, pure orange is probably the rarest color found in diamond (Figure 22).

A designation of pure orange requires that there be no hint of brown. Such a subtle and delicate hue is induced by a broad absorption band centered at about 480 nm, in the blue, the opponent color or complement of orange. This feature has been known for some time; the center responsible for it remains unknown. Nitrogen is thought to be involved, but it is not yet known if such gems tend to be associated with one mine or area. According to colored-diamond dealers, there are lists of buyers waiting for stones of this exceptional tint.

Much more common are brownish orange diamonds, colored by an intense H3 absorption, combined with brown graining. Some type Ib stones might also belong to this color group.

Treated orange diamonds are common. They all have a brownish modification of their hue, often called "burnt orange." They are colored by a very strong H3 center, sometimes accompanied by H4 centers as well. Old-timers sometimes mention a very peculiar "cyclotron orange," induced by the early method of cyclotron treatment. These stones are so rare that we have never studied one, and there appears to be no published photograph or spectrum available.

Violet: A New Color

"Violet" is a term that has only recently been used to describe diamonds (Figure 23). It is used only for extremely rare stones, all of them hydrogen-rich diamonds from the Argyle mine in Australia. Their absorption spectrum resembles that of the grayish blue gems from the same mine, except that they show additional absorption between 550 and 600 nm. Here again, the defect is most likely hydrogen-related, but the details are not known. No treated violet diamonds are known to exist. It remains to be seen how many violet stones will surface in the next few years.

Figure 23. Hydrogen is believed to be the cause of color in these gray and grayish violet and blue diamonds. The colorless (E-color) reference stone on the left weighs 0.35 carats. (Stephen Hofer.)

Diamonds in Black and White

Diamonds also come in black, gray, and white. Black diamonds did not go unnoticed in earlier times, as illustrated by the 67.50-carat Black Orlov that once belonged to the Russian princess Nadia Vygin-Orlov. In the 1990s, black diamonds and black gems in general have begun to come back into fashion (Figure 24). Black diamonds are colored by numerous tiny, black, plate-like inclusions, believed to be mostly graphite. In some stones the inclusions are so pervasive that the graphite makes them electrical conductors. Because of all their inclusions, black diamonds are very difficult to polish, and they rarely attain an appearance that truly qualifies them as gems.

Black diamonds are sufficiently popular to have justified their production by irradiation treatment: Poor-quality, low-clarity faceted diamonds are irradiated very intensely, generally with neutrons. The blue-to-green color created becomes so dark that the diamond appears black. Thus treated black diamonds are only imitations of their natural counterparts.

When one refers to white diamonds, it is usually to describe, although incorrectly, near-colorless gems. Nevertheless, true white diamonds do exist (Figure 25). Fancy white diamonds are also referred to as "opalescent" diamonds. They are colored by their scattering of light – the process that makes milk white. In this particular case, all of the wavelengths that together make up white light are sent in all directions by tiny inclusions within the diamond. In each direction of observation, they recombine to give white light. The exact nature of the myriad submicroscopic inclusions responsible for this phenomenon is unknown. However, we have noticed that virtually all white diamonds contain nitrogen exclusively as B aggregates and platelets. These defects represent forms of advanced nitrogen aggregation or diffusion in the crystal. Therefore, one can speculate that a clue to the mysterious origin of color in white diamonds is that they have experienced as thorough a "maturation process" as has been documented in diamond.

Gray is a mixture of black and white. However, gray diamonds are not colored by a mixture of the coloring processes operating in black diamonds and white diamonds. Most gray diamonds are actually hydrogen-rich. Their color is produced by a variety of absorption features, the same as found in the spectra of grayish blue Argyle stones. Hence the color probably is due to hydrogen-related defects. For these diamonds, the absorptions are about equally intense for all wavelengths, and the result is a gray color.

For unknown reasons, some type IIb diamonds, all of which are supposed to contain boron, are gray in color. Until the absorption data associated with such gray diamonds were published there had been no scientific documentation that boron could cause both gray and blue type IIb stones. The difference between type IIb diamonds of blue and gray color remains unexplained. It does not seem logical that the same center could induce either gray or blue. Certainly more research is needed to understand this curious phenomenon.

Figure 24. Black diamonds owe their color to a myriad of inclusions, generally identified as graphite. After being somewhat neglected, they came back into fashion in the mid-1990s, as in this jewelry of Jean-Pierre Kurz (the largest stone is 20 mm across). (Shane McClure/courtesy of Gemological Institute of America.)

Figure 25. The term "white diamonds" is generally used to refer (incorrectly) to near-colorless diamonds. However, truly white, milky, opalescent gemstones do exist, such as this round brilliant measuring 4.25 mm. The nature of the inclusions responsible for their color is unknown. (Emmanuel Fritsch/courtesy of Gemological Institute of America.)
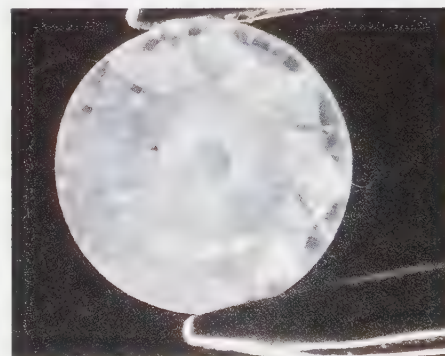
CONCLUSION

Colored diamonds are more popular now than ever before. Over the past 10 years they have increasingly been appearing in jewelry stores, most notably in the United States and Southeast Asia. Such demand has led to the faceting of diamonds that 20 years ago would have been considered industrial grade, a development that is particularly true for some brown and "olive" diamonds.

The new interest in colored diamonds has prompted a great deal of new research, and new absorptions have been discovered. Yet one of the more fascinating aspects of colored diamonds is that the atomic-scale causes of many colors remain mysteries. Among the unexplained tints are some of the most attractive: red, pink, and pure orange. Such mystery, of course, only increases their appeal.

Even as they are receiving more notice today, natural colored diamonds remain rare, especially for colors other than gray, brown, and yellow. They play to the craving for the unusual and unknown in the public at large, as well as the desire for the authentic and the natural. Fancy colored diamonds have a bright future, as they have the timeless potential to fascinate both the artist and the craftsman and rouse the curiosity of the scientist.

Figure 26. An assortment of colored diamonds in jewelry. The intense yellow oval stone weighs 29.16 carats. (Harold and Erica Van Pelt/ courtesy of Harry Winston, Inc.)

NOTES

[1] The term "black light" is used for the lowest-energy form of ultraviolet light, produced by inexpensive electric lamps. Further discussion can be found in Chapter 12.

[2] This definition does not accurately correspond to the general definition of phosphorescence in physics, which accounts for behavior at rates much faster than can be perceived by the human eye.

[3] Further details on the mechanisms of luminescence in minerals and gems (including diamonds) can be found in the book by Robbins (1994).

[4] The term *saturated* is used for intense or vivid colors, and *desaturated* for colors that are grayish or brownish.

[5] A carbuncle is a red stone, normally a garnet, ruby, or spinel; so a "blue carbuncle" is a misnomer. Many Holmes enthusiasts who also know gems consider the stone a sapphire, but Holmes referred to it as "crystallized charcoal," and therein lies the problem.

[6] See Fritsch et al. (1995).

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Robbins, Manuel (1994). *Fluorescence: Gems and Minerals under Ultraviolet Light*. Geoscience Press, Phoenix, Ariz. Chapter 15 provides a detailed review of colored-diamond luminescence.

Many articles about colored diamonds have been published in the gemological and trade literature since about 1985. These can be found in the diamond-trade magazines such as *New York Diamonds* or *Diamant*, in more general jewelry-trade publications such as *Jeweler's Circular Keystone* or *Jewellery News Asia*, and in the more scientific publications, such as *Gems & Gemology* or *Journal of Gemmology*. Of course, scientific articles dealing with subjects related more or less closely to color in diamonds are plentiful and can be found in a wide variety of professional physics journals, too numerous to be cited here.

3

The Origin of Diamonds: Earth Processes

MELISSA B. KIRKLEY

ANYONE VISITING A JEWELRY STORE to buy a diamond ring or perhaps just to browse may not realize that the gem diamonds we admire come from an ancient and distant source, that the crystals glistening in their stunning settings once were locked away in rocks deep within the Earth, that they and their encasing rocks were ripped from that site, carried up from the depths, and erupted from volcanoes at the Earth's surface. Later, some of them may have tumbled downstream for many kilometers after they were weathered out of their volcanic host rocks. The diamond's journey from the depths of the Earth to its surface was slow, although the final few kilometers were traveled at catastrophic speed; the ages of diamonds themselves span hundreds of millions of anniversaries. As we examine this journey, beginning at the sites where diamonds are mined at the surface, and going back to their source in the Earth, where they were formed, we will also learn much about the Earth and its processes. We will see that diamonds offer an incomparable and unique, although indirect, window deep into the Earth.

DIAMOND MINES

Diamonds are won from the Earth by a variety of methods that operate on scales ranging from the work of a few diggers with primitive hand tools to huge open-pit and underground mines from which millions of tons of ore are extracted each year. Whatever the scale, two types of deposits are mined: (1) alluvial deposits, which yield diamonds that have been transported by water and deposited in streambeds and on beaches, and (2) hard-rock deposits – that is, the diamond-bearing volcanic rocks known as kimberlite and lamproite

(Figure 1). Alluvial deposits are not the foremost sources of diamonds and will not be discussed further here.

Most diamonds are mined from kimberlite, a rare type of volcanic rock. Because some kimberlites yield diamonds, all kimberlite volcanoes have been more closely studied than would be warranted by their small size and their restricted distribution worldwide. The largest known kimberlite body, Mwadui, in Tanzania, has a surface area of 146 hectares (361 acres). The more common, non-kimberlite volcanoes like Mount St. Helens or Kilauea are more than 150 times that size. But because they derive from deep within the Earth, deeper than any other known volcanic rock, kimberlites have been diligently sought and intensively studied. In addition to carrying diamonds to the surface from the depths of the Earth, kimberlites are our only sources for samples of some types of rocks that are formed at those depths. A great deal has been learned about the interior of the Earth from studying these samples, as will be discussed in a later section.

Lamproite is another volcanic rock that has only recently been found to carry diamonds. In the late 1970s, diamonds were discovered in streambeds in

Figure 2. Cross section of the Earth with detail of crustal structure. The Earth is divided into a central inner and outer core, mantle, and crust (below). The thinnest crust lies under the ocean basins, and thick crust forms the continents (bottom). The lithosphere (rock sphere) below the crust is shown darker than the more mobile asthenosphere (weak sphere).

EARTH STRUCTURE

Some knowledge of the Earth's structure is needed to appreciate the formation and significance of diamonds. The Earth is stratified into three concentric layers – the core, the mantle, and the crust – that evolved into their present configuration within a few hundred million years of its coalescence 4.5 billion years ago (Figure 2, below). The Earth's radius is roughly 6,280 kilometers (km). The radius of the core is 3,370 km. Composed of an iron-nickel alloy with unknown minor amounts of other elements, the core accounts for a large fraction of the mass of the Earth; it does not appear to interact much with the overlying mantle. The mantle is the vast middle 2,900 km of the Earth's radius, sandwiched between the core and thin crust, and is composed largely of magnesium and iron silicate minerals. The mantle may be divided into two layers that behave distinctly, each circulating (convect-

ing) extremely slowly via a creeping, plastic, convective flow. Mantle flow contributes to the incremental movements of the plates that float on the top of the mantle – the processes that are known as plate tectonics. The moving plates form the crust, a thin surface layer composed of rocks that are much richer than the mantle in certain elements (e.g., sodium, potassium, aluminum, silicon, zirconium, uranium) and are relatively less dense than the rocks of the mantle. The oldest, thickest (average 35 km thick), and least dense plates of the crust host the continents, and the younger, denser crust (averaging 6 km thick) holds the ocean basins (Figure 2, bottom). The crust is an accumulation of material that was "distilled" from the mantle by melting and solidified on reaching the surface. The continental plates are the oldest portions, whereas the crustal plates under the oceans are younger and are continuously augmented by partial melting of the mantle. This melting occurs in the top tens of kilometers of the mantle because of the lower pressures near the Earth's surface; the melted rock flows up at the joints where two plates meet, forming the mid-ocean ridges. The melt (magma) extracted from the mantle to form the ocean crust is perhaps 10 percent of the volume of the mantle that experiences melting – hence the term "partial melting." The plates that constitute the crust under the oceans are slowly returned to the mantle through the process of subduction: Along the joint where two plates collide, one will sink under the other, and gradually it will plunge into the top layer of the mantle.

the Kimberley region of western Australia and were traced back to the weathered remains of a large lamproite volcano. That lamproite pipe was developed into the Argyle mine, which at its peak produced an astounding 40 percent, by volume, of the world's annual diamond production – 40 million carats per year. In terms of value, however, Argyle's share of world diamond production was only about 5 percent, because the diamonds were of relatively poor quality and low value, averaging only $5–$10 (U.S.) per carat. Because kimberlite pipes are more common and productive sources of gem diamonds, most of our attention will be given to kimberlites in this chapter.

KIMBERLITE PIPES

Kimberlite volcanoes are known as pipes because they typically have a carrot or inverted-cone shape with steeply sloping (about 80°) walls. This shape is surprisingly consistent, regardless of the type of rock that the kimberlite broke through on its way to the surface, whether soft, like shale, or hard, like granite.[1] Kimberlites contain a lot of gas, predominantly carbon dioxide, and under the pressure that is exerted at great depths, the gas would have remained dissolved in the kimberlite magma, just like the carbon dioxide dissolved in champagne that gives it its effervescence upon being uncorked. From its starting depth, a kimberlite ascends at a rate of approximately 10–30 km per hour,[2] which is still sufficient to penetrate the continental crust in only a few hours. The hypothesized model is of a toothpaste-like viscous liquid traveling upward by exploiting tensional cracks in rock as the infiltrating magma continues to dilate and fracture the crust: When the overburden pressure becomes lower than the pressure of the magma flow, the gases dissolved in the kimberlite begin to dissociate from the matrix and expand, thus increasing the fluidity and volume. The gas and magma fluid gush explosively through cracks in the rocks above, much like uncorking a hot bottle of champagne. The released gases drive the magma and entrained rocks and diamonds up to the surface at ultrahigh velocities of eruption. As the kimberlite breaks through to the surface, the pipe's characteristic shape, known as a diatreme, is reamed out by a furiously swirling fluid mix of kimberlite magma rock, mineral fragments, and expanding gases. It is believed that in some cases eruptions occurred several times within a given pipe, although the time frame for a series of eruptions is not well understood. The theory is that a series of brief, rapid intrusions can occur within days, or there may be major lapses between eruptions – perhaps millions of years – before more kimberlite melt works its way up from depth to erupt again (Figure 3).[3]

At the top of a kimberlite pipe there is a crater zone, although erosion will quickly strip away most of that easily weathered portion of a kimberlite vol-

WHAT IS KIMBERLITE, AND WHERE IS IT FORMED?

Kimberlite, the rock in which diamonds were found at Kimberley, South Africa, is a mixture of rock material from within the Earth whose most important constituents are (1) fragments of peridotite, eclogite, and possibly wall rock (the hosting "country" rock), (2) large crystals (megacrysts) of peridotite or eclogite affinity that have been considerably altered at low temperatures both by fluids in the kimberlite and by ground water, and (3) the matrix, (the crystallized kimberlite magma). The kimberlite magmas are rich in magnesium and iron (are "mafic"), as well as potassium and volatile compounds, and they crystallize into olivine, serpentine, phlogopite (a potassium-magnesium mica), calcite, garnet, ilmenite, spinel, and a few other minerals. Kimberlite magma is produced at great depths, more than 150 km within the Earth, much deeper than most volcanic sources, which typically are at depths of less than 60 km. The origin of kimberlite magma is still controversial, but the theories invoke heating of peridotite coexisting with carbonate minerals and phlogopite or reactions of potassium- and volatile-rich fluids with peridotite.

Figure 3. This cross section sketch of a typical kimberlite pipe shows the carrot-shaped profile. The root zone is the point where the high velocity eruption commences, in which exsolved gases blow out the fragmented kimberlite (tuff breccia) including volcaniclastics that form the volcano's tuff ring. The crater zone partially refills with ejecta that falls or washes into the crater. Depth measurements show the levels of erosion for various kimberlite pipes in South Africa. (Adapted from Hawthorne, 1975, and Mitchell, 1995.)
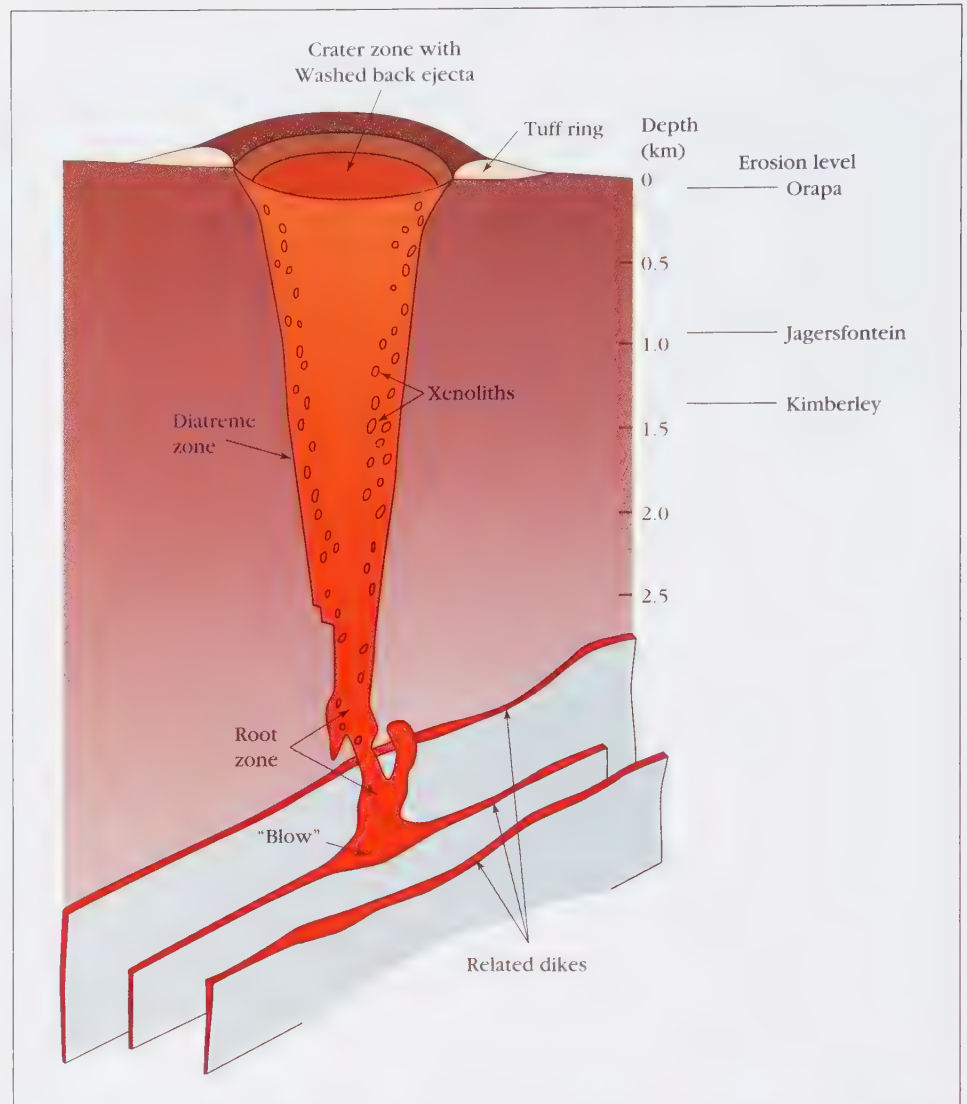
Figure 4. Beds dipping from upper right to lower left show deposition of volcaniclastic debris back into the crater at the Orapa pipe. (John Gurney.)

cano. The material that was blown out of a kimberlite volcano probably landed in a pile around the vent, looking much like a small version of the active volcanoes we know today. But most of that material was eventually washed away by rain or washed back into the central zone of the crater by rain or dispersed by other weathering processes, so that the crater zones of the kimberlites that have been recognized look much like the mud, gravel, and sand deposits laid down by lakes or rivers (Figure 4). Indeed, the finding of a few minerals from the mantle in an area may be the only hint that a kimberlite pipe is nearby. The recently discovered kimberlite field in the Northwest Territories of Canada has numerous pipes in which the eroded crater material covers the pipes to considerable depths.[4] Those kimberlites undoubtedly will provide interesting material for studies of the content and formation of kimberlite pipes.

Lamproite pipes tend to have a champagne-glass shape: a broadly flaring pipe over a narrow conduit (Figure 5). Those broad pipes typically filled up with airfall volcanoclastic material (ash, cinders, lapilli, etc.) that later was again intruded by lamproite lava. The shapes of lamproite pipes and lamproite eruption styles suggest that those melts were less highly gas-charged than were those of kimberlites and that lamproite eruptions were less violent. However, new scientific interpretations argue that lamproite magmas rise to where they encounter groundwater; the explosive boiling of that water assists the formation of a flaring lamproite crater.

The kimberlite magma that remains in the cracks in the earth's crust leading to the surface crystallizes as dikes (vertically oriented sheet-like bodies of rock). Kimberlite dikes are rarely more than 1 meter thick, and they do not form a continuous sheet from the mantle to the surface. Rather, they tend to form as thin, discontinuous lens-shaped segments that pinch and swell in an echelon pattern (Figure 6), suggesting that as the kimberlite melt works its way up from the mantle and forces its way through cracks, those cracks tend to close up again behind it. Such dikes form the roots of the kimberlite pipes, and all pipes that have been mined to sufficient depths have been observed to diminish into dikes. However, not all kimberlite dikes have pipes above them. In South Africa, kimberlite dikes without pipes are known in several localities and are mined on a small scale.[5] It is not clear whether there were pipes above those dikes that were eroded away or whether the dikes never broke through the surface to produce pipes.

DIAMOND SOURCES: THE EARTH'S MANTLE

As discussed in Chapter 1, diamonds are minerals – naturally occurring crystalline substances. Minerals are the components of rocks. In this section we

Crater formation

Volcanoclastics filling

Lava pond filling
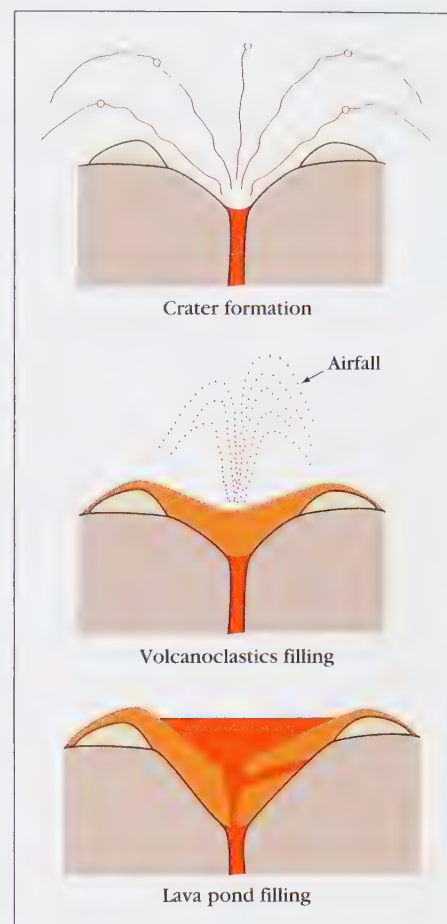
Figure 5. Lamproite pipe eruption. Top: *Initial eruption, powered by gases from lamproite magma or its boiling ground water, corrodes the country rock to form champagne-glass shape and tuff ring.* Middle: *Eruption produces volcanoclastics that partially fill the crater and form tuff ring.* Bottom: *Crater with lava pond. (Adapted from a sketch by Barbara Scott-Smith.)*

Figure 6. Kimberlite dikes form melt-swollen lenses. Such lenses are connected in complex networks in three dimensions and expand locally in width when kimberlite magma flows through a lens. (Adapted from Clement et al., 1973.)

Scale 0 20 40 60 80 100

Meters
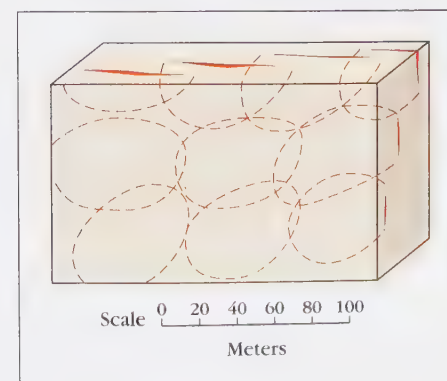
THE CONDITIONS OF DIAMOND FORMATION

When the pipes containing diamonds proved to be volcanic, it was finally accepted that diamonds had come from some depth within Earth and therefore had been produced at high pressures and temperatures. Determining the magnitude of that pressure required years of estimation and experimentation, as partially documented in the section on the history of diamond synthesis in Chapter 13. Figure 7 shows a diagram for the pressure and temperature (*P–T*) conditions at which two forms of carbon are stable, based on data from experiments in diamond synthesis. Such data allow us to estimate the geologic conditions at which diamond can form from graphite or be transformed into graphite. The important feature is the slope of the boundary between diamond and graphite: An increase in temperature will counteract the force that compresses carbon atoms together to stabilize the structure of a diamond. The curves representing *P–T* conditions within the Earth, known as *geotherms*, show that conditions below continents differ from those below oceans.

will consider when, where, and how diamonds crystallize and as components of which rocks.

Kimberlite and lamproite pipes are the diamond sources that are accessible to us, and kimberlite mines have produced most of the world's diamonds. But the diamonds in a kimberlite or lamproite pipe are there largely by accident, crystals disaggregated from the rocks it passed through.[6] Diamonds do not crystallize in kimberlite or lamproite as a primary mineral in the way that gray quartz or pink feldspar will crystallize in a granite; they are merely passengers. The ultimate sources of diamonds are far below the surface of the Earth, at depths of 200 km or more, in the upper portions of the mantle. In the mantle, the temperature and pressure conditions, on the order of 1,000°C and 50 kilobars, respectively, are ideal for the crystallization of diamonds.

The parent rocks in which diamonds are crystallized can be identified by two methods. First, in the kimberlites and lamproites that yield diamonds, small crystals of diamond will sometimes be found still encased in fragments of their original parent rocks. Such fragments are known as *xenoliths* (literally, "foreign rocks") and are pieces of the deep basement beneath the pipe. Second, sometimes there are tiny mineral inclusions within diamonds that will reveal the crystals that grew simultaneously with and adjacent to the host diamond. Analysis of the compositions of such inclusions can lead to deductions about the coexisting minerals that constitute the rocks of the mantle in which the diamond crystals grew.
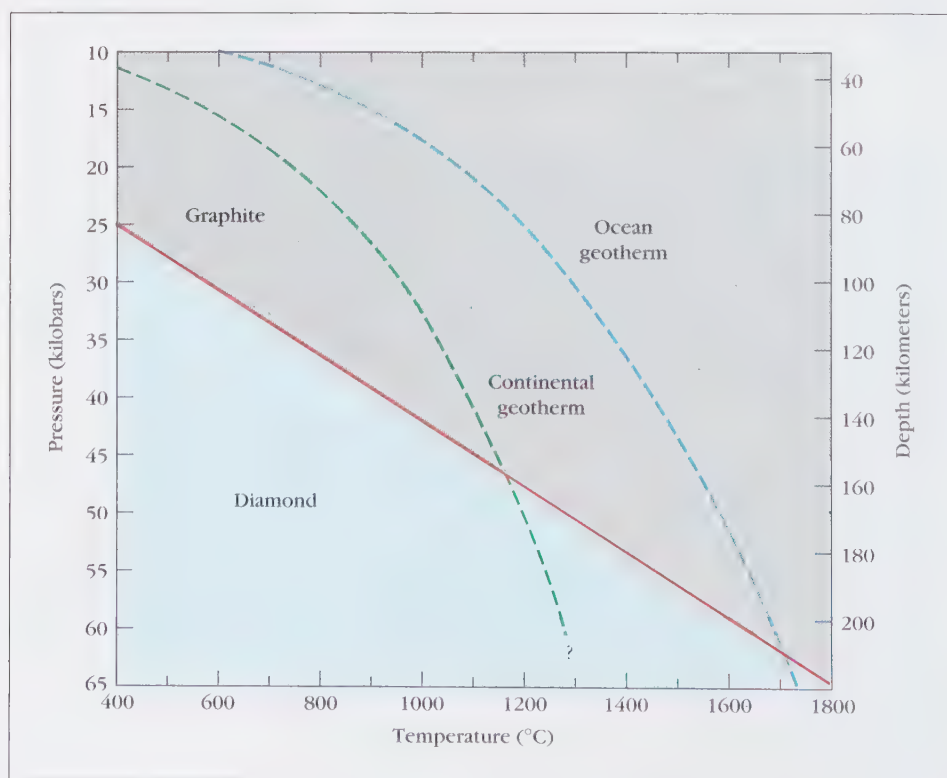
Figure 7. P–T diagram for the stability of diamond–graphite. The average geotherms beneath continents and oceans are shown as dashed curves.

DIAMOND INCLUSIONS AND MANTLE MINERALS

The mineral inclusions found in diamonds can provide pristine samples of the environments in which the diamonds crystallized. If there is only a single mineral inclusion in a diamond, it is always somewhat enigmatic, because it cannot uniquely define a rock (an assemblage of minerals we would recognize as, say, harzburgite or eclogite). So diamonds that have two or more inclusions featuring different minerals are particularly important indicators of origins. Inclusions in which two minerals are in contact with one another are even better, because there is little possibility of entrapment at different stages in the diamond's growth. Other features that are striking but enigmatic are the shapes of inclusions. Although many inclusions look like irregular blobs, some have been forced into the shape of a diamond crystal, rather than the shapes they would have had if they had grown unfettered. That mimicry of the diamond morphology is sometimes called *xenohedry* ("taking on a foreign shape"). Thus again the indomitable nature of diamond is reflected in its ability to superimpose its shape on other minerals because of its strong chemical bonds.
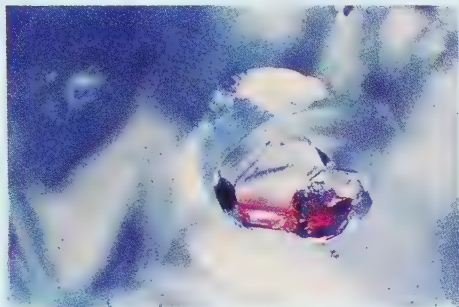
Purplish pink G10 garnet, the signature of garnet harzburgite with diamonds (garnet is about 30 μm across). (Rory O. Moore.)

Red chrome pyrope, typical of peridotites (pyrope is about 2 mm across). (Martin Prinz.)

Orange G5 garnet, typical of eclogite, that shows conspicuous octahedral forms imposed by the enclosing diamond (about 0.5 mm across). (Martin Prinz.)
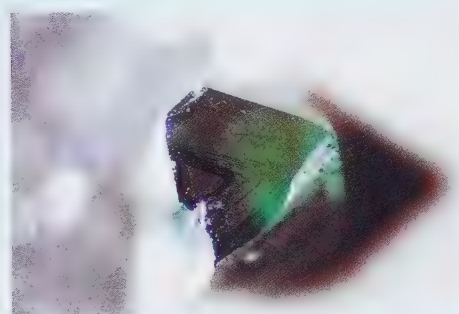
Green chromian diopside, typical of peridotites (about 0.4 mm across). (Martin Prinz.)
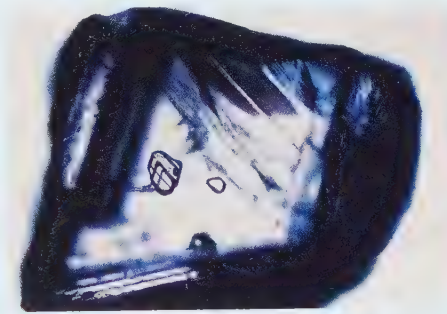
Two pale green inclusions of omphacite, a clinopyroxene between diopside and jadeite, typical of eclogite (diamond is about 3 mm across). (Rory O. Moore.)
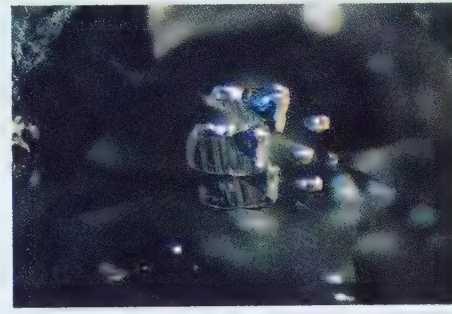
Blue kyanite, representing a kyanite eclogite, grospydite, or similar rock (kyanite about 80 μm across). (John I. Koivula/courtesy of Gemological Institute of America.)
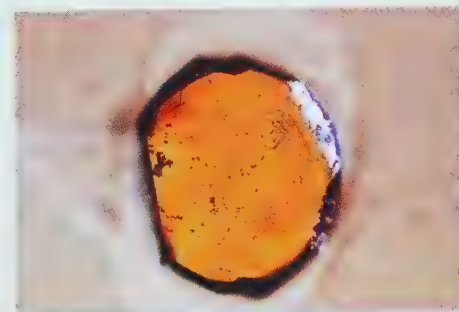
Brown olivine, an unusual color for this mineral, the main constituent of peridotites (about 0.2 mm across). (Martin Prinz.)
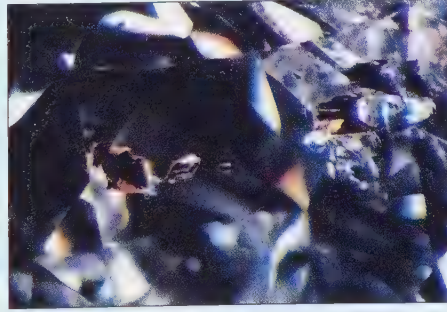
A grain of chromite, an indicator of a peridotite source; slight reddish brown color typical of picrochromite. (0.25 mm long). (John I. Koivula/courtesy of Gemological Institute of America.)
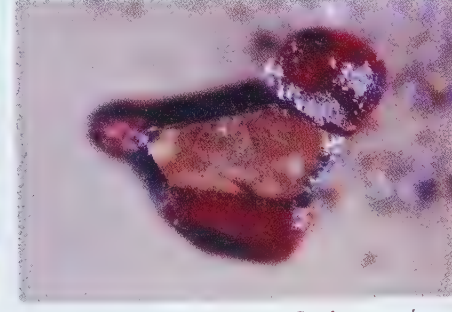
A pair of red chrome pyropes flanks an orthopyroxene, defining a garnet peridotite for this inclusion (about 0.3 mm across). (Martin Prinz.)

MINERALS OF THE MANTLE

Garnet: a family of minerals of variable compositions, typically lying among the following:

Pyrope: $Mg_3Al_2(SiO_4)_3$; chromian pyrope contains some Cr in place of Al

Almandine: $Fe_3^{2+}Al_2(SiO_4)_3$; more common in crustal rocks

Grossular: $Ca_3Al_2(SiO_4)_3$; common in crustal rocks

G5 garnet: an orange-to-red almandine-pyrope ($\sim$60 : 30 percent), with about 1–5 weight percent[7] CaO

G10 garnet: a purplish red pyrope with roughly 10 percent almandine, 3 percent grossular, and 3–15 weight percent Cr_2O_3

Clinopyroxene: a subfamily in the pyroxene family, including the following:

Diopside: $CaMgSi_2O_6$; chromian diopside contains some kosmochlor

Omphacite: $CaNaMgAlSi_4O_{12}$

Jadeite: $NaAlSi_2O_6$; found only as a compositional part of mantle clinopyroxene

Kosmochlor: $NaCrSi_2O_6$; found only as a compositional part of mantle clinopyroxene

Olivine: $(Mg, Fe^{2+})_2SiO_4$; the most abundant mineral in the upper mantle

Orthopyroxene: $(Mg, Fe^{2+})_2Si_2O_6$; a subfamily in the pyroxenes

Kyanite: Al_2SiO_5; a blue mineral found in a few eclogites and more common in the crust

Amphibole:

$KNaCa(Mg, Fe^{2+})_5Si_8O_{22}(OH)_2$: K-richterite, a species associated with some mantle xenoliths

Mica:

$K(Mg, Fe^{2+})_3Si_3AlO_{10}(OH)_2$: phlogopite, the mica most commonly found in mantle xenoliths

Oxides:

Ilmenite: $(Fe^{2+}, Mg)TiO_3$; picroilmenite is the magnesian variety

Rutile: TiO_2

Chromite: $(Fe^{2+}, Mg)Cr_2O_4$; picrochromite or magnesiochromite is the magnesian variety

Sulfides:

Pyrite: FeS_2

Pyrrhotite: $Fe_{1-x}S$ ($x = 0$–0.17)

Each of those methods for identifying the parent rocks in which diamonds crystallize has its advantages. The xenoliths tend to show a more comprehensive suite of minerals that were growing alongside the diamond. On the other hand, the mineral inclusions within a diamond crystal are uniquely protected from processes that usually alter the compositions of the same minerals outside the diamond. In that sense, one can think of a diamond as a space capsule from the inner Earth. Inclusions in diamonds are the only sources of mineral grains that have pristine compositions from the Earth's mantle. The composition of such an inclusion never exactly matches the composition of a diamondiferous xenolith from the same pipe, because the xenoliths have been exposed to mantle and crustal processes from which the inclusion has been protected. However, the chemical differences between the mineral inclusions in diamonds and the same minerals found in xenoliths from the same pipe provide useful information about chemical processes in the mantle. Most such differences can be attributed to fluid (gas and/or liquid) interactions with the xenoliths.

Studies of diamondiferous xenoliths and inclusions in diamonds indicate that diamonds can crystallize in various kinds of mantle rocks. However, two main rock types are recognized as the major sources of diamonds in the mantle:

harzburgite and *eclogite*. Those two diamond sources have different stories to tell concerning diamond formation and earth processes.

Harzburgite

Harzburgite is a rock composed of two minerals: olivine and orthopyroxene. Diamondiferous harzburgites typically contain Cr- and Mg-rich garnet (pyrope variety) as well, and they are known as garnet harzburgites. Similarly, diamonds that contain olivine, orthopyroxene, and/or Cr- and Mg-rich garnet inclusions are known as harzburgitic diamonds.
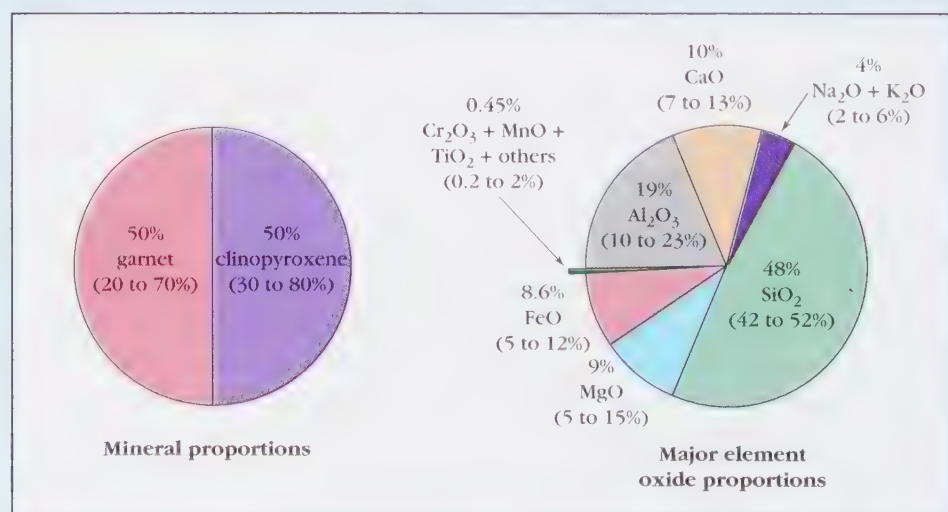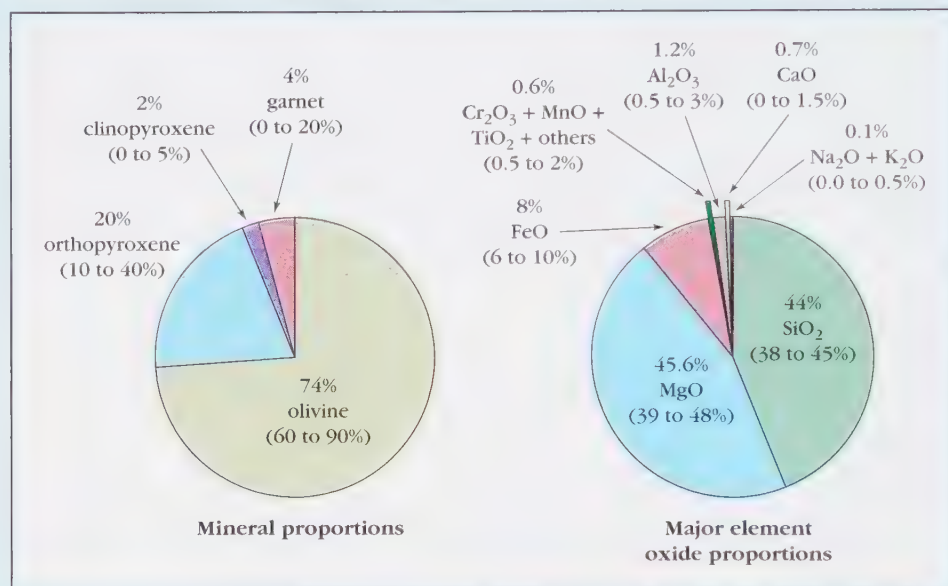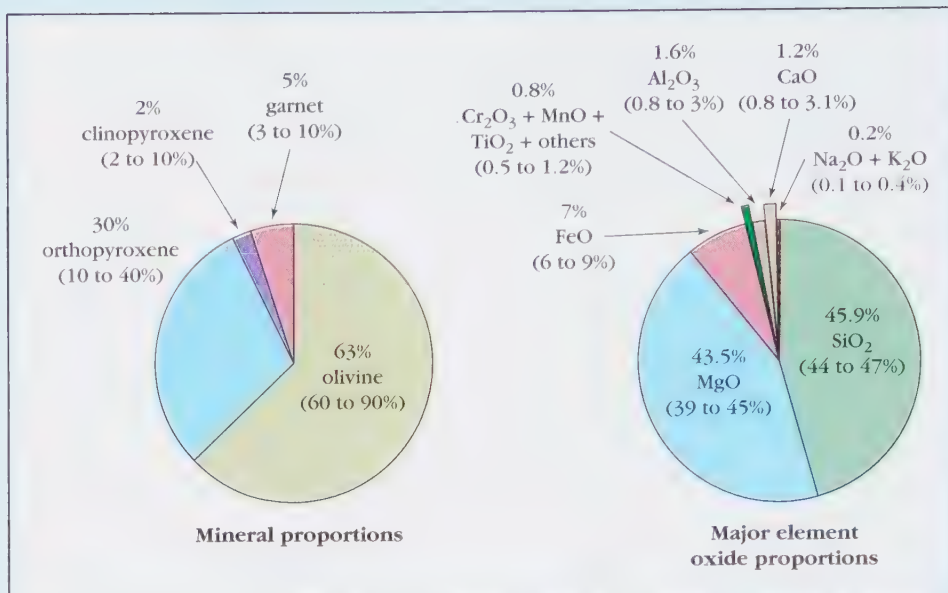
The mantle is believed to be composed predominantly of garnet lherzolite, which differs from garnet harzburgite by virtue of containing more than a trace of clinopyroxene. The abundance of clinopyroxene is an important indicator of the mantle's fertility — that is, the ability of the mantle to produce basaltic melt, the kind that rises to crystallize as rocks on the ocean floor and to fuel some volcanoes. If lherzolite is heated sufficiently for melt to form and migrate out of the rock, it is usually the clinopyroxene that melts first and is removed from the lherzolite as melt. If lherzolite melts sufficiently to remove all clinopyroxene, the residue remaining in the mantle will be harzburgite. Harzburgitic rocks, including those that yield diamonds, are interpreted as the residues remaining after a melt has been removed from a typical portion of the mantle, which was garnet lherzolite before the melting event. Diamonds are known to crystallize in garnet lherzolite, but a far more common source rock is garnet harzburgite, which suggests that there may be some interesting connections between diamond formation and the extrusion of mantle melts.

What Harzburgite Reveals

Whereas most harzburgites are infertile, having already lost any clinopyroxene they may have had, diamondiferous harzburgites contain certain "incompatible elements," which suggests that they have experienced an additional process. Incompatible elements are so called because they cannot be readily incorporated into the common rock-forming minerals of the mantle. The sizes of the atoms (actually, charged ions, in the chemistry of rock-forming minerals) of the incompatible elements tend to be too large to fit into the available sites in the mineral structures, except perhaps for clinopyroxene, the most common host mineral. As a result, when the temperature of a rock is raised to the point of melting, the incompatible elements it contains tend to migrate into the melt and be expelled with it. Because diamondiferous harzburgites are already depleted of clinopyroxene, they would also be expected to be depleted of incompatible elements. But that is not the case. Thus, it would appear that incompatible elements were reintroduced into these harzburgites at some time after melts were removed. We are therefore dealing with at least a two-stage

THE IMPORTANT MANTLE ROCKS: LHERZOLITE, HARZBURGITE, AND ECLOGITE

Lherzolite is a variety of peridotite, a rock composed principally of olivine (gem variety, peridot, hence the name), and it is considered to constitute most of the mantle. Harzburgite is another kind of peridotite, and garnet harzburgite contains at least 3 percent garnet. Eclogite is a very different kind of rock compositionally, defined by predominant garnet and omphacitic clinopyroxene. All three are dense, ranging from 3.3 to 3.5 grams per cubic centimeter, very close to diamond's high density of 3.52.

5%
garnet
(3 to 10%)

2%
clinopyroxene
(2 to 10%)

30%
orthopyroxene
(10 to 40%)

63%
olivine
(60 to 90%)

Mineral proportions

1.6%
Al_2O_3
(0.8 to 3%)

1.2%
CaO
(0.8 to 3.1%)

0.8%
Cr_2O_3 + MnO +
TiO_2 + others
(0.5 to 1.2%)

0.2%
Na_2O + K_2O
(0.1 to 0.4%)

7%
FeO
(6 to 9%)

45.9%
SiO_2
(44 to 47%)

43.5%
MgO
(39 to 45%)

**Major element
oxide proportions**

4%
garnet
(0 to 20%)

2%
clinopyroxene
(0 to 5%)

20%
orthopyroxene
(10 to 40%)

74%
olivine
(60 to 90%)

Mineral proportions

1.2%
Al_2O_3
(0.5 to 3%)

0.7%
CaO
(0 to 1.5%)

0.6%
Cr_2O_3 + MnO +
TiO_2 + others
(0.5 to 2%)

0.1%
Na_2O + K_2O
(0.0 to 0.5%)

8%
FeO
(6 to 10%)

44%
SiO_2
(38 to 45%)

45.6%
MgO
(39 to 48%)

**Major element
oxide proportions**

50%
garnet
(20 to 70%)

50%
clinopyroxene
(30 to 80%)

Mineral proportions

10%
CaO
(7 to 13%)

4%
Na_2O + K_2O
(2 to 6%)

0.45%
Cr_2O_3 + MnO +
TiO_2 + others
(0.2 to 2%)

19%
Al_2O_3
(10 to 23%)

48%
SiO_2
(42 to 52%)

8.6%
FeO
(5 to 12%)

9%
MgO
(5 to 15%)

**Major element
oxide proportions**

Garnet lherzolite (top)
Garnet harzburgite (middle)
Eclogite (bottom)

process when examining the compositions of diamondiferous harzburgites: melt removal, followed by incompatible-element enrichment without addition of clinopyroxene.

Incompatible-element enrichment in the mantle probably is accomplished by fluids: mixtures of carbon dioxide (CO_2), water (H_2O), and melts that migrate through the rocks. The Earth's mantle was long considered to be too hot for the survival of fluids – it was assumed that they had all been expelled into the crust, hydrosphere, and atmosphere. However, samples of mantle rocks brought to the surface by kimberlite pipes attest to the presence of fluids in the mantle. In addition to the main mineral phases mentioned earlier, xenoliths in kimberlites commonly contain minerals that have water or carbon dioxide in their crystal structures. Such minerals are considered to represent the crystallized products remaining after mantle fluids have migrated through the rock. Some xenoliths consist almost entirely of hydrous minerals and other easily melted minerals such as clinopyroxene. One of those xenoliths is shown in Figure 8, composed of **m**ica, **a**mphibole, **r**utile, **i**lmenite, and **d**iopside (acronym MARID). Mica and amphibole are both hydrous minerals, and rutile, ilmenite, and diopside, in close association, will melt at relatively low temperatures. Other xenoliths contain phlogopite or amphibole adjacent to harzburgite minerals typical of a melt-depleted mantle. However, those xenoliths are consistent with a deep origin, so they attest to the action of fluid-rich melts in the mantle and the consequent enrichment in incompatible elements.

Figure 8. This MARID xenolith (consisting of Mica, Amphibole, Rutile, Ilmenite and Diopside) was found in place in kimberlite at the Monastery Mine, Lesotho (the pen is 14 cm long). (Rory O. Moore.)

Harzburgitic Diamonds Are Much Older than Kimberlite

Xenoliths in kimberlite provide evidence of mantle processes such as melt extraction and migration of fluids; however, because those processes have altered the original mantle rocks, we must turn to the inclusions found in diamonds to gain information on the pristine mineral compositions of mantle rocks. One very interesting and important bit of information we can learn from inclusions in diamonds is the age of the diamond. Rocks can be dated because they contain certain radioactive atoms that decay to form stable atoms of other elements. The ratio of the daughter atoms produced

divided by the parent atoms increases with time in a predictable manner, and that ratio can be measured with a mass spectrometer, a technique widely used in geochemistry. The parent-daughter isotope systems commonly used are rubidium-strontium (Rb-Sr), samarium-neodymium (Sm-Nd), and uranium-lead (U-Pb). Because such dating techniques generally require a few milligrams of material for analysis, it is extremely difficult to obtain accurate results from individual diamond inclusions, which rarely are more than 100 micrometers in size (less than a few micrograms). That problem has been circumvented by accumulating numerous minute inclusions from many diamonds so as to have enough material to date: Because the inclusions are considered to have crystallized simultaneously with the diamond, the age of the inclusions will give the age of the diamond. Such data indicate that harzburgitic diamonds are 3 billion years old, much older than the kimberlites in which the diamonds are found.[8] Earlier researchers had reached similar conclusions,[9] but the sound scientific basis presented in the landmark publication of these data was considered conclusive proof that diamonds had not crystallized in the kimberlite or lamproite rocks that hosted them at the surface, a matter that had puzzled geologists for a century.

Diamondiferous Harzburgite Resides at the Base of Cool, Thick Crust

Laboratory experiments have been used to try to determine the conditions under which rocks crystallize. In a laboratory, a natural rock sample or a mixture of the appropriate chemicals can be subjected to high temperatures and pressures to determine what conditions will cause the given composition to melt. In other experiments, melt compositions can be observed during cooling to investigate the $P-T$ conditions at which various minerals will crystallize. Once sufficient data are accumulated, it is usually possible to state the conditions for crystallization of a given rock knowing only the compositions of its minerals. Such experiments have provided the information necessary to estimate the $P-T$ conditions at which diamonds and their host rocks crystallized in the mantle.

The temperature of the Earth generally increases at increasing depths, which entail increasing pressures. A surprising finding from studies of diamondiferous harzburgites is that their mineral compositions indicate that they were formed at lower temperatures than were most mantle rocks at comparable pressures (Figure 7). That suggests that diamonds were formed in a deep but relatively cool part of the Earth's mantle. If it was cooler, then it must have been more rigid than the hotter, more ductile mantle adjacent to it. That might suggest the picture of a vast, stiff keel or root descending beneath the crust to depths where diamonds could crystallize. Augmenting such a model is the observation, known as Clifford's rule, that diamondiferous kimberlites are found in continental regions underlain by an Archean basement, rocks older

than 2.5 billion years.[10] Those oldest regions of the Earth's crust therefore underlie some of the thickest crustal plates, those that host the continents. It appears that in Archean times there was a unique process accompanying crustal formation: a combination of melt extraction, fluid interaction, and diamond crystallization that sometimes left a relatively cool, rigid, deep keel beneath a continental plate.

The Geothermal Regime of a Continental Plate Was Much the Same in the Archean as It Is Now

In order to have been picked up by kimberlite or lamproite, 3-billion-year-old diamonds must have been preserved at great depth within a continental keel until a much younger kimberlite or lamproite erupted through the keel. If the temperature of such a continental keel had risen appreciably, that would have destroyed the diamonds. Because these ancient diamonds clearly were preserved, that tells us that the thermal regime beneath the continents must be similar now to what it was 3 billion years ago.

Eclogite

Eclogite is another kind of mantle rock in which diamonds crystallize. Its main mineral components are garnet and clinopyroxene and thus it has a fertile composition, similar to that of modern-day basalts. In fact, if a basalt is subjected to high pressures and temperatures, its minerals will recrystallize primarily into garnet and clinopyroxene – an eclogite. Some eclogite xenoliths were exposed to such high pressures that the garnet and clinopyroxene were blended into one mineral, as evidenced by higher silica (SiO_2) content in the garnet than would be expected in a normal garnet structure.[11] Such a high silica content in garnet is possible only at high pressures, and it indicates that the eclogite containing such garnet was derived from depths in the mantle greater than 300 km.

Some eclogite xenoliths found in kimberlites contain as much as 10 percent diamond, by volume. In such quantities, diamond is not just a minor accessory mineral, but a major mineral component of the rock (Figure 9). In contrast, the diamonds in the kimberlite itself usually are at concentrations of less than 1 part per million. Clearly, a kimberlite magma does not need to pick up much diamond-rich eclogite from the mantle in order to account for all of the diamonds contained in an average kimberlite pipe.

Diamondiferous Eclogites Are Younger Than Diamondiferous Harzburgites

In contrast to the situation for harzburgitic diamonds, the age dates for eclogitic inclusions in diamonds have been found to be 3 billion years old and younger.[12] The wide range of ages determined for eclogitic diamonds implies

Figure 9. This rare sample shows a diamond octahedron projecting from a piece of eclogite, about 2 cm across, characterized by orange garnets and green omphacite, from the Ardo kimberlite, Barkly West District, South Africa. (Rory O. Moore.)
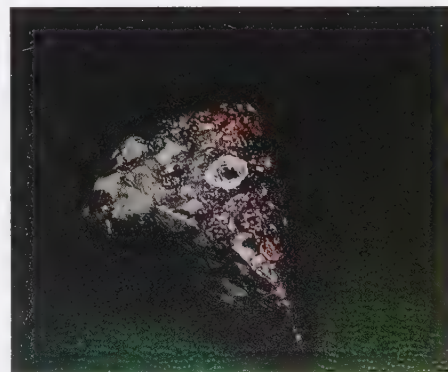
that they are the result of a continuous process rather than a unique one that occurred 3 billion years ago. To understand the process by which eclogitic diamonds originate, it should be useful to look at the possible sources of carbon in eclogitic diamonds.

Carbon Isotopes Indicate Organic Sources of Carbon Emplaced by Plate Tectonics

The relative amounts of the two most common carbon isotopes, ^{12}C (carbon atoms with six protons and six neutrons) and ^{13}C (carbon atoms with six protons and seven neutrons), in any carbonaceous substance are controlled by processes that separate the isotopes on the basis of the small differences between them. Separation of isotopes is called *fractionation*, and carbon-isotope compositions are reported as changes in ^{13}C ($\delta^{13}C$).

"Normal" mantle carbon is considered to have $\delta^{13}C$ values between -10 and -1 per mil, with the most common values being -6 to -5 per mil. That range was determined through numerous analyses of carbon isotopes in substances considered to be representative of the mantle from which they came, such as mantle-derived volcanic melts and gases. At the high temperatures and pressures at which diamonds crystallized in the mantle, not many processes are capable of fractionating carbon isotopes efficiently. Even changes of state, such as diamond crystallization from carbon dioxide or methane gas, would result in only very small isotopic changes. So it can be expected that most of the carbon in the mantle will have $\delta^{13}C$ values between -10 and -1 per mil. That range is, in fact, manifested by most harzburgitic diamonds. Researchers were surprised to discover that eclogitic diamonds show a wide range of $\delta^{13}C$ values, from -34 to $+3$ per mil (Figure 10).

Because high-temperature mantle processes are not able to fractionate isotopes, a source for the carbon in eclogitic diamonds must be sought among other low-temperature materials in the Earth that have similar $\delta^{13}C$ values. Organic matter derived from plants and animals has low $\delta^{13}C$ values of -25 to -35 per mil, similar to the values for those eclogitic diamonds at the low end

Figure 10. Histograms of the carbon-isotope data for eclogitic and harzburgitic diamonds: the narrow negative $\delta^{13}C_{PDB}$ range for harzburgitic diamonds indicates a homogeneous mantle source for the diamond's carbon, whereas the large range and some significantly negative $\delta^{13}C_{PDB}$ values indicate both mantle and crustal organic sources of carbon. (Adapted from Kirkley et al., 1991b.)
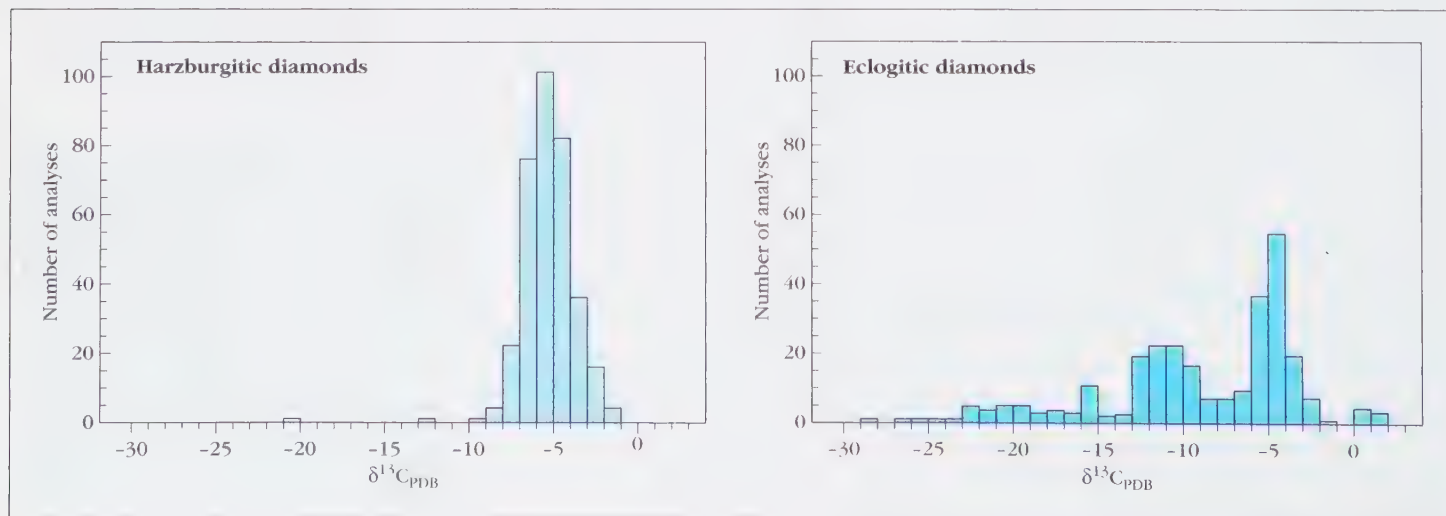
of the observed range. Moreover, oceanic carbonates such as sea shells and limestones have $\delta^{13}C$ values only a few counts on either side of zero, as do those eclogitic diamonds at the high end of the range. If it were known that eclogitic diamonds had crystallized from carbon derived from such organic and inorganic sources, the full range of isotopes observed in eclogitic diamonds would be explained.[15] Is it possible that organic matter and carbonates could have been transported into the Earth's mantle to provide carbon for diamond formation? The mechanism that might have been able to do that is known as *subduction*.

Subduction is a direct consequence of the process whereby oceanic crust spreads away from the mid-ocean ridges. The Earth has a finite surface, and so formation of new crust in one place requires destruction elsewhere. Because oceanic crust is compositionally basaltic and dense, more dense than continen-

ISOTOPE GEOCHEMISTRY AND CARBON'S SIGNATURE

Studies of the isotopes of carbon and other elements are carried out in the field of *stable-isotope geochemistry.* Through the history of the universe, stars have burned and exploded, creating the matter from which the solar system, the Earth, and we humans are made of – literally – stardust. The Earth contains its chemical elements in the proportions that it inherited from the cosmic soup at the end of planetary formation 4.5 billion years ago – at least, that is true for the majority of elements, called "stable elements," that do not have isotopes that undergo slow spontaneous decay. "Radioactive elements" are those that decay, such as ^{235}U (uranium, with a mass number of 235) or ^{40}K (potassium 40) and, in the process, create heat, radiation, and daughter elements and reduce their numbers over time. These unstable isotopes and their rates of decay can be used to date rocks in the field of *radiogenic-isotope geochemistry* or *geochronology.* In the case of carbon, we estimate, on the basis of solar radiation and the compositions of

certain meteorites (chunks of the earliest solar-system material), that the initial ratio of ^{13}C to ^{12}C was about 0.0111 (there is also a radioactive ^{14}C that is produced in the upper atmosphere as a spallation product of ^{14}N). The interesting issue is how the ratio changes as carbon is transformed chemically through both inorganic and organic reactions. Fundamentally, an atom of ^{13}C tends to move slightly more sluggishly than a lighter atom of ^{12}C. When dry ice (frozen carbon dioxide) sublimes (i.e., changes directly from a solid to a gas), the first molecules to evaporate contain more of the lighter ^{12}C atoms. If one measures the $^{13}C/^{12}C$ ratio in the earliest volume of carbon dioxide and compares it to the ratio in a later volume, the first volume will have a notably smaller $^{13}C/^{12}C$ ratio (i.e., more ^{12}C). The selectivity or "fractionating" processes are most effective where the thermal energy (the temperature) is low because increasing thermal energy would outweigh the small mass differences in reactions. Low temperatures are the provenance of the crust, oceans, and atmosphere. Life forms also have important impacts: Plant photosynthesis increases

the ^{12}C in organic material relative to that in atmospheric carbon dioxide. Plant eaters have slightly ^{13}C-enriched and virtually unfractionated fat; carnivore's protein is like that of their prey. Through these mechanisms and carbon reservoirs, the isotope ratio for a substance is a record of its original source and how it has changed (fractionated) as a result of the transformations of carbon from one form to another.

The accepted format for presenting such isotope information is the difference between a standard material (PDB for carbon[13]) and the "unknown" normalized to the value in the standard and then expressed in parts per thousand (*per mil*), the notation being $\delta^{13}C$.[14] Some averages or ranges of $\delta^{13}C$ values are as follows: whole Earth = -7 to -6; atmosphere = -7.0; marine mollusks = -1.7 to $+4.2$; coal = -25; grasses = -14 to -11; humans = -14 to -8. The rule of thumb is that organic carbon has distinctly negative $\delta^{13}C$ values, inorganic Earth has mildly negative values, and organic carbonate has values near zero.
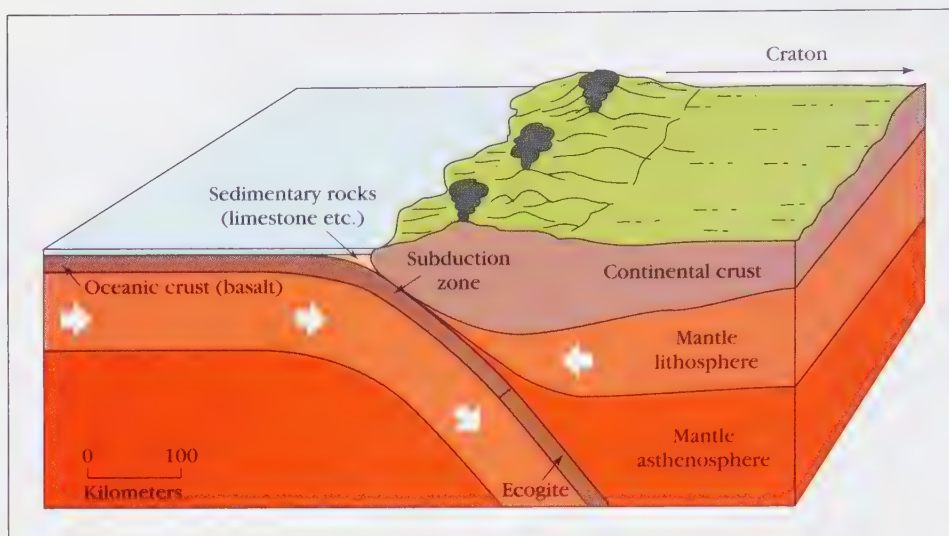
tal crust, it is usually thrust under the continents in the competition for surface area, or perhaps it sinks into the mantle because of its own density. The descent of older, colder oceanic crust is the process of subduction (Figure 11). Seismology can distinguish a subducting slab of oceanic crust to depths of hundreds of kilometers and confirm its descent. Such a slab is difficult to trace at greater depths, in part because of technical limitations but also because of recrystallization of the basalt to eclogite. Seismic resolution of different rock layers is produced by the contrast in their densities; that contrast diminishes dramatically when basalt (density of about 2.9) is transformed to eclogite (density of about 3.5) in the mantle (with density of about 3.4). The eclogite that forms from subducted basalt can either descend into the mantle or be pasted (underplated) onto the continental keel at temperatures and pressures where diamonds can grow. Any organic matter and carbonate that was present within the basaltic slab is now available to provide carbon for diamond growth. When that carbon recrystallizes, the resulting diamond will exhibit $\delta^{13}C$ values that reflect those crustal carbon sources.

The wide range of carbon-isotope compositions, outside of the expected mantle range, is not the only evidence that supports a subducted source of carbon for eclogitic diamonds. Oxygen has three stable isotopes (the common ^{16}O, the less common ^{18}O, and the rarer ^{17}O), and they are also used to study fractionation processes and earth-material reservoirs. The oxygen-isotope ratios in eclogite xenoliths are similar to the ratios found in hydrothermally altered basalts from the seafloor.[16] There is no known fractionation process for oxygen isotopes in the mantle that could produce the oxygen-isotope values ($\delta^{18}O$) observed in eclogite xenoliths, so we conclude that that isotopic signature belongs to basaltic oceanic crust that was recrystallized to eclogite. Support for a seafloor origin for the eclogites fits nicely into the model of subducted carbon. The sulfide mineral inclusions in eclogitic diamonds also

exhibit a wide range of values for sulfur isotopes ($\delta^{34}S$) that can be explained only by fractionation processes that occur at low temperatures and pressures (i.e., in the Earth's crust).[17] Thus, various sources of stable-isotope data support the model of subducted seafloor basalts being recrystallized as eclogites, in which diamonds crystallized from carbon recycled from organisms that inhabited and died on an ancient seafloor.

The different ages of eclogitic and harzburgitic diamonds now can be more easily understood. Whereas harzburgitic diamonds crystallized as a result of processes unique to an early period in Earth history, eclogitic diamonds formed by processes related to subduction and seafloor spreading. In addition, carbon-based life forms are not known to have existed on the Earth during its earliest years. Only after simple organisms such as algae had developed on the seafloor would organic carbon be available in subducted oceanic crust to be recrystallized as diamond.

SUMMARY

The picture as we understand it for diamond formation involves relatively cool harzburgite keels at the base of the thickest, oldest parts of the Earth's crust. Those keels probably were formed in the earliest stages of the growth of the continents. From carbon in the mantle, diamonds crystallized in these keels during or shortly following their formation (Figure 12), some 3 billion years ago. Later subduction of the basaltic oceanic crust resulted in some portions of it adhering to the bases of the continental keels and recrystallizing there as eclogite. The basaltic crust contained carbon, some of organic origin, that recrystallized as diamond. Heating beneath or fluid infiltration of the continental keel caused kimberlite melts to form and, under the right conditions, they ascended the 200–300 km distance to the Earth's surface, bringing samples of the Earth's mantle for scientists to study and diamonds for us to use and enjoy.
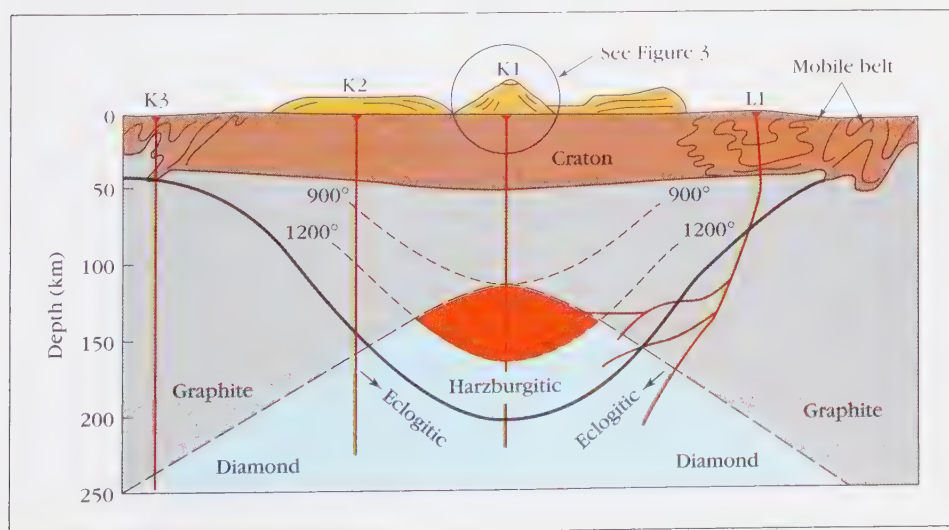
ETCHED DIAMONDS AND CARBON STABILITY

Many natural diamond crystals have rounded faces or faces richly decorated with trigons. These features are the result of etching: Such diamonds were once larger and have lost mass in the latest portions of their "lives" deep within Earth. This fact raises questions about the timing of the etching and the stability of diamond in the Earth. Within a few kilometers of Earth's surface, diamonds are unstable but are so strongly bonded that they survive intact. However, as they are transported up from the mantle in kimberlite magma, there is sufficient temperature and time to permit etching. This is the explanation for etching most often cited, but it has been strongly questioned.[18] It could also be that diamonds were etched during their long residence in the mantle, responding to changes in surrounding conditions. These changes pertain less to the stability of diamond versus graphite than to diamond versus carbon dioxide (CO_2) or methane (CH_4). In fact, these latter stabilities are as important as the former and have generated much debate about the concentrations of hydrogen and oxygen in the mantle and the cratonic keels. Too much oxygen or hydrogen and either carbon dioxide or methane are the stable substances, not diamond or graphite. Such conditions strongly affect the mantle rocks as well. Diamonds have survived, so the conditions are somewhere between the two extremes, but the debate about etching continues.

Natural Sources of Diamond Other than the Earth's Mantle

GEORGE E. HARLOW, VLADISLAV S. SHATSKY,
AND NIKOLAI V. SOBOLEV

DIAMONDS FROM THE CRUST

One of the important geologic developments of the past decade is the recognition of an Earth process that subjects slices of the crust to so-called ultrahigh pressures – those in which sometimes even diamond can form. Until about a decade ago, it was believed that large expanses of the metamorphic rocks exposed at the Earth's surface had never descended much deeper than the thickness of the crust, that is, to about 65 km, where the pressure would be about 20 kilobars (kbar). Moreover, it was believed that those high-pressure rocks were limited to pieces of the ocean crust that had been undergoing sub-duction into the mantle but were arrested in their descent by collisions with pieces of continents, which shoved them back to the surface. In studies of the Alps, a previously discounted observation of evidence for a very high pressure form of silica (quartz is silica) called coesite was confirmed. That evidence proved that sedimentary rocks had reached depths of at last 100 km (35 kbar). However, that record was broken by some rocks discovered in Kazakhstan.

After the discoveries of diamonds in Siberia during the 1950s, Soviet scien-tists extended their surveys for diamonds and diamond-indicator minerals to alluvial gravels in many parts of the Soviet Union. Very small "microdia-monds," averaging only 12 micrometers across (less than 0.0005 inch, less than one-sixth of the diameter of a human hair), were discovered in concen-trates from streams draining a hummocky terrain in northern Kazakhstan (Fig-ures 13 and 14). After extensive research, including mapping, digging, and drilling, diamonds were discovered in metamorphic rocks that were distributed over a region measuring 100 by 300 km, but the rock layers were only a few kilometers thick (maximum). Those rocks must have been pushed 120 km into the Earth and returned intact, and that discovery has revolutionized our ideas of what can happen to the Earth's crust. The minerals in those rocks, including garnets, pyroxenes, micas, carbonates, and diamond, indicate that the rocks were buried to depths where they reached 900–1,000°C and 40 kbar. Dia-mond is stable at those conditions, and those temperatures are colder than for the normal conditions represented by the continental geotherm. The interpre-

Figure 13. Kokchetav Massif in northern Kazakhstan. (Adapted from Shatsky et al., 1995.)

tation is that a collision between two tectonic plates drove a slab of cold continental crust to those depths, but the slab did not remain long enough to heat up to "normal" Earth temperatures. The question arises how the slab got back up, because it had to return relatively quickly, faster than erosion would have exposed it. The most attractive model postulates that the slab became detached from its down-going neighbors and was virtually squirted back toward the surface along a slippery boundary, aided by its own buoyancy (Figure 15).

DIAMONDS FROM OUTER SPACE AND THEIR TERRESTRIAL COUNTERPARTS

Diamonds have also been formed by the processes occurring in cataclysmic cosmic collisions, as recorded in both meteorites and astroblemes. The collision of an asteroid with the Earth can produce high-pressure shock and heat (shock metamorphism) sufficient to transform the carbon in the impacted rocks into diamonds. Soviet scientists discovered such diamonds in the 1970s, but the information did not become public until recently. One such impact in Siberia, at the 35-million-year-old Popigari crater, with a diameter of 60 km, transformed graphite into polycrystalline diamond aggregates up to 1 centimeter across. Diamonds are believed to have been associated with all major impacts and perhaps to have been blasted broadly around the planet, so dia-

Figure 15. Collision and return of UHP terranes, permitting formation and preservation of diamonds in the continental crust. (Top) the down-going subducted ocean crust (green) has a thin covering of sediment (gray) that gets sheared off and driven upward (inset), which appears to be caused by continental collision (middle) that ultimately squeezes the diamond-bearing metamorphic rocks back into the crust (bottom).
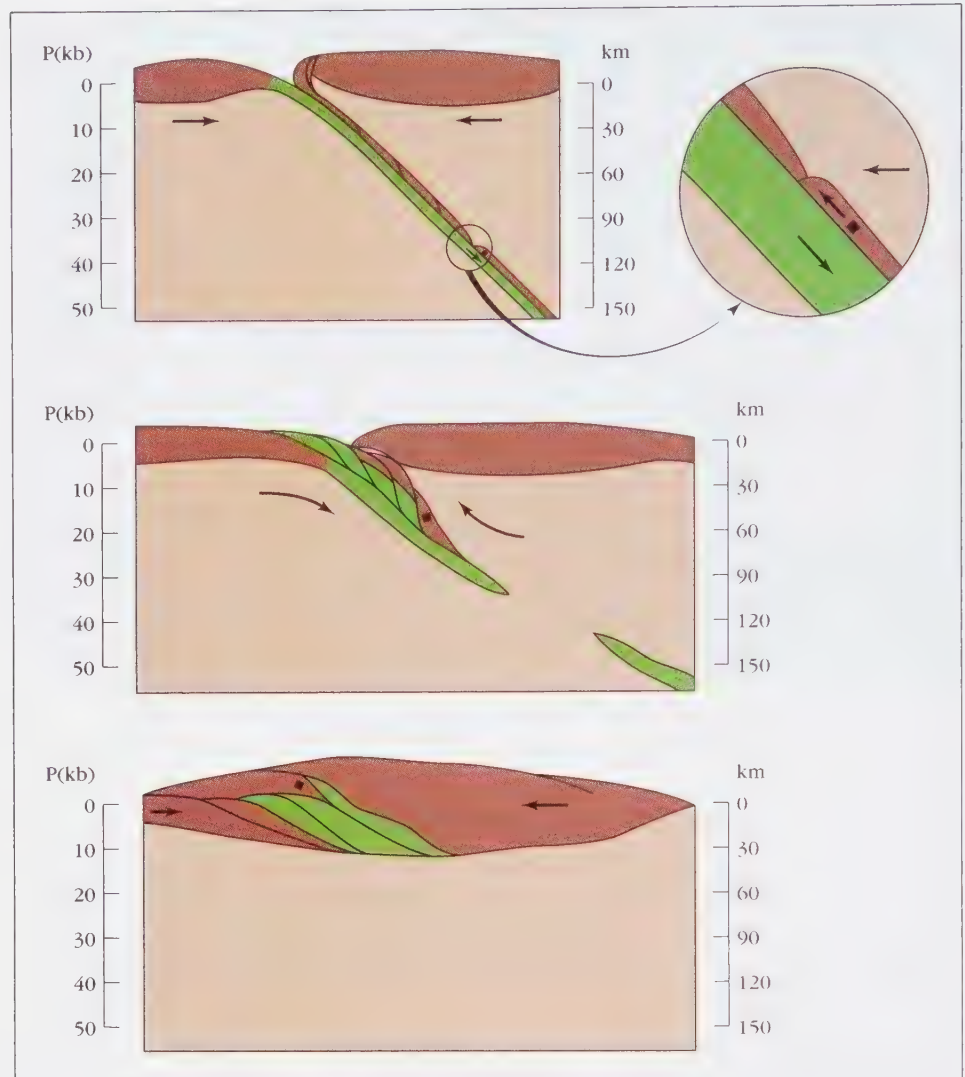
monds could join iridium anomalies as indicators of those ancient catastrophes, including the Cretaceous–Tertiary event that coincided with the extinctions of the dinosaurs. This subject is very new, and many exciting discoveries have yet to be announced.

Diamonds have been recognized in meteorites for many years, but only in 1987 were extremely small fragments of diamond, with a median diameter of only 10 angstroms (1 Å equals one ten-billionth of a meter), discovered in meteoritic material that predates the solar system (pre-solar grains). Those nano-diamonds are so small that they do not have the normal properties of diamond; for example, their density is low, only about 2.3, and they form a gel in water. They are postulated to have formed by chemical vapor deposition (CVD) fueled by star deaths (novae and supernovae); outgased methane and other carbon-rich gases from dying stars would be transformed via electrical discharges into diamond.

NOTES

[1] Kieffer (1984); many studies of the dynamics of volcanic eruptions have been carried out at Los Alamos National Laboratory.

[2] That rate was calculated by Eggler (1989) and has been widely accepted in the scientific community.

[3] Personal communication from Susan W. Kieffer (January 1997).

[4] Progress reports covering the discovery and development of these kimberlites can be found in Canadian mining-industry newspapers and magazines, such as *Northern Miner*.

[5] For a more detailed description of kimberlite dikes in South Africa, see Gurney and Kirkley (1996).

[6] The kimberlite nomenclature is very complex. A recent review, including the restatement of orangite as another rock of the kimberlite type containing diamonds, was published by Mitchell (1995).

[7] G5 and G10 garnets were defined by Dawson and Stephens (1975) through the use of cluster analysis of compositions of garnets of mantle provenance.

[8] Richardson et al. (1984).

[9] For example, Kramers (1979), at the University of Witwatersrand's Bernard Price Institute of Geophysics, South Africa.

[10] Clifford (1970).

[11] Pyroxene solid solution in garnet was first identified in naturally occurring substances (i.e., inclusions in diamonds from the Monastery kimberlite pipe, South Africa) by Moore and Gurney (1985). Until that time, it had only been predicted from experiments. It suggests that the host diamonds were formed at depths of more than 300 km.

[12] Richardson (1986) and Richardson et al. (1990) have obtained some age dates for eclogitic inclusions in diamonds.

[13] The material is a fossil belemnite (*Belemnitella americana*) collected from the Peedee Formation (Cretaceous) of South Carolina.

[14] $\delta^{13}C = \{[(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{standard}]/(^{13}C/^{12}C)_{standard}\} \times 10^3$.

[15] In order for diamond to precisely duplicate the $\delta^{13}C$ values of organic and carbonate carbon, one has to assume that there was no fractionation of isotopes involved in the crystallization of diamonds from the source carbon. At the high temperatures in the diamond stability zone of the mantle, fractionation would be so small as to be considered negligible. Further discussion of the possible sources of carbon in diamond is available (Kirkley et al., 1991b).

[16] Oxygen isotopes in eclogite xenoliths have been measured by a number of workers, as summarized by Kirkley et al. (1991b).

[17] Chaussidon et al. (1987).

[18] Haggerty (1986).

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4

Diamond Sources and Their Discovery

ALFRED A. LEVINSON

DIAMONDS ARE MENTIONED in Indian manuscripts dating to more than 2,000 years ago, and until the eighteenth century India was the only significant source of this gemstone. Since then, new deposits have been discovered around the world, and they have been found at an increasingly dramatic rate in the twentieth century. Diamonds are now mined in about 25 countries and on all continents except Europe and Antarctica. Some major new sources have led to changes in the economic aspects of the diamond industry.

The locations of diamond deposits are determined by the geologic fact that diamonds are found primarily in two rare types of rocks – kimberlite and lamproite. These rocks occur as "pipes" (cone structures pushed to the surface by volcanic activity) only in cratons, those portions of the Earth's crust that have been stable for long periods of time. Diamond-bearing kimberlites of economic significance are found in archons, which are those portions of cratons that are older than 2.5 billion years. Protons, which are those portions of cratons that are 1.6–2.5 billion years old, are less likely to have diamond-bearing pipes, and when they do, the pipes are likely to be lamproites, as at the Argyle mine in Australia. Tectons, which are those portions of cratons between 800 million and 1.6 billion years old, are unlikely to contain either kimberlites or lamproites. These relationships are illustrated in Figure 1.

When a diamond-bearing kimberlite or lamproite pipe reaches the surface of the Earth, it is subject to weathering and erosion, which results in the release of its diamonds. The diamonds thus released can be transported for varying distances before they become concentrated into any one of a variety of secondary deposits. Such concentrations can remain close to the primary source and form deposits referred to as eluvial (above a pipe) or colluvial (adjacent to a pipe), as at Mbuji-Mayi in Zaire. When greater distances are involved, allu-
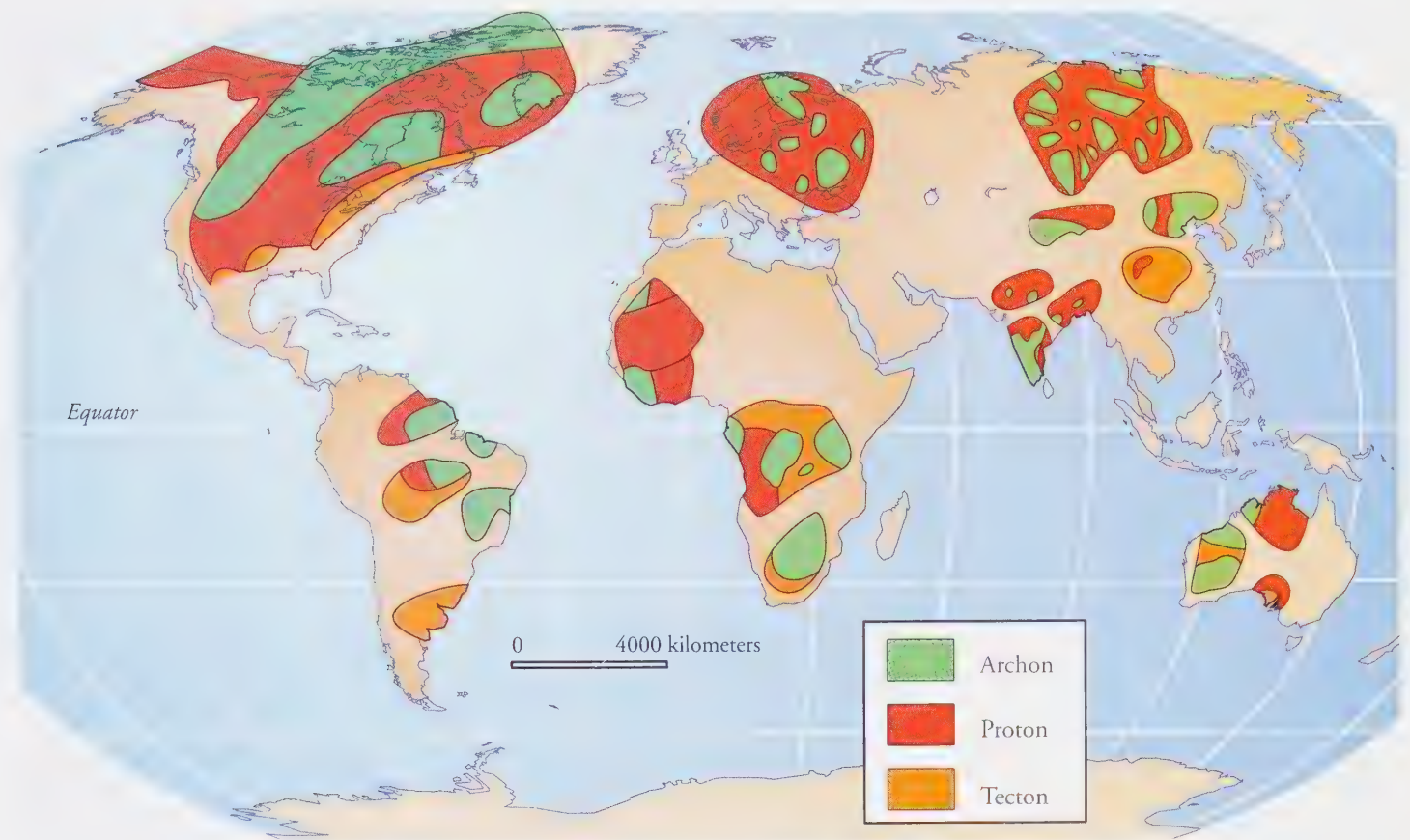
Figure 1. World distribution (except for Antarctica) of cratons. (Adapted from Levinson et al., 1992.)

Figure 2. The five main historical diamond producing regions of India. (Courtesy of A. J. A. Janse.)

vial (stream-transported) deposits are formed, such as those found in India, Brazil, and Angola. When diamonds are transported for even greater distances, to a marine environment, either onshore or offshore marine deposits can form, such as those in Namibia.

FROM ANTIQUITY UNTIL 1730: THE INDIAN ERA

India is the cradle of the diamond industry. Diamonds probably were discovered there before the fourth century B.C.E., and some of the world's legendary stones, among them the Koh-i-Noor, Great Mogul, Hope, and Nizam, were mined in India. Except for small numbers of diamonds from Borneo, possibly found as early as the sixth century C.E., India was the world's sole source until about 1730, when diamonds were discovered in Brazil.

Over the centuries, numerous deposits scattered over five different areas in India have been mined for diamonds (Figure 2). All but one of those deposits are secondary (e.g., alluvial). The most famous deposits in India are popularly

known as the Golconda mines, but in fact, Golconda, a city ruin located about 10 kilometers (km) west of the present city of Hyderabad, was a commercial and diamond-trading center, and no mines ever existed there (Figure 3).

Production

Diamond production in India has varied in quantity over the centuries, probably reaching its peak during the late 1600s. Even at its peak, production was not large by today's standards, perhaps 50,000 to 100,000 carats annually. Only a small percentage of that output would have been used for gems. Some industrial-grade diamonds would have been used as abrasives, such as for drilling holes in beads; most would have been discarded. Such limited production was one reason that, through the ages, only a trickle of large stones (more than 1 carat) ever reached Europe, most of which were used in adornments for sovereigns and their consorts.

Estimates of the total amount of diamonds produced by the Indian mines

from antiquity to the present vary considerably, but about 21 million carats of rough diamonds (predominantly gems) seems reasonable. That would average to about 10,000 carats of rough per year since their discovery.

With the discovery of diamonds in Brazil, the position of India as the pre-eminent producer of diamonds was lost forever. By about 1750, Indian production was insignificant, although an occasional large stone was found thereafter, such as the 340-carat rough Nizam, found around 1835. However, since the 1970s, India has played a major role in the diamond trade, as it has become the world's major cutting center for small diamonds and an important manufacturing center for diamond jewelry.

Today, the Majhgawan pipe near Panna is the only producing diamond mine in India, with production of up to 20,000 carats annually. That mine is scientifically significant because it was the first diamond-bearing pipe ever discovered. It was found in 1827, 40 years before the discovery of the South African pipes. Although it was different from other diggings in the area in that it contained clay instead of sand or gravel, it was, like other diamond deposits in India, considered alluvial until 1930, when its primary nature was recognized. It is now classified as a lamproite. Recently, there has been renewed interest in exploration for diamonds in India by major international mining companies, as well as by an agency of the Indian government; however, it seems unlikely that there will be increased diamond production in the foreseeable future.

Figure 4. John Mawe's Treatise on Diamonds and Precious Stones, *published in 1823, illustrates "peculiar diamonds" from India and Brazil. (Jackie Beckett/courtesy of American Museum of Natural History.)*

FROM 1730 UNTIL 1870: THE BRAZILIAN ERA

For 140 years, from about 1730 until significant production began in South Africa in 1870, Brazil was the main source of the world's diamonds. Its prominence began with the recognition in 1725 that some small, shiny stones recovered by *garimpeiros* (prospectors or miners, generally unlicensed) mining an alluvial gold deposit near the town of Tejuco, now known as Diamantina, in the eastern part of the state of Minas Gerais, were diamonds (Figure 4). After 1730, a steady supply of small stones was available, although marked annual fluctuations in output were characteristic of some periods.

The discovery of the Brazilian deposits was, on one hand, extremely timely, as the Indian deposits were approaching exhaustion; in the latter years (about 1725–30) of Indian production, only 2,000–5,000 carats of rough arrived annually in Europe. But on the other hand, by the late 1730s the Brazilian production had increased the world supply manyfold, to about 50,000 carats annually (possibly up to 100,000 carats), which caused a collapse in prices, with rough stones selling for as little as 30 percent of their previous prices.

Figure 5. Diamond deposits in Brazil, all secondary, are found in many widely separated localities throughout this vast country (producing regions are the shaded area), but the deposits in the states of Minas Gerais, Bahia, Mato Grosso and Roraíma are or have been the most important. (Adapted from Cassedanne, 1989.)

Figure 6. Brazil yielded both diamonds and gold, as shown in this conglomerate mass from John Mawe's *Travels in the Interior of Brazil (1812). (Jackie Beckett/courtesy of American Museum of Natural History.)*
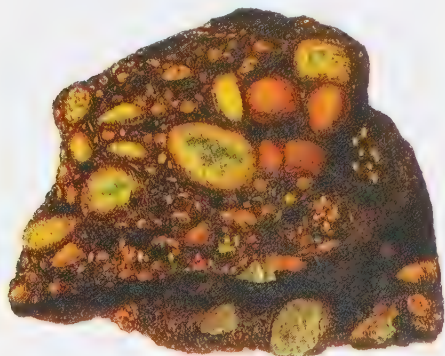
Following the initial discovery near Diamantina, there were new diamond finds throughout the eighteenth century, the most important being those in other parts of Minas Gerais (e.g., the Coromandel area) and in the states of Bahia and Mato Grosso (Figure 5). In 1912, rich deposits were discovered in the northernmost province in the state of Roraíma. Thus diamond deposits in Brazil are widespread, almost from border to border in both the north–south and east–west directions (6,000 and 4,500 km, respectively).

Geologic Nature of the Mines

The Brazilian diamond deposits are all secondary and thus owe their existence to the erosion of kimberlites or other primary diamond-bearing rocks that have yet to be identified (Figure 6). The individual deposits generally are small in volume, and some have only low-grade concentrations of diamonds, resulting in limited mining operations.

Kimberlite pipes were not found in Brazil until 1968. Since then, hundreds have been found, but none contains diamonds in economic quantities.

Production

Although the total diamond production from Brazil since 1730 clearly has been considerable, reliable records of annual production simply do not exist, and any reported data on production will be estimates. Nevertheless, such estimates indicate that in the period from 1730 to 1849, production, both official and illicit, was uninterrupted and ranged from 25,000 to 100,000 carats annually, enough to quadruple the diamond supply to Europe (Figure 7).

In 1850 and 1851, production rose as high as 300,000 carats annually following the discovery of rich deposits in Bahia. In other periods, such as from 1853 to 1861, the output was relatively stable at about 190,000 carats annually; however, that rapidly declined, leading to a great shortage of rough diamonds in the European cutting centers in the late 1860s.

When competition from South African deposits began in 1870, Brazilian production dropped precipitously; for example, officially, only 5,000 carats were produced in the year 1880, and 3,000 in 1896. Total production from 1730 until 1899 was about 13 million carats, of which nearly all would have been gem quality, as there was little need for industrial diamonds during that period.

Following a slow and erratic revival of the Brazilian diamond industry in the early part of the twentieth century, production has gradually increased and
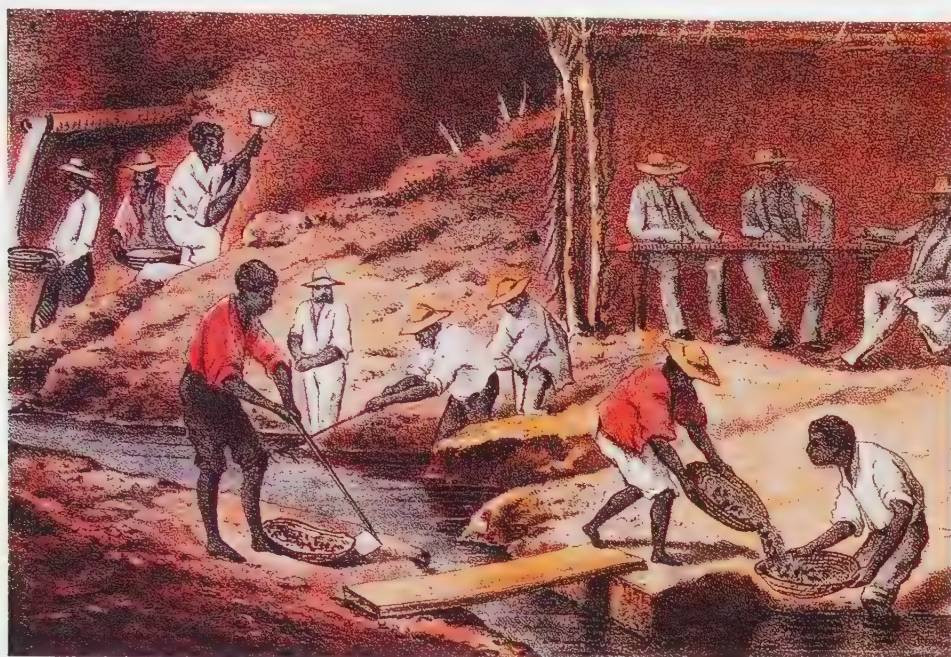
Figure 7. With mine officials nearby, Brazilian slaves wash the gravel from riverbeds to clean off the heavy mineral deposits in which diamonds are found. From an 1884 publication. (Courtesy of New York Public Library Picture Collection.)

is now estimated at up to 2 million carats annually (currently 40 percent industrials). Thus the total Brazilian production from 1730 to 1995 should total about 47 million carats.

Since 1970, Brazil has been explored by several major international mining companies, looking primarily for kimberlites with economic promise, but thus far they have been unsuccessful. It is difficult to make a profit mining secondary deposits in Brazil, owing, among other factors, to the presence of *garimpeiros* and laws favoring them. Nevertheless, exploration continues, as Brazil has enormous geologic potential because it contains several major cratons (Figure 1). For the immediate future, Brazil, because of its secondary deposits, likely will retain its position as sixth or seventh largest supplier of rough diamonds to the world market, as exploration for economically viable primary sources continues (Table 1).

Guyana and Venezuela

Closely associated with Brazilian diamonds, specifically those from the northern state of Roraíma, are deposits, also secondary, in adjacent Guyana and eastern Venezuela, where diamonds were first found in 1890 and 1901 (Figures 1 and 5). The diamonds in those three contiguous countries are geologically related in that all three areas are on the Guyana Shield, but their primary source has not yet been located. A second area with alluvial diamonds also exists on the Guyana Shield, but exclusively in western Venezuela (the Guaniamo district), and its source has been traced to Precambrian kimberlites

TABLE 1

Rough diamond production by country, 1995

Country	Production ($\times 10^6$ carats)
Australia	40.8
Zaire	20.0
Botswana	16.8
Russia	12.5
South Africa	9.1
South America (predominantly Brazil, but also Venezuela and Guyana)	2.0
Angola	1.9
Namibia	1.3
Ghana	0.8
Central African Republic	0.6
Guinea	0.5
Sierra Leone	0.3
Zimbabwe	0.2
All other countries	0.5
World total	107.9

Source: Metals & Minerals Annual, 1996, p. 27, published by Mining Journal Ltd., London.

in the area. The characteristics of the diamonds from the two areas differ significantly, suggesting that a common source is unlikely.

Over the years, Guyana and Venezuela have been minor diamond producers, with total production since 1890 of about 4.5 and 14 million carats, respectively. Although annual production has varied considerably, in recent years their combined production has supplied some 0.5–1 percent of the world's diamonds, and that is likely to continue.

FROM 1870 TO THE PRESENT: AFRICA AND THE MODERN DIAMOND INDUSTRY

The sudden influx of Brazilian diamonds into Europe in the 1730s not only lowered the price of rough diamonds but also undermined the concept that diamonds were exclusively for royalty. Because the European kings and nobles were unable or unwilling to buy all the diamonds that became available, diamonds began to be sold to anyone who could afford them. Over the next century, diamond jewelry became increasingly popular with the emerging middle class whose new prosperity enabled them to purchase luxuries. Diamonds were being acquired by commoners, and luxury was experiencing a democratization. That can be considered the beginning of the modern diamond industry.

Although most of the new Brazilian production was marketed in Europe, by the middle of the eighteenth century diamonds were becoming increasingly available in the major cities of North America, such as Boston, New York,

Figure 8. Increases in total annual world production of natural rough diamonds (both gem and industrial) from 1860 to 1995, on a weight (number of carats) basis. An arrow marks the year in which each of the major sources began significant production (more than 100,000 carats annually). From 1860 until 1870, the small production entering the world markets came almost entirely from Brazil.
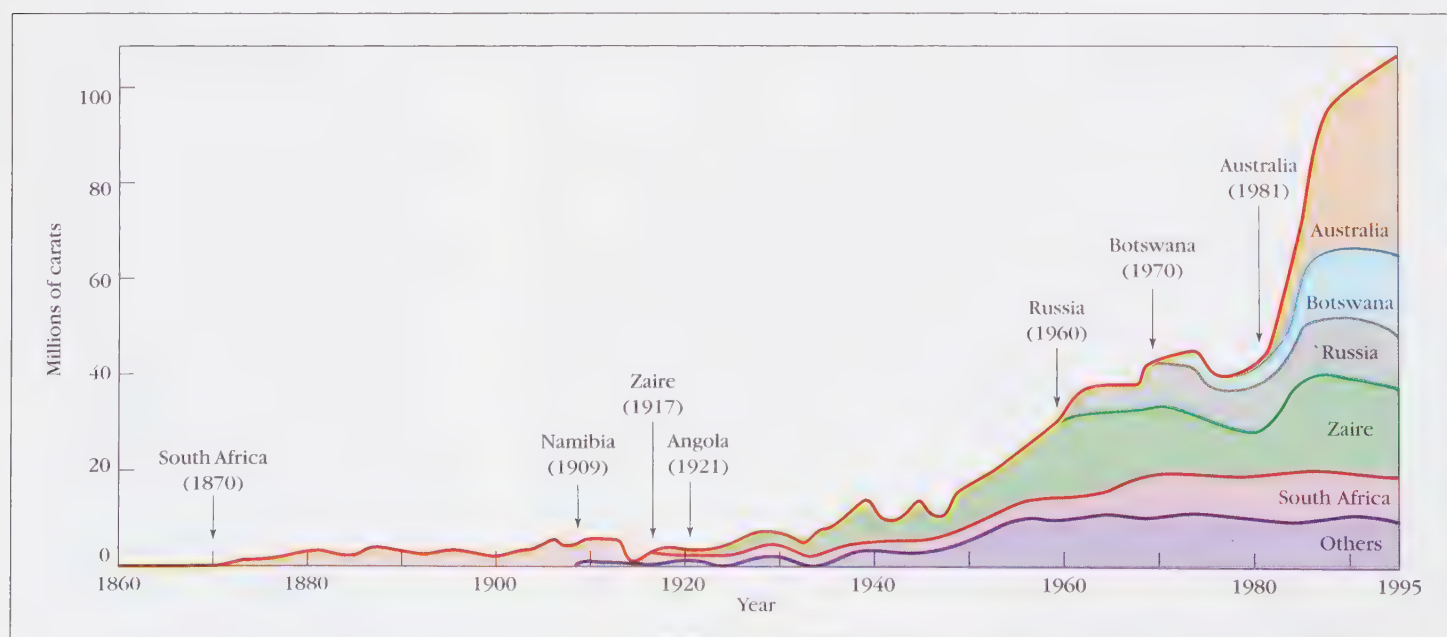
Philadelphia, and Charleston. Martha Washington, for example, had a diamond wedding ring, and in 1813 Dolley Madison had diamond jewelry.

Unfortunately, the dramatic increase in the demand for diamonds in the latter part of the 1860s corresponded with the decline in production from Brazil. The diamond-cutting industry, which by then had grown to about 2,200 cutters worldwide, mostly in Amsterdam and Antwerp, was experiencing massive unemployment because of the decreasing supply of Brazilian rough, India and Borneo having long since become insignificant sources.

That concern came to a dramatic end in 1868, when the diamond deposits in South Africa began to produce in quantities that could hardly be imagined (Figure 8). It had taken the mines of Brazil about 200 years to equal the total production (about 21 million carats) of India over the previous 2,000 years, but it took just 15 years (1868–82) for South Africa to reach that production figure.

Just as the Indian diamond mines were becoming exhausted in 1725, major deposits of diamonds were found in Brazil, and just as the Brazilian mines were becoming depleted in the 1860s, major discoveries were made in South Africa (Figure 9). The South African discoveries coincided with a considerable increase in wealth in the United States. Thus there was a ready market for diamonds, and there was no immediate drop in prices like that seen when Brazilian diamonds had suddenly appeared on the world market in the 1730s.

South Africa

The first recorded discovery of an authentic diamond in Africa occurred at some time between December 1866 and February 1867 in a gravel deposit on the De Kalk farm, located on the southern bank of the Orange River, about 50 km (30 miles) northwest of Hopetown and about 700 km (435 miles) northeast of Cape Town. The stone, fittingly named the Eureka (Figure 10), was subsequently cut into a 10.73-carat diamond. The credit for the discovery is somewhat clouded because there are several versions of the event. However, the generally accepted account holds that the finder was Erasmus Jacobs, the 15-year-old son of a poor farmer named Daniel Jacobs who lived on the De Kalk farm (Figure 11).

Alluvial Deposits: Hopetown, Lichtenburg, and Namaqualand

The first South African diamond deposits, near Hopetown, did not differ significantly from the diamond fields of India, Borneo, and Brazil, in that they were alluvial deposits located in unconsolidated sands and gravels in the streambeds and banks

Figure 9. The first diamonds reported in South Africa (and all subsequent major finds until 1903, when the Premier mine was discovered) were located between the Orange and Vaal rivers. Note that the mines in the Kimberley vicinity are shown here in relative positions, because they are clustered in such a small area that their locations cannot be shown precisely. The inset indicates the area shown in the map. (Adapted from Janse, 1995.)
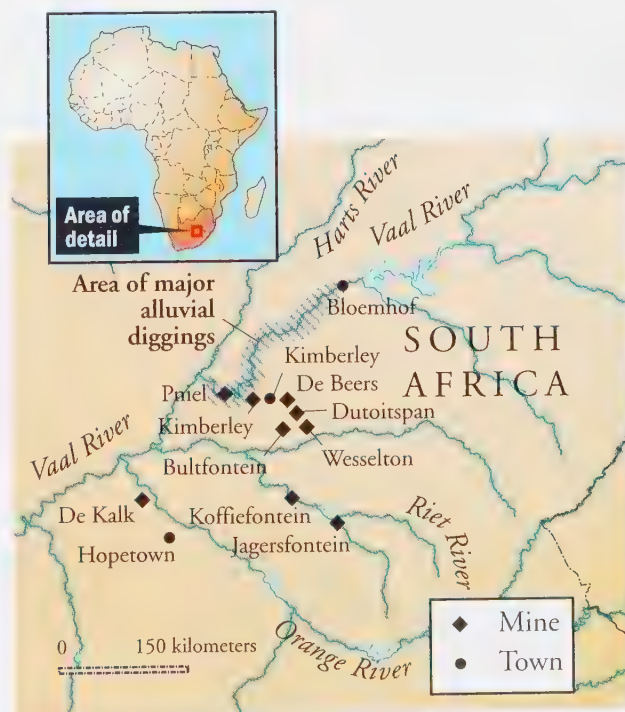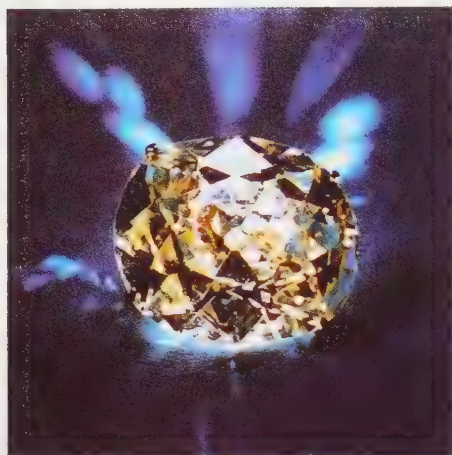
Figure 10. The 10.73 carat yellow Eureka diamond was faceted from the first recorded diamond found in Africa, in late 1866 or early 1867, on the De Kalk farm near the Orange River. It is now owned by the government of South Africa and is displayed in the houses of Parliament in Cape Town. (Courtesy of De Beers.)

Figure 11. Erasmus Jacobs is credited with finding the first diamond in Africa. This photo was taken about 1907, when he was about 55 years old. (Courtesy of De Beers.)
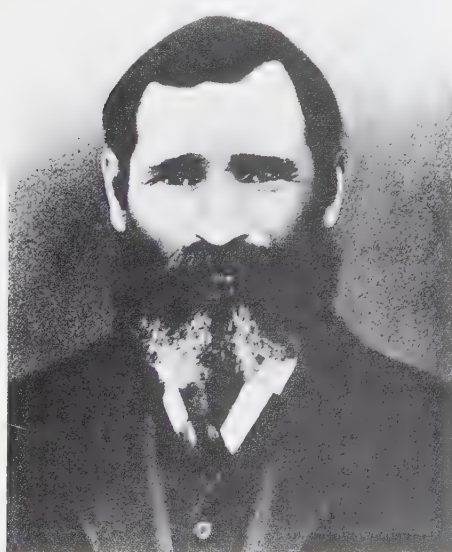
of the existing river valleys, as well as in elevated terraces representative of older, abandoned river valleys. As the recovery was carried out in the rivers and streams, with the aid of water, those alluvial deposits became known as "wet diggings."

In 1867 and 1868 the mining operations in the alluvials of the Orange and Vaal rivers and related tributaries did not result in much diamond production; statistics for those two years indicate that only 200 carats were produced. In 1869 and 1870, however, production increased substantially to 16,550 and 102,500 carats, respectively, all of which can be considered to have been of alluvial origin. South African production in 1871 and 1872 reached 269,000 and 1,080,000 carats (Figure 8), of which the alluvials contributed only a relatively small amount, particularly in 1872. The kimberlite pipes discovered in late 1869 had begun to produce at unprecedented rates. By 1872, with most of the production coming from the newly discovered pipes, the annual South African diamond output was three times what the Brazilian alluvial deposits had produced in either of their peak years (1850 and 1851).

Until 1912, practically all of the alluvial diggings were in the lower Vaal River basin, but after 1880 diamonds were continually being found farther north, toward Bloemhof (Figure 9), and in other parts of central South Africa. In 1926, after many years of comparatively little alluvial production (about 200,000 carats annually), enormous alluvial deposits were discovered in gravels in the high plateau country near Lichtenburg, 175 km (110 miles) north of Bloemhof (Figure 12). From 1926 to 1929, more than 4 million carats were produced from the Lichtenburg area; however, production dropped off dramatically thereafter, and today that area is worked only sporadically.

In 1925, diamonds were discovered in sands and gravels on the coast in Namaqualand, in northwestern South Africa. Since then, they have been discovered, sometimes in exceptional concentrations, at various places along a strip of coastline from the mouth of the Orange River south to Hondeklip Bay and beyond (Figure 13). Some of the deposits are at beach level, others are in raised terraces, and some are offshore at shallow depths. Offshore deposits are now being developed at depths ranging down to about 100 meters (300 feet), where De Beers had two vessels working in 1995.

Those coastal and offshore diamonds are assumed to have originated from the weathering of a primary source (i.e., kimberlites) in the South African craton and to have been transported up to 1,000 km (621 miles) to their present locations. The diamonds found in those deposits are of very fine quality (about 95 percent gems), as inferior stones tend to be destroyed during such long transport. (A kimberlite field in Namaqualand much closer to·the coastal deposits does not contain diamonds.) Production from Namaqualand has been continuous since 1926, although there have been extreme variations from year to year. In recent years, the Namaqualand production has averaged between 5 and 10 percent of the South African total.

Figure 12. The officials (upper right-hand corner) have read the formal proclamation, and the starting flag has been dropped for the rush to stake claims near Lichtenburg on August 20, 1926, where diamond-bearing alluvial deposits had been discovered earlier that year. The rush drew 10,000 prospective mineowners. (Courtesy of De Beers.)

Discovery and Characteristics of Kimberlite Pipes

In late 1869, diamonds were discovered about 20 km (12 miles) from the nearest Vaal River diggings, totally remote from any streams or rivers. That discovery forced everyone to rethink the theories about the origin and occurrence of diamonds – theories that had been in place for more than 2,000 years. The diamond-containing rock was compact and hard, so that it had to be crushed and the diamonds extracted by hand. We now refer to that kind of rock as kimberlite. Further, because the new deposits were not close to water sources, washing the diamond-bearing ore as part of the extraction process was not possible. Thus the deposits were referred to as dry diggings, in contrast to the wet diggings along the Orange, Vaal, and other rivers, where diamonds were easily recovered from the unconsolidated sands and gravels.

There are several versions of the sequence in which the various dry diggings were discovered. The most recent study, by A. J. A. Janse, gives the order as Bultfontein (September 1869), Dutoitspan (October 1869), Jagersfontein

Figure 13. The main onshore and offshore areas where diamonds are being mined along the coasts of Namaqualand (South Africa) and Namibia. The broken line trending northwest above the Orange River in Namibia represents the inland boundary (approximately 100 km, or 62.5 miles, from the Atlantic Ocean) of the Sperrgebiet, established in 1908 by the German government, where exploration for diamonds was prohibited, and still is, except in specific situations. (Adapted from Janse, 1995.)

Figure 14. The Big Hole (Kimberley mine) began production in July 1871 and produced continually until it was closed permanently in July 1914. It yielded 14.5 million carats of diamonds. (Courtesy of De Beers.)

(July 1870), Koffiefontein (July 1870), De Beers (May 1871), and Kimberley, also known as the Big Hole (July 1871; Figure 14). Four of those deposits – Bultfontein, Dutoitspan, De Beers, and Kimberley – fell within a circle 5 km (3 miles) in diameter, within which the city of Kimberley was established in 1871. The other two, Koffiefontein and Jagersfontein, were 90 and 150 km (55 and 92 miles) to the southeast. Up to 15 other kimberlites, only some of which contained diamonds, were known in the vicinity of Kimberley, but it was not until 1890 that another large pipe of economic significance (the Wesselton) was discovered only about 3 km (2 miles) from Bultfontein and Dutoitspan.

The diamond deposits of the dry diggings were initially found in various soft, friable, yellowish and reddish weathered surface materials that became known as "yellow ground." When the mines began to reach depths of 17 to 27 meters (55–90 feet), the nature of the rock changed. Under the soft yellow ground was a harder, compact bluish rock, initially called "blue ground," but beginning in 1897 it began to be referred to as "kimberlite" in various publica-

tions. As mining progressed deeper, the conical nature of the kimberlite pipes became evident, and therefore the traditional explanation that diamonds occurred in surface deposits (i.e., relatively shallow and extensive alluvial deposits), or else in rocks compressed from ancient surface deposits, was not applicable to the occurrences in the vicinity of Kimberley.

In 1872, Emil Cohen, a German mineralogist, was the first to suggest that the dry diggings were actually cylindrical columns that represented volcanic conduits and that the diamonds contained in them were brought up from far below and had no necessary relationship to rivers. The term "pipe" was first applied to these volcanic conduits in 1874, and since 1897, when the term "kimberlite" first appeared in print, the term "kimberlite pipe" has gradually gained universal acceptance.

The five mines in the Kimberley cluster and the nearby Koffiefontein and Jagersfontein mines were sources of fabulous wealth. From 1872 to 1903 they provided about 95 percent of the diamonds that entered the world market, generally about 2 to 3 million carats per year.

The Kimberley mine, the richest in the Kimberley area, operated continuously until 1914, when it was closed because its kimberlite ore was mined out. The six others in the Kimberley area have been closed from time to time since 1908 because of the world wars, the Great Depression, and oversupply. Today, four are still active more than 100 years after their discovery: Bultfontein, Dutoitspan, Wesselton, and Koffiefontein. However, their combined production in recent years has averaged only about 700,000 carats annually, a mere 0.7 percent of the present world production of about 108 million carats annually (1995 data). It is likely that all the mines still active in the Kimberley area will close permanently by about 2010 because they are already close to the bottom of their kimberlite ore reserves.

Formation of the De Beers Consolidated Mines

When the pipes were discovered, in 1869 through 1871, an individual was permitted one claim, 31 feet by 31 feet. For example, the Kimberley mine, the Big Hole, consisted of about 430 such claims, but each claim could be divided into fractional parts, with the result that in 1872 there were about 1,600 separate holdings, some as small as one-sixteenth of a claim, or about 7 square yards. It is obvious that it would be difficult and dangerous to work such a small claim to any significant depth (Figures 15 and 16). In the interest of efficiency and safety, the rules prohibiting amalgamation of claims were relaxed in 1872 and totally eliminated in 1876. That paved the way for small companies to take over claims from individual miners and attracted the attention of many entrepreneurs (Figure 17). Two of them, Cecil Rhodes and Barney Barnato, would play major roles in the world of diamonds.

Cecil John Rhodes arrived in South Africa from England in 1870 at the age

Figure 15. By 1872, as miners dug deeper, the walls that served as roadways between the claim pits at the Kimberley mine had started to collapse, making mining difficult and unsafe. The roadways, which ran north-south, were 15 feet wide, with 7.5 feet taken from the sides of each bordering claim (31 × 31 feet), making the working surface of each claim 31 × 23.5 feet. (From Williams, 1906; Jackie Beckett/ courtesy of American Museum of Natural History.)

of 17 and soon migrated to Kimberley. He purchased a mining claim in the De Beers mine and, in addition, made considerable money in partnership with others by pumping water from flooded claims. He returned to England in 1873 to enroll at Oxford, but left considerable assets in South Africa in the care of friends, who continued the pumping business and bought more claims with the profits. When Rhodes graduated in 1881, he returned to South Africa, where he and his associates formed the De Beers Mining Co. Ltd.,
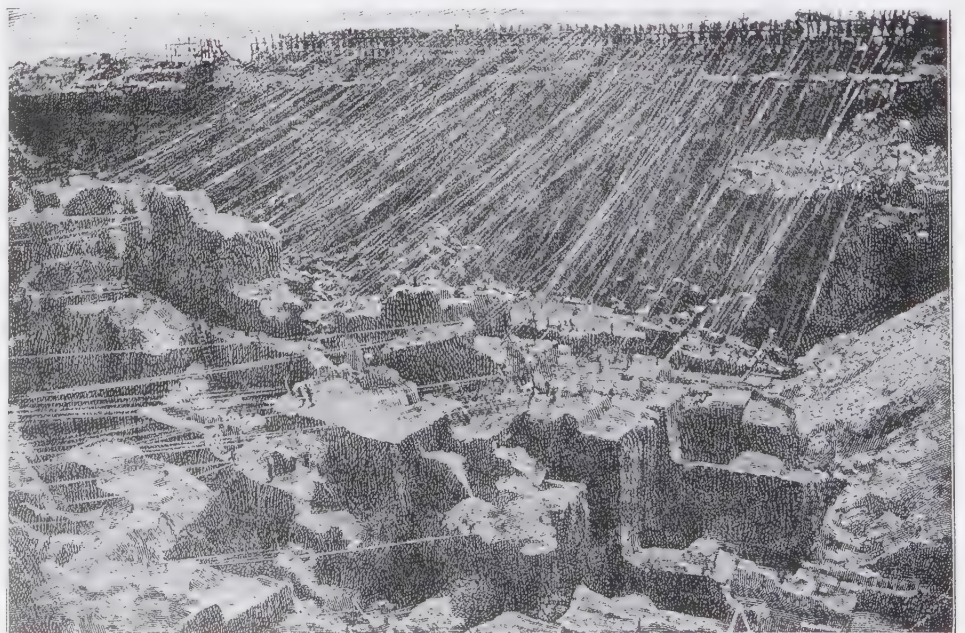
Figure 16. The Kimberley mine in 1874 was a mass of ropeways ingeniously constructed to rush buckets of extracted material to the top, where they were quickly dumped and the buckets sent back into the mine. (From Williams, 1906; Jackie Beckett/courtesy of American Museum of Natural History.)
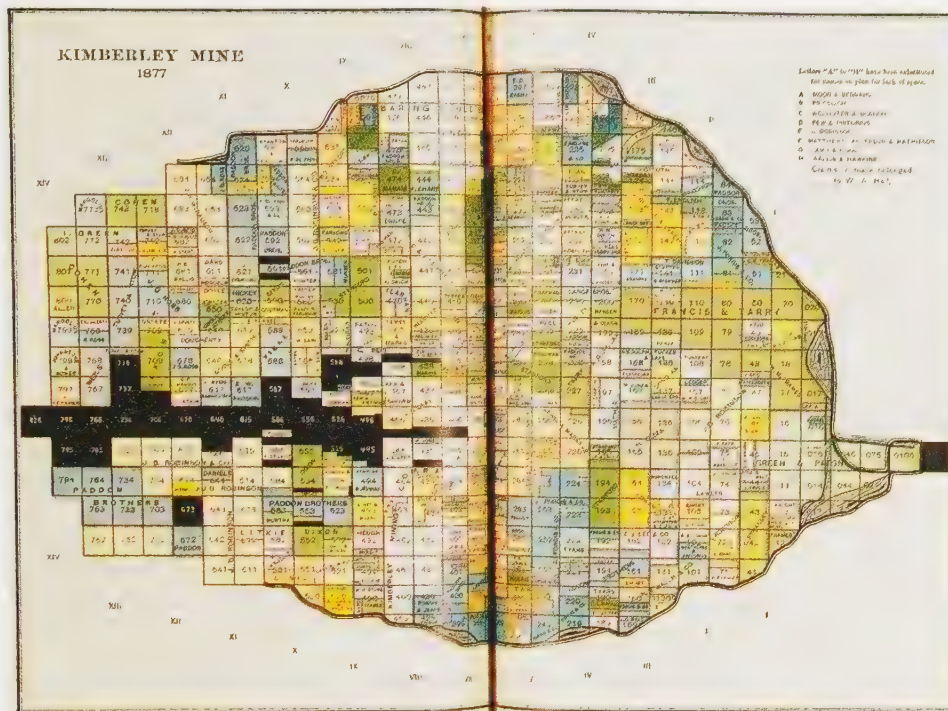
Figure 17. The Kimberley mine in 1877, when the prohibition on amalgamating claims was fully lifted, was still divided into many small claims. The central vertical distortion in the image is the result of this two-page spread reproduction. (From Williams, 1906; Jackie Beckett/courtesy of American Museum of Natural History.)

which actively continued to buy claims. Abetted by a drop in world prices because of oversupply and the expensive technical problems of mining ever deeper, Rhodes and his associates were able to buy more and more claims. By 1887 he had gained complete control of the De Beers mine (Figure 18).

Analogous, in some ways, was the history of Barney Barnato. He arrived in South Africa in 1873 at the age of 20, also from England, and in 1876 bought four mining claims in the Kimberley mine. He soon made a huge profit. In 1881 he formed the Barnato Diamond Mining Co., which he enlarged and eventually merged with Kimberley Central Mining Co., making it the largest company in the Kimberley mine by 1883. However, he never did gain complete control of the Kimberley mine, whose remaining claims were held by a French company that refused to sell to Barnato.

To take control of the Kimberley mine from Barnato, Rhodes initiated a series of brilliant financial maneuvers. First, Rhodes had his De Beers Mining purchase the French company. Then Rhodes sold the French company to Barnato's Kimberley Central for 20 percent of the shares of the latter plus £300,000 in cash. Barnato remained the largest, although not the majority, shareholder in Kimberley Central, and he thought he could still control the company. Rhodes next began to buy up the outstanding shares in Kimberley Central. When Barnato realized what was happening, a vicious bidding battle ensued, driving shares of Kimberley Central to great heights. Ultimately Barnato capitulated. He sold Kimberley Central to Rhodes for £5,338,650 [$25 million (U.S.)], paid for by what was at that time the largest check ever issued.

Figure 18. Cecil John Rhodes, master entrepreneur of the South African diamond mines and founder of De Beers Mining Co. Ltd., controlled 90 percent of the world's diamonds at the end of the nineteenth century. At his death in 1902 he left most of his fortune to Oxford University, funding the prestigious Rhodes scholarships that bear his name. (From Williams, 1906; Jackie Beckett/courtesy of American Museum of Natural History.)

In 1888 Rhodes merged Kimberley Central into a new company, De Beers Consolidated Mines Ltd., which he controlled.

The stage was then set for one company, De Beers Consolidated Mines Ltd. (henceforth, De Beers), to control almost all of the world's diamond production, except for some South African alluvial production and minimal production from Brazil, and to adjust the supply of diamonds to fluctuations in world demand. But there were, and continue to be, two factors that might threaten that dominant position: a serious drop in the demand for diamonds, and the discovery of new mines that would operate beyond the direct control of De Beers.

The Premier Mine

The dominance of the Kimberley mines controlled by De Beers as the only important source of the world's diamonds was not challenged until 1902, the year Rhodes died. In that year the Premier mine was discovered by Thomas Cullinan, who later became chairman of the Premier Diamond Mining Company. The mine was located about 500 km (300 miles) northeast of Kimberley and about 30 km (18 miles) east of Pretoria (Figure 19). With a surface area of 32.2 hectares (80 acres), it was three times as large as Dutoitspan (10.6 hectares, 26 acres), the largest pipe known prior to 1902.

Production started in May 1903, and on January 25, 1905, the famous Cullinan diamond, named after the mine's discoverer, was found. It weighed 3,106 carats. More than 300 other stones larger than 100 carats were recovered from 1903 to 1930. In 1904, its first full year of operation, the Premier mine produced almost 750,000 carats, and that increased to an average of almost 2 million carats per year from 1907 to 1914, when the mine was closed for 2 years during World War I. The annual production from the Premier mine was the largest in the world in each year of its first decade; its production was comparable to the combined annual production from all of the De Beers mines.

The Premier mine was the first major challenge to De Beers, which had enjoyed virtually complete control of rough-diamond production since its formation in 1888. The effect of that huge production on prices in the world market was further exacerbated when the management of the Premier mine chose to establish their own marketing organization rather than use the channels already established by De Beers. It was not until 1917 that De Beers managed to acquire the majority of shares·in the Premier mine, but from that time on De Beers was in a position to control the production at Premier and integrate it into the overall De Beers production strategy. De Beers purchased the remainder of the Premier shares in 1977. Today, the Premier mine is per-

Figure 19. Major diamond mines currently producing in South Africa, Namibia, Botswana, Angola, and Zaire. (Adapted from Janse, 1995.)

haps the eighth or ninth largest producer in the world, at 1.6 million carats (1995 data), and it appears to have a remaining life of about 25 years. Only about 20 percent of its production is of gem quality, so about 320,000 carats of gem rough now enter the market each year from the Premier.

The Finsch Mine and Venetia Mines

In 1958 the Finsch mine was discovered about 160 km (100 miles) northwest of Kimberley (Figure 19). It was the first kimberlite pipe of major economic importance to be found since the Premier mine in 1902. De Beers purchased the mine in 1963. A large pipe (17.9 hectares, 44 acres), the Finsch came into full production in 1967 and produced about 2.5 million carats annually through the 1970s, increasing the De Beers production from South Africa by one-third. With a current annual production of 1.7 million carats, the Finsch is an important mine, ranking slightly ahead of the Premier (1.6 million carats). Like the Premier, it yields about 20 percent gems and has about 25 years of life remaining.

In the mid-1970s, almost a century after the original discoveries at Kimberley, a whole new field of 12 kimberlites was discovered by geologists prospecting for copper in northern South Africa. De Beers acquired a lease and developed the Venetia mine from one of those pipes, now the most important mine in South Africa (Figure 19). The Venetia pipe is large (12.7 hectares, 31 acres) and yields about 40 percent gems. Production began in 1991, and the mine produced almost 5 million carats annually in 1993 and 1994, but in 1995 that dropped to 4.4 million carats. Production in that range is anticipated for the next 20 years.

The most productive mine in South Africa in terms of the number of carats produced and the value of its production, the Venetia mine is one of the great diamond mines of the world. In all of Africa, only the Jwaneng mine in Botswana surpasses it in weight of diamonds produced and value. The Venetia mine was not found until almost 100 years after the discovery of the Kimberley mines, even though during that time South Africa had been continually and exhaustively explored using the most modern exploration techniques that were available.

From 1990 to 1995, South African production ranged from 8.2 to 10.2 million carats annually (Figure 8, Table 1), placing it fifth on the basis of weight (behind Australia, Zaire, Botswana, and Russia), with 8.4 percent of the world's production. The three major pipes (Venetia, Finsch, and Premier) accounted for about 85 percent of that production. However, in terms of value [about $1.2 billion (U.S.), or about 20 percent of the total value of world sales of rough], South Africa ranked third behind only Botswana and Russia. It is expected that South African production will be maintained at these levels for the next several decades. It will also be possible to increase production from the Finsch mine and especially the Venetia mines, as they are currently underproducing.

Namibia

In 1908, a railroad worker found diamonds in the sand dunes near Kolmanskop, Namibia, which at that time was the colony known as German Southwest Africa (Figure 13). Although there are kimberlites in Namibia (the Gibeon field), they do not contain diamonds. Therefore, the Namibian diamonds, like those in the alluvial deposits of Namaqualand, are believed to have originated from kimberlites in the interior of South Africa.

In 1909, almost 500,000 carats were produced, and by 1913 production had climbed steadily to more than 1.2 million carats (Figure 20). During those early years, the diamonds produced were small, about 15–20 points, but also like those from the alluvial deposits in Namaqualand, they were predominantly gems and were easily sold. That was the second major diamond discovery in 6 years (after the Premier mine) that was operating beyond the control of De Beers.

The German government issued an imperial edict in January 1909 that established a government monopoly in the Namibian diamond trade and ordered that the diamonds be sold only by Diamant Regie, a quasi-governmental agency in Berlin. Thus both Namibian diamonds and diamonds from the Premier mine were being sold outside the De Beers marketing channel at the

Figure 20. In the early days, from 1908 to 1910, diamonds were recovered from the coastal sands in Namibia by workers crawling on hands and knees. (Courtesy of De Beers.)

Figure 21. After World War I, Germany lost control of Southwest Africa (Namibia) and the buildings of its works in Kolmanskop were abandoned to blowing sands of the Namib Desert. (John Van Couvering.)

same time. By 1911, De Beers was supplying only 31 percent of the diamonds entering the world markets, and its near-monopoly, especially of gem diamonds, was broken, at least temporarily. Furthermore, Europe was experiencing a financial downturn, diamond prices were falling, and World War I was not far off.

Consolidated Diamond Mines/Namdeb Diamond Corporation

After World War I, South Africa gained control of Namibia via a mandate from the League of Nations and sold the diamond deposits to Consolidated Diamond Mines (CDM), in which the Anglo American Corporation, controlled by Ernest Oppenheimer, was a major shareholder (Figure 21). CDM was formed in 1920 to take over and work various diamond concessions and properties in the Sperrgebiet ("forbidden zone") area of Namibia. In 1929, CDM was transferred to De Beers. In 1994, CDM was reconstituted as Namdeb Diamond Corporation Ltd., and it is now jointly owned by the Namibian government and De Beers under the name Centenary.

Onshore Mining

Mining resumed in the Kolmanskop and Elizabeth Bay regions in the 1920s. In 1928 there were major diamond finds in the sands of marine terraces (raised beaches) along the coast southward toward Orangemund. By 1935, those onshore locations were yielding large diamonds (1.25–1.32 carats) at sites close to the mouth of the Orange River, the river route for diamonds from the interior of South Africa.

In 1965, mining of diamond-bearing terraces (beaches) on the foreshore (that part of the beach uncovered at low tide) was initiated (Figure 22). That was an engineering challenge that used massive sand walls to expose submerged diamond-bearing terraces so that they could be mined as much as 200 meters (650 feet) seaward of the high-water mark and 20 meters (65 feet) below mean sea level.

Fifty-six percent of Namibia's current diamond production comes from the 130-km (80-mile) onshore coastal strip north of the Orange River, including the foreshore areas. However, those reserves are dwindling, and production is increasingly coming from deep offshore mining.

Marine (Offshore) Mining

The next logical extension of mining the raised beaches and the foreshore would be submarine mining, the mining of submerged areas farther out to sea, where there were at least eight different levels of buried terraces and beaches, ranging from 20 to 120 meters below modern sea level. They had been forming continually since about 25 million years ago, when the sea level was as

much as 500 meters lower and the shoreline was as much as several hundred kilometers farther into the Atlantic Ocean.

Submarine mining was attempted unsuccessfully in 1954, but in the early 1960s Marine Diamond Corporation, a small company, expanded those efforts and from 1961 to 1963 extracted more than 50,000 carats from the seafloor relatively near the coast. Marine Diamond was subsequently acquired by De Beers and was essentially the forerunner of De Beers Marine (Pty.) Ltd., which now operates mining and prospecting vessels primarily off Namibia, and to a lesser extent in South African waters (Figure 23).

Figure 23. A mining vessel in the De Beers Marine fleet working off the coasts of Namibia and Namaqualand. It is capable of operating in depths up to 200 m (660 feet). (Courtesy of De Beers.)

De Beers Marine is the main contractor for Namdeb, which owns the Namibian mining leases. Other companies also have leases for marine exploration in Namibia and South Africa; however, Namdeb and De Beers Marine dominate by virtue of their extensive lease holdings and advanced technology. Most of the other operations are small, and some employ divers, who are limited as to how deep they can go and how far from shore.

The success of deep marine (offshore) mining is reflected in the production data from Namibia. In 1989, only 21,545 carats were recovered by Namdeb, but that rose steadily to 457,397 carats in 1995, which represented 34 percent of the Namdeb total (1,341,184 carats) from all sources. No production has yet been reported from the deep seabed off Namaqualand.

Origin of the Deposits

A unique combination of geologic and geographic factors was responsible for the presence of diamonds in large concentrations off the west coast of southern Africa in Namibia and South Africa: the presence of many diamond-bearing kimberlite pipes in the Orange River basin, extensive erosion of those pipes over the past 100 million years, and the consistent drainage along the ancient and current paths of the Orange River that transported diamonds from the interior west to the Atlantic Ocean (Figure 24). Wave and wind actions in the Atlantic Ocean toward the north resulted in a drift of the diamonds in that direction. They also had a grading effect, with the stones of decreasing sizes being swept increasingly farther north. Thus it is possible to selectively locate and mine specific areas of the seafloor for diamonds of a given size.

In 1995, Namibia produced 1.3 million carats of diamonds, making it the eighth largest producer of diamonds, on a weight basis. Calculations indicate that 1.5 billion (U.S. billion) carats of diamonds, 90–95 percent of gem quality, can be expected in the marine seabed off the shores of Namibia and South Africa on the continental shelf. That is the largest known resource of gem-quality diamonds in the world, and it is almost 14 times the current annual world production of about 108 million carats, even ignoring the fact that most of the world's current production is not of gem quality.
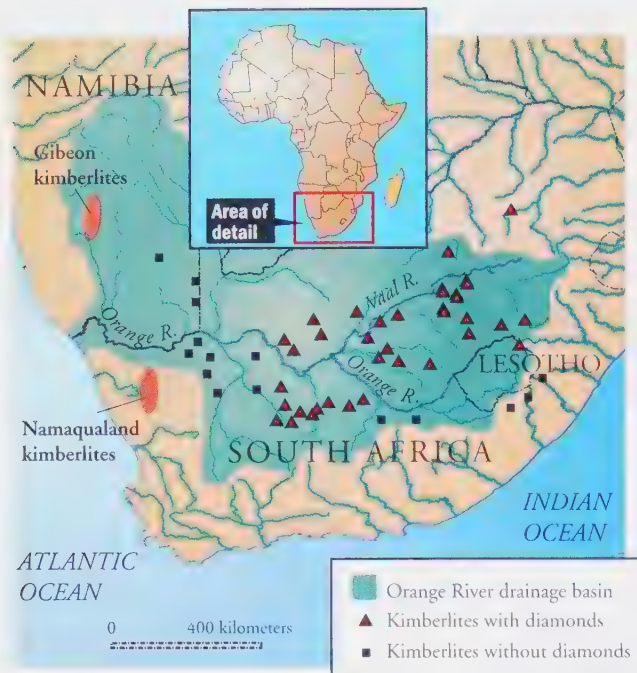
Figure 24. The Orange River drainage basin in southern Africa showing the present position of the Orange and Vaal rivers, the locations of kimberlites with and without diamonds in the Orange River basin and the Gibeon (Namibia) and Namaqualand (South Africa) kimberlite fields, both of which are barren of diamonds. Alluvial-deposit diamonds have been found throughout the basin, but the vast majority has been transported west to the Atlantic Ocean, where they now rest in marine, beach, and related deposits. (Adapted from Gurney et al., 1991.)

Zaire

From 1903 to 1909, diamonds were found in gravel deposits in several rivers in the headwater area of the Congo (now Zaire) River in the tin- and copper-rich areas of the Shaba province, southeastern Zaire (formerly the Belgian Congo), but there has never been significant production. The diamonds are believed to be derived from kimberlites of no economic promise on the Kundelungu Plateau in the same general area (Figure 19).

The first important diamond production in Zaire came from the Tshikapa (also called Kasai) area, where diamonds were discovered in 1907 in alluvial deposits in and along the Kasai River and its tributaries. Those diamonds, about 40 percent with gem value, were of excellent quality, although generally small (average 0.1 carat). In 1917, more than 100,000 carats of rough from that area entered the market, thus signaling the emergence of Zaire as a significant diamond producer.

The Tshikapa region has been a steady producer of good-quality small stones, generally at least 200,000 carats annually; since the late 1980s, perhaps 600,000 carats. The original source of the diamonds has not been found. Most likely they came from the weathering of kimberlites in northeastern Angola.

One of the world's most prolific sources of diamonds is the deposit at Mbuji-Mayi (today known as Miba), about 300 km (180 miles) east of Tshikapa. The first diamonds were found along the Bushimaie River and its tributaries in 1918, and they originated from several small kimberlites discovered in 1946. The diamonds, typically cubes with an opaque coating, were found in eluvial (directly above) or colluvial (transported downslope) deposits originating from the kimberlites, as well as alluvial deposits in associated streambeds).

Production of diamonds from Mbuji-Mayi began in 1921, and by 1928 the output reached 1 million carats. From 1961 to 1964 it reached a peak of about 18 million carats annually, of which only about 2 percent were gems (although that was a small proportion, it was 360,000 carats of gem rough). In recent years, production from the mines has decreased to about 5 million carats per year.

Zaire is now the world's second largest producer of diamonds, by weight (20 million carats in 1995), after Australia. Of that, 6 percent are of gem quality (much of that from the Tshikapa area), 40 percent are of near-gem quality (cuttable Indian goods), and the rest are of industrial quality. The bulk of the Zaire production is from alluvial deposits, most of which is smuggled out of the country. The Mbuji-Mayi mine produced about 5.6 million carats in 1995, and that was sold to De Beers.

Angola

The main diamond deposits in Angola are found in the Lunda Norte area in the northeastern part of the country, just south of the Tshikapa fields of Zaire (Figure 19). The first diamonds were found in 1912, when exploratory surveys in Zaire along the diamond-bearing rivers in that country were extended into Angola. In recent years, the main producing region in Angola has been the Cuango River valley (about 80 percent of the total production), with smaller production sites near Lucapa and Andrada. The production is almost totally from alluvial deposits. Only very limited production comes from the gravels overlying or adjacent to a few kimberlite pipes.

Alluvial Production

Production of diamonds began in 1916, and Angola became a major source in 1921, when 100,000 carats were produced. That gradually increased, reaching 2.4 million carats in 1973, but since then annual production has been erratic, ranging from 270,000 carats (1986) to 2.7 million carats (1993), because of a civil war. Nevertheless, 1.9 million carats were produced in 1995 from both legal and illicit sources, which ranks Angola as the sixth largest producer in the world, based on weight. Those diamonds were predominantly gems (about 70 percent), and about 15 percent weighed 2 carats or more.

Kimberlites

The first kimberlites were found in 1952, and since then the number has risen to about 600, mainly in the northeastern part of the country. Those pipes probably are the sources of the diamond-bearing alluvial deposits in Lunda Norte and in the adjacent Tshikapa area in Zaire.

The kimberlite pipes have great economic potential. However, they have not been thoroughly evaluated, owing to the ongoing civil war and social unrest that began about the same time as their discovery. At least five promising pipes have been identified in Lunda Norte, some of which are large – the Catoca pipe covers 66 hectares (163 acres). Systematic exploration for additional pipes would be justified on geologic grounds, and numerous international companies, including De Beers, have shown interest.

Production is likely to increase considerably in the near future, and in the next decade the development of large production from one or more kimberlite pipes is a reasonable possibility. Thus, Angola has the potential to join a select group of the world's major suppliers of diamonds, those that produce more than 10 million carats annually.

Botswana

The discovery of three rich kimberlite-pipe deposits by De Beers in Botswana (formerly Bechuanaland) from 1967 to 1973 was one of the two

great success stories in diamond exploration in the twentieth century, the other great find being in Russia. All diamond production in Botswana comes from kimberlite pipes.

Much of Botswana is situated on the Kalahari Craton, the same geologically ancient, stable plate that is host to all the famous diamond-producing pipes in South Africa, from Kimberley to Venetia. Therefore, on the basis of geologic considerations, it was prudent to extend the search for diamonds to Botswana, as was done by several mining companies beginning in the 1950s. In 1959, three small alluvial-deposit diamonds were found in the Motloutse River, in northeastern Botswana, but they could not be traced to a primary source.

The Orapa Mine

Two-thirds of Botswana is covered by the Kalahari Desert, a vast expanse of sand dunes separated by grass- and bush-covered valleys with no surface water. De Beers began exploration in 1955, centered in the less sandy, eastern part of the country. In 1967, after 12 years of prospecting, the Orapa pipe was found, one of 30 known pipes in a large kimberlite field. Orapa is the only known kimberlite pipe in Botswana that is not overlain by sand.

The Orapa pipe covers 106.6 hectares (263 acres), the second largest economically important kimberlite pipe in the world (the largest is the Mwadui, in Tanzania). Production began in 1970, and through 1978 Orapa had produced 2.5–3.0 million carats annually; that has since increased to about 5.5 million carats.

The Letlhakane Mine

Two smaller pipes, Letlhakane 1 (11.6 hectares, 29 acres) and Letlhakane 2 (3.6 hectares, 9 acres), were discovered in 1968, one year after Orapa, 48 km (30 miles) to the southeast. Those pipes came into production in 1976 with 300,000 carats per year, and that gradually increased over the next decade. Since 1990, they have produced about 1 million carats annually.

The Jwaneng Mine

After the discoveries of Orapa and Letlhakane, prospecting shifted into the Kalahari Desert, and the Jwaneng pipe was found in 1973 (Figure 25). It is one of 11 kimberlites in an area covered by 25–60 meters (82–198 feet) of sand. The Jwaneng pipe consists of three lobes, with a combined area of 54 hectares (133 acres). Mining began in 1982 at an annual rate of 5 million carats, which gradually was increased, so that since 1990 it has ranged from 8.5 to 10.5 million carats. At present, Jwaneng is the second most productive mine in the world in terms of weight of diamonds recovered (about 10.5 million carats produced in 1995), after the Argyle pipe in Australia. It is the most productive in terms of revenue generated.

Figure 25. The Jwaneng open pit mine in Botswana is the most valuable diamond mine in the world. Its production of about 10.5 million carats in 1995 had a value of about $1.2 billion (U.S.). (Rory O. Moore.)

Botswana is now the world's third largest producer of diamonds, by weight (number of carats), surpassed only by Australia and Zaire, both of which produce predominantly industrial diamonds or poor-quality gems of low value that are not generally used for jewelry. In terms of value, however, since the early 1990s Botswana's diamond production has been the highest in the world (20–25 percent of world production by value).

Botswana's diamond reserves, especially at the Orapa and Jwaneng mines, are immense. Those mines should produce for at least another 75–100 years at the present rate. At this time, all three mines are open pits, and a 50 percent increase in production was reported at the end of 1996.

Other Diamond-producing Countries

There are 10 additional countries in Africa that currently produce diamonds or have produced them in the past in negligible to minor amounts (less than 1 million carats per year). Those countries are, in approximate order from south to north, Lesotho, Swaziland, Zimbabwe, Tanzania, the Central African Republic, Ghana, Sierra Leone, Guinea, Liberia, and the Ivory Coast. From Table 1 it can be seen that in 1995 only five of those countries produced more than 200,000 carats of rough diamonds, mostly from alluvial sources: Ghana, the Central African Republic, Guinea, Sierra Leone, and Zimbabwe. All of those countries are located on cratons and therefore could be significant producers when diamond-bearing kimberlites or lamproites are found.

RUSSIA: THE FIRST MAJOR PRODUCER OUTSIDE OF AFRICA

Alluvial-deposit diamonds were discovered in the Ural Mountains in 1829 as a by-product of gold mining, but they were little more than mineralogical curiosities and were never mined commercially. In the late 1930s, Vladimir S. Sobolev recognized similarities in geologic structure and Archean age between the central Siberian Shield (Yakutia Craton) and the Kalahari Craton underlying South Africa and Botswana. He concluded that major diamond deposits

Figure 26. The Yakutia Craton in eastern Siberia is the world's second most productive craton for gem diamonds, after the Kalahari Craton in southern Africa. It is divided into 15 archons surrounded by protons. Only the Anabar Shield and Aldan Shield portions are exposed; the rest of the craton is covered with sedimentary rocks into which the kimberlites have been intruded. The main producing kimberlite areas are the Malaya Botuobiya field (B) and the Daldyn and Alakit fields (A). Important kimberlites that are producing or may produce in the future are cited. (Adapted from Levinson et al., 1992.)
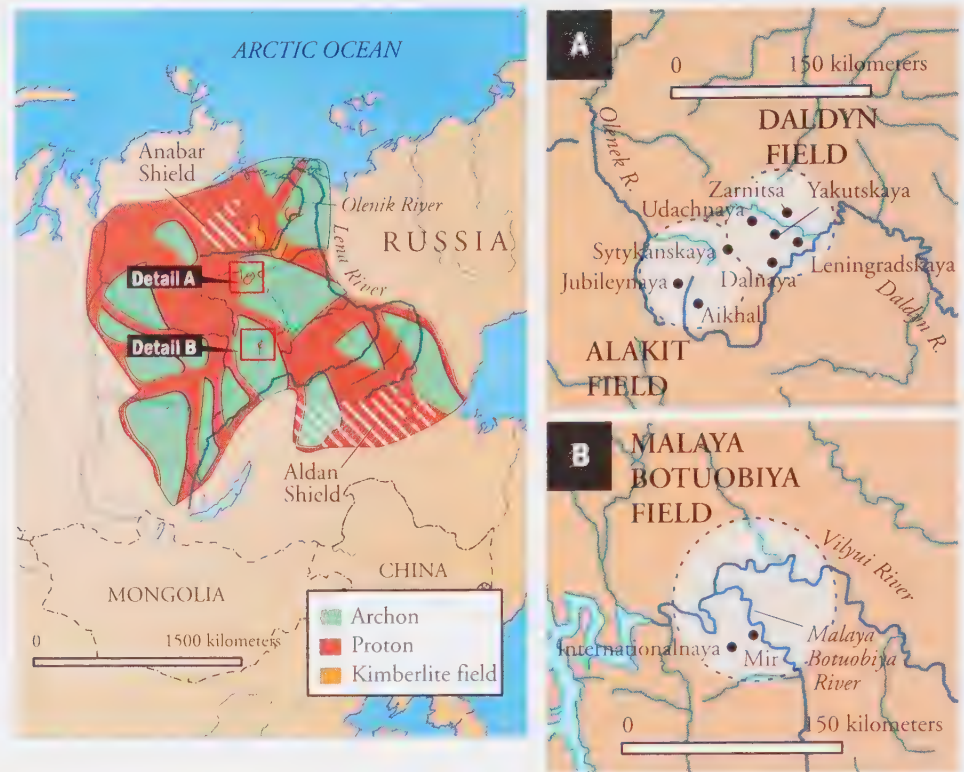
might be found in Siberia. Prospecting based on that assessment began in 1947, and within a decade Russia had one of the two greatest exploration successes of the twentieth century.

Exploration parties worked under extremely difficult conditions in various parts of Siberia. The main exploration technique was to follow the trails of diamond-indicator minerals (e.g., pyrope, garnet, and ilmenite) in streambeds in the hope of finding their primary sources in diamond-bearing kimberlites. In 1953, the first diamond was found in a gravel deposit in the Malaya Botuobiya River, a tributary of the Vilyui River (Figure 26), in the Siberian republic of Sakha (formerly Yakutia), and in 1954, the first kimberlite, Zarnista ("dawn"), was found in the Daldyn field. In the summer of 1955, two very rich and important kimberlites, Mir ("peace") and Udachnaya ("success"), were discovered within 10 days of each other, but about 400 km (250 miles) apart. By 1956, more than 500 kimberlites had been discovered.

Kimberlites

There are now about 1,000 known kimberlite pipes or dikes on the Siberian Platform in 20 kimberlite fields, most of which are located in the northeastern part of Sakha. At least 150 of those contain diamonds, but only 7 have produced diamonds economically, and they are found in three fields: Malaya Botuobiya, Daldyn, and Alakit (Figure 27). The most famous of those pipes

are Mir (it has produced some of Russia's best diamonds, but is now flooded), Internationalnaya (small, extremely high-grade output, but now mined out), and Udachnaya (the main producer today). In addition, there is Jubileynaya ("jubilee"), a large pipe that had been expected to be in production by the mid-1990s, but has been delayed.

Diamondiferous kimberlites have been discovered more recently on the Baltic Shield near Arkhangel'sk, on the White Sea in northwestern Russia, near the border with Finland. Some are believed to be very rich, and it is expected that at least one (Lomonosovskaya), and perhaps as many as five, will be developed into mines. That kimberlite field, like those in Sakha, lies close to the Arctic Circle and will be difficult to mine in that harsh environment. It faces many hurdles before production can begin.

Figure 27. The Internationalnaya kimberlite, near the Mir pipe, has terminated above-ground operations, and underground operations have been hampered by waters that emit toxic gases. (Courtesy of Almazy Rossi-Sakha Co., Ltd.)

Production

The first diamond mining in Russia began at Mir in 1957, augmented by mining of the alluvial deposits associated with many of the Russian kimberlites. That was soon followed by mining at Internationalnaya, Udachnaya, and other sites.

Production increased slowly after 1957, in part because of the difficulty of mining in an inhospitable and remote area, but by 1970 annual production had reached 7.85 million carats. From 1971 until 1985 it ranged between about 9 and 11 million carats. From 1986 to 1991, production peaked at about 15 million carats annually. Unofficial estimates put production above 20 million carats between 1978 and 1987. During the 1980s, the Russians stockpiled diamonds, and some estimates suggest that at its peak the stockpile reached about 80 million carats, worth about $8 billion (U.S.) including about $1 billion in cut gems, about one-third of which were of gem quality. That was a huge reserve, in view of the fact that the total value of rough diamonds sold by De Beers in 1995 was $4.83 billion (U.S.).

Since 1992 and the fall of the Soviet system, annual production has gradually decreased to about 12.5 million carats. Such figures are based on weight and do not take into account the fact that the Russian production has a relatively high percentage of gems (20–25 percent); therefore, for much of the period from 1970 to 1990 the value of Russian production exceeded that of any other country.

At 12.5 million carats annually, Russia is the fourth largest producer, on the basis of weight (Table 1). In terms of value, that production is worth $1.2 billion (U.S.), second behind Botswana. About 80 percent of the current production comes from Udachnaya, the only mine now fully operational. It is

probably the third most productive mine in the world today, based on the number of carats produced, behind the Argyle in Australia and Jwaneng in Botswana.

Other mines, such as Mir, are in serious disrepair because of flooding, mud seepage, or leakage of dangerous gases from the enclosing rock formations, and some have reached depths at which underground mining must be initiated. Therefore, these mines are not contributing as much to overall Russian production as they did. Foreign loans have recently been secured to renovate the existing mines and develop new ones. For the foreseeable future, Russian production likely will remain at about its current level, which represents about 12 percent of the world's supply, on a weight basis, and about 20–25 percent of the world's gem-quality stones.

Marketing

The mid-1950s discoveries of major, high-gem-content diamond pipes in Russia could have posed the first threat to the maintenance of an orderly market for rough diamonds since De Beers had gained control of Namibian production about 40 years earlier. However, beginning in 1957, De Beers and Russia entered into a series of long-term contractual relationships, the details of which have never been revealed, that funneled most of Russia's rough exports to the international markets through De Beers. Some of the Russian production was used internally for the development of a cutting industry, and the cut gems were sold internationally, but independently of De Beers.

Since about 1993, relations between De Beers and Russia have been strained at times, in part because of Russia's need for hard currency. Russia and De Beers signed a memorandum of understanding in February 1996, maintaining the De Beers position as the exclusive buyer of most of the Russian rough diamonds for export and essentially continuing the previous arrangements, with some modifications. However, as of early 1997, it is unclear whether or not that agreement will be extended.

AUSTRALIA: THE WORLD'S CHIEF
SOURCE OF DIAMONDS

Diamonds were first found in Australia in 1851 as isolated grains encountered during the washing of alluvial gold in New South Wales. The most productive of several areas was discovered in 1875 near Copeton, New South Wales, about 450 km (280 miles) north of Sydney. The total recorded production from all deposits in New South Wales amounted to about 202,000 carats, but the unrecorded production probably was much larger. Most of the dia-

monds were small and of low quality, and no primary source for the diamonds in eastern Australia has ever been found.

Alluvial-deposit diamonds were found in Western Australia, near Nullagine, in 1895, but their source still is not known. Serious exploration for diamonds in Western Australia by several major companies, including De Beers, did not begin until the late 1960s.

Discovery of the Argyle Mine

In 1971, a consortium of five small companies formed the Kalumburu (later Ashton) Joint Venture to explore for diamonds in the northwestern part of Western Australia. The consortium specifically investigated the Kimberley Plateau area. Geologically, part of that region is a craton underlain by very ancient rocks (i.e., an archon) (Figure 1), and thus it has important similarities to the diamond-bearing Kalahari Craton in South Africa and Botswana and the Yakutia Craton in Siberia.

Exploration began in 1972, and by 1976 the first kimberlite was discovered in the Ellendale area. That led to the discovery of diamonds in several alluvial deposits. Eventually, in 1979, after 7 years of exploration, the large AK1 pipe (46 hectares, 114 acres), now called the Argyle mine (Figure 28), was discovered by following a trail of diamonds recovered from gravel deposits in Smoke Creek.

The rock hosting the diamonds at Argyle is not kimberlite; rather, it is another very rare type of rock originating in the Earth's mantle, called lamproite, which is similar to kimberlite. The Argyle pipe is unique in two ways: (1) It is the first primary diamond deposit found in any rock other than kimberlite, although several diamond-bearing lamproites have subsequently been recognized. (2) It is not located within the most ancient part, the archon part, of the craton, but rather is found in the younger proton section. The theoreti-

Figure 28. Aerial view of the Argyle diamond mine and processing plant in the remote Kimberley region of Western Australia. (Courtesy of Argyle Diamonds.)

cal basis for modern diamond exploration had to be revised to take into account the lessons learned from the discovery of the Argyle pipe.

There are at least 100 other lamproites in the Kimberley area of Western Australia, many of which contain diamonds, though not in economic quantities. There are also numerous kimberlites, and likewise they have shown no economic potential.

Diamond Characteristics

The diamonds from the Argyle mine are small, averaging about 0.08 carat or 8 points, and its largest crystal found in May 1992, by which time more than 200 million carats had been mined, weighed 41.7 carats. The vast majority (more than 90 percent) are classified as brown or yellow in color, with only 5 percent of the production considered to be of gem quality. About 45 percent is low-quality, near-gem material that is cut in India, and the remainder (50 percent) is of industrial grade.

A unique feature of the Argyle mine is that it yields very small but consistent numbers of rare and valuable pink and red (or purple) diamonds (Figure 29). In the 11-year period from 1985 to 1995, Argyle produced a total of 600 such stones, weighing 498.07 carats in cut form, or about one stone per week averaging 0.87 carat (cut). They are sold by tender and in recent years have gone for about $100,000 (U.S.) per carat.

Figure 29. The Argyle mine yields extremely rare and valuable pink diamonds here set in elaborate drop earrings. (David Behl.)

Production

Production in the Argyle area began in 1981 with the mining of alluvials that had been eroded from the pipe and concentrated in adjacent streams. Mining of the Argyle pipe began in late 1985, and by 1986 the total production had reached 29.2 million carats, primarily from the pipe, making Australia, from that time forward, the largest producer of diamonds, by weight. Since then, production has gradually increased to an annual rate of about 41 million carats, and alluvial production has essentially ceased. The Argyle mine produces (1995 data) about 38 percent of the world's diamonds, on a weight basis, but only about 6 percent on a value basis.

The Argyle mine will continue to be the world's leading producer of diamonds until about 2005. After that time, it will no longer be economically feasible to continue to operate the Argyle as an open-pit mine. A decision will have to be made within the next few years whether or not to prepare for underground mining, a much more expensive technique that normally can be expected to produce fewer diamonds on an annual basis.

Exploration for new diamond deposits continues unabated in various parts of Australia, such as in the Northern Territory, where there are several archons and protons. Exploration is also being conducted offshore along the northern

coast, north of Argyle, in the hope of finding marine deposits analogous to those off the coasts of Namibia and Namaqualand (South Africa). However, no major finds have been reported.

Marketing

From the start of production in 1981, most of the Australian (i.e., Argyle) production was marketed through De Beers, with a small amount (5 percent) retained by Argyle for sale on the open market. However, at the end of June 1996, Argyle announced that it would no longer market its diamonds through De Beers. Argyle has now begun marketing operations in Antwerp and India, but it is too early to determine what effect this change will have on the diamond market. Most of the Argyle production has been going and will continue to go to India.

OTHER PRODUCING AREAS

There are three other countries in which diamonds have been produced or soon will be produced: China, the United States, and Canada.

China

Alluvial-deposit diamonds were found in two provinces of China, Hunan and Shandong, in the middle of the nineteenth century. There was minor alluvial production in Shandong starting in the late 1940s, and some stones larger than 100 carats were found. The first kimberlite pipe was found in 1969, and since then kimberlites or lamproites have been found in 14 of 27 provinces and autonomous regions.

China has three cratons containing archons or protons that are geologically favorable for the presence of diamond-containing primary rocks. These are being actively explored by Chinese and international companies. At present, at least six kimberlite pipes and dikes are producing diamonds. About 250,000 carats have been produced annually since 1980. The diamonds are relatively small, and all are used internally for domestic gem cutting or industrial purposes.

United States

Diamond mining in the United States has been negligible in the past; however, as significant portions of the country are underlain by ancient cratons (Figure 1), it is possible that important sources of diamonds will be found in

the future. That suggestion gains plausibility from the fact that ever since the early 1840s, diamonds, usually as isolated alluvial occurrences, have been found in such widely separated parts of the United States as the Appalachian and Great Lakes regions and California.

There are numerous kimberlites or lamproites in scattered parts of the United States, ranging from New York to Wyoming in an east–west direction, and from the Upper Peninsula of Michigan to Arkansas in a north–south direction, but most do not contain diamonds. All can be correlated with various cratons that underlie the United States. The most famous of those bodies are the diamond-bearing lamproite near Murfreesboro, Arkansas, and the recently discovered kimberlite cluster close to the Colorado–Wyoming border.

In 1906, the first diamond from a primary host rock in the United States was found at Prairie Creek, near Murfreesboro, Arkansas. That rock was classified as lamproite in 1984. From 1907 to 1933, more than 100,000 stones, averaging 0.25 carat per stone, were produced from that locality. Although a large percentage of the diamonds were of gem quality (40 percent were considered white) and the pipe was large (29 hectares, 72 acres), the mine was not profitable, and formal mining ended in 1919.

In recent years, that locality has been designated the Crater of Diamonds State Park, and it has been a mecca for hobbyists and tourists who pay a small fee to search for diamonds, which are theirs to keep. A 4.23-carat faceted canary yellow from that locality was worn by Hillary Rodham Clinton to presidential inaugural activities in 1993. Recent studies have shown that the pipe is not economically viable as a mine.

Kimberlites were first identified along the Colorado–Wyoming border, known as the "state-line kimberlite district," in 1964, and since then more than 100 kimberlites have been identified within 80 km north and 150 km south of the border. Diamonds were first identified from those rocks in 1975. Several large companies evaluated the pipes in the 1980s, but concluded that they would be unprofitable.

In June 1996, a mine was opened at Kelsey Lake, Colorado, with anticipated production of about 20,000 carats for 1996, and as much as 100,000 carats annually at peak production, starting in 1997. It is the first operating diamond mine in the United States since the end of formal mining at the Prairie Creek mine in Arkansas in 1919.

Canada

Most of Canada is underlain by cratons, making occurrences of diamond-bearing primary rocks such as kimberlite seem likely (Figure 1). In eastern Canada, the first kimberlite was found in 1946. Subsequently, numerous kimberlite pipes and dikes have been discovered in several areas in Ontario and Quebec. Some are diamondiferous, but none shows economic promise at present. Exploration is continuing.

In western Canada, diamond exploration was begun in the 1970s by several large companies, particularly in Saskatchewan and the Northwest Territories. In Saskatchewan, a diamond-bearing, but noneconomic, kimberlite was found in 1988 about 30 km (18 miles) northwest of the city of Prince Albert. In 1989, about 100 km (62 miles) east of Prince Albert, the first of about 100 kimberlites was discovered. Many of those kimberlites are large, and many contain diamonds, but none appears economically promising at this time. Exploration for additional pipes in that region is continuing.

In the Northwest Territories, intermittent explorations by major companies for kimberlites were unsuccessful, and most of the companies had withdrawn from that area by the end of the 1980s. Dia Met Minerals, a small company whose chairman, Charles E. Fipke, had a decade of experience in diamond exploration in various parts of the world, continued the search. Fipke followed the trail of diamond-indicator minerals to the Lac de Gras region, about 300 km (186 miles) northeast of the territorial capital at Yellowknife, and in April 1990 a kimberlite was located under Point Lake (Figure 30). Eventually, Dia Met and its Australian partner, BHP Minerals, found at least 77 kimberlites on their claims, of which at least 42 contain diamonds, with several showing economic promise.

Five of those relatively small pipes (1.8–4 hectares, 4.4–9.9 acres), being operated as if they were one mine, are scheduled to begin production in the second half of 1998. Annual production of 3 million carats (about 30 percent gems) from that mine is expected by 2000. It is believed that in later years that production could double. The projected mine life is 25 years. That one mining project should propel Canada into the position of sixth leading producer of diamonds, on a weight basis, with about 3 percent of the world's production.

The spectacular discoveries by Dia Met/BHP sparked the greatest rush to

Figure 30. The first kimberlite pipe discovered in the Northwest Territories is under Point Lake. The surface of the kimberlite lies about 50 m (165 feet) below the surface of the lake, which is 600 m (1,969 feet) wide. The white objects on the far shore are trailers, on the property as of 1992. (B. T. Evans.)

stake claims ever seen in Canada, and possibly the world. More than 100 kimberlites have now been found in the Northwest Territories alone, many of which are diamondiferous and are now being evaluated by several companies for their economic viability.

The Canadian discoveries are only the latest in what has been a fabulous century of diamond production. The improved understanding of diamond sources, both pipes and their weathered products, combined with improved technology and a steady demand, means that the future is bright for discovering diamonds.

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The World's
Great Diamonds

The diamonds that are called great are both physically large, usually more than 50 carats for near colorless stones or 30 for blues and pinks, and have an additional claim to fame, such as their history, cut, uniqueness, or sheer magnificence. On the pages that follow, we present a number of diamonds that are universally accepted as "great" because of their grandeur and grand histories.

The Hope

A 45.52-carat antique cushion-cut blue diamond mounted in a pendant surrounded by smaller white diamonds, the Hope is perhaps the best-recognized gem in the world. It is a recut version of the Great Blue that was part of the French crown jewels. It is one of the Indian diamonds, probably from the Kollur deposits, brought back to Louis XIV by Jean-Baptiste Tavernier in 1668. Originally weighing 112³⁄₁₆ carats (about 110.5 metric carats), the Tavernier Blue was recut from an irregular form to a heart shape of 67⅛ carats by the king's diamantier, Pitau, and set in an Order of the Golden Fleece.[1] Stolen during the French Revolution and probably recut in London in its present form, it was acquired by the banker Henry Philip

Hope sometime after 1830 for an estimated £18,000. The Hope family sold it in 1901 after which its history is complicated. It came into the hands of jeweler Pierre Cartier in 1909. By refaceting its girdle and creating a new mounting, Cartier endeavored to interest Mrs. Evalyn Walsh McLean, daughter-in-law to Edward B. McLean, owner of the Washington *Post*, in the Blue. The deal was completed in 1910 or 1911. In 1949, two years after Mrs. McLean's death, Harry Winston bought the Hope, which had been evaluated for $176,920, and in 1958 presented the fabulous blue diamond to the Smithsonian Institution. It is displayed in the Harry Winston Gallery at the National Museum of Natural History, where it is the most revered object in all the Smithsonian collections. (Courtesy of National Museum of Natural History, Smithsonian Institution.)

The Regent

A 140.5-carat cushion-cut water-clear, yet faintly blue, diamond. The original stone weighed 410 carats and was discovered in 1701 at the Partial mine along the Krishna River. By an unresolved set of transactions, it was sold to Thomas Pitt, a merchant and

The Hope

president of Fort Madras, for the equivalent of about £20,000. In 1702, Pitt's son brought the stone to England and had it cut to its present form by Joseph Cope. But the elder Pitt was the subject of unflattering rumors about how he acquired the diamond, then known as the Pitt. Disputes ensued which led him to sell the gem to Philippe d'Orléans, regent of France, in 1717 for £135,000, the highest price paid for a gem to that time. With the name of Regent, the diamond was set above the rim of the coronation crown of Louis XV in 1722. Stolen in 1792 with the other French crown jewels, the Regent was found in the attic of a Parisian house and was used as collateral for several loans to finance the French Revolution and ensuing wars. Napoleon treasured the Regent as a talisman and had it

mounted in the guard of his ceremonial consular sword and later in his imperial sword. Last set in a Greek-style diadem for Empress Eugénie in the 1880s, the Regent was one of the several diamonds not auctioned by the Third Republic in 1887. It is displayed today in the Galerie d'Apollon at the Louvre. (Courtesy of Réunion des Musées Nationaux.)

The Sancy

This pale-yellow pear-shaped diamond weighing 55.23 carats has a bewildering history. Its origin in India is lost, so the tale begins with French diplomat Nicolas Harlay de Sancy (1546–1627) who acquired several

diamonds including the Great Sancy either through the Ottoman Court in Constantinople or via Dom Antonio, prior of Crato and claimant to the throne of Portugal, who fled to England after his defeat in 1580 to Philip II of Spain. In 1589, Nicolas de Sancy pledged some of his diamonds to Henry III of France to raise troops and later to Henry IV. By 1595, Sancy needed money himself and searched for buyers throughout Europe; James I of England paid 60,000 ecus in 1604. During the civil war in England, Charles I sold the crown jewels to support the Royalists, and the Sancy passed in 1657 to the Duke of Epernon who in turn sold it to Cardinal Mazarin, the powerful first minister to the French crown. Mazarin bequeathed his ample collection of diamonds to the crown, and the Sancy became a prized jewel that appeared in a variety of settings including the pendant that Queen Marie Leszczyńska wore for great state occasions (see Figure 16, Chapter 6). To support the army during the French Revolution many jewels were sold, including a 53¾-carat diamond to the marquessa of Iranda in Madrid; undoubtedly this was the Sancy. The stone changed hands in Spain, going to Queen Maria Luisa, the wife of Charles IV (r.1788–1808), and then to Manuel Godoy, a bodyguard who became prime minister and her infamous lover. In 1828, Prince Nicholas Demidoff bought it and the next year bequeathed it to his son Paul, whose wife retained it after Paul died, but not without a famous lawsuit over a failed contract to sell this great diamond.

The next owner of the Sancy was Sir Jamsetjee Jejeebhoy, a Bombay merchant, who exhibited it in Paris in 1867. Apparently it was sold to Lucien Falize in 1889 and then to William Waldorf Astor in 1892, becoming a prized possession of his daughter-in-law, Lady Nancy Astor, the first woman to sit in the English House of Commons. In 1978, the fourth Viscount Astor sold the Sancy to the Banque de France and Musées de France for a reported $1,000,000. The Sancy diamond now resides with the Regent in the Galerie d'Apollon of the Louvre. (Courtesy of Réunion des Musées Nationaux.)
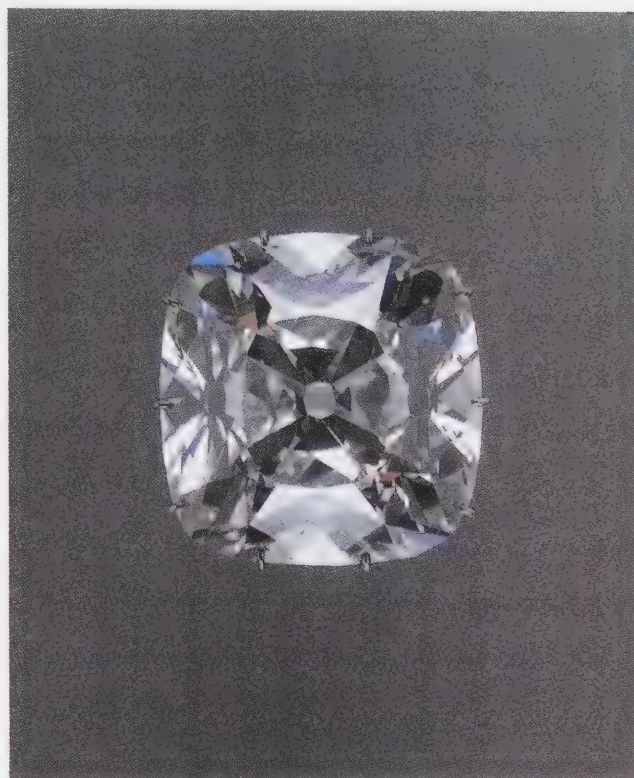
The Regent

The Sancy

The Tiffany

The Tiffany

A yellow octahedron weighing 287.42 carats was discovered in the early stages of mining in Kimberley, South Africa, probably at the Kimberley mine, in 1877 or 1878. The crystal was shipped to Paris, where George F. Kunz, the famed American gemologist working for Tiffany & Co., supervised the cutting of the rough into a 128.54-carat canary-yellow cushion with a total of 90 facets. This number is larger than typical for the time, which was 58 facets, yielding a greater degree of sparkle. Tiffany bought the stone in 1879 and brought it to New York. Although, there have been many opportunities to sell this superb fancy yellow diamond, it has become such an icon for the firm that the concept of selling the Tiffany diamond would seem sacrilegious. (Courtesy of Tiffany & Co.)

The Koh-i-Noor – "Mountain of Light"

Perhaps the most famous of all diamonds, the Koh-i-Noor also has the longest history. Indian legend claims this colorless gem was the forehead ornament in a statue of the son of Surya, the sun god in Vedic mythology, that was mounted on a statue of Shiva, as his third eye, in the village of Thanesar. However the history begins, a chronicle from 1304 counted the diamond, then weighing in excess of 600 carats, among the possessions of the rajah of Malawah. After his successful invasion of northern India, Babur, a descendant of Tamerlane, was given the stone in 1526 either upon entering Agra or in an act of submission by the mother of the vanquished sultan of Delhi, Ibrahim Lodi. The stone thus became known as Babur's diamond. Historians surmise that it remained a prized ornament of Mogul Indian court ceremonies, although Humayun, Babur's son, may have taken it from India during challenges to his rule.

The traveler Jean-Baptiste Tavernier described a number of great Indian diamonds but never mentioned Babur's diamond. His closest reference to one like it is a description of a transparent ornament that dangled within the Peacock Throne at the time of Aurangzeb (1618–1707). Nadir Shah of Persia invaded India in 1739, but his conquest did not yield him the fabled diamond. His vanquished opponent Muhammed Shah, so it is told, hid the jewel in his turban. But Muhammed Shah's secret was revealed by his neglected first wife – or a courtesan, depending on the source of the history – so Nadir Shah planned a feast where, by custom, turbans were exchanged. Upon the exchange, Nadir Shah undid Muhammed's turban, and out rolled the great diamond – "Koh i noor (mountain of light)!" Nadir Shah exclaimed, or so the story goes. Intrigue was as much a part of the stone's history as its Persian owner's until dethroned Shah Shuja sold it to Sikh ruler Ranjit Singh (1780–1839) in re-

turn for protection. The British acquired the Koh-i-Noor from the Treasury of Lahore after the second Sikh war in 1849, by which time the stone weighed only 186 carats; the government kept it as part of repayment by the East India Company for war debts. The stone was presented to Queen Victoria, who had the cutter Voorsanger of the Coster Company in Amsterdam modify the oblong diamond from an Indian-style cut to an oval brilliant, removing a major flaw in the process and reducing the gem to 108.93 carats. The Koh-i-Noor is now mounted in the queen mother's crown on display in the Tower of London. (Courtesy of Historic Royal Palaces.)

The Koh-i-Noor

The Orlov

The Orlov

At 189.6 carats, this faintly bluish-green diamond is intimately associated with the Great Mogul diamond, and both provide vivid although incomplete histories. The connection is their similar appearance and shape, like half a pigeon's egg, and the fact that the Great Mogul's history ends roughly when the Orlov's begins. The Great Mogul was recovered from the Kollur deposits in the mid-seventeenth century, with an original weight in excess of 787 carats, and was one of the great Indian diamonds that Jean-Baptiste Tavernier recorded in his chronicle *Les Six Voyages . . .* (see Figure 17, Chapter 5). The Mogul ruler Aurangzeb (1618–1707) had the stone cut in Italy by Hortensio Borgio, but Aurangzeb considered it a botched job and fined Borgio 100,000 rupees for the mistake. The authenticated history of the stone ends with the fall of the Mogul dynasty to the Persians, after which nothing is recorded of the stone. No diamond of appropriate appearance resides among the Iranian crown jewels.

The earliest information on the Orlov makes better fable than history but ends with the authentic diamond in the Russian imperial scepter. One story places the diamond in the eye of a statue of Vishnu in a Hindu temple at Srirangam, on a river island in Madras state. Allegedly, a French soldier involved in the eighteenth century English-French battles over Tiruchirapalli (Trichinopoly) learned of the fabulous diamond and spent years of obeisance to the priests to gain access to the innermost enclosure of the idol. On a stormy night he stole it and escaped to the English side where he sold the gem to a sea captain for £2,000. He in turn sold it in London for £12,000, where it was sold to an Armenian who passed through Amsterdam on his way to Russia.

Another vivid tale begins with the Persian sacking of Delhi in 1739 and an Afghan soldier in Persian service who appeared slightly later in Bassorah (now Basra, the Iraqi port city). There the poor soldier offered Grigori

Cullinan I

Safras, an Armenian merchant, a hoard of stones but apparently grew suspicious and left for Baghdad, where he sold the lot to a Jewish merchant. Safras followed and learned from the soldier that the gems had been sold. Unsuccessful in convincing the trader to sell, Safras and his brothers duped and poisoned the merchant and, then, made off with the diamonds. Safras increased his share by killing his brothers and moved – small wonder – to Amsterdam, where he set up his business.

Count Grigori Orlov was one of Catherine the Great's lovers and was partially responsible for her ascent to the throne on the death of her husband, Peter III, in 1762. Spurned by Catherine for other lovers, Orlov left Russia in 1775 for Amsterdam to acquire Safras's best diamond for 400,000 rubles. He returned to St. Petersburg and presented the diamond to Catherine on her Saint's Day to regain his favored position. Alternatively, it is surmised that Catherine sent Orlov as an agent to avoid buying the diamond herself and thereby belie her roots as a frugal German. The empress endowed the diamond with Orlov's name and had it set in the imperial scepter immediately below the golden eagle. The Orlov and Imperial Regalia are housed in the Diamond Fund collection of the Kremlin State Museums, along with large diamonds discovered in Yakutia (Sakha) since the 1950s. (Courtesy of Russian Diamond Treasury.)

Cullinan II

The Cullinans

In 1903, far from the Kimberley area, Thomas Cullinan, heading the Premier Syndicate, opened a kimberlite mine that would produce a quarter of the diamonds greater than 400 carats; it was named the Premier mine. It was a pit only 9 meters deep on January 26, 1905, when the mine's surface manager was informed of a stone protruding from the mine's wall and glinting in the sun's rays. He climbed to the point and pried out a phenomenal colorless diamond the size of a fist, weighing 3,106 carats (621.2 grams, or 1.37 pounds) with the recorded exclamation, "Cor, Mr. Cullinan will be pleased when he sees this!" Indeed. The rock of a diamond, dubbed the Cullinan, was first displayed in the Standard Bank in Johannesburg and then was transported to London for viewing by Edward VII. The company had difficulty finding a buyer at £500,000, but General Louis Botha, a former Boer adversary, suggested that the Transvaal government acquire

The Dresden Green

given to the firm I. J. Ascher in Amsterdam. The diamond was too large to facet as a single piece and contained flaws that needed to be removed. Cleaving was chosen as the best method to divide the diamond, four days being required to gouge a 6.5 mm deep kerf for a specially designed cleaving steel. On February 10, 1908, Joseph Ascher succeeded in the cleaving on a second swift strike – the first broke the cleaving steel – after which he promptly fainted. Further difficult cleaving yielded nine fragments that were fashioned into these Cullinan diamonds:

I	550.20 carats	Pear shape
II	317.40 carats	Cushion cut
III	94.40 carats	Pear shape
IV	63.60 carats	Cushion cut
V	18.80 carats	Cushion cut
VI	11.50 carats	Marquise
VII	8.80 carats	Marquise
VIII	6.80 carats	Oblong brilliant
IX	4.80 carats	Pear shape

The Cullinan I, also called the Great Star of Africa, is the largest known colorless diamond gem and was mounted into the redesigned British royal scepter. The Cullinan II, the Lesser Star of Africa, was mounted in the British imperial state crown. The other stones were awarded to the Ascher firm as payment, but were either acquired by the King for Queen Alexandra or were given to the royal family by the Transvaal government. (Courtesy of Historic Royal Palaces.)

The Dresden Green

it as a gift for King Edward in celebration of the grant of responsible government. After suitable politicking in the Legislative Assembly, the Transvaal government ultimately paid £150,000, 60 percent of which was returned as a tax on diamond mining.

The task of fashioning the Cullinan was

The 41-carat pear-shaped Dresden Green is the only large naturally colored green diamond (see Chapter 2). The earliest mention of the Dresden Green is in a letter dated 1726, in which Baron Gautier, assessor at the Geheimes Rath's Collegium in Dresden, refers to an offer from a London merchant to sell the diamond to August I "Der Starke" (the Strong; 1670–1733), the Elector of Saxony, for £30,000. A model of the dia-

mond, probably made before 1741, resided in the collection of the physicist Sir Hans Sloane with a catalogue entry attributing Marcus Moses, a London diamond merchant, as the buyer of the original stone in Golconda, India, and valuing it at £20,000. Ultimately, the diamond was bought by August II in 1742 at the Leipzig Fair from a Dutch merchant named Delles at a price estimated at 400,000 thaler.

The Dresden Green and perhaps the Saxon White diamond (a 49.71-carat cushion cut) were mounted in an Order of the Golden Fleece in 1742 by court jeweler J. F. Dinglinger, but the Dresden Green's present mounting is in a hat ornament fashioned by the court jeweler Diesbach in 1768. In the Dresden palace, the Georgenbau Schloss, the Saxon prince electors fashioned a set of rooms decorated in green for displaying their jewels – the fabled Grünes Gewölbe, or Green Vault. The Soviet Trophy Organization commandeered the Saxon jewels at the end of World War II, taking them to Moscow; they were returned to Dresden in 1958. With other fabulous jewels and garniture, the Dresden Green is displayed in the Albertinum Museum, but reconstruction of the Georgenbau Schloss will recreate the Grünes Gewölbe for the Saxon treasures. (Courtesy of State Art Galleries, Dresden.)

The Kasikci or
Spoon Maker's Diamond

The Kasikci or
Spoon Maker's Diamond

Istanbul, formerly Constantinople, sits at the crossroads of the world and was a center of the diamond traffic coming from India since the sixth century. Given the power and wealth of the Ottoman Empire, it is perhaps surprising that there is only one great diamond, the Kasikci or Spoon Maker's Diamond, in the treasury of the Topkapi Palace Museum. The complex, pear-shaped, rose-cut diamond weighs 86 carats.

According to a colorful story about this diamond that yielded its name, it was discovered in a garbage dump by a fisherman who sold it to a silversmith, a spoon maker, who paid three spoons for the diamond. It was then traded to a goldsmith and from him to other traders. Finally, a dispute broke out among the traders. The sultan learned of the dispute and settled it by keeping the stone for himself; however, as it is a story, we do not know which sultan it might have been. (Courtesy of Topkapi Palace Museum.)
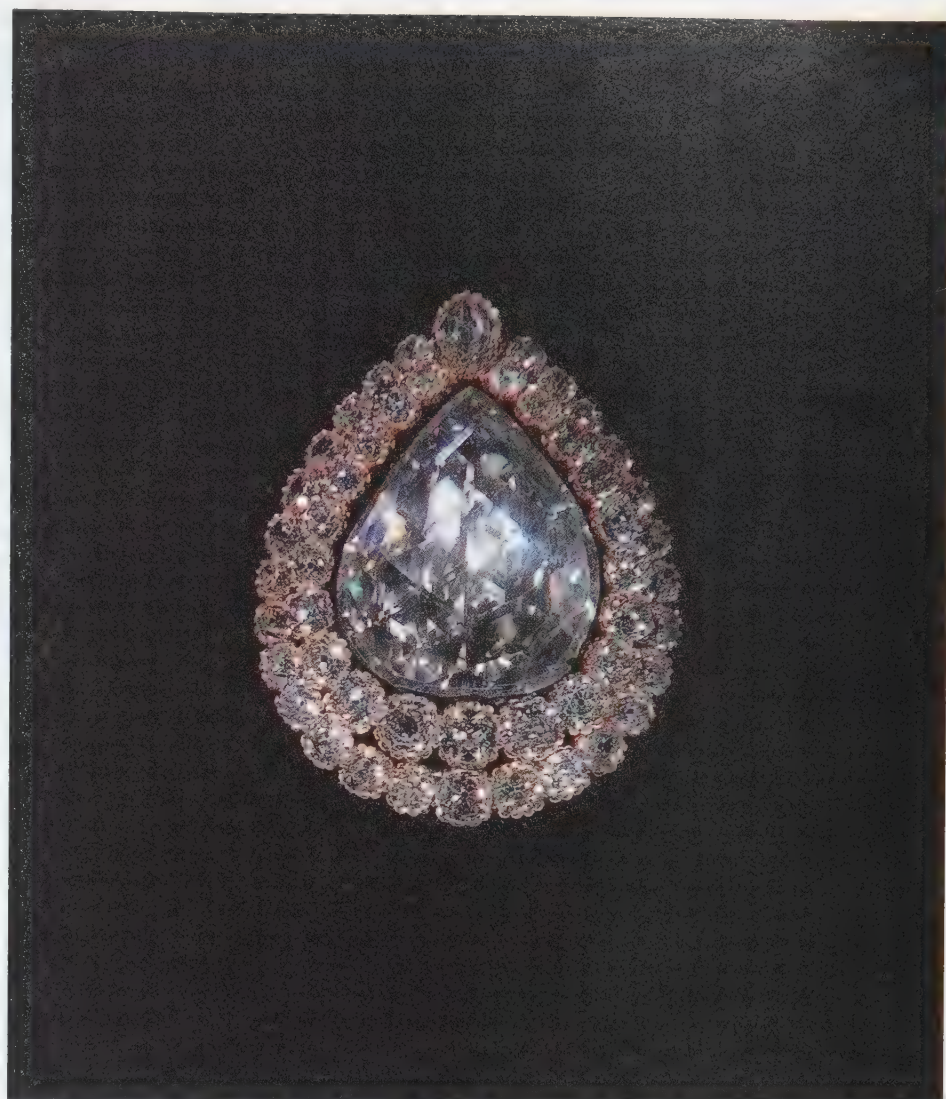
The Centenary

The Centenary

On July 17, 1986, the Premier mine in South Africa produced one of its many great diamonds – an irregular crystal of "the finest water" – weighing 599 carats. This timely discovery permitted Julian Ogilvie Thompson, chairman of De Beers, to announce its discovery at the celebration of the company's 100th year in Kimberley in March 1988 and to give it a fitting name, the Centenary. The task of designing a suitable form for the Centenary fell to Gabi Tolkowsky, a designer of modern symmetric cuts and grand nephew of Marcel Tolkowsky, who established the fundamentals of the modern brilliant cut in 1914. Set up in the basement of the De Beers research facility in Johannesburg, a team of three took a year to design and build the equipment to fashion the stone. Although the latest techniques were available, the fashioning commenced with cleaving off 50 car-

ats of unfavorable portions, and the finishing took nine more months. The finished Centenary weighs 273.85 carats with 247 facets accentuating its brilliance and fire. (Courtesy of De Beers.)

The Shah Jahan Table Cut

This table-cut or flat diamond, measuring 44.6 by 33 by 3.6 mm and weighing 56.71 carats, is one of several that have been credited as a match for the Great Table viewed by Jean-Baptiste Tavernier at Golconda in 1642 (see Figure 18, Chapter 5). However, the attribution is probably an error, the Darya-i Noor and Noor ul-Ain table cuts in the Iranian crown jewels being much more likely matches.[2] Nevertheless, the Shah Jahan Table Cut strongly resembles the diamond of octagonal outline in a turban ornament in a portrait of Shah Jahan (Figure 19, Chapter 5), and the stone correlates reasonably well with a description by Tavernier of a table cut weighing 60 ratis (about 54 carats) shown him by Aurangzeb, Shah Jahan's son, in 1665. Like other Mogul treasures, the table cut appears to have departed India with the Persian invasion in the mid-eighteenth century, after which it may have found its way into the Russian Treasury. The Shah Jahan was offered at auction by Christie's in Geneva in 1985 but was not sold. The diamond exhibits a feature common in gems shaped for Mogul use, a pair of drill holes by which a stone could by sewn to a turban or garment to impart both pomp and courtly fashion. (Courtesy of Christie's Images.)

NOTES

[1] Modern carats are metric, 5 carats to the gram as defined in 1907, and are designated with decimal notation. Prior to 1914 there existed many carat standards that usually were measured with fractions of carats and cannot be converted to metric carats without knowing the standard. In this book we have not attempted to sort out the distinctions except to the extent that decimal notation refers to metric carats and fractions refer to an earlier system. Balfour (1992) provides more information on this problem.

[2] Meen and Tushingham (1968), p. 27

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5

Following the History of Diamonds

GEORGE E. HARLOW

Figure 1. An Indian gold necklace with flat-cut diamonds, pearls, and emeralds (enamel on the opposite side), from the early nineteenth century, a typical style for Indian adornment for many centuries. (Harold and Erica Van Pelt/courtesy of American Museum of Natural History.)
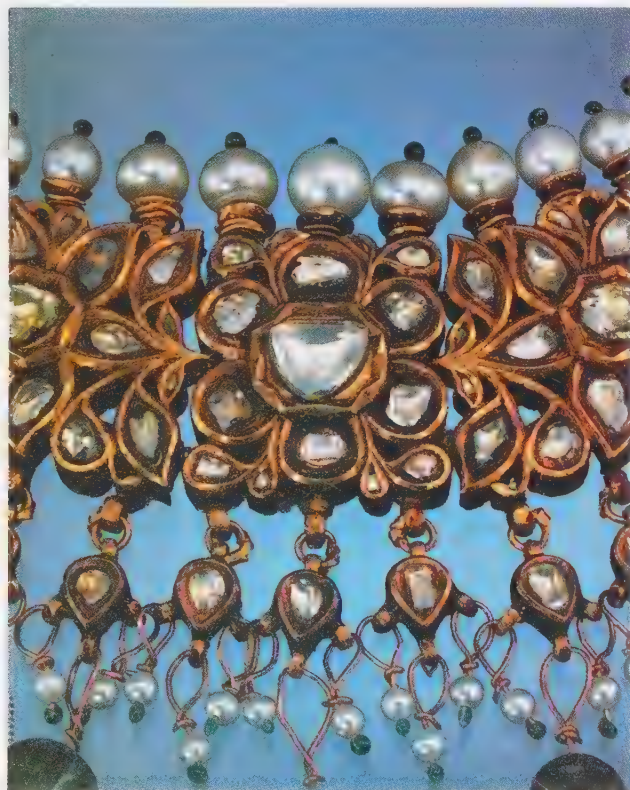
WHAT IS IN A NAME? When digging into the early history of anything, one can encounter the problem of signification: Did a given word have the same meaning in, say, Homer's time that it has today? "Diamond" is a fine example of that problem. The western European context for "diamond" is derived from the Late Latin *adamas* and the earlier Greek διαμάντε, transliterated as *adamao* – "I tame" or "I subdue." The adjective *adamas* was used to describe the hardest substances known, and ultimately it was transformed to the noun that was synonymous with the mineral diamond.

Depending on the time and place, the hardest substance known may have been the mineral we know as diamond, but if diamonds were not yet known, then *adamas* may have been used to designate corundum, the next hardest mineral, which is much more common than diamond (the gem variety of corundum is sapphire); or in contexts in which neither of those minerals was known, *adamas* may have been used for something else that was considered "indomitable." Thus, in dealing with the early written records, particularly the Greek and Roman texts, one must be careful about deciding that *adamas* signifies the mineral we know as diamond. When it comes to correlating the archaeological findings with the written record, one looks for diamonds in art objects or in the remains of archaeological sites, as well as for the "tracks" of diamond – that is, objects that were fashioned using diamond as an ultrahard tool. After all, diamond is the ultimate material for scratching, engraving, and polishing all hard materials, and the only one for fashioning another diamond.

DIAMOND HISTORY STARTS IN INDIA

The problems of translation and interpretation notwithstanding, there is overwhelming agreement that before the sixth century C.E.,[1] India was the only known source of diamonds, and there was no non-Oriental source until discoveries in the New World in the early eighteenth century. India is the focus of our examination of the earliest mentions of diamonds in literature, the myths and conceptions surrounding them, their uses as adornments and tools, and their role in the expansion of trade – all the factors that have made them the valued objects they are today. We do not know when diamonds were first recognized in India, but we can offer estimates based on the earliest evidence.

The words most frequently used for "diamond" in Sanskrit are transliterated as *vajra*, "thunderbolt," and *indrayudha*, "Indra's weapon" (Figure 2). The symbolism of the thunderbolt and its use as the principal weapon of Indra, the warrior god of Vedic religion, already indicates much about the Indian perception of diamonds. The earliest known text that mentions *vajra*, discovered only in 1905, is the *Arthasastra*. This Sanskrit text, attributed to Kautiliya, a minister to Chandragupta, who founded the Mauryan Dynasty in northern India, is generally dated to 320–296 B.C.E., but could be as recent as 150 C.E.[2] Translated as *The Lesson of Profit*, it is a manual for administration and taxation and it includes a few entries on diamond and other gems.

The *Arthasastra* provides the following information about diamonds: The sources included four places and two mountains, as well as the general statement that "the mine, the stream and miscellaneous are the sources."[3] The attributes that added up to excellence in all gem materials were "hexagonal, square or round, of a flashing color, having a suitable form, clear, smooth, heavy, lustrous, with lustre inside and imparting lustre – these are the excellences of gems."[4] For diamonds, color was "like the cat's eye, the *sirisa*-flower [blue-green], cow's urine, cow's fat, pure crystal [or] the *mulata*-flower [unknown], and of the color of any one of the gems."[5] Thus there was little constraint on color. But the most informative statements are that "[a diamond that is] big, heavy, capable of bearing blows, with symmetrical points, capable of scratching a vessel [containing water], revolving like a spindle and brilliantly shining is excellent. That [diamond] with points lost, without edges and defective on one side is bad."[6] Although the description in the *Arthasastra* is somewhat vague, the basis for differentiating sapphires and rubies from diamonds was more than color, and it has been argued that the form with "symmetrical points" that could scratch ("the *vajra* in the glass [?] vessel filled with water scratches the vessel when shaken") and would

Figure 2. A Trichinopoly painting (1820) of Indra riding his white celestial elephant, Airavata. Indra has the demeanor of a peaceful god, although he is still carrying stylized versions of his weapons, including indrayudha *(the thunderbolt, a* vajra*) in his lower right hand. (Courtesy of Trustees of the Victoria and Albert Museum.)*

revolve brilliantly shining is strong evidence that a fine *vajra* was a diamond octahedron. Recall that *vajra* means "thunderbolt"; so flashing brilliance must have been an important characteristic. All those attributes of color, luster, form, and hardness can be particularly assigned to diamond. There are two other relevant comments: that some diamonds and other gems were imported from the south[7] and that export of gems was forbidden.[8] From that evidence it has been argued that diamonds must have been discovered, recognized as something special, ascribed value and virtues, and hoarded and traded (imported) at some time before 400 B.C.E.

What about archaeological evidence? There have been no reports of diamonds being found as artifacts at any archaeological sites dating to periods earlier than 100 C.E. However, there is indirect evidence of diamond during much earlier periods. In the late 1980s, two doctors of orthodontics and dentistry turned their attention from drilled teeth to the archaeological evidence concerning drilled beads and the history of drilling stones. Leonard Gorelick and John Gwinnett looked at the morphology of holes drilled in hard stones (carnelian, quartz, garnet, etc.), made by using a bow to spin an iron spindle with two small diamond splinters hafted at its end, an archaic but still-used method for drilling beads in Cambay, India. The holes are cylindrical and are characterized by conspicuous concentric grooves, unlike the marks left by any other modern or ancient drilling technique – the signature of that particular diamond technology (Figure 3). As beads are common archaeological finds, those with concentric groves in a cylindrical hole can be evidence of the use of diamond even when no diamond drill or documenting literature can be found. By studying beads from sites in Sri Lanka, India, Thailand, Yemen, and Egypt, Gorelick and Gwinnett discovered evidence for the use of diamond drills prior to about 700 C.E. at all of the sites studied, and as early as the fourth century B.C.E. in Yemen. Their findings do not extend the presence of diamond to an earlier period, but do provide confirmation of what was already known, and their data indicate export of either the beads or the drilling technology.

Attributes of Diamonds

The *Ratnapariksa* of Buddha Bhatta, a manual from the fifth century C.E., translated roughly as the *Examination of Precious Stones*, describes the attributes, valuation, and sources of principal gems.[9] Such a manual is referred to as a *ratna sastra*. The *Ratnapariksa* is a compendium of prior knowledge and a summary of the Indian perspective, and it is far more informative about diamonds than is the *Arthasastra*. Buddha Bhatta introduced his summary of the attributes of diamond with its "origin myth." Origin myths are among the most significant legacies of any culture. In Hindu culture, the origins of all things are considered to carry great significance, and the story of the origin of

Figure 3. Drills that use twin diamonds (top) leave concentric grooves in the holes these drills form in hard-stone beads, as shown on the silicone cast (bottom). The concentric grooves are diagnostic of the use of a twin-diamond drill. (From Gwinnett and Gorelick, 1991.)

diamond from a mighty king, Bala, offers a magnificent insight into what Indians deemed of value:

There was a powerful king of the Danavas named Bala,[10] endowed with great strength [and he] proved his valor by conquering the three worlds.[11]

In more than one battle, Divaspati was vanquished by him, and the wife of Heros, Sachi, was not able to raise her head with pride.[12]

The gods could not defeat this indomitable warrior in open combat; so they requested him, in the guise of a favor, to become the victim of their sacrificial ritual (*yagna*).[13]

The powerful Bala exceeded the highest serenity of great souls: in the pride of his courage he replied "yes" to the gods.

Firm in his resolve and asking for nothing in the face of the agony that extinguished his life-giving breath, he was tied to a stake by thirteen strings, like an animal; he was bound by his own word.

His birth being pure and so pure his deed, that the remains after the flames, the bones of his body, became the seed of gems (and had the power of the gods in them).

Gods, Yakshas, Siddhas, [and] Serpents made a great plundering of those seeds of precious stones.[14]

In their hasty flight through the clear sky, they dropped some pieces, and everywhere the pieces fell.

In the sea, the rivers, the mountains, the forests [those] seed, by [their] inconceivable weight, became the resting places [the deposits].

Clearly, diamond was seen as the essence of purity ("His birth being pure and so pure his deed") and indomitability ("this indomitable warrior") in the mysticism and culture of India. The powerful but evil Bala yielded to the plea of the good gods to sacrifice himself to the *yagna*, thus transforming himself into the powerful gems and gaining a measure of redemption. Thus diamonds contained powers derived from the gods. There was a hierarchy of those powers; some could be good, others bad, resulting in good or bad traits bestowed upon the owner or possessor. They are presented in the order in which they appear in the *Ratnapariksa* (Figure 4): "Of these stones [the 'seeds'], some proved suitable for destroying the Raksas [evil spirits], poison, serpents, illnesses, sins; the others for depriving such efficacy [11].[15] Those [diamonds] born under a bad [astrological] sign, on an ill-fated day, are filled with fatal influences and stripped of all beneficial qualities [12]. The king who desires happiness must collect and wear some well-verified stones [13]." The first characteristic that was important was color, which was associated with and restricted to particular castes: "The diamond of the Brahmin [priests] must have the whiteness of the conch, of the lotus, of rock crystal [white to colorless]; that of the Kshatriya [landowners and war-

*Figure 4. One origin myth for diamond (*vajra*) in Sanskrit is from the* Vajrapariksa, *one of the* ratna sastras, *and defines the mythic origin, purity, and power of the king of gems. (Courtesy of Special Collections, University of Pennsylvania Library.)*
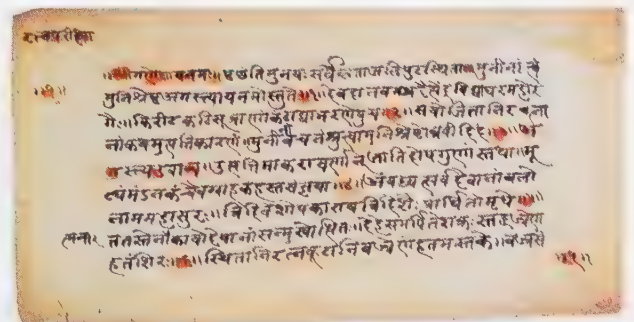
riors], the brown color of the eye of the hare [probably verging on red]; that of the Vaisya [merchant class], the pretty nuance of a petal of a *kadalî* [yellow]; that of the Sudra [lower classes, laborers], the sheen of a burnished sword [gray to black] [23]." However, only kings could possess diamonds of any color. Other *ratna sastras* add that the red of coral and the yellow of saffron were reserved for kings. Another variation in later sources was that the colors of diamonds were the "castes" of diamonds; for example, colorless diamond was the Brahmin of diamonds.

Buddha Bhatta continues: "It is not enough for the wise to pay attention to the classification of color in the selection of diamonds: If the diamond possesses the requisite qualities, it is the source of benediction; if not, a cause of misfortune [27]. The diamond with a single broken or cleaved point, otherwise having all the other appropriate qualities, should not be carried by those who desire happiness in this world [28]. A diamond that has a dull point, the extremity cleaved, the interior strewn with colored blemishes or drops, such a *vajra* [thunderbolt], like the one of Vajrabhrt [Indra 'bearing the bolt'], will soon inspire Sri[16] to envy another abode [29]." Furthermore, "a diamond having a portion with the color of blood or that is glittering with red spots will quickly bring death to the carrier, even to the Master of death [30]."

The discourse then focuses on the qualities of diamond associated with higher virtues. The ideally shaped diamond has "six sharp points, eight very flat, similar, and symmetrical sides, and twelve straight and sharp edges" – a definitive description of an octahedron (Figure 5). "A diamond with six points, pure, without blemish, pronounced and sharp terminations, with a beautiful nuance, light, with well-formed faces, without fault, illuminating space with fiery reflections of the rainbow, a diamond of this sort is not easy to find on earth [32]." And it was only a "pure" person who could benefit from the per-

Figure 5. Only in the form of a colorless octahedron does a natural diamond exhibit the rainbow reflections associated with faceted colorless gems. That was its most revered quality in India and was believed to be the source of diamond's most beneficial powers. Dark-colored octahedra were of much less value and interest. Both diamonds are about 8 mm across. (Denis Finnin/courtesy of American Museum of Natural History.)

fect diamond's pure power: "He who, having pure body, always carries a diamond with sharp points, without blemish, free from all faults; that one, as long as he lives, knows each day will bear some things: happiness, prosperity, children, riches, grain, cows, and meat [33]. He who wears [such] a diamond will see dangers recede from him whether he be threatened by serpents, fire, poison, sickness, thieves, flood or evil spirits [34]." Again, it is the perfect transparent octahedron with the salutary virtues – and value: "The diamond affected by a blemish, even very small, even though barely perceptible, has only one-tenth of its [the perfect diamond's] value, or even less. The diamond, large or small, with many defects obtains not even one one-hundredth of its value [41]."

The ultimate aspect of the diamond's power was its capacity to disperse colors, the "fire" from the diamond octahedron, which took precedence over all else, even offsetting flaws or an imperfect shape: "Even if it has blunt points, if it has a speck, a scratch, a crack, the diamond that has the reflection of the rainbow procures wealth, grain and sons [50]. The king who carries, so it is said, a beautiful diamond with glittering flashes has a force that triumphs over all other powers and becomes master of all neighboring lands [51]." Another Indian lapidary text, the *Agastimata* (Finot, 1896), adds that "the stone that one cuts with a blade or that one wears down by repeated rubbing becomes useless, and its beneficial virtue disappears; that, on the contrary, which is absolutely natural has all its virtue." That described the effective prohibition on cutting (cleaving) and polishing that persisted into Europe, as reflected in the legend of Akbar and in the term *archeiopoietos* – not made by hand.

Another critical property of diamond described in the *Ratnapariksa* is its hardness: "The gems and the metals that exist on earth are all scratched by the diamond: the diamond is not [scratched] at all by them. A noble substance scratches that which is noble and that which is not; the diamond scratches even the ruby. The diamond scratches all and is not scratched by any [48]." However, that was expressed as an observation and was not associated with any effect the hardness property of diamond would provide to the owner.

The geometric and optical properties of diamond were imbued with mystical significance, a hallmark of Hindu religious beliefs. Those mystical properties translated into talismanic force. Diamond octahedra were powerful protectors – no wonder it was forbidden to reshape them. The octahedral form was important because only that natural form can yield the maximum in brilliance and play of colors, as from a prism. Macles can be brilliant, but they do not show the rainbow colors of the high-dispersion octahedra, and the rounded forms can look very ordinary indeed. But that is not to say that the hardness of ill-shaped and thus inferior crystals or fragments could not be used to good effect in drilling beads, as demonstrated by the archaeological evidence.

Eight locations were listed as sources for diamonds, including the Gulf of Cambay in northwestern India, the Kalinga coast on the Bay of Bengal, the river Veinganga in the Chanda district, Behar, some place like Ayodhya, and

DIAMONDS AND BUDDHISM

In another work from India, dating to perhaps as early as the third century C.E., the *Questions of King Milinda*,[17] the diamond was seen as a symbol of religious virtue for Buddhists.

Just, O King, as the diamond is pure throughout; just so, O King, should the strenuous Bhikshu [truth-seeker], earnest in effort, be perfectly pure in his means of livelihood. This, O King, is the first quality of the diamond he ought to have.

And again, O King, as the diamond cannot be alloyed with other substance; just so, O King, should the strenuous Bhikshu, earnest in effort, never mix with wicked men as friends. This, O King, is the second quality of the diamond he ought to have.

And again, O King, just as the diamond is set together with the most costly gems; just so, O King, should the strenuous Bhikshu, earnest in effort, associate with those of the highest excellence, with men who have entered the first or second or third stage of the Noble Path, with the jewel treasures of the Arahats, of the recluses of the threefold wisdom, or of the sixfold insight. This, O King, is the third quality of the diamond he ought to have. For it was said, O King, by the Blessed one [Buddha], the god over all gods, in the Sutta Nipâta:

Let the pure associate with the pure,
Ever in recollection firm;
Dwelling harmoniously wise,
Thus shall ye put an end to griefs.

the Ganges plain. Some of the places listed do not correspond with diamond deposits but may have been trading centers where diamonds could be purchased. The Himalayas were listed, but it is believed that that was primarily to maintain consistency with the origin myth and the suggestion that diamonds came from the mountains.

Another important question that arises from the Indian literature is the nature of the trade in diamonds with the rest of the world. The *ratna sastras* provide detailed pricing schemes for diamonds, so obviously there was a market for them at the time of those writings, between 400 and 1000 C.E., but they contain no explicit statements about exportation, such as is found in the *Arthasastra*. Trade was an important issue, as we will see later, but there is no clear picture of its amount or constraints in the Indian diamond literature. However, the *ratna sastras* make it clear that the finest colorless diamonds, the transparent octahedra with rainbow reflections, were reserved for kings. Obviously, such diamonds would not be legally exported.

DIAMONDS REACH EUROPE

Although there were contacts between southern Asia and the Mediterranean lands in ancient times, the problem of signification with respect to *vajra* and *adamas* requires careful examination to evaluate when the Greeks and Romans learned of the truly hardest of substances. The earliest citation of *adamas* for which we have evidence came from the Greek poet Hesiod in the eighth century B.C.E., but it probably was in reference to iron, because of its "unbreakable quality." Theophrastus (ca. 372–287 B.C.E), a student of Aristotle and author of *De lapidibus* (*On Stones*), referred to *adamas*, along with *anthrax*, but most likely was discussing corundum and emery (a natural stone consisting of corundum and magnetite that was used in a crushed form as an abrasive for centuries both before and after his time). Theophrastus has been credited with ascribing gender to stones, so as to allow for reproduction, as will be discussed later.

Diamond is mentioned in various versions of the Hebrew Bible, but again there is a problem of signification. Exodus (38:15–30) describes the making of the breastplate of Aaron (or of the High Priest or of Judgment), which contained a white or colorless stone labeled *yahalom*, "the smiter," which when translated from Hebrew became *adamas*, "indomitable," in Greek, hence diamond. However, much work on that problem has led to the alternative interpretation that *yahalom* was onyx. Various factors point in that direction. One is the size of the breastplate, which probably was 8–9 inches (20–23 centimeters) on a side, requiring stones that would measure more than 2 inches in diameter. Next, all of the stones on the breastplate were engraved with the symbols of the

tribes of Israel, and the engraving was carried out with emery as the abrasive. Finally, Exodus was written at some time between the tenth and seventh centuries B.C.E. and then translated into Greek in the third century B.C.E., well before any dates consistent with either extensive knowledge of diamond or export of diamond from India, let alone a stone 2 inches across. That citation of diamond appears to be a misnomer, and the "smiter" may have referred to onyxes being engraved into seals for pressing into clay.

In Volume 37 of his encyclopedia *Historia naturalis*, which enshrined both science and error indiscriminately and would be a primary source of classical information for Europeans over the next 1,500 years, Pliny the Elder (23–79 C.E.) summarized what was then known about *adamas* in Greece and Rome: "[15.4] The substance that possesses the greatest value, not only among precious stones, but of all human possessions, is adamas; a mineral which for a long time, was known to kings only, and to very few of them. . . . The ancients supposed that adamas was only to be discovered in the mines of Æthiopia, between the Temple of Mercury and the island of Meroë; and they have informed us that it was never larger than a cucumber seed, or differing at all from it in colour."[18] There are several problems here. No such diamond sources existed in Africa, although trade routes via Yemen and the Red Sea might have been purposefully confused by the traders to protect what might have been illicit trade. Meroë was a Cushite city in what is now the Sudan, and so the island might have been one off the Egyptian coast in the Red Sea (Figure 6). However, Ajasson[19] assigned both "Æthiopia" and the "Temple of Mercury" to India. Stones the size of a cucumber seed certainly would have been lesser diamonds (if diamonds at all) and thus would have been destined for use in engraving or drilling holes in beads.

Pliny continues: "The Indian adamas is found, not in a stratum of gold, but in a substance of a kindred nature to crystal (quartz); which it closely resembles in its transparency and its highly polished hexangular and hexahedral [cube] form." The former morphology is consistent with corundum (forming roughly hexagonal prisms and pyramids), but not diamond, and the latter, if the cube, is rare in diamonds. However, both can be found with gold in deposits of streambed gravel (placer deposits), because gold, corundum, and diamond are all heavy and durable (the gems mechanically so, and gold because it is chemically inert and can self-weld into nuggets).

Figure 6. Diamonds were traded out of India by both sea and land routes. Classical stories of sources in Ethiopia and the legend of the Valley of the Diamonds may have originated because of the circuitous trade routes and attempts to mask the ultimate source of diamonds, India. Rulers of the intervening lands often kept finer diamonds traversing their territories, thus diminishing the quantities of diamonds that could reach the Mediterranean region. (Adapted from Legrand, 1980.)

Figure 7. Historical literature and modern research indicate that Roman sapphires were fashioned with the help of diamond engraving tools. The Fitzwilliam Sapphire Cameo, from the first century C.E., an engraved Roman sapphire of Aphrodite, undoubtedly was fashioned with the aid of diamond, although its authenticity as a Roman work is currently in question. (Courtesy of Fitzwilliam Museum, Cambridge, England.)

Figure 8. Diamonds, typically yellow-to-brown octahedra with a protruding pyramid, were mounted in Roman rings from the first through third centuries C.E. as talismans for good luck. The presence of these dark diamonds in Rome is evidence of the Indian ban on the export of more attractive colorless stones. (Courtesy of British Museum.)

Furthermore, "these stones are tested upon the anvil, and will resist the blow to such an extent as to make the iron rebound and the very anvil split asunder. Indeed its hardness is beyond all expression, while at the same time it quite sets fire at defiance and is incapable of being heated; owing to which indomitable powers it is, that it has received the name which it derives from the Greek." Whatever was tested with hammer and anvil certainly was not diamond. The hardness description would be appropriate for diamond. The difficulty in heating it would be true under some circumstances; however, given sufficient heat, diamonds ultimately will burn and disappear. The heat description seems more relevant to the forging of iron and the association of *adamas* with iron. "When, by good fortune, this stone does happen to be broken, it divides into fragments so minute as to be almost imperceptible. These particles are held in great request by engravers, who enclose them in iron, and are enabled thereby, with the greatest facility, to cut the very hardest substances known. Adamas, too, overcomes and neutralizes poisons, dispels delirium, and banishes the groundless perturbations of the mind; hence it is that some have given it the name of 'ananchites.'"[20]

The sum of details here would seem to indicate that Pliny never actually saw a diamond larger than the fragments used for engraving, but described features common to both diamond and corundum, relayed by him as the summary wisdom of the day. The engraver aspect is particularly relevant to a synonymy between this variety of *adamas* and *vajra*, but the alleged powers also suggest communication of the basic Hindu attributes. It is quite possible that diamond octahedra were scarce to nonexistent in the ancient Mediterranean region.

The combination of the archaeological evidence and the written history helps to refine our estimate of the date at which diamond would have been available in Rome. It would have been impossible to produce engraved sapphires of great precision without the aid of a diamond engraving tool. A subsequent chronicler of the early third century C.E., Caius Julius Solinus, wrote that "for engraving, sapphire is by no means adapted, as it defies grinding; it is not, however, invincible for it is engraved and cut into shape by the diamond [which can be used] for marking gems of any kind."[21] Likewise, the Roman poet Manilius, in *Astronomica* (16 C.E.), referred to the "point of a stone more precious than gold," which indicates the value attributed to a diamond point as an engraving tool. (Curiously, early Chinese references to diamond[22] said that it came from Rome in iron scribes; their interest in diamond was strictly as an engraving or carving tool, primarily for jade, or as a drill for beads and pearls.) A few Roman artifacts, including a cameo of Aphrodite (Figure 7) and a fine intaglio of the emperor Augustus wearing a radiate crown, serve to place diamond engraving tools in Rome soon after 14 C.E., as he is depicted in the same fashion on coins during the reign of Tiberius (14–37 C.E.). Thus diamond clearly was present in the Mediterranean during or before the first century C.E.

A historical source that played a prominent role in the Middle Ages was the

lapidary text by Damigeron, perhaps known as "Evax," a Hellenistic writer in Alexandria at some time between the first and fifth centuries C.E. His text shows influences of Eastern traditions and the Gnostic dualism of sympathy and antipathy and repeats Indian beliefs in the magical powers of diamond.[23]

As far as we know, diamonds made their first appearances in Roman jewelry between the first and third centuries C.E., when small yellow-to-brown octahedra were set in rings as "points" (Figure 8). Pliny reported that such rings were worn for diamond's talismanic power to ward off evil. However, those are believed to have been the last uses of diamonds in jewelry for about 1,000 years. There is no firm evidence, but the virtual disappearance of diamond jewelry appears to have coincided with the decline of Roman power and the ascendance of Christianity, which was legitimized by Constantine in 313 C.E. One interpretation is that the associations of diamond with pagan beliefs and talismanic or magic powers would have been anathema to Christian doctrine. Also, the role of diamonds in the breastplate of the High Priest, even if a misinterpretation, would have been a Hebrew association to be eschewed in Christian symbolism. In the early years of Christianity, opulence and adornment were not viewed favorably. Perhaps visually attractive diamonds were not available to provide an alternative perception to counteract the negative associations. For whatever reasons, diamonds were relegated to minor entries in the history books at the close of the Roman era.

DIAMONDS IN LEGEND AND MYTH

Unfortunately, the field of myths and legends is so nebulous that it can be stretched to cover any metaphysical or mystical interpretation regarding the role of diamond. Here we shall consider only two topics that have long fascinated scholars and clerics and for which there have been some efforts of interpretation: the legend of the Valley of the Diamonds and the myth that diamonds could be cleaved only by application of goat's blood.

The Valley of the Diamonds figures in a Hellenistic legend from the third century B.C.E. that made its way west after Alexander the Great (356–323 B.C.E) conquered Persia and invaded what is now northern India. Thus the time of the legend roughly coincides with the first trading contacts between the Mediterranean cultures and southern Asia. Other versions of the story come from the voyage of Sinbad the Sailor in the Arabian tales of *A Thousand and One Nights* and from Marco Polo's *Book of Marvels* (1298). It has been suggested that the legend was intended as a deterrent to any treasure-seekers looking for the diamond mines. The phenomenon of the diamonds adhering to the piece of flesh has been attributed to the Hindu tradition of sacrificing cattle at the opening of a mine, although Kunz (1938) considered that attribution

THE VALLEY OF THE DIAMOND

Aristotle says that no one except Alexander ever reached the place where the diamond is produced. This is a valley, connected with the land Hind. The glance cannot penetrate to its greatest depths and serpents are found there, the like of which no man hath seen, and upon which no man can gaze without dying. . . . Now, Alexander ordered that an iron mirror should be brought and placed at the spot where the serpents dwelt. When the serpents approached, their glance fell upon their own image in the mirror, and this caused their death. Hereupon, Alexander wished to bring out the diamonds from the valley, but no one was willing to undertake the descent. Alexander therefore sought counsel of the wise men, and they told him to throw down a piece of flesh into the valley. This he did, the diamonds became attached to the flesh, and the birds of the air seized the flesh and bore it up out of the valley. Then Alexander ordered his people to pursue the birds and to pick up what fell from the flesh.[24]

Figure 9. A drawing from a nineteenth-century Turkish manuscript on astronomy portraying the Valley of the Diamonds. Fatty flesh with adherent diamonds can be seen carried by and falling from scavenging birds, just as in the description of the tale derived from Aristotle and al-Kazwini. (Courtesy of Pierpont Morgan Library, New York City; M.788.f.83r.)

doubtful (Figure 9). The possibility of diamonds sticking to grease or to a greasy piece of meat might be said to have some basis in fact. The use of fleece to recover gold from rivers is well known; the gold adheres to the greasy lanolin in the fleece. Diamonds, which also have a strong affinity for grease and tend to be concentrated in placer deposits, might be recovered in the process. If those latter interpretations are valid, then the legend might indeed have concerned diamond, or *adamas* as *vajra*, although there is no evidence that illustrious Alexander ever held a diamond.

The myth of cleaving diamond using goat's blood was first cited in Pliny's *Historia naturalis*.[25] His statement (see box) is a marvelous mixture of a Greco-Roman perspective, Gnosticism, and mysticism: the opposition of good and evil, *sympathia* and *antipathia*; diamond as the symbol of strength, purity, and indomitability (all straight from the Indian origin myth); the he-goat, cantankerous and smelly (though without negative connotations in Vedic mythology and even in the rest of *Historia naturalis*). Allegedly,[26] a goat's blood was warmer than that of other animals and could be used for tempering iron, with some symbolic potential for transferring the goat's foulness to an iron blade, which thereby would become a more lethal weapon. Finally, the gods were invoked to provide the wisdom pointing to the nonintuitive method of cleaving the diamond. So that myth promulgated the concept that the pure and indomitable could be conquered only by the foul and evil, a lesson that must have had resonance in the Christian paradigm prior to the age of science and empiricism. That myth persisted in lapidaries through the eighteenth century. As to the origin of the myth, many authors have speculated that it was yet another cover-up by the small cadre of craftsmen and traders who wanted to keep diamonds mysterious and their proprietary knowledge secret. An alternative interpretation espoused by Ohly[27] and repeated by Tillander is that the myth is a misinterpretation of Pliny and the Latin *temperare*, which can mean harden or soften, depending on the context. The crux of the misinterpretation is that the tempering of the iron blade was the real issue, not the "softening" of the diamond.

Diamonds appear to have been extremely rare or nonexistent in the culture of Europe for hundreds of years after the rise of Christianity and the fall of the Roman Empire. One reason, in addition to the apparently waning fascination with diamonds because of their links to pagan mysticism, was that the same period saw the rise of Persia and Islam. Persia and the new Middle Eastern states gained control over much of the trade with India, and their rulers, who had a taste for ornamentation, apparently skimmed the cream of the larger and more attractive diamonds. Once the Christian paradigm had become secure and it became possible to entertain ideas from the classical and Eastern traditions without the expectation of being burned at the stake for heresy, the virtues of diamonds began to be recalled, and the brilliant stones began to exert their power in the new Western culture.

POISON, SEX, AND OTHER
ADAMANTINE INSPIRATIONS

During the Middle Ages, and continuing up to the eighteenth century, there was a rediscovery and reiteration of the lapidary writings from the past. The writings included a mix of Theophrastus, Damigeron, Pliny, and Solinus. The strictly Christian writings followed an acceptable, Platonic, medicinal tradition, but Spanish writings contained additions from Arabic sources that retained the Aristotelian traditions of astrology and magic; some included contemporary meditations and a taste of alchemy. As is well stated by Kunz in *The Curious Lore of Precious Stones* (a work that can be difficult to follow, or believe, but is at least documented with numerous citations), "this complex origin of the traditions explains their almost incomprehensible contradictions regarding the virtues assigned to the different stones, and the fact that the qualities of one stone are frequently attributed to another one, so that, in the later works on this subject, it becomes quite impossible to present a satisfactory view of the distinguishing qualities and virtues of the separate stones."[28] The writings were codified in works known as lapidaries, briefly surveyed here; they sadly lack any verification or any standard of empirical evaluation such as we have come to expect in modern scientific investigation.

Marbodus (Marbode), bishop of Rennes (1035?–1123), wrote *De lapidibus*, a treatise on gems, drawing heavily on Damigeron, Pliny, and Theoprastus from the classical period, and dealing with the occult and medicinal attributes of gems. Remarkably, that work lacked the usual Christian symbolism of the period, such that Evans believes that the bishop crafted that pagan poem as an exercise in verse. He described diamond: "This stone has aptitude for magical arts, indomitable virtues it provides the bearer, nocturnal spirits and bad dreams it repels, black poisons flee, disputes and screams are changed. Cures insanity, strikes hard against enemies. For these purposes the stone should be set in silver, armored in gold, and fastened to the left arm."[29]

Hildegard von Bingen (1098–1179), abbess of the Rupertsberg convent, who was canonized for her mystic visions, wrote on natural history, medicine, and cosmology, as well as music, poetry, and theology.[30] Living downstream from a center for fashioning agates, what is now Idar-Oberstein, she was knowledgeable about ornamental stones and observed that diamond had sovereign virtues over evil, resisting the power of the devil both by day and by night. Furthermore, diamond "would only heal a person if held in his hand while making the sign of the cross."[31] Efficacy was enhanced when the diamond was taken into the sickbed and warmed to the body or in the mouth. Another oral effect was that a diamond placed in the mouth of a liar or nag would cure the person.

Alphonso X of Castile (1221–84) sponsored the *Lapidario*, a work that straddled the tradition of medicinal treatises and the Arabic tradition that

CLEAVING DIAMONDS

Now with reference to those affinities and repugnances which exist between certain objects, known to the Greeks as "sympathia" and "antipathia," phænomena to which we have endeavoured to draw attention throughout these books, they nowhere manifest themselves with greater distinction than here. This indomitable power, in fact, which set at nought the two most violent agents in Nature, fire, namely, and iron, is made to yield to the blood of a he-goat. The blood, however, must be no otherwise than fresh and warm; the stone, too, must be well steeped in it, and then subjected to repeated blows: and even then, it is apt to break both anvils and hammers of iron, if they are not of the very finest temper. . . . Surely a discovery, such as this, must have been due solely to the munificence of the gods.

touted the magical powers of stones, because it was written by several authors in a court open to ideas from both East and West. In one section, it was said that diamond should be used only to treat chronic cases of bladder disease; in another, diamond was said to be deadly if swallowed; yet diamond could confer courage. And in an astrological interpretation it was stated that "Saturn has power over the stone named Ademuz in Greek, Almez in Arabic and in our language, diamond . . . And when Saturn is well receded from the moon and rising, and if in this hour someone should take this stone and should have descending on it the truth of the stars in which are written the eight major letters of the alphabet of Saturn that men found before they could read other letters, and should enter in a place where there are people who love each other, the love will go bad due to the stone and be ruined."[32]

Sir John Mandeville, who claimed to be an Englishman, is credited with being the author of *Le grand lapidaire*,[33] but is better known as the author of *The Travels of Sir John Mandeville, Knight* (1356), a well-crafted piece of fiction that borrowed from Marco Polo and others to describe a world-class journey to the East. He wrote that "it happens often that the good diamond loses its virtue by the sin and incontinence of him who bears it." He also revived an animist tradition that diamonds were alive and could reproduce sexually – in his version, if placed with some rock and watered with May dew.

Garcia da Orta, once physician to the viceroy of Goa (a former Portuguese colony on the Malabar coast in southwestern India) and noted pharmacognician and herbologist, reported on mining and related topics in India. Goa became a major trading center for goods going to Portugal and Europe in the sixteenth century, including diamonds of less than 25 mangelins (48.6 carats), as larger diamonds were reserved for the nazims (Figure 10). Goa provided an excellent vantage point for observing diamond transactions in India. Resolving the debate whether diamond was a poison or an antidote, he determined that diamonds, either as stones or as powder, were not poisonous: In 1563, when observing slaves working in the mines, he saw that those who swallowed diamonds suffered no ill effects.[34] Another of his observations may explain one source of the alleged sexuality and animism of diamonds: Periodically the galleries of the mines would be closed and then reopened, whereupon apparently "new" diamonds would be discovered and removed. Because diamonds had to be released from stubborn rock, temporary closings to allow natural weathering and oxidation to soften the rock were standard. That process lent credence to the misperception that new diamonds were being formed.

Diamonds were believed to render the owner courageous and fearless. Thus nobles like Cosimo de' Medici (1389–1464), Henri II of France, and perhaps the dukes of Burgundy used them as symbols in rings and·even wore them into battle. Girolamo Cardano, an Italian physician, mathematician, and author of *De gemmis et coloribus* (1566), commented on the virtues of diamond, although most of that work was a compilation from earlier texts. He

Figure 10. Portuguese merchants set up trading centers such as Goa on the Malabar coast of India. This Portuguese navigator in Goa displays the mix of cultures. (Courtesy of Trustees of Victoria and Albert Museum.)

compared the power of the diamond to the light of the sun; if viewed directly, it would blind. "It indeed renders fearless, but there is nothing that contributes more to our safety than prudence and fear; therefore it is better to fear."[35]

François Ruet, a medical doctor from Tiguri (probably Zürich, Switzerland), recorded the celestial virtues of stones in his *De gemmis aliquot* (1566), including a story of two diamonds that produced offspring, caused, he conjectured, by the "celestial energy in the parent stones" that led to a transformation of air to water and water to diamond.[36] Ruet also considered diamond to be "a gem of reconciliation,"[37] for it enhanced the husband's love for his wife – somewhat of a role reversal when compared with our modern gift-giving practices.

Benvenuto Cellini (1500–71) provided a wealth of information in his *Treatises on Goldsmithing and Sculpture* (1568), including a description of techniques for fashioning diamond. However, he did not place diamond at the apex in his hierarchy of gems; ruby and emerald were placed higher. In his autobiography he described his terror when he thought he had been poisoned with crushed diamond powder while wrongfully imprisoned in 1538 and his relief after crushing a glinting fragment in his food; it was not diamond. He later learned that an enemy had indeed tried to poison him, but the supplier who was given a diamond to crush into powder substituted crushed citrine.

Anselmus Boetius de Boot, court physician to Rudolph II of Germany (1552–1612) and author of *Gemmarum et lapidum historia* (1604), repeated earlier descriptions of the gems but expressed doubt about what he had recorded. In addition, he thoroughly documented the technology for faceting diamonds, thereby providing one of the first comprehensive references.

CRYSTAL TO GEM

A critical transformation of diamonds as dark crystals to diamonds as fashioned glittering gems was necessary to raise diamond to its contemporary preeminent position as a symbol or jewel. That depended on an end to the taboo on reshaping and polishing diamonds, the development of technology for fashioning diamonds, and a supply of diamonds of good color, clarity, and size sufficient to fuel the entire enterprise. Only a few hundred years after the Roman talismanic rings were made, Isidore of Seville (ca. 560–636), a powerful bishop and scholar, wrote a great encyclopedia, the *Origins*, that recapitulated classical knowledge; he mentioned the fact that diamonds were "small and dull" – not a surprising view for that time.

Medieval crowns worn by the rulers of the Holy Roman Empire featured no diamonds until the fourteenth century, and then only a few small points. However, such crowns were rich with sapphires. Those hard gems were always

in an irregularly smoothed form, not fully rounded cabochons. Softer gems such as amethyst were faceted, and carnelians were fully rounded, undoubtedly by the use of emery, but in the case of the hard sapphire, faceting with emery would have been a hopeless task. The sources for all fine sapphires at that time were the southern and southeastern parts of Asia, so we know that they were being imported to Europe in small quantities. (A curious feature in many of the large sapphires is a hole drilled directly through the stone. We can reasonably assume that such sapphires had previously been used as beads and that the drill hole had been made with a hafted diamond by an Indian craftsman.) It would appear that diamonds were virtually unavailable for many centuries, and despite the comments on diamond in Pliny's work and other lapidary texts of the time, diamonds were not used as engraving points in the West.

Small numbers of diamonds began appearing in European regalia and jewelry in the thirteenth and fourteenth centuries. An important event in the diamond's rise to prominence was a sumptuary law issued by Saint Louis (Louis IX of France, 1214–70) stating that women could not wear diamonds; diamonds were reserved for the king. Crowns with diamonds that were reliably described or preserved from that period include the crown of Princess Blanche or an English queen (ca. 1370–80), in the Residenzmuseum, Munich (Figure 1, Chapter 6), and probably the Great Crown of England,[38] pawned by Richard II in 1379. The crown of Princess Blanche contains small octahedral crystals set as points at the center of pearl clusters, although the diamonds are not the aesthetic focus of that beautiful artifact. Another early documentation of regalia is a 1379 inventory for Charles V ("the Wise") of France that records a bejeweled scepter with a diamond in the center of a group of four pearls. It has been suggested that those earliest ornamental and regal diamond points were polished, but some appear to be natural, except perhaps for removal of

Figure 11. Venice was the key trading center between western Europe and eastern regions like India and China prior to the sixteenth century. Consequently the trade in diamonds went through Venice, and cutting techniques were developed there by the end of the fourteenth century. (Courtesy of Metropolitan Museum of Art, Rogers Fund, 1919, 19.49.3.)
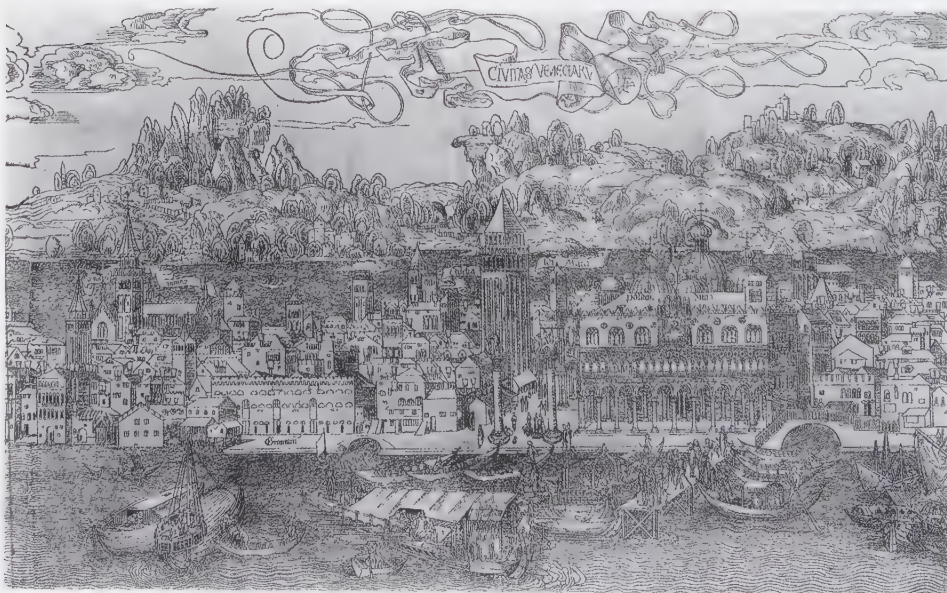
coatings of foreign minerals.[39] The pieces that have survived support the argument that the techniques of true polishing and reshaping of diamonds, which require diamond abrasive, may have just reached northern Europe by 1380.

Helping diamonds rise on the feminist front, Agnès Sorel (ca. 1422–50), mistress (and allegedly a domineering one) of Charles VII of France (1403–61), was the first woman to publicly defy the French sumptuary law prohibiting diamonds for women; during her short period of influence she was credited with prompting increased use of diamonds at the French court in the elaborate goldwork produced for both men and women (see Chapter 6).

DIAMOND CUTTING AND TRADING

The early history of diamond trading and cutting is not well understood, though nonetheless very interesting. The earliest evidence of cutting, dating to soon after 1330, comes from Venice, long the trading capital for goods entering Europe from the East (Figure 11). The cutting technique followed the trade route to Bruges (earliest cutting documentation from 1465) and Paris (probably late fourteenth century). The earliest documentation of diamond trading in Antwerp is from 1447. The diamond cutters composed only a small group (Figure 12), and they were excluded from the guild system that controlled goldsmithing, so Jews were able to pursue the craft. Even before the defeat of the Moors in Spain in 1492 and the Inquisition in Spain and Portugal, Jews had begun to flee those countries. They were welcome in the Low Countries. Following the Portuguese discovery of a sea route to India, the trade in diamonds from Goa to Lisbon and Antwerp flourished, as did the Jewish merchant class in the Low Countries in the sixteenth century (Figure 13). The East India Company tried to maintain a monopoly of trade with the non-Portuguese areas in India for Amsterdam, but eventually gave up in 1664. The arrival of Portuguese Jewish merchants in London at about that time and the English diplomatic alliance with Portugal increased London's interest in the diamond trade, and London became an important center by the end of the seventeenth century.

Soon after 1380, true gems, fashioned diamond jewels, began to appear in Europe. For that to have happened, there had to have been a steadily increasing trade in diamonds, including some availability of colorless stones, in addition to the development of diamond-cutting skills. Whether the taboo on modifying a diamond crystal had lost its potency or experimentation had led to attempts to enhance a diamond's appearance is not clear. Was it a coincidence that the art of cutting (actually cleaving and polishing) diamonds developed at approximately the same time in Europe and India? The literature is not clear, but a transfer of technology seems more likely than coincidence.
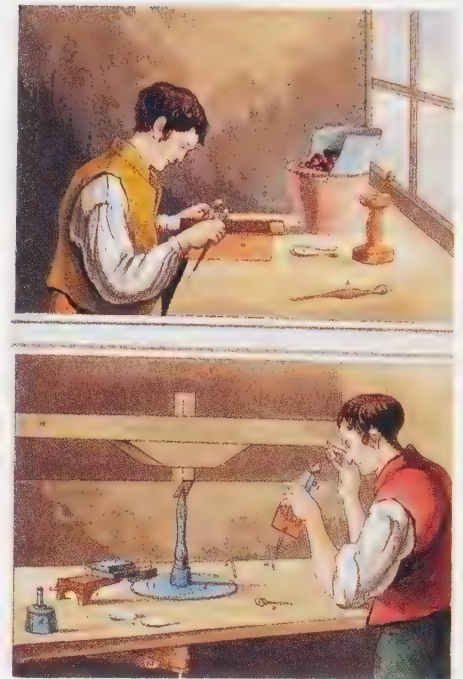
Figure 12. The techniques developed in Europe for cutting diamonds became standardized within a hundred years of their fifteenth-century development and have remained little changed. (Above) a diamond cutter uses one diamond to brute, or shape, another diamond; (below) a cutter examines the polish on a "dopped diamond" while another diamond polishes on the lapidary wheel or scaife. (From Mawe, 1823; Jackie Beckett/courtesy of American Museum of Natural History.)

Figure 13. Anna Lopez Jimenez was born to a wealthy merchant family and married Baron Simon Rodriguez d'Evora, a famous Portuguese diamond dealer (the "little king") who lived in Antwerp. She displays her status with her diamonds, wearing a point-cut ring on her wedding finger and an oval brooch with table-cut diamonds. Detail from painting attributed to Otto van Veen. (Courtesy of Maagdenhuis Museum, Antwerp.)

Whatever the relation of cutting and trading, beginning early in the fifteenth century, European exploration for trade routes to the East brought a major revolution in the availability of diamonds in the West. By 1499, the Portuguese navigator Vasco da Gama had pioneered the sea route eastward around the Cape of Good Hope, allowing Europeans an end-run around the Arab monopoly on trade with Asia and increasing the quantity and quality of diamonds coming to Europe from India.

At the height of the wealth and power of the dukes of Burgundy in the fifteenth century, that court developed a ravenous taste for sumptuous fashions and gold jewelry, including the use of diamonds in fine goldwork (most of those stones have since been lost, but there is little doubt that they were pol-

ished stones). Burgundy controlled the Low Countries, where cities like Bruges and Antwerp were important commercial and artistic centers, beginning to compete with Paris as the most important diamond-cutting centers (Figure 14). Charles the Bold (1433–77), duke of Burgundy, had many diamonds among his treasures, including what was said to be the largest diamond in Christendom at the time (perhaps the yellow Florentine diamond) and a head-dress sporting the Feather Jewel (including many pearls, spinels, and four diamonds) surmounted by the Three Brethren[40] with a large (perhaps 30-carat), central, trihedrally faceted point-cut diamond. In 1477 there was an important development in the evolving role of diamonds: The Hapsburg emperor Maximilian I gave a diamond engagement ring to Mary of Burgundy, heir to the decreased treasury and lands of Charles the Bold (Figures 15 and 16).

Among the important events in the increasing contacts with the Middle East and South Asia and the trade in diamonds were the voyages of Jean-Baptiste Tavernier (1605–89), documented in *Les six voyages de J.-B. Tavernier en Turquie, en Perse et aux Indes* (1676; Figure 17). Born in Paris, he was the son of an engraver and geographer from Antwerp and a jeweler himself. Tavernier began his first voyage in 1631 and made his later voyages at the behest of Cardinal Mazarin and then Louis XIV of France. He visited the major mines east of the Deccan plateau and described many large diamonds that he saw, including the Great Mogul, the Great Table, and the Shah, belonging to the Mogul emperor Aurangzeb (Figure 18). As a merchant explorer, he returned with a

Figure 14. This brooch showing a fashionably dressed couple in a love garden features a table-cut diamond, probably cut in Bruges, which was one of the earliest cutting centers and was under the control of the dukes of Burgundy. Ca. 1430–40; gold, enamel en ronde bosse, ruby, and diamond. (Courtesy of Kunsthistorisches Museum, Vienna.)

Figures 15 and 16. The union of Hapsburg Emperor Maximilian I (by Bernhard Strigel, ca. 1500) and Mary Burgundy (ascribed to Niclas Reiser, ca. 1500), was celebrated by the exchange of a diamond betrothal ring, an early instance and perhaps the first royal one. (Courtesy of Kunsthistorisches Museum, Vienna.)

wealth of commercial data and many diamonds. He brought back more than 20 diamonds larger than 20 carats and sold or gave many of them to Cardinal Mazarin (already owner of the Sancy and the Mirror of Portugal) and Louis XIV (the Tavernier Blue, destined to become the Hope). His stories and diamonds fed the growing fascination and desire of Europeans for the king of gems. He died in Moscow during his seventh voyage, on his way to Persia.

It would be an oversight not to mention something of the great diamond treasures amassed by the Moguls, the Persians, and the Ottoman Turks. The land routes between Europe and India passed through Persia and the Middle East. The Muslim conquest of India began around 1000 C.E. with the taking of Bihar and upper Bengal. Under Mogul rule (1526–1857), art and architecture flowered (Figure 19), and with the increasing production of diamonds, lavish objects were created such as the Peacock Throne of Shah Jahan (1592–1666), which is said to have held both the Koh-i-Noor and Akbar Shah diamonds as the peacock's eyes. Tavernier visited the treasury of Aurangzeb in 1665, and the story about the diamond eyes is probably a misreading of Tavernier's description. Many of the great riches of Persia were won when Nadir Shah sacked Delhi in 1739, taking the jewels and Peacock Throne back to Teheran, where many of those diamonds reside today among the Iranian crown jewels. Sadly, the Peacock Throne of Shah Jahan was dismembered after Nadir Shah's death to defray the expenses of Persian royalty.[41] The Ottoman conquests of much of

Figures 17 and 18. European contact with Indian diamond miners is depicted below in this frontispiece engraving from Jean-Baptiste Tavernier's Les six voyages . . . (Amsterdam edition, 1678). Tavernier reported seeing numerous large diamonds in his Indian visits. Included in the figure below right are the Great Mogul (1) which was probably recut and thus lost to history; the grand duke of Tuscany's diamond (2, not seen in India), which was the true Florentine and also the Austrian Yellow; the Great Table (3); a 155 3/4 carat diamond (4) acquired by Tavernier and shown after faceting (5); a 63 carat acquisition (6); and another comparison of cut stone and original rough diamond (7 and 8). (Jackie Beckett/courtesy of American Museum of Natural History.)

Figure 19. Prince Khurran, later the fifth Mogul emperor, Shah Jahan, by Nadir uz-Zaman (c. 1616–17), admires a turban ornament containing a large emerald above an octagonal diamond that may have been the great Shah Jahan Table Cut diamond. (Courtesy of Trustees of Victoria and Albert Museum.)

the Near East and the southern Mediterranean coast from the fifteenth through nineteenth centuries enriched their treasury enormously, though not quite so lavishly with diamonds. The important diamonds included the Kasikci or Spoon Maker's and the Shining Star diamonds of Sultan Ahmet I (r. 1603–17), on exhibit in the Topkapi Palace museum in Istanbul. Both the Iranian and Ottoman collections were expanded in the nineteenth and early twentieth centuries, so that diamonds from southern Africa are also on display.

I must close this chapter with an important point: The historical trail of diamonds can be elusive because diamonds are rarely left behind as evidence. Diamonds have always been too valuable to be left very long in historical settings that later become unfashionable, and so they have often been recut, if necessary, and reset in more contemporary ornaments. That was as true for the fifteenth century as it is for the twentieth century. Only in the relatively small collections of national treasures or museums is the historical record truly well preserved, and those collections account for only the tiniest fragment of the past wealth. Consequently, often it is in catalogues, paintings, diaries, photographs, and movies that we find the most comprehensive record of the indomitable diamond in its temporary jewelry housing.

A Historical Overview of Diamond Cuts

BENJAMIN ZUCKER

As noted in the preceding pages, the earliest appearance of a diamond in a setting was the natural octahedral crystal in a ring. Probably by the fourteenth century those "points" began to appear, with polished flat surfaces rather than the natural surface, which has trigons and is not perfectly flat. The presumption is that natural crystals, imperfect but preferably "of the clearest water," were polished and fashioned with diamond grit on a flat lap to create a jewel that would mimic the shape of the point of the octahedron. The fundamental advance was not the polishing of a gem, but the polishing of diamond with diamond, which required the rejection of a long-standing taboo.[42] That refinishing of a natural diamond in medieval times can be said to have been the first type of diamond faceting – the creation of the *point cut*.[43]
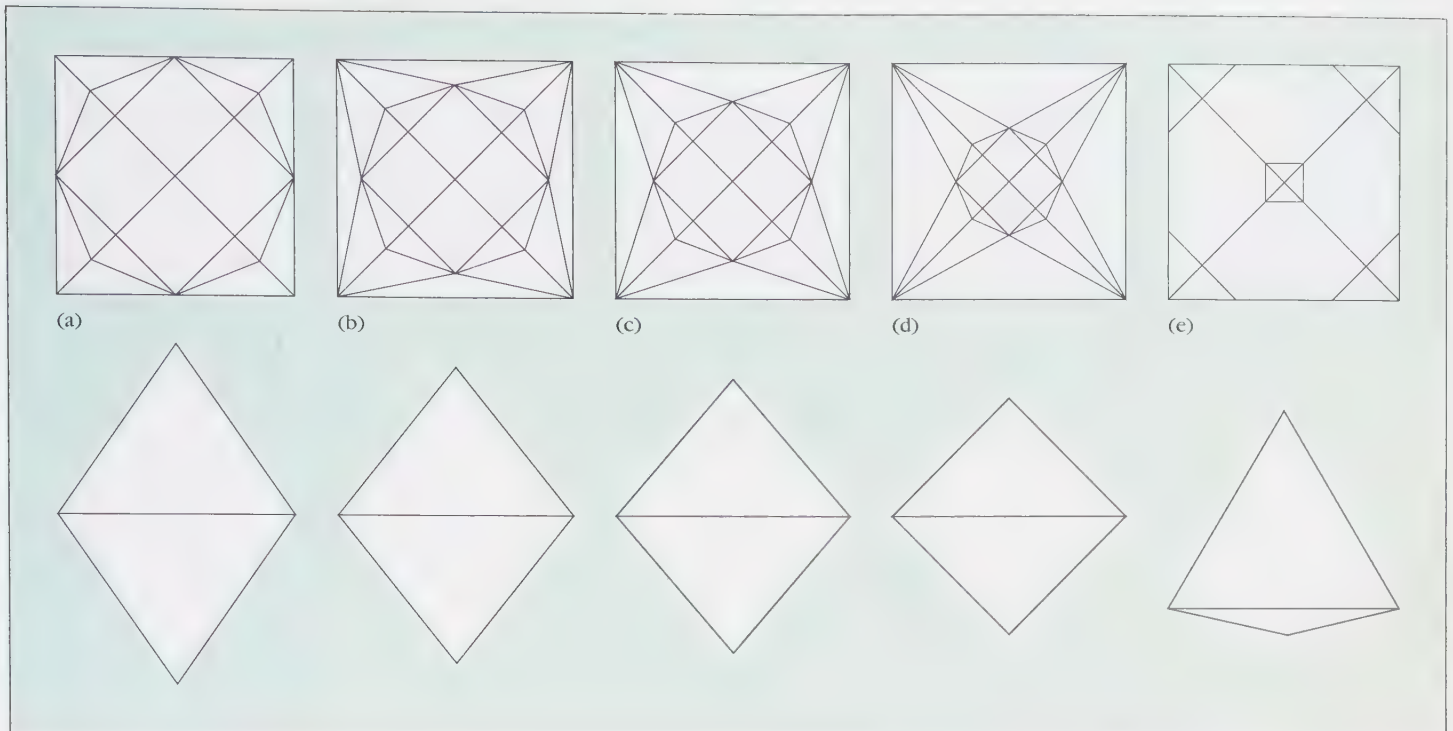
The point cut as an exact refinement of the octahedron is not easy to produce because the octahedral surface is the hardest surface of a diamond.[44] In a study of the history of diamond cuts, Herbert Tillander[45] profiled point-cut diamonds as they appear from the viewer's perspective when directly over the top of a stone, just as many paintings from the sixteenth and seventeenth centuries show them. One sees a shadowy square, an ×, and a few lines projecting from the interior of the stone. The appearance and size of the dark shadow can provide an approximate measure of the crown angle[46] that the diamond cutter used. In Figure 21, view (a) is for a true octahedron, views (b) through (d) show sequentially shallower angles, and view (e) shows the very steep angles of a sharp point. Most of the early points that have survived or have been portrayed have crown angles below those of the octahedron (Figure 22), perhaps implying that the polishing had to be done at an angle from the hard octahedron face, or reflecting the need to maximize the size and appearance of the finished diamond. Tillander also argued that points were fashioned from macles, such that a crystal was not even oriented like an octahedron but was fashioned to mimic the revered pointed shape. Macles and irregular diamonds certainly would have been more readily available than good octahedra, for the Mogul rulers made sure that they skimmed off all the better stones at the source in India.

The successor to the point was the *table cut*, a simple truncation of the point with a polished, flat, table surface. Optically, the table cut greatly increased the amount of light returned to the eye, imparting brilliance and fire. Such stones appeared by the middle to late part of the fifteenth century, and
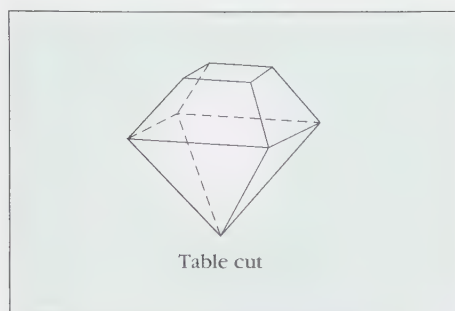
Figure 23. The table cut.

certainly point cuts were ground down into table-cut diamonds[47] (Figure 23). Table-cut stones were popular through the sixteenth century and into the seventeenth century; many more of them have been preserved in jewelry than have point cuts. Several variants on the table cut were seen during that period, with rectangular, lozenge, and tapered cuts being fashioned for use in crosses and specially shaped jewelry.

Around the year 1500, diamond cutters began to cleave dodecahedral-shaped diamond crystals into the *rose cut*. A rose-cut diamond has a flat bottom and a triangular faceted crown, often resembling a geodesic dome (Figure 24). The rose cut is an efficient means of producing an expansive gem from a relatively flat piece of diamond, such as a macle. The rose cut has considerable brilliance but little fire, and, as Tillander warned, it is not to be confused with the rosette – a shield cut that often would be set in groups of four to eight to resemble a flower or rose (Figure 25). The rose cut continued to enjoy great popularity until the nineteenth century.

Figure 24. A pear-shaped rose-cut diamond mounted in a ring. Diamond, gold, silver, enamel; from before 1734. (Courtesy of State Art Galleries, Dresden.)

Figure 25. Enameled gold pendant with a central diamond rosette formed by 12 diamonds surrounded by alternating rubies and emeralds from the first third of the sixteenth century; 5.2 cm across. (Courtesy of State Art Galleries, Dresden.)

The next advance in the cutting of a diamond with a table (the top, flat facet) was the development of the *brilliant cut*, whereby facets were added to the table cut, further adding to the diamond's brilliance, especially by candlelight. By the middle of the eighteenth century, the square brilliant cut and the cushion brilliant cut (or old-mine cut) were the common diamond shapes found in rings, exquisite necklaces, and bracelets (Figure 26). That shape would evolve into the cut with the purest, most mathematically accurate balance between brilliance and dispersion – the modern round brilliant cut. The round brilliant's optimum angles and proportions were published by the Antwerp cutter Marcel Tolkowsky in 1914. Previous cuts that had featured a tapered base (pavilion) had mimicked the octahedron shape but had been too deep to maximize the brilliance and fire returned to the viewer. Today's modern brilliant has changed somewhat from Tolkowsky's design, but it maintains the fundamental proportions based on the refractive index and the coefficient of dispersion (Figure 27).

Cushion cut brilliant
top view
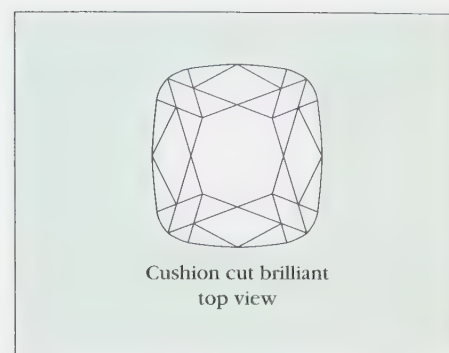
Figure 26. The cushion cut or old-mine cut.

NOTES

[1] Deposits in Borneo were discovered around 600 C.E. by Hindus, but they were taken over by the Malays and later the Chinese (Spencer et al., 1988). It is unclear whether any of those stones reached Europe.

[2] The dating abbreviations for eras used in this book are B.C.E. ("before the common era," traditionally referred to by Christians as B.C.) and C.E. ("of the common era," likewise referred to as A.D., *anno domini*).

[3] Kangle (1972), line 2.11.38.

[4] Ibid., lines 2.11.33–6.

[5] Ibid., line 2.11.39.

[6] Ibid., lines 2.11.40–1.

[7] Ibid., lines 7.12.22–4.

[8] Ibid., line 2.21.22.

[9] All references to the *Ratnapariksa* of Buddha Bhatta come from Finot (1896) and were translated from French to English by the author, or from Sanskrit to English with the help of C. E. Nehru.

[10] The Danavas were a middle- to lower-echelon group of gods who, because of some wrongdoing, were cursed and considered evil. "Bala" means "power" or "strength."

[11] The three worlds composed the universe of the Vedic gods (heaven, or celestial; air, or atmospheric; and earth, or terrestrial); thus Bala conquered all the lesser gods.

[12] Divaspati or Divapati (lord of the gods) is one of Indra's other names, but the thrust of the poem is that Bala conquered even the gods and held their wives captive.

[13] A sacrifice by fire was regarded as the fundamental agency of creation in the Vedic scriptures. Sacrifice was a benevolent act, and the sacrificed would be received by the gods; a selfish, niggardly being would be punished by them.

[14] Yakshas are the same as Rakshas, goblins or evil spirits; Siddhas are saints or saintly spirits.

[15] The numbers refer to the stanza/line numbers in the *Ratnapariksa*.

[16] "Sri" has a variety of meanings, but here probably denotes the beautiful goddess.

[17] From Kunz (1938), translated from the Pali by T. W. Rhys Davids.

[18] Pliny the Elder (1962).

Figure 27. Round brilliant cut of Tolkowsky. Ca. 1914.

Brilliant cut (modern)
top, bottom, and side views
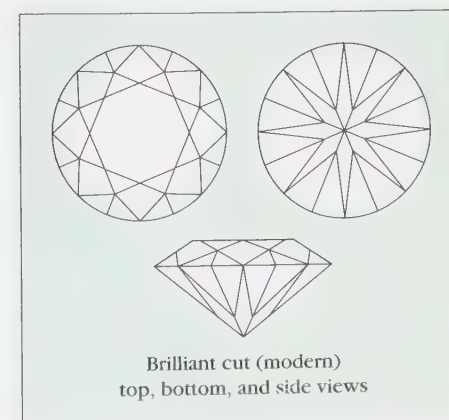
[19] J. B. François Etienne Ajasson de Grandsagne (b. 1802) published an annotated French translation in 1829–33.

[20] Problem in translation; it probably means "preventer of suicides."

[21] Stanza 30.33 in Caius Julius Solinus, *Collectanea rerum memorabilium*, quoted from p. 550 of Gorelick and Gwinnett (1988).

[22] Laufer 1915).

[23] Evans (1922), pp. 20–3; the Gnostics were a late Hellenistic and early Christian sect whose beliefs sprang from Indian mysticism and the occult. Much early Christian doctrine had to be formulated to oppose the Gnostics.

[24] Kunz (1938), p. 75, citing Dr. Julius Ruska, *Das Steinbuch aus der Kosmographie des al-Kazwini*.

[25] Pliny the Elder (1962), vol. 37, 15.

[26] Ohly (1976); Tillander (1995), p. 19.

[27] A study of this topic is provided by Ohly (1976).

[28] Kunz (1938), p. 15.

[29] Evans (1922), p. 35; my rough translation from the Latin.

[30] Information drawn from Kunz (1938) and Bruton (1978), but probably derived from her *Physica* (ca. 1151–8).

[31] Bruton (1978), p. 9.

[32] Evans (1922), pp. 49–50.

[33] Cited by Kunz (1938), p. 103, as *Le grand lapidaire de Jean de Mandeville*, from the edition of 1561 by J. S. del Sotto (Wien, 1862, p. 8). Mandeville claimed to be an Englishman who lived in Normandy and wrote in French; he may have been Jean de Bourgogne (also known as Jean or Jehan à la Barbe, a physician from Liège, Belgium) or Jean d'Outremeuse (1338–1400). Citations by Legrand (1980) for plates in *Lapidaire* in the Bibliothéque Nationale give the author as Jean de Mandeville (1300–72).

[34] Kunz (1938), p. 153. Referenced as Garcias ab Orta, *Aromatum historia* (Latin version by Clusius) (Antwerp, 1579, p. 172) (*Colloquios dos Simples e Drogas e Cousas Medicinais da India*, Portuguese original published in Goa, 1563, and Lisbon, 1573).

[35] Kunz (1938), p. 70.

[36] Ibid., p. 41.

[37] Ibid., p. 70.

[38] Scarisbrick (1994), p. 17.

[39] Tillander (1995).

[40] See Tillander (1995) and Legrand (1980) for details.

[41] Meen and Tushingham (1968), p. 55.

[42] That taboo is discussed in this chapter.

[43] It is not known whether early point cuts were octahedra that were "improved" or were some other form that had been cleaved or polished to resemble an octahedron.

[44] Variations in hardness are discussed in Chapter 1.

[45] Tillander (1995), p. 25.

[46] The crown angle is measured from the vertical axis of the gem, as from the viewer's sight line.

[47] Bruton (1978), p. 210, gives Anselmus de Boot as a source.

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6

Regal Ornaments: Six Centuries of Diamond Jewelry

DIANA SCARISBRICK

PREEMINENT among precious stones for its luster, hardness, and brilliance, the diamond evolved from the solemn grandeur of the early point cut to the fiery splendor of the multifaceted brilliant cut over several centuries. Although the exact circumstances in which faceting progressed from the first polished point cut through the table cut, the lozenge cut, the rose cut, and the brilliant cut were poorly recorded, no such mystery surrounds the settings created for them. From the middle of the fourteenth century there is documentary evidence (wills, inventories, invoices) showing how the successive generations of artisans were inspired to produce jewelry worthy of the extraordinary qualities of diamond. Among all the craftsmen from every nation who have taken up the challenge, none have been more successful than the French, whose exquisite and sumptuous art has been admired since the Middle Ages.

The universal recognition of French supremacy has meant that the story of diamond jewelry over the past six or seven centuries has been relatively homogeneous, for styles in the Western world have followed those originating in Paris. At first the goldsmiths of that city demonstrated how best to use small stones of rudimentary cut, and then during the Renaissance they used more varied jewels to frame and dramatize narrative compositions, as well as to create devotional and regal objects. As supplies increased and new cuts were introduced, diamond jewelry became synonymous with baroque splendor, rich and massive. Thereafter, the jeweler saw his task as that of displaying the stones to their best advantage, adapting designs to their size, cut, and brilliance. By the closing decades of the nineteenth century, the beauty of the stone was considered sufficient in itself, and designs became less artistic, more uniform and monotonous. Displays of affluence reached new heights during the belle époque, from about 1880 to 1914, when more diamonds became available than ever before because of the discovery of new sources in South Africa, and

more were worn than ever before, often at the expense of taste. The most significant developments in the twentieth century in regard to diamonds have been the progressive democratization of the diamond and the challenge to the traditional supremacy of the Parisian jewelers that has come from Italy and the United States. This chapter, which is concerned with the evolution of Paris-inspired jewelry reserved for the upper ranks of society, is illustrated by examples from tsarist Russia and the courts of the king of Poland and the elector of Saxony that show how closely the French fashions were followed internationally. Obviously this chapter is but a brief introduction to the vast, rich history of jewelry and the place of diamonds in it.

Figure 1. The enameled gold and jeweled crown that Princess Blanche, daughter of Henry IV of England, wore at her wedding in 1402. Point cuts (or natural points) are set in the centers of the pearl clusters. English (?), c. 1370–80. (Courtesy of Residenzmuseum, Munich.)

THE MIDDLE AGES

We can assume that diamond jewelry was already well known among the nobility by the middle of the fourteenth century, when the statutes of the Parisian goldsmiths' guild prohibited the cutting of crystal to look like diamonds. During the next century, cuts were no longer limited to the point cut; the range available included the table cut, the shield cut, and the hog-back cut. Diamonds were mounted in combination with pearls and colored gems, especially sapphires, *en cabochon* (ground and polished to a rounded convex form) in jewelry further embellished with translucent and opaque enamels.

The most prestigious jewels were used in the crowns, coronets, and jeweled garlands (known as chaplets) worn by the nobility at weddings and other festivities (Figure 1). In 1360, the favorite chaplet of Jeanne de Boulogne, queen of France, was composed of clusters of pearls, each centered on a diamond, and there were similar motifs on the tall pinnacled crown of Queen Anne, wife of Richard II of England. In 1424, diamonds were set in the fleurons (strawberry leaves) in the crown of King Charles VII of France; derived from the stemma, a Byzantine symbol of royalty, the fleuron has signified rank ever since. Diamond jewels were also worn on hats. The taste of the dukes of Burgundy for rich, elaborate ornaments is illustrated by the famous plume set with two large shield-shaped diamonds and one table-cut diamond amid pearls and balas rubies captured by the Swiss when they defeated Charles the Bold at the battle of Granson in 1477.[1] Smaller diamonds were ingeniously fitted together into flower-like rosettes, simply mounted, such as that depicted on the black velvet cap worn by Princess Margaret, daughter of Emperor Maximilian I, in her portrait by the Master of Moulins (Figure 2).

Collars and chains were worn by all persons of consequence, and they often were embellished with diamonds. As a New Year's gift in 1406 to please the art-loving Jean, duke de Berry, his treasurer gave him a collar of round gold links, with each enclosing the duke's personal badge (a bear) studded with

Figure 2. Margaret of Austria as a child, with a diamond rosette pinned in her hat. Master of Moulins, 1483. (Courtesy of Photo RMN, Musée de Château de Versailles.)

Figure 3. Greek cross crosslet set with lozenge-shaped and table-cut diamonds within a white rose, mounted in the center of the circlet of the silver gilt enameled and jeweled crown of Princess Margaret of York. English, 1461 (restored 1865). (Courtesy of Cathedral Treasury, Aachen, Germany.)

table-cut diamonds. In 1468, all the different diamond cuts were liberally used for a chain of lover's knots framing the initial A, to each side of a huge table-cut diamond, that Antoinette de Maignelais lent her lover, Duke François II of Brittany. He wore his best point, table, and heart-shaped diamonds in a pendant, and the custom of displaying specimen stones in that way was recommended by Olivier de la Marche in *Triomphe des dames* (1490) for an ideal lady who should "hang round her neck a very notable pendant . . . of the best diamonds that are polished pure and of good aspect and so well cut into facets you shall not know which is the first." Those diamonds might be combined into a variety of motifs, reflecting the gothic love of nature, religious devotion, or obsession with heraldry and courtly love. Exemplifying the various types of crosses (Greek, Latin, crutch-shaped τ) is the cross crosslet (a cross whose arms and upright terminate in small crosses) seen in the front of the crown bequeathed by Margaret of York in the treasury of Aachen Cathedral (Figure 3). Hog-back diamonds often were mounted to form the letters IHS, the sacred monogram, taken from the Greek abbreviation for the name of Christ (Figure 4); one was made for Duke Philbert of Savoy in 1482. Such cipher jewels might spell out the acronym for a motto or a person's initials. The important armorial jewels were the royal fleur-de-lis, a white rose (symbol of the house of York), an ermine (the motif of the duchess of Brittany). That duchess had her famous heart-shaped diamond mounted as a pendant on a chain with the figure of her patron, Saint Margaret. Another heart-shaped diamond belonging to Charles the Bold had two pearls hanging below.

The brooch that was used to fasten a tunic at the neck was given a rich and ornamental character by the diamond. One of the earliest reported examples dates to 1350 and was in the collection of the Black Prince, a connoisseur of gems and the eldest son of Edward III of England. It was a cluster, with the great diamond in the middle encircled by colored stones and pearls. Another diamond, "flat and round in the fashion of a mirror," was set into a brooch for Jean, duke de Berry (1409), and in Scotland, the most important brooch owned by James III was the one "with the grete diamond with the diamonds set about" (1488). The ciphers and heraldic symbols used for pendants – fleur-de-lis, crowns, the carpenter's plane of Jean sans Peur, the bear of the duke de Berry – were repeated for brooches, as were flora and fauna. There were lambs, stags' heads, rose branches, and red and white pansies, which may have been intended to convey the message "think of me." Naturalism merged with religion in the motif called the Pelican in Its Piety, here in a brooch showing a pelican feeding its young with its own blood, symbolic of Christ's Passion, nobly perched on a scroll embellished

with a diamond (Figure 5). The exceptional artistic quality that the wealth of the dukes of Burgundy could command is illustrated by a brooch evoking the world of medieval romance: two lovers holding hands in a garden, their refined heads highlighted by a triangular diamond glittering between them (see Figure 14, Chapter 5).

The ideal of courtly love was also expressed in bracelets. Antoine de la Salle's *Petit Jehan de Saintre* (1459) tells how a great lady took the youthful Jehan as her knight and proceeded to instruct him in the art of chivalry. That meant that he had to buy a bracelet enameled with their mottoes and richly embellished with gems, including six good diamonds. It was a design echoing that ordered by François II of Brittany, inscribed *à ma vie* (for life), amid a collection of point and table diamonds of different sizes. More frequent was the favorite symbol of a heart, set with a lozenge diamond, the back enameled with black tears, for sorrow, hung from a simple chain at the wrist. The fifteenth-century fashion for the figurative is represented in the collection of Henry V of England by a bracelet composed of two gentlewomen holding flowers in their hands and crowned with circlets, with diamonds glittering among rubies, sapphires, and pearls. That the skills of the goldsmith were matched by those of the stone setters is confirmed by the miniature painting of the Garter insignia lost by Charles the Bold at Granson in 1477: The motto *honi soit qui mal y pense* (shamed be he who thinks evil of it) fashioned in hog-back diamonds runs the length of the blue velvet band, and more diamonds embellish the pearl-and-ruby tag and buckle. Epitomizing the luxurious tastes of the dukes of Burgundy, it foreshadows the increasing prominence of diamond.[2]

THE RENAISSANCE

In the first half of the sixteenth century, monarchs such as François I in France (r. 1515–47) and Henry VIII in England (r. 1509–47) were rivals in the arena of splendor, seeking to acquire the best stones to be set into jewelry that often reflected the influence of Greek and Roman art. The new decorative vocabulary included the classical *putti* (representations of Cupid-like children), acanthus-leaf ornamentations, scrolls, nymphs, satyrs, bucrania (sculptured ornaments featuring garlanded ox skulls), cornucopias, masks, and military trophies, as well as elements from architecture (rounded arches, columns, and pediments). The stones, their flaws disguised by foil backing, were set in more decorative trefoil, quatrefoil, and polyfoil collets (collars) that from about 1540 were enriched by gold chasing (embossing or polished engraving) and enamels. Those enamels varied from black to the *verde et rossi a fiori* (green and red flowers) chosen by Isabella d'Este at the beginning of the century to blues, whites, and bright green. Most frequently, diamonds were used in composi-

Figure 6. Front-view drawing of Benvenuto Cellini's design for a diamond cope clasp for Pope Clement VII. God the Father is enthroned on a large point-cut diamond held up by cherubs within a border of table-cut diamonds, rubies, and sapphires. Created in 1530–1, this masterpiece of Renaissance jewelery was melted down in 1797 to pay the indemnity exacted from the Vatican by Napoleon. Watercolor by F. Bartoli, 1780. (Courtesy of British Museum.)

Figure 7. Enameled gold and diamond hat medallion representing the conversion of St. Paul. Point-, table-, and rose-cut diamonds emphasize the shields of the soldiers, the horse's harness, and the doorway of the house. 4.2 cm across, mid-sixteenth century, French or Italian. (Courtesy of Waddesdon Bequest, British Museum.)

tions that balanced wrought gold, bright enamels, colored gems, and silvery pearls. During the Renaissance, diamonds never dominated in jewelry, which was almost always a cultural or spiritual statement as well as a display of wealth. That attitude was expressed by Benvenuto Cellini (1500–71), sculptor, metalsmith, and great master of the Renaissance, when he described in his autobiography how he set a huge diamond for Pope Clement VII to wear as the clasp, or morse, for his cope: "What I had done was to place the diamond exactly in the center of the whole work with the figure of God the Father gracefully turning to one side seated above it so the design was beautifully balanced and the figure did not detract from the jewel. With his right hand raised God the Father was giving a blessing and beneath the jewel I placed three cherubs supporting the Father with raised arms. The middle one was full, the other two in half relief. Round about I had designed a crowd of cherubs beautifully arranged with the other gems. God the Father was draped in a flowing mantle from which the other cherubs peeped out"[3] (Figure 6).

Cellini also made badges for men to wear in their hats, usually medallions illustrating, in relief, episodes from the Bible, classical mythology, or history, where the role of the diamond was limited to adding emphasis to the scene depicted or to providing a frame for the scene. There are diamonds studding the columns of a building and the horse trappings and shields of the soldiers in the badge showing the conversion of St. Paul, said to have been a gift from Don John of Austria (1547–78) to Camillo Capizucchi (Figure 7). Similarly, there were large and small diamonds embellishing the large medallion representing Peace, riding in a triumphal chariot, that Gabrielle d'Estrées (1573–99), mistress of Henri IV of France, pinned in her hat. Diamonds studded the golden tiara that Isabella d'Este wore to the wedding of Lucrezia Borgia, and there were diamonds in a fleur-de-lis crown worn by Queen Elizabeth I of England in the Armada portrait of 1588.[4] Elizabeth I is depicted in the Pelican portrait wearing a magnificent example of a jeweled headband or *bilament*. It is centered on a huge point-cut diamond framed in rubies within a border of enameled white daisies.[5]

During the Renaissance, collars and chains became even more magnificent. England's young Edward VI (1537–53) had a chain of gold with white enameled wreaths, in which was written *Ich dien* (I serve), linked to coronettes and ostrich feathers of enameled gold and set with 30 diamonds, obviously made before his accession, because the motto and feathers were those of the prince of Wales. Queen Elizabeth I owned diamond collars with Tudor roses and one with knots representing the badges of the great families of Bourchier and Maltravers. Philip II of Spain gave his wife, Mary Tudor (1516–58) of England, a collar hung with their crowned initials, each set with a point-cut or table-cut diamond and hung with pearls. In addition to such cipher and heraldic collars there were others that alluded to antiquity, such as that of Gabrielle d'Estrées, in which Jupiter presided over the seven planets within a border of rose-cut

and table-cut diamonds. The introduction of the rose cut, with the top surface broken into many facets, was an important development, for it released more brilliance from a stone than had the earlier cuts.

The brooch, previously so important, came to be eclipsed by the pendant, the quintessential Renaissance jewel that expressed many aspects of the culture. The medieval cross and devotional cipher were brought up to date by borders of chased scrolls, acanthus, or strapwork, and Roman capitals were used instead of gothic characters. The Celliniesque sculptural style was reflected by the pendant enclosing figures of the four Evangelists between the arms of a diamond cross crosslet attached to Mary Tudor's girdle in a portrait by Hans

Figure 8. Mary I of England (r. 1553–58) showing diamonds in the tau (crutch-shaped) cross at her neck, in the large pendant holding allegorical figures, and in the cross crosslet in the medallion hanging from her waist. The arms of this cross support the figures of the Four Evangelists – Saints Mark, Matthew, Luke, and John. 106.6 × 80.9 cm., Hans Eworth, 1554. (Courtesy of Society of Antiquaries of London.)

Figure 9. Enameled gold and jeweled monogram pendant, the diamond double A, for August, elector of Saxony, and Anna, his wife, surmounted by a ruby crown and framed with masks, putti, fruit, strapwork, and two emeralds. German, 1548. (Courtesy of State Art Galleries, Dresden.)

Figure 10. Enameled gold and cameo medallion representing Prudence gazing into a diamond mirror, with four loops at the edge for sewing onto a hat. Jewels combining cameo elements carved from hard stones (here chalcedony) with wrought and enameled gold are known as "commessi." 5.7 cm high, French (?), c. 1550–60. (Courtesy of J. Paul Getty Museum, Los Angeles.)

Eworth[6] (Figure 8). Above, hanging from her neck, was a huge diamond flanked by full-length figures wearing Roman armor. The personal cipher was transformed into a massive assertion of individuality, as illustrated by the jewel incorporating the diamond initials of Anna and her husband August, elector of Saxony (r. 1553–86), flanked by figures and masks and other "antiques" (Figure 9). Multipetaled-rosette diamond pendants were similarly classicized by mountings featuring motifs derived from antiquity, with the backs sometimes engraved with arabesque ornamentation derived from the Middle East. Each of those pendants was a miniature work of art, but none more so than the *commessi*, which combined the ancient technique of engraving hard-stone cameos in relief with the skills of the Renaissance goldsmith. One of the most remarkable examples, depicting Prudence gazing into a diamond glass as she meditated on the past and future, was lent by Edward VI to Lady Clifford to wear at her wedding to Sir Andrew Dudley; it must have been much like the piece now at the J. Paul Getty Museum (Figure 10). The jeweled clusters seen on the cap, bodice, and skirt are variations on the widespread themes of dress ornaments (buttons, aiglets tying slashes and seams together, girdles and

squares for the neck) that might be set with diamonds. The insignias of the orders of chivalry were used to make men appear more splendid. Diamonds were grouped together to compose the figures of St. Michael and St. George in the insignias of the Order of St. Michael and the Order of the Garter so that their members could display their wealth, magnificence, and privileged status (Figure 11).

Whereas most Renaissance jewelry restated in classical language the forms and types long in use during the Middle Ages, there was at least one important new jewel: the miniature case. Beginning in the 1560s, that was worn over the breast and was therefore designed to harmonize with the splendidly wrought gold ornaments displayed at the neck, on the head, and sometimes on the sleeve.

THE SEVENTEENTH CENTURY

Around 1600, the history of jewelry took a new direction, as the stones began to assume more importance than the settings, marking the end of the golden age of the goldsmith. The role of metal was reduced to no more than a framework, and with that change enamel disappeared from the front of the jewelry, relegated to the backs only. The rose cut, often seen in combination with the old point and table cuts, came into general use, and when the brilliant cut appeared in the 1660s, Robert de Berquen, a Parisian jeweler, described the diamond as "a sun shining among precious stones."[7] That development coincided with the substitution of silver for the traditional gold in jewel settings, to avoid the yellow reflections cast over a stone's white brilliance. Closely packed together in continuous lines or clusters, the diamonds were mounted in substantial collets, with engrailed (scalloped) borders. The classicisim of the Renaissance was followed by a return to naturalism, in the form of sprays of leaves and flowers, by ribbons tied into "knotts," and by simplified geometric lozenges, ovals, and circles. Symbols (hearts, crosses, memento mori) and ciphers remained in fashion, and new designs (stars and crescents) particularly suited to the display of gems began to appear. That period, ushered in by Anne of Denmark (1574–1619), queen of James I, in England and by Marie de Médicis in France, reached a climax with the almost unbelievable splendor flaunted at the court of Versailles during the reign of Louis XIV in France.

An innovation attributed to the artisans of Louis XIV was the parure (a set of jewelry matching in stones and design). One of the grandest, made by the court jeweler Pierre Montarsy for the wedding of Mademoiselle d'Aubigné in 1698, comprised earrings, two pendants, loops and clasps for the sleeves, 32 buttons, and a large bowknot; thus attired, the bride seemed to be clothed in flashing light. Men sought to achieve the same effect with quantities of dia-

Figure 11. (Top), enameled gold St. George and the dragon with hog-back diamonds studding armor and horse trappings. Order of the Garter, 6.5 cm high, English, sixteenth century. (Courtesy of private collection.) (Bottom), enameled gold and mother-of-pearl St. Michael with diamonds of different cuts. Part of the Order of St. Michael, 5 cm high, German, c. 1550. (Courtesy of State Art Galleries, Dresden.)

monds set in buttons, loops, and buckles. Like Louis XIV himself, they were never overwhelmed by such displays, thanks to the French genius for making magnificence elegant.

For the first 30 years of the seventeenth century, the aigrette (a spray of feathers) was worn on the side of the head by women of fashion, with or without bodkins (stiletto-shaped hairpins) headed by fine large stones. Then, when women's hair began to be worn flat and in ringlets framing the face, the bodkin came into its own, often headed by jewel replicas of insects, sprigs of flowers, or plain clusters. In the 1680s, when high, padded hairstyles returned, so did the aigrette, but so lavishly jeweled that only the very richest could afford them. The designs of Marcus Gunter[8] were typical: Each aigrette was a stem of acanthus bent under the weight of showers of briolettes (oval or pear shapes, faceted all around) and rose-cut diamonds. The theme of words and inscriptions was adopted by Marie-Louise d'Orléans to frame a huge octagonal diamond for her hair; small stones spelled out the name of her husband, Charles II, king of Spain, whom she married in 1679. It was the same for men, who reserved their best stones for the hat. In England, James I wore the famous Sancy diamond in that way, and his favorite, the duke of Buckingham, wore a diamond anchor, alluding to his appointment as Lord High Admiral of England. Others had jeweled bands to encircle the high crowns of their hats. At the end of the seventeenth century, a turned-up brim fastened with a diamond loop and button was the fashionable choice.

In spite of a long-standing preference for earrings featuring the natural form of pear-shaped pearls, diamond earrings began to be worn more frequently than ever before, some of them shaped as drops paved with diamonds, in imitation of the pearls. Marie de Médicis had a large collection: table and point cuts set in black enamel, dotted with white, heart-shaped pendants and small stones set in the shapes of crowns and blackamoors. A new theme was death, expressed by skulls, whose sockets were set with rose-cut diamonds swinging within green wreaths of laurel. The girandole, a three-drop pendant style hanging from a top cluster, seems to have been introduced by Anne of Austria, wife of Louis XIII of France; versions of it appear in every set of engraved jewelry designs published during the following century (Figure 12). In England, the duchess of Marlborough owned some of the most impressive earrings. Her best pair was composed of "pretty large" brilliant-cut drops hanging from "very fine" rose-cut tops. The stones had come from the sovereigns of Europe in gratitude for the victories of her husband, John Churchill, first duke of Marlborough, over Louis XIV in the War of the Spanish Succession (1701–14).

Although many women preferred to wear pearls at the neck, some did set their diamonds in chains and necklaces, often in combination with pearls. It was not until the end of the century that the collet necklace became virtually obligatory for court festivities. The brilliant-cut stones, graduated in size from

Figure 12. Watercolor of a girandole earring with briolettes hanging from top section set with rose cut diamonds in a spray of acanthus. The light reflecting from all sides of the swinging briolettes would have been eye-catching. Marcus Gunter, Siena 1703. (Courtesy of Rohsska Museum of Applied Art and Design, Goteborg, Sweden.)
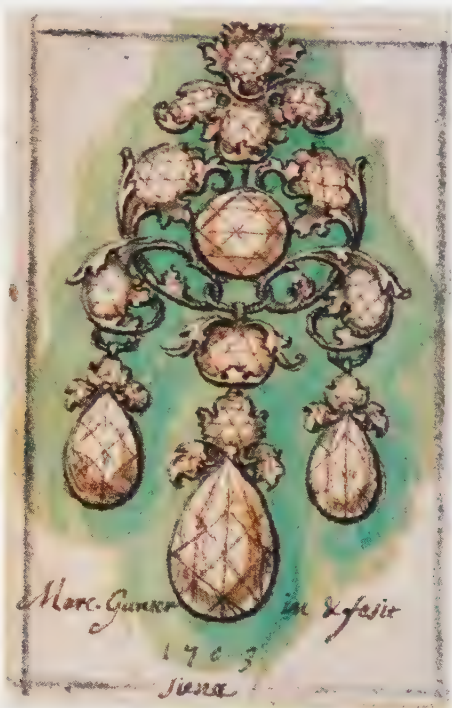
the center, encircling the neck with rays of light, might also be hung with a dia-
mond cross attached to a slide or "coulan" worn on a neck ribbon.

Filling the space between a low-cut neckline and the waist, the breast jewel,
or "stomacher," assumed a prime place in women's jewelry. Hélèna Fourment
wore one for a portrait by her husband, Peter Paul Rubens, in the 1630s; a sim-
ilar piece is in the collection of the Victoria and Albert Museum: a mass of
stones mounted around a large center rosette and hung with drops (Figure 13).
The most representative piece of seventeenth-century breast jewelry, the bow-
knot, first appeared in the collection of Anne of Austria in 1631, and versions

*Figure 13. Enameled gold and diamond breast
jewel. The table-cut stones are aligned in
curved rows centered on a starlike cluster, and
others are set in five pendant drops. This ex-
ample of the "pea-pod" style, which marked
the beginning of naturalism in seventeenth-
century jewelry, is close to an engraving pub-
lished by Balthasar Mersier in Paris in 1626.
12.6 × 7.3 cm. (Courtesy of Trustees of
Victoria and Albert Museum.)*

Figure 14. Watercolor of a brandebourg *composed of long sprays of acanthus centered on a large diamond set among quantities of others, all rose cuts. These rectangular stomachers were inspired by the frogging on the tunics of Prussian soldiers. Marcus Gunter, 1695. (Courtesy of Rohsska Museum of Applied Art and Design, Goteborg, Sweden.)*

Figure 15. Miniature of Louis XIV of France within a silver frame set with rose-cut diamonds and surmounted by a crown with Bourbon fleur-de-lis, similarly set. The silver laurel border is a later addition. Given by King Louis to the Bolognese scholar, Carlo Cesare Malvasia (1616–93), who dedicated his book Felsina Pittrice *(1678) to Louis. Miniature by Jean Petitot (1675–91), setting by Pierre Montarsy, court jeweler. 8.5 × 5 cm, French, 1681. (Courtesy of Collezion Communali d'Arte, Bologna.)*

of it, set with table-cut and rose-cut stones, were included in the designs of Gilles Legaré, published in 1663. One of the most spectacular of the versions recorded by Marcus Gunter in 1689 was a pyramidal structure of acanthus leaves and branches studded with rose-cut stones and hung with briolettes. In 1695 he depicted a *brandebourg*, a long, bar-shaped design, also of acanthus leaves, in the form inspired by the attachment frogs on the jackets of Prussian soldiers (Figure 14).

The prestige of the miniature is confirmed by the number that were framed with diamond wreaths (Figure 15) or with diamond ciphers and symbols on the enameled covers. For most of the century they were displayed as pendants, but the duchess of Marlborough introduced the fashion of wearing them on the wrist. Hers was bequeathed to her daughter, the duchess of Montagu, and was described in her will as "a picture of her father covered with a large diamond and hung to a string of small pearls for a bracelet." Because pearls were favored for bracelets, the role of the diamond, with only a few exceptions, was limited to embellishing clasps and centerpieces.

THE EIGHTEENTH CENTURY

When J. H. Pouget, in *Traité des pierres précieuses* (1762), declared that "we are now in the age of the diamond," he might well have added that most diamond jewelry was by then being designed for women rather than men. The standard for the courts in Dresden, Madrid, St. Petersburg, and London was set in Paris, where, under the influence of Madame de Pompadour, mistress of Louis XV, jewelry reached a level of artistry rarely equaled since. The jewelry at first reflected the lighthearted nat-

uralism of the fanciful rococo style, and then in the last decades of the century attention turned to the symmetry and geometric outlines of neoclassicism, using honeysuckle, palmettes, and fret motifs *à la grecque*. The jewelry was always of breathtaking elegance, revealing the full beauty of the rose- and brilliant-cut stones. The diamonds were secured unobtrusively by claws, paved together in silver settings, both open and closed, which from the 1760s were backed with gold to avoid tarnishing the skin and dress. Enamel, which had

Figure 16. Portrait by C. Van Loo (c. 1747) of Queen Marie Leszczyńska, wife of Louis XV of France, wearing the Sancy as a pendant to her diamond necklace. Other fine diamonds are worn as earrings and in the set of brandebourgs *at her breast. (G. Blot/H. Lewadowski, Photo RMN/courtesy of Musée de Château de Versailles.)*

been banished for some years, returned late in the century in a distinctive shade of royal blue, used to outline borders and to make background plaques, providing an attractive contrast for motifs and ciphers wrought in diamonds. Because it was considered vulgar to parade diamonds by day, they were reserved for candlelit evening occasions – plays, operas, masquerades, balls, and evenings of card games.

Late in the century, rather than a miscellany of jewels of different types, a matching parure set would be worn at all important social events. The most spectacular of Madame de Pompadour's seven parures comprised a butterfly for her hair, earrings, and a necklace centered on a bowknot with pendant cross, all mounted in white and fancy (pink, yellow, and green) diamonds. Such designs, which sought to imitate the patterns on silk brocades, were made possible by the jeweler G. F. Strass, who succeeded in enhancing the natural colors of the diamonds by skillful tinting.

Queen Marie Leszczyńska, wife of Louis XV, remarked that whereas a man was usually judged by what went on inside his head, a woman was admired for the quality and quantity of the jewels she wore on her head. Aigrettes, feathers, sprigs, butterflies, birds, ribbons, and bowknots glittered on snow-white powdered hair and on the fronts and sides of caps and bonnets. In the 1770s and 1780s, when hair, padded out artificially, was piled extremely high and then topped by nodding plumes, there was even more space for jewels, which often were compared to the stars twinkling in the heavens.

Whether the hair was worn high or low, the ears were left uncovered, and so earrings were almost as indispensable as clothing. With her pale primrose morning gown, the heroine of Samuel Richardson's *Clarissa Harlowe* (1747–8) wore neat diamond snaps on her ears, below her Brussels lace cap, and diamond buckles in her shoes. At night, the grand girandole appeared in all its splendor, the junction between its drops and its top softened by the addition of flowers and leaves. Beginning in the 1770s, in keeping with the trend toward simplified luxury, there was a fashion for earrings with a single, but longer, brilliant-cut diamond drop swinging between chains hanging from a button.

Whereas for many, the resplendent effect of a single row of diamonds at the neck sufficed, there were alternatives, using smaller stones. Rococo designers mounted them in flowers entwined with ribbons and hung with festoons and set them against bands of silk or velvet to show off the glittering pattern. They might center on an elegant bowknot or elaborate cross, and those who owned impressive stones attached them there. It was in that way that Queen Marie Leszczyńska wore the famous Sancy diamond, high on the neck, below a choker of diamond flowers (Figure 16). The most celebrated necklace of the century was the ill-fated *collier de la reine*. More than any other incident, its history demonstrates the ascendancy of the diamond. It was mounted with 17 large brilliants into a row, from which hung three festoons fringed with pen-
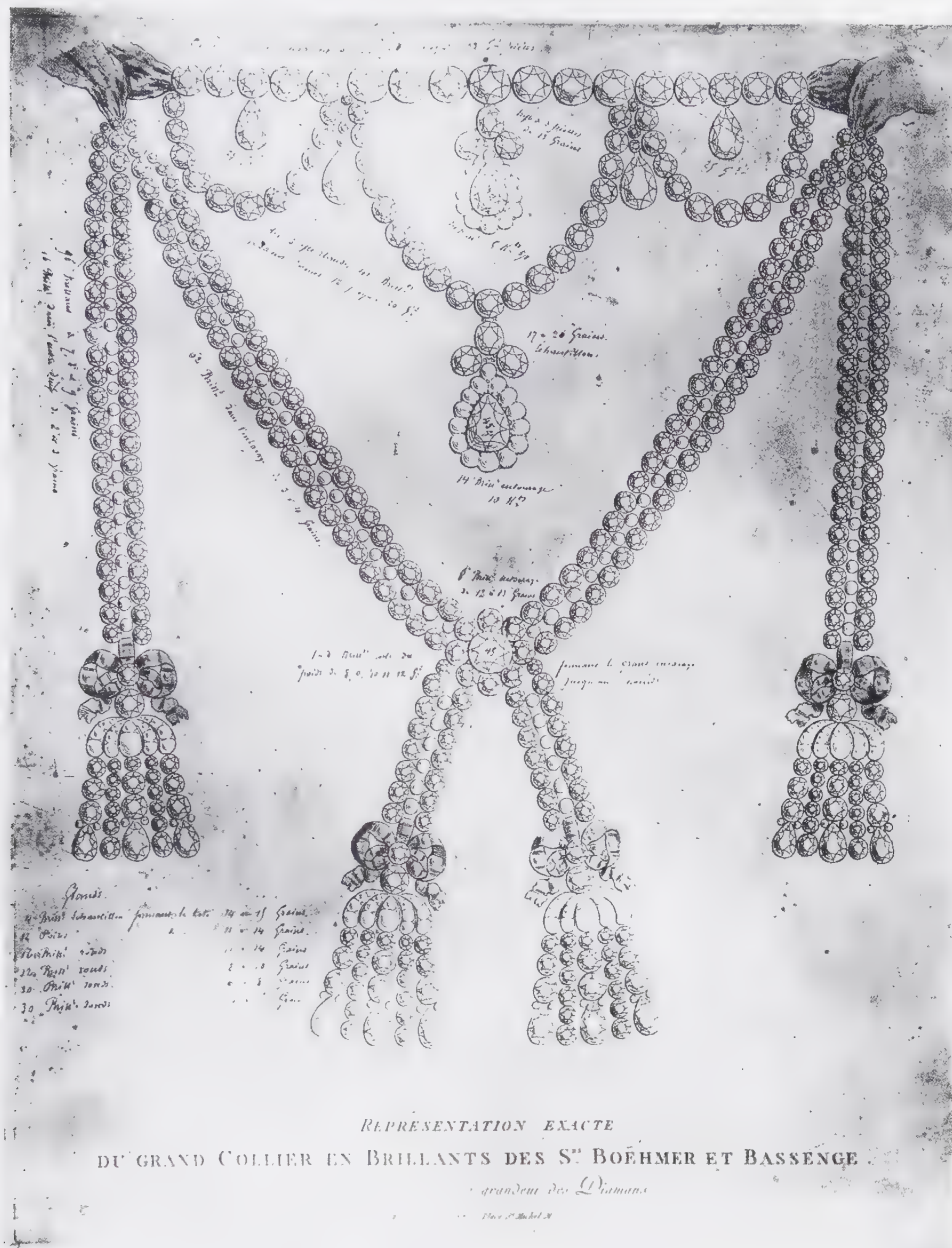
Figure 17. Engraving of the famous Queen's Diamond Necklace created by Boehmer and Bassenge for Madame du Barry, favorite of Louis XV of France. When he died, the necklace was offered to the wife of his successor, Queen Marie Antoinette, who refused it. Soon after, the necklace was given by the jeweler to the Comtesse de la Motte, posing as agent of the Cardinal de Rohan whom she had tricked into buying the necklace on behalf of the queen. The countess and her fellow conspirators took some of the diamonds to London and sold them before they were arrested and brought to justice. Unfortunately the scandal involving so many courtiers was very damaging to the queen's reputation, and her name is always associated with the necklace. The design with its swags and tassels illustrates the late eighteenth-century taste for resplendent simplicity. (Courtesy of Harlingue-Viollet, Paris.)

dant drops within two long chains terminating in four bows from each of which hung five tassels (Figure 17).

Marvels of ribbonwork and floral bouquets, the stomachers were worn on all full-dress occasions. Like the girandole earring, the bowknot was a design that survived the transition from the baroque to the rococo and neoclassical periods. It might be a set of three or four, graduated in size, or one single ornament, of which the most outstanding must have been the famous Dresden Knot (Figure 18), with 51 solitaires and 611 small stones centered on a 22-carat stone. In 1788, Marie Antoinette commissioned G. F. Bapst to fashion a bunch of wild roses and hawthorn tied with ribbon to be worn on the breast,

Figure 18. Silver bowknot stomacher set with 662 brilliant-cut diamonds. Although ribbons tied to bows were one of the favorite motifs in eighteenth-century court jewelry, few could ever have been as magnificent as this. 21 cm across, Christian August Globig, 1782. (Courtesy of State Art Galleries, Dresden.)

showing that naturalism continued to please those who could afford the best, even up to the eve of the French Revolution. There were also quantities of smaller brooches and loops flashing out light from shoulders, sleeves, and skirts, represented by the set of 46 openwork diamond leaves from the Russian crown jewels, now in the Victoria and Albert Museum. Empresses and queens might also display their diamonds in tassels hanging from the shoulders and in openwork trimmings imitating lace.

As for men, although increasingly eclipsed by women, they continued to regard diamonds as indications of status. Giovanni Casanova confessed in *Histoire de ma vie* that "I certainly looked rich . . . my rings, snuff boxes, watch-chain covered with diamonds and the cross on a ribbon which were covered with diamonds created the required impression of importance." The artistic mastery achieved by those who fashioned such jewels for royalty is illustrated by an amazing range of diamond aigrettes, epaulettes, buttons, buckles,

insignia, and sword hilts, as well as the hat loop mounted with the famous Dresden Green diamond for the elector of Saxony in midcentury, which, happily, survives (Figure 19).

THE NINETEENTH CENTURY

After the chaos that followed the French Revolution, Napoleon managed to establish himself as emperor, restoring order and bringing prosperity. Recognizing the importance of pomp and display, he identified his authoritarian government with a luxurious form of classicism that recalled the splendors of Louis XIV. A team of artists led by the painter J.-L. David and the architects Charles Percier and Pierre Fontaine devised that grandiose Imperial style, as expressed in jewelry by the father-and-son partnership of M. E. and F. R. Nitot. Diamonds played the leading role in the magnificent parures created for court life, setting the standard not only for France during the First Empire but also internationally until the outbreak of World War I.

It was significant that the sword Napoleon commissioned to celebrate the victories that had brought him political power was mounted with the 140.5-carat Regent, the most valuable diamond in the French state collection. With that at his side and more diamonds flashing out from his cap, his uniform buttons and buckles, and the insignia around his neck he must have seemed the very personification of authority. Of the many parures made for his empresses to wear with their gold-embroidered white satin gowns and red velvet trains, the most splendid must have been that made for the empress Marie-Louise in 1811 (Figure 20). For her hair there were eight strings of diamonds, a coronet topped by the imperial eagle, a tiara, and a comb set with large brilliants amid palmettes. Her girandole earrings were mounted with six beautifully matched drops "of the finest water," and her necklace of 22 brilliants was centered on the $28\frac{1}{2}$-carat pale-pink Guise diamond. There were more huge stones in the belt, emphasizing her high waistline, and others shone from the clusters on her dress and covered the miniatures on her bracelet clasps. That was the grand manner that jewelers would reinterpret over the next century for European crowned heads, aristocrats, the many New World millionaires, and others enriched by banking and industry. Like Marie-Louise, women everywhere would continue to provide the showcase for the wealth and success of their husbands, and the diamond parure would claim pride of place in every rich bridal jewel case.

After the collapse of Napoleon's empire in 1815, the renewed demand for jewelry in the grand manner took a different form, reverting to the naturalism of the prerevolutionary period. Empress Eugénie, who married Napoleon III in

Figure 19. Silver hat jewel with rose- and cushion-cut diamonds. The pin is in the form of a bow linked to a cluster of rose cuts by a double chain of rose- and cushion-cut diamonds. Friedrich August III, elector of Saxony and duke of Warsaw, wore this splendid ornament in his hat on gala occasions as part of an all-white diamond suite that also comprised a shoulder knot, buttons for waistcoat and coat, buckles for belt and shoes, sword, cane, and insignias of the Order of the Golden Fleece and of the Polish Eagle. 13.5 cm long. Christian or August Globig, Dresden, ca. 1782–89. (Courtesy of State Art Galleries, Dresden.)

1853, imagined herself a second Marie Antoinette, and the splendid parures fashioned under her influence continued that natural style, which, with variations, remained in fashion even after the end of the Second Empire in 1870.[9]

The diamond parures during the period of romanticism and the Second Empire comprised jewels for the head and for the bodice (Figure 21). Instead of tiaras of classical design, women wore twin branches of leaves (ivy, olive, chestnut) or flowers (eglantine, hawthorn, jasmine, cornflowers) and even such fruits as red currants and grapes. Those branches hung down the side of the face, often terminating in long diamond fringes. From the ears there might hang long briolettes, conservative girandoles, or bunches of grapes. Because of the importance accorded the stomacher, or *sévigné* (so called for Marie de Sévigné, a seventeenth-century lady of fashion noted for her letters chronicling life in France, who is shown wearing one in a portrait), necklaces became less prominent and usually were plain collet-style rivières. Instead, the best stones were mounted in *sévignés*, designed as bowknots or more often as branches of leaves and flowers, echoing those on the head. The leading Parisian master jewelers, Fossin, Lemonnier, and Massin, strove to make each bloom as naturalistic as possible, mounting them on trembler springs so that every movement would show them off from a new vantage point. They might be tied with undulating ribbons or might culminate in long drops falling down to the waist in threads of white light, *en pampilles*. As in the late eighteenth century, backgrounds of royal-blue enamel provided a contrast with the sparkling motifs applied to them. By the 1860s, the selection of flowers was less varied, the wild rose and daisy being the favorites (Figure 22), together with stars and crescents, all chosen for their versatility and symbolism.

The passion for luxury, which continued after the end of the Second Empire in 1870, reached its peak during the belle époque. Diamonds, once the prerogative of royalty and the socially prominent, became available to anyone who could pay for them, because of the increased supply after the discovery of diamonds in South Africa. Seen under flickering gaslight or the new glare of electric lighting, their brilliance showed to greater advantage than that of colored stones, and designers began to incorporate them in far greater numbers than at any earlier time in history. As an alternative to silver and white gold, jewelry was increasingly executed in platinum, which could carry the weight of many stones in a lighter setting. The surface would be broken up by the millegrain technique into countless tiny points of light, so that not only the diamonds but also the metal seemed to shimmer with white fire. That effect was further enhanced by the increasing sophistication of faceting as new cuts were introduced. The leading jewelers, Chaumet, Cartier, and Boucheron in Paris and Tiffany in New York, offered a style that was gracious and elegant, an up-to-date version of the neoclassicism of the Louis XVI period. The motifs were derived not so much from late-eighteenth-century jewelry as from architecture, wrought iron, Sèvres porcelain, textiles, tassels, and book bindings.

Figure 20 (opposite). Empress Marie-Louise of France in white and silver court dress and jewels from her all-white parure, standing beside the imperial crown, similarly set with diamonds. Her tiara, comb, necklace, girandole earrings, and belt are all set with stones of such value that this must be the most fabulous of all parures made during the nineteenth century. François Regnault Nitot, official jeweler to Napoleon, amassed the collection of historic diamonds and set them in the simplified classical style preferred by the emperor. Painted by Robert Lefèvre, 1811. (Courtesy of Chaumet Collection, Paris.)

Figure 21. This brooch is a variant on the peaceful U.S. symbol of the bald eagle clutching olive branches and encircled by a laurel wreath, here clutching arrows presumably to recognize the War of 1812. Although of English craftsmanship, the theme has a decidedly American perspective; hence a presumed American origin. (Courtesy of A La Vieille Russie, New York.)

Figure 22. Gold-and-silver tiara in the form of a garland of daisies. These flowers, which may have been added subsequent to the paved diamond leaves, were favorites in nineteenth-century jewelry from the mid-1820s. This excellent example of naturalistic design was worn on formal occasions and for receptions and weddings; c. 1860. (Courtesy of Earl and Countess of Rosebery.)

Epitomizing the grand manner, tiaras crowned hair piled up *à la Pompadour*. Among the huge variety of designs taken from classical art, nature, and heraldry there were a few that seemed to show the diamond to better advantage than ever: the type hung with briolettes, like drops from a waterfall; the *kokochnik*, or Russian fringe design, which stood up like a halo over the brow (Figure 23); the magnificent triple sun, flashing out brilliant rays in every direction. A Mary Stuart design, with a V-shaped peak over the brow, after the portrait of that queen in her widow's weeds, was made for those in love with the Renaissance. A contemporary note was struck by the winged tiara, inspired

by the helmets worn by the Valkyries in Wagner's epic operas. Diamonds were set in the aigrettes worn on less formal occasions, with osprey plumes waving behind them; they came as bunches of flowers, leaves, grass, feathers, stars, crescents, and rising suns, and there was even a pair of brilliants trembling at the ends of invisible platinum wires. With so much emphasis on the tiara and aigrette, earrings became overshadowed, often reduced to solitaires plainly mounted as studs. Because gowns were cut very low, there was plenty of room for necklaces, many fringed with aiguillettes (shoulder-cord decorations) or hung with festoons linked by bowknots. Velvet neck ribbons had become stylish again in Paris, sometimes worn with a centerpiece or *plaque de cou* (neck plaque), often mounted with a magnificent stone framed like a picture. Princess Alexandra, wife of Edward, prince of Wales, helped popularize the dog collar, a jeweled band around the throat, which she wore to cover a scar on her neck; such collars were particularly flattering for women with swanlike necks. In addition, lovers of luxury might have diamond chains terminating in tassels or medallions cascading down the front of the dress.

Almost as reflective of rank as the tiara, the stomacher inspired jewelers to create some extraordinary masterpieces (Figure 24). There were bowknots with tassels, openwork rose patterns imitating lace that were draped over the shoulders, and a spray of flowers made long enough to pin from shoulder to waist, as described by the *Illustrated London News* in 1886: "one such in the form of three fully opened conolvuli accompanied by several leaves of natural form and size arranged as an elegant long spray with stems tied together by a bow with flowing ends of ribbons – the whole being of diamonds of different sizes set in silver." No woman could have too many diamond brooches, and though many

Figure 24. Platinum and diamond stomacher or corsage ornament designed as two sprays of lilies, stems crossed. This elegant jewel illustrates the fashion for the eighteenth-century naturalistic diamond jewelry that was revived in the Gilded Age. About 26 cm across, made by Guesdan for Cartier, Paris, 1906, to the order of Mrs. Richard H. Towsend. (Louis Tirilly/courtesy of Cartier Collection, Geneva.)

represented the traditional hearts, stars, crescents, reptiles, and animals on a small scale, there were also more important sets of butterflies, stars, flights of swallows, and pairs of peacock feathers, which might be pinned to the bodice or veil when required. The last decades of the nineteenth century were not a great period for bracelets, usually no more than rigid, gem-studded bangles that were hidden under the billowing leg-of-mutton sleeves. The hourglass silhouette, with tightly boned bodice, tiny waist, and long trailing skirt in the fashionable pastel shades or blacks and whites, was well suited to the belle époque taste for sumptuous display. The first threat to that long-enduring fashion came in 1908, with Paul Poiret's straight, narrow tunic dresses, which were worn with little toques or turbans on the head. The budding revolution in style was accelerated by the cataclysm of World War I, which brought an end to the long years of peace, prosperity, low taxation, and inexpensive labor. Thus vanished the brilliant social life of the belle époque. Yet when the war ended in 1918, to be followed by an era of social and political change, so deeply entrenched was the love of luxury that it was not long before the diamond reemerged, but this time in settings more compatible with the modern taste for simplicity.

The Diamond Love and Marriage Ring

DIANA SCARISBRICK

Among the various types of jewels in which the diamond has played a leading role, none is of greater human interest than the smallest of all: the diamond rings given to pledge one's love and to seal a marriage. Seen in historical perspective, the modern engagement ring is the most recent link in a long chain reaching far back into the past. Rings as forms of adornment date back several millennia, but the earliest surviving writings on rings as tokens of love are from the Roman playwright Plautus in the second century B.C.E.,[10] and wedding rings are known because of inscriptions that occasionally recorded the marriage contracts sealed in the presence of the emperor's image.[11] The custom was continued and Christianized by the fourth century C.E., as St. Augustine implored priests to permit weddings without an exchange of rings for those who could not afford them. Rings of the Byzantine period were thick gold bands with round or oval bezels depicting the couple face to face, or receiving Christ's blessing on their union.[12] The significance of the wedding ring was clearly

Ring A. Stirrup ring with dark brown octa-hedral diamond crystal. Prior to fifteenth century. (All photographs in this section by Peter Schaaf/courtesy of Zucker Family Collection.)

defined in the seventh century by the bishop and chronicler Isidore of Seville (ca. 560–636): "It was given by the spouser to the espoused whether for a sign of mutual fidelity or still more to join their hearts to this pledge and that there-fore the ring is placed on the fourth finger because a certain vein is said to flow from thence to the heart."

By the thirteenth century there had been some changes, and according to Dante's *Purgatorio*[13] (ca. 1310), all who could afford them had wedding rings set with gems, chosen not only for their beauty but also for the various proper-ties attributed to them in the lapidaries. The diamond, which at that time was available only in its natural octahedral form, was set standing up, like the top of a pyramid, in a plain stirrup-shaped ring (Ring A).

By the fifteenth century, designs had evolved from their early simplicity to more elaborate styles, exemplified by an Italian wedding ring with the stone set in a quatrefoil bezel and the broad hoop inscribed *Lorenzo a Lena*.[14] It was because of its extraordinary hardness and its alleged resistance to fire and abil-ity to withstand hammer and anvil that the diamond had come to be acknowl-edged as symbolic of fidelity. That concept was expressed in the pageantry devised for the wedding of Costanzo d' Aragona and Camilla d' Aragona, held at Pesaro on May 25, 1475, which was recorded in an album of 32 miniatures, now in the Vatican library: There are diamond rings and flames painted on the tunic worn by Hymen, the god of marriage, a handsome youth crowned with roses. He stands beside an altar on which a huge diamond ring binds together a pair of flaming golden torches, explained in verse:

> Two torches in one ring of burning fire,
> Two wills, two hearts, two passions,
> Are bonded in marriage by a diamond.[15]

That symbolism struck a chord, and no sixteenth-century royal marriage was complete without a diamond ring. Thus, in 1518, when Cardinal Wolsey officiated at the proxy marriage of Princess Mary (the 2-year-old daughter of Henry VIII), a diamond ring was placed on her finger on behalf of her bride-groom, the baby dauphin of France. That marriage contract was later annulled, and 4 years later the princess was betrothed to her cousin, the emperor Charles V, with a ring set with diamonds forming his initial K (Karolus). Jacopo Typotius, in *Symbola divina et humana*, explained the meaning of the diamond ring used at the wedding between Marguerite d'Angoulême and Henry II of Navarre in 1527: The round hoop signifying eternity and the diamond bezel signifying glory represented a king and a queen bound together by an everlast-ing love, and from their happiness would ensue prosperity, symbolized by twin cornucopias flanking a diamond.[16] That significance was also appreciated by Mary, queen of Scots, for although three rings were used when she married Henry Stewart, Lord Darnley, in 1565, she insisted that only one, that con-taining a diamond, be the instrument of marriage.[17]

Only the ring made in 1546 for the marriage of Albrecht V, duke of Bavaria, to the Hapsburg princess, Anna of Austria, survives to illustrate the splendor of those royal Renaissance wedding rings. It is a rosette set with 16 lozenge-cut diamonds radiating out from a gold center in a cusped bezel supported by a wreathed and beaded hoop.[18] That triumph of complicated stone-setting demonstrates that the skills of the sixteenth-century goldsmith matched those of the cutter, who by that date had mastered the shield, triangle, hog-back, and flat table cuts. The popular table cut usually was set in a high quatrefoil bezel, the petals of which were subdivided into arches, whose lower tier was engraved with scroll, ribbon, or arabesque ornaments filled with bright green, red, blue, black, and white enamels, harmonizing with the white stones or rare fancy colored stones (Ring B). As a particular refinement, the petals of the quatrefoil might also be studded with diamonds, either table cut or point cut, the latter being compared to a hedgehog (Ring C).

Such virtuoso technical skills reached their peak in the gemmel (from the Latin *gemellus*, "twin") ring, formed of two identical hoops and bezels (most often set with a diamond and a ruby) that pivoted at the base to open up and then close neatly to form what appeared to be a single ring (Ring D). That provided a tangible illustration of the permanence of the union symbolized by the diamond, as reinforced by the inscription (usually in Latin) on the band, translated as "What God has joined together let not man put asunder" (Mark 10:9), which provided the philosophical basis for the ring's design. It was with such a ring that the Protestant reformer Martin Luther married Katharina von Bora in 1525, and its appeal remained strong well into the seventeenth century.[19]

Around 1600 the gemmel was merged with the fede (faith) motif: two hands clasped in mutual love and trust, and sometimes grasping a heart.[20] Both motifs, the *fede* and the heart (crowned, wounded by Cupid's arrow, or burning with passion) were used independently of the gemmel and set with diamonds. Their purpose for weddings or as love gifts is confirmed by inscriptions such as *Amour pour amour*[21] and "Dudley and Katherine united 1706."[22] A famous diamond-bordered ruby heart that the Swedish king, Gustavus Adolphus, gave his beloved Ebba Brahe was treasured in her family, and in each subsequent generation it was copied for an engagement ring.

Although many people made do with plain wedding bands inscribed with their names, the date, and a message or posy (from poesy, "little poem"),[23] those who could afford them still preferred diamonds. They came from all classes: the well-born Christian, daughter of Lord Kinloss, who married the earl of Devonshire in 1608; the bourgeois aunt of the diarist Samuel Pepys, "mighty proud of her wedding ring lately set with diamonds." Mary of Modena kept the diamond ring sent by the future James II of England for their proxy wedding in 1673, and in 1719 their son, the pretender to the title of James III, used it when he married the Polish princess Maria Sobieska.[24] Faceting had progressed so that with the new rose and brilliant cuts the Cam-

Ring B. Ring with table-cut pink diamond in quatrefoil collet with enameled and chased ornament. Sixteenth century.

Ring C. Ring with 5 octahedral diamond crystals. Sixteenth century.

Ring D. Gemmel ring with ruby for love and diamond for endurance with the Latin verse inscribed (see text). Life and death are symbolized by the internal figures of a baby and a skeleton. Southern Germany?, 1631.

Ring E. Ring with pointed diamond crystal that may be natural octahedron. Seventeenth century.

Ring F. Ring with 2 small rose-cut diamonds and a square table-cut diamond set in silver. Eighteenth century.
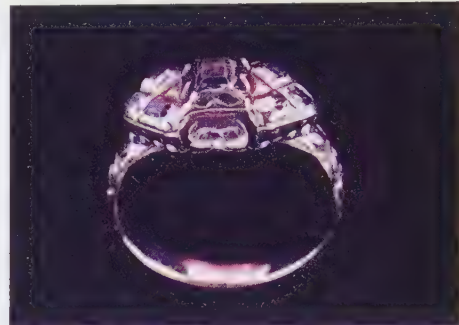
Ring G. Ring with 7 small table-cut diamonds. Seventeenth century.

Ring H. Ring with 8 table-cut diamonds. Seventeenth century.

bridge scholar Thomas Nicols, in *A Lapidary of Precious Stones* (1652), could describe the diamond as "a hard, diaphanous, perfectly transparent stone which doth sparkle forth in its glory very much like the twinkling of a starre." To avoid yellow reflections, silver was gradually substituted for gold settings. Solitaires were mounted in box bezels (Rings E and F) or held in eagle claws, but the majority of smaller stones were composed into decorative clusters – oval or round, cruciform shapes, rosettes, and groups of seven with a larger center stone set between two groups of three (Ring G). Shoulders were no longer projecting, but flat, engraved with foliate scrolls, and sober black or blue and white enamels ornamented the sides and backs of the bezels (Ring H).

In reaction to such solemnity, eighteenth-century rings began to show a rather more lighthearted approach to love and marriage. The vocabulary widened to include new themes – the turtle doves sacred to Venus, the black-amoor enslaved by love worshiping a diamond sun (representing his lady love), with the hoop inscribed with the declaration *J'adore ce qui me brule.*[25] Jeweled hearts, twinned (Ring I) and single (Ring J) rings, ruby and diamond ribbons tied into a lover's knot (Ring K), pretty clusters (Ring L), and flowers (Ring M) delight the eye with their sparkle and glitter. For Jeanne-Antoinette Poisson, marquise de Pompadour, who set the standard in taste and fashion during the rococo period, a ring was set with a diamond engraved with two crowned

Ring I. Twinned heart ring with emerald, pear-shaped rose-cut diamond, and tiny rose-cut diamonds, surmounted by crown of 5 rose-cut diamonds. Eighteenth century.

Ring J. Crowned-heart ring with old-cut brilliant-shaped diamond, 2 pear-shaped rose-cut diamonds, tiny rose-cut diamonds, and diamond chips. Eighteenth century.

Ring K. Ring with small diamond and ruby chips set in a lover's knot. Eighteenth century.

Ring L. Ring with emerald, rubies, and 12 small modified brilliant-cut diamonds and 3 silver-set diamonds. Eighteenth century.

Ring M. Ring with 6 rose-cut diamonds and large oval rose-cut diamond set into a flower. Eighteenth century.

Ring N. Ring with 13 small simplified brilliant-cut diamonds on blue enamel. Early nineteenth century.

hearts and bordered by brilliants tinted green. She also liked to wear a cameo depicting her lover, Louis XV, for that was the age of the portrait ring. Such rings, whether set with hard stones or miniature portraits, were, like wedding rings, protected by keepers, narrow bands set with diamonds all around the circumference (Ring N).

Styles changed again in the 1770s, when in response to neoclassical influences rings became more geometric (Ring O), symmetrical, and large in scale, covering the finger up to the knuckle. At that time the fashionable diamond wedding ring would have a pointed oval or lozenge bezel, called a *marquise*, for Madame de Pompadour. That style would be revived many times during the next two centuries. It might be set with one solitaire or with several smaller stones displayed against a deep-blue glass or enamel ground. The bridegroom might order rings of that design enclosing his miniature or a lock of his hair, framed in brilliants, or his bride's new monogram worked in rose diamonds applied to the bezel. Rose diamonds might also be used to spell out messages formerly expressed symbolically: *je vous aime, aimes moi, souvenir,* and the rebus LACD, which when pronounced phonetically means *elle a cédé* (she has yielded).

No fashion endures forever, and by 1800 the elongated neoclassical shapes

Ring O. Ring with 2 square table-cut diamonds flanking a rectangular table-cut diamond. Eighteenth century.

Ring P. Firmament (starry sky) ring with 8 small and one larger old-cut diamonds. Early nineteenth century.

Ring Q. Memorial hoop ring with 18 graduated old-mine cut diamonds. Nineteenth century.

Ring R. Ring with 13 small diamonds on each side flanking 3 larger old-cut diamonds and 6 small diamonds. Early nineteenth century.
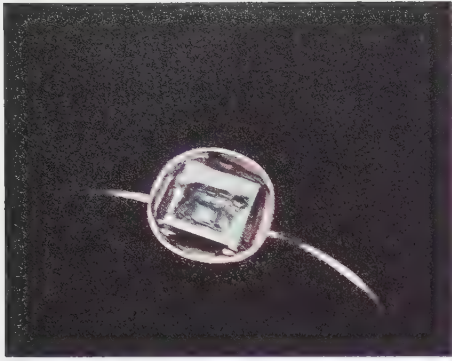
Ring S. Seal ring with engraved square table-cut diamond. Nineteenth century.

Ring T. Ring with "hand and crowned heart" with pear-shaped diamond of modified brilliant cut and diamond chips. Nineteenth century.

Ring U. Ring paved with more than 60 simplified brilliant-cut diamonds. Early nineteenth century.
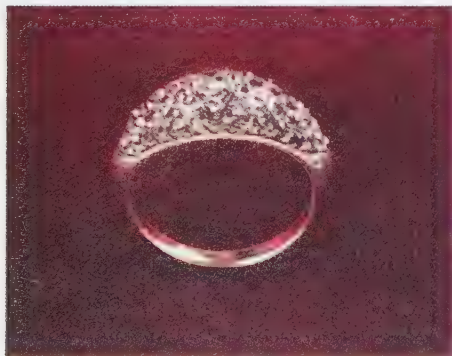
had been replaced by broader squares (Ring P) and circles, though diamonds were still set on deep-blue grounds, often with a white border. Hoops broadened considerably (Ring Q) or were joined in two, three (Ring R), or more circles. That was the period of romanticism, when the past seemed so much more attractive than the prosaic present, and motifs from imaginary golden ages (Ring S) were revived, including the heart-in-hand design, interpreted in a paving of diamonds (Ring T). The style of setting diamonds in that way, so that hardly any metal would show, dominated Victorian designs and anticipated the invisible settings of the twentieth century (Ring U). It was a diamond ring of that style that the young Prince Albert gave Victoria as a memento of their first meeting in 1839, rather than one ornamented with the then-fashionable symbolism of snakes, ivy, pansies, and forget-me-nots.

It was during the second half of the nineteenth century that today's custom of a bride having two rings became firmly established: one for her engagement, the second for the wedding itself. It became the engagement ring that bore the gem, whereas the ring given as a pledge at the marriage service was no more than a plain band, though in the United States sometimes a half diamond hoop. The diamond, because of its immense prestige, and because, large or small, it holds the eye more than any other stone, became the first choice for the engagement ring, as for centuries it had been for the wedding ring worn alone. After the discovery of diamonds in South Africa, diamond ownership became democratized, and for the first time in history the supply could meet the demand. The trade catalogues of leading jewelers showed the designs offered: solitaires of different sizes, and smaller stones in combinations of half hoops, double or single clusters, panels, fan marquises, and two-part or crossover styles, from as little as £2 each. An important innovation of the 1880s was the creation of the Tiffany setting, whose six platinum claws secured all the facets. Still made today, it is one of the great success stories in the New York diamond market. Soon after that, platinum was universally adopted for diamond rings because of its light weight and brilliance.

Discussing the proprieties of marriage, E. F. Cushing, in *Culture and Good Manners* (1926), declared that "an engagement ring is a matter for serious thought on the part of the young man. The best that his pocket can afford is what he desires and a ring that will please his fiancée's taste is even more important. Either by asking her directly or from someone who knows her preferences he finds out her desire and tries in every way to fulfill it. The solitaire diamond as large and as perfect as he could afford has for many years been the standard engagement ring." Recognizing its appeal, twentieth-century jewelers have concentrated on the stone itself, so that the setting has been reduced to a skeleton, culminating in the Niessing tension ring, in which the diamond is poised between the two halves of the split platinum hoop. The cuts of the white and fancy colored stones have been exemplars of mathematical perfection, with the smaller stones being used in combinations so that each particular form of

faceting has made its own special contribution to the total blaze of brilliance that the piece presents.

The diamond offers a wonderful sight, giving pleasure to others as well as to the wearer, which Nancy Mitford understood, writing in *Christmas Pudding* (1932): "The diamond is a stone possessed for the female mind however unsophisticated of curious psychological attributes." She went on to compare its magic with that of a love potion. Emblematic of the permanence, stability, and sincerity of affection, beautiful in itself, no gem can compare with it.

NOTES

[1] The hat plume is depicted in a miniature on parchment in the Historisches Museum, Basel.
[2] The insignia of the Order of the Garter is depicted in a miniature on parchment in the Historisches Museum, Basel.
[3] *Cellini* (1956).
[4] National Portrait Gallery, London.
[5] Walker Art Gallery, Liverpool.
[6] Tate Gallery, the Hans Eworth *Portrait of a Lady of the Wentworth Family.*
[7] de Berquen (1661/1669).
[8] Scarisbrick (1985).
[9] The sale of the jewels of Empress Eugénie is described in Chapter 10.
[10] Kunz (1917).
[11] Boardman and Scarisbrick (1977), ring no. 115.
[12] Ibid.
[13] Canto V, v. 134–6: Siena mi fe; disfecemi Marema, / Salsi colui che innanellata pria / Disposando m'aveva con la sua gemma. (The murderous [Nello dei Pannochieschi of] Marema plighted his troth to [Pia du Tolomei of] Siena with a ring set with a gem.)
[14] Dalton (1912), no. 984.
[15] Diamond Information Centre (1988), p. 7.
[16] Scarisbrick (1993), p. 60.
[17] Ibid.
[18] Ibid., p. 66.
[19] Ibid., p. 106.
[20] Bury (1984), pl. 36a.
[21] Antwerp Diamond Museum (1993).
[22] Bury (1984), pl. 16a.
[23] Evans (1931).
[24] Diamond Information Centre (1988), p. 17.
[25] "I adore that which consumes me," Chadour (1994), no. 849.

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7

The Value of Diamonds in English Literature

CAROLE SLADE

U NLIKE the motion picture, which can convey the dynamic shim-
mer of diamonds, and painting, which can capture the brilliance if
not the movement of diamonds, literature must translate diamonds into lan-
guage. English writers have most often depicted diamonds indirectly, with
figurative devices – such as metaphor, symbol, and personification – except in
the nineteenth century, when novelists gave diamonds some starring roles. The
figurative use of diamonds has not reduced them to merely decorative value,
however. Renaissance playwrights drew on the symbolic associations of dia-
monds to express unspeakable anxieties about the religious and ethnic purity
of England as a nation. Victorian writers employed diamonds to dramatize
some of the most urgent concerns of the nineteenth century. As the sun began
to set on the British Empire, diamonds expropriated from India and South
Africa signified the power that England still exercised, but they also raised
doubts about the morality of draining wealth from colonial peoples. And
because they were so easily transported, diamonds represented the forces that
already were destabilizing the English class system. Even more menacing than
the prospective displacement of England and its aristocracy were scientific
developments that threatened to eclipse human history. Like Darwin's theory
of evolution and the discoveries of fossilized dinosaur bones, geologic explana-
tions of the origin of diamonds revealed an expanse of time that exceeded the
knowledge and even the existence of human beings. In using diamonds to
express concerns such as these, English writers have given them a symbolic
value that exceeds their monetary worth and even their physical beauty.

Before the nineteenth century, diamonds were so rare in England that even
Shakespeare, whose plays were often performed for the royalty who owned the
diamonds, probably learned about diamonds mainly from reference works.[1]
Most of Shakespeare's references to diamonds are metaphors for the ideal

woman. To be comparable to a diamond, the Shakespearean woman required virtue, beauty, wisdom, fidelity, and, most important, chastity. The plot of *Cymbeline* turns on a wager that Imogen is not as flawless as her husband Posthumus's diamond ring. When Posthumus is banished, Imogen gives him the ring as an emblem of her fidelity: "This diamond was my mother's. Take it, heart,/ But keep it till you woo another wife,/ When Imogen is dead" (1.2.112–14).[2] The treacherous Jachimo challenges Posthumus to test the comparison of Imogen to a "most precious diamond": Jachimo will keep the ring if he can seduce her. Punning on Imogen's capacity for resistance and the hardness of diamonds, Posthumus is confident that "the stone's too hard to come by" (2.4.46). Imogen definitively rejects Jachimo, but he manages to learn enough intimate details about her to convince her husband that she surrendered to him. The diamond, when associated with her apparent betrayal, no longer seems beautiful to Posthumus: "It is a basilisk [serpent] unto mine eye,/ Kills me to look on 't" (2.5.107–8). The diamond eventually forces out the truth, however. When Imogen's father recognizes the ring, Jachimo admits his deception, restoring luster to both woman and diamond.

Diamonds themselves usually signify wealth in Renaissance literature. Shakespeare resolved the plot of *Love's Labor's Lost* not with love but with money, in the form of diamonds (most comedies end with marriage, but here love's labors are lost). The king of Navarre suspends his courtship with a princess by giving her diamonds:

> *Princess* [to her attendants]: Sweet hearts, we shall be rich ere we depart,
> If fairings come thus plentifully in.
> A lady wall'ed about with diamonds!
> Look you what I have from the King. (5.2.3)

While functioning as money, these diamonds also identify the princess as a Shakespearean paragon of womanhood. They hint at the king's possible return, and they represent his means of making her wait faithfully.

These two connotations of diamonds – wealth and ideal womanhood – coincide in two important plays in which they represent wealth belonging to Jews. Not permitted to own land or practice most professions, Jews often relied on portable wealth, such as cash, gold, and gems. The diamonds and other gems in Christopher Marlowe's *The Jew of Malta* (ca. 1588) "inclose infinite riches in a little room," permitting Barabas to hide them under a floorboard when Christians attempt to seize them. Barabas also possesses a metaphoric diamond, his daughter Abigail, who is coveted by Lodowick, son of the governor of Malta.

> *Lodowick*: Well, Barabas, canst help me to a diamond?
> *Barabas*: O, sir, your father had my diamonds.
> Yet I have one left that will serve your turn:–

I mean my daughter: [*aside*] but ere he shall have her
I'll sacrifice her on a pile of wood. (act 2, scene 3)[3]

Barabas can let his diamonds go, but he will not surrender his daughter to a Christian husband.

Influenced by Marlowe's play, Shakespeare gave Shylock the same kinds of diamonds in *The Merchant of Venice* – wealth and a precious daughter. On learning of her elopement with a Christian, Shylock professes to care more about the diamond she took from him than about her absence: "A diamond gone, cost me two thousand ducats in Frankfort! . . . I would my daughter were dead at my feet, and the jewels in her ear!" (3.1.87, 91). The placement of this speech, immediately following Shylock's argument that a Jew experiences the emotions common to every human being, and preceding his sentimental expression of sorrow for the loss of his wife's turquoise ring, suggests that Shylock does value his daughter over his diamond. Shakespeare scholar James S. Shapiro has proposed that Shylock's wish to see jewels in his daughter's ear refers to the Venetian law requiring Jewish women to pierce their ears.[4] Thus interpreted, Shylock's speech asserts his preference that she die Jewish rather than live Christian. Reading *The Merchant of Venice* through the prism of its diamonds, then, reveals the characters' preoccupation with the differences – in religion, custom, and ways of making money – that Shylock personifies.

In the nineteenth century, diamonds were often displayed to celebrate national holidays and anniversaries: Queen Victoria marked the fiftieth year of her reign with a Diamond Jubilee. The general public became fascinated with diamonds. Although scientists had begun to understand the chemistry and geology of diamonds, legends attributing their origin to substances such as volcanic lava, frozen rainwater, compressed vapor, and petrified wood continued to grab the popular imagination. In an 1869 issue of the *Gentleman's Magazine*, a "Continental experimentalist" announced his discovery that diamonds were "masses of meteoric nature."[5] The fact that many diamonds were discovered just lying about seemed to confirm the idea that diamonds were gifts from the heavens. By the 1870s, excavations of diamond mines in South Africa should have validated their earthly origin, but many Victorians continued to regard diamonds as supernatural entities, both divine and demonic. Writers represented the magical powers of diamonds with personification, the rhetorical technique of animating an object by giving it human characteristics or feelings.

In an essay entitled "The Diamond Necklace" (1833), Thomas Carlyle made diamonds the actors in what he called the romance, or fiction, of history.[6] A philosopher and historian, Carlyle illustrated the limitations of human capacity to know history with his version of the infamous affair of the diamond necklace made in France around 1774 (see Figure 17, Chapter 6). He suggested the mysterious powers of the 500 diamonds in the necklace by attributing action to them (see box).

THE DIAMOND NECKLACE
by Thomas Carlyle

A row of seventeen glorious diamonds, as large almost as filberts, *encircle*, not too tightly, the neck, a first time. Looser, gracefully fastened thrice to these, a three-wreathed festoon, and pendants enough (simple pear-shaped, multiple star-shaped, or clustering amorphous) *encircle* it, *enwreath* it, a second time. Loosest of all, softly *flowing round* from behind, in priceless catenary, *rush down* two broad threefold rows; *seem to knot themselves*, round a very Queen of Diamonds, on the bosom; then *rush on*, again separated, as if there were length in plenty; the very tassels of them were a fortune for some men. And now lastly, two other inexpressible threefold rows, also with their tassels, will, when the Necklace is on and clasped, *unite themselves* behind into a doubly inexpressible six-fold row; and so *stream down*, together or asunder, over the hind-neck – we may fancy, like the lambent Zodiacal or Aurora-Borealis fire [italics added].

In the well-known nursery rhyme, a "little star" twinkles like "a diamond in the sky," but these diamonds twinkle like the big stars in the sky.

Carlyle portrayed the jeweler, a Monsieur Boehmer, as having the hubris to consider himself the maker of the necklace when he was merely an arranger. Boehmer knew little of the history of the diamonds: "the first making of them"; "the first digging of them in the far Indian mines"; "how they lay, for uncounted ages and aeons . . . silently embedded in the rock"; the countless thefts and exchanges of them, sometimes for no more than "a little spirituous liquor"; and their various adventures "on the fingers of tawny or white Majesties." Nevertheless, Boehmer attempted to exceed nature as a creator by making "a jewel this universe has not matched."

The necklace was spectacular, and it was also expensive. Boehmer could not sell it at the price he asked. Madame du Barry, who had commissioned it, went into exile before he completed it. Marie Antoinette, on whom he urged it, was impoverished and perhaps, as Carlyle's narrative suggests, already worried about her neck. Boehmer refused to recoup his investment by dismantling the necklace, and four years later, just as he had nearly completed a sale at a much reduced price, the necklace disappeared. The lengthy trial of numerous suspects failed to yield a conclusion, but Carlyle wrote his own finale. In a fictional letter from Mecca, Carlyle indicated that the necklace traveled across the Bosporus to its place of origin, where the stones were liberated. For Carlyle, the ancient provenance of diamonds gives them "Experience for Philosophy to teach by," reminding human beings that because history always exceeds their efforts to know it, fiction comes closer than fact to conveying its truth.

Although diamonds served Carlyle well for explaining his philosophy of history, he might have made similar arguments with other examples. The diamonds in two Victorian novels, both early forms of the mystery novel – *The Moonstone: A Romance* (1868) by Wilkie Collins and *The Eustace Diamonds* (1873) by Anthony Trollope – are not interchangeable with any other valuable object, however. These diamonds are not what Alfred Hitchcock called a McGuffin, a device for furthering the plot that could be anything at all because it is "actually nothing at all."[7] Because the nature of diamonds is essential to the plots of these novels, diamonds can be said to have contributed to the development of the subgenre of the realistic novel, now known as the mystery or detective novel. Collins's *The Moonstone* was the first to develop the character of a detective and give him an important role in solving a mystery, the theft of a diamond.[8] (Collins gave his diamond the name Moonstone, though in reality a moonstone is not a diamond but an iridescent feldspar.)

Like Carlyle's romance of the diamond necklace, Collins's story of the diamond known as the Moonstone has many narrators, none of whom ever discovers the whole truth of its history and whereabouts. Collins attributed the elusiveness of his Moonstone to its mysterious properties. As Gabriel Betteredge, the novel's most reliable narrator, describes it, the Moonstone is an

enormous, beautiful yellow diamond that seems to draw its observers into an abyss (see box). The Moonstone is delivered to Rachel Verinder on her eighteenth birthday by Franklin Blake as a legacy from their mutual uncle, Colonel John Herncastle. Because Herncastle had killed Indian guards for it and then lied to his general about the theft, the diamond immediately seems sinister. The unset stone, which Rachel wears fastened with a silver wire, replaces the "life and sparkle" of the birthday party with its own. In Betteredge's words, "the Devil (or the Diamond) possessed that dinner-party." When the diamond disappears during the night, the local police investigate but only create even more mysteries. Lady Verinder calls in Sergeant Cuff from Scotland Yard. Nearly every other character also conducts inquiries, but none discovers the complete truth.

Collins originally intended to designate the diamond as a "serpent's eye," a stone belonging to a cult of snake worshipers, but then decided on an association with Vishnu, the Indian god of the moon.[10] He based the Moonstone on several actual diamonds: the Orlov, the Pitt, the Koh-i-Noor, and the Sancy. From the Orlov, Collins borrowed the diamond's sacrilegious transposition from the eye of an Indian god to the handle of a dagger, from which his Colonel Herncastle extricated it. Lady Constance Russell claimed that Collins saw the Pitt diamond, a 410-carat stone owned by the British merchant Thomas Pitt. Pitt had the diamond cut, and then he sold the largest part of it to France, where, renamed the Regent, it was set in the crown jewels.[11] Like Collins's Moonstone, this diamond exhausted its owner by forcing him, as Pitt complained, to spend his time and fortune protecting the "too precious stone." Another diamond Collins read about and might have seen was the Koh-i-Noor, in legend the third eye on a statue of Shiva, but actually a Mogul treasure taken by a Persian shah and then confiscated by the British during the Anglo-Sikh wars. Taken to England in 1849, it was displayed in 1850 to mark the 250th anniversary of the founding of the East India Company. Because the Koh-i-noor had a flaw similar to the one Collins gave the Moonstone, Queen Victoria sent the stone to Amsterdam, where it was recut from 186 carats down to 108.93. King described this cutting as "a most ill-advised proceeding," but nonetheless the recut diamond was set prominently in Victoria's crown.[12] The Sancy diamond shared the destiny of Collins's Moonstone, in that it disappeared in an unsolved robbery during the French Revolution and was returned to India in 1865, purchased by a Bombay businessman.[13]

In keeping with many legends about diamonds, Collins linked the character of the diamond to that of its owner: "there was a defect, in the shape of a flaw, in the very heart of the stone." Rachel mirrors both the beauty and the flaw in the diamond. According to Betteredge, she is "devilish self-willed sometimes . . . but the finest creature, nevertheless, that ever walked the ways of this lower world." And the sacred nature of diamonds in the Hindu religion provides divine protection for the stone: the god in whose forehead it was origi-

> It *was* a Diamond! As large, or nearly, as a plover's egg! The light that streamed from it was like the light of the harvest moon. When you looked down into the stone you looked into a yellow deep that drew your eyes into it so that they saw nothing else. It seemed unfathomable: this jewel, that you could hold between your finger and thumb, seemed unfathomable as the heavens themselves. We set it in the sun, and then shut the light out of the room, and it shone awfully out of the depths of its own brightness, with a moony gleam, in the dark.[9]

nally set "predicted certain disaster to the presumptuous mortal who laid hands on the sacred gem, and to all of his house and name who received it after him."

Collins's Moonstone had had generations of Brahmins, or high-caste priests, as guards, and when it was stolen, they and their successors enslaved themselves to its recovery. (Collins seems not to have known that the diamond sacred to Brahmins was white, not yellow.) A trio of Indians, often disguised as jugglers, appears in the background of every scene. After elaborate intrigues, the three recover the diamond, kill the thief, and vanish to India. A year later, Ralph Murthwaite writes the Verinder family from India with news of the diamond's destination: "there in the forehead of the deity [Vishnu], gleamed the yellow Diamond, whose splendour had last shone on me in England, from the bosom of a woman's dress." Collins saw justice in the restoration of the Moonstone, even if he did not go so far as to condemn the colonial depredation of India's patrimony.

In Anthony Trollope's novel *The Eustace Diamonds,* diamonds function more like a McGuffin, although not entirely: it is difficult to think of another object of sufficient fascination and value to drive this extended plot. *The Eustace Diamonds* is not primarily a mystery novel, but a social satire and character study. Diamonds are the means by which Lizzie Eustace, a vulgar and self-absorbed young woman, attempts to improve her position in nineteenth-century British society, which Trollope depicts as even more petty and materialistic than she is. She begins her social climbing on a high rung, marrying Sir Florian Eustace, a man with a huge fortune who is "vicious" and, despite his relative youth, "dying." One evening he lets Lizzie wear a necklace of diamonds with a diamond-studded Maltese cross. Although he mentions that this is a "family jewel" to be inherited by Eustace sons, Lizzie convinces herself that the necklace belongs to her. When Sir Florian dies, she keeps it.

Trollope uses diamonds much as Shakespeare did – to represent individual integrity and national stability. He establishes the virtue of Lucy Morris, a governess who serves as a foil to Lizzie, using diamond as a metaphor: "The charm of [Lucy's] face consisted in the peculiar, watery brightness of her eyes – in the corners of which it would always seem that a diamond of a tear was lurking whenever any matter of excitement was afoot." When Lizzie wears the diamonds, they accentuate her character flaws: "Lady Eustace was a woman of whom it might almost be said that she ought to wear diamonds. She was made to sparkle. . . . The only doubt might be whether paste diamonds might not better suit her character."

Soon after this wearing, the diamonds are stolen from her, then recovered, then stolen again. The Eustace family tries to establish that the necklace is an heirloom and thus cannot be transferred outside the family, while Lizzie counters that as a gift it is her property. The court decision classifies the necklace not as an heirloom but as "paraphernalia." According to the British law of the day, anything can be an heirloom, even pots and pans, as long as it evokes

familial pride, but gems, except those belonging to the Crown or set in a medal of honor, are not heirlooms, because the likely event of their resetting or recutting would strip them of sentimental value.

While apparently favoring Lizzie, the ruling strips her of the protection afforded by the diamond necklace. When regarded as a Eustace family heirloom, it gave her the attendant status, but as paraphernalia, the diamonds have only monetary significance. They are taken to Vienna, where they are recut, then to Hamburg, where they are made into a necklace for "an enormously rich Russian princess." During the trial of Mr. Benjamin, the jeweler who arranged the final theft and transported the necklace abroad, Lizzie is accused of perjury and theft, but is not tried. Lizzie knows that while unmarried she is vulnerable, so she takes the first available suitor. He has few prospects for the future, apart from spending Lizzie's money, but he does have a past, rumored to include several marriages, that almost certainly will rebound to deprive Lizzie of any remnants of the social position represented by the necklace.

In addition to taking starring roles in these Victorian novels, diamonds continued to be represented metaphorically. In his sonnet "That Strong Heraclitean Fire" (1888), Gerard Manley Hopkins compares the soul to an "immortal diamond":

> In a flash, at a trumpet crash,
> I am all at once what Christ is, since he was what I am, and
> This Jack, joke, poor potsherd, patch, matchwood,
>   immortal diamond,
>   Is immortal diamond.[14]

In this stanza Hopkins argues that Christ's transformation into "immortal diamond" at the Resurrection promises resurrection of the individual soul at the Last Judgment. Even while using diamonds metaphorically, Hopkins evokes their durability and radiance, and he summons the capacity of diamonds, evident throughout English literature, to intimate the deepest mysteries of human life.

NOTES

1 Kunz (1916), pp. 32–7.
2 All quotations from Shakespeare's plays are from Evans and Tobin (1997).
3 Ellis and Bentley (1956).
4 Shapiro (1996), p. 120.
5 Cotter (1990).
6 Traill (1896–1901), pp. 324–402.
7 Truffaut and Scott (1967), pp. 98–9, cited by Hennelly (1984), p. 27.
8 Published in 32 weekly installments in England and America, *The Moonstone* sold better than Dickens's *Great Expectations*. (Tinsley, 1900, pp. 114–15, cited by Lonoff, 1982, pp. 170, 260).

[9] All quotations are taken from Collins (1966).

[10] Collins's notebooks for the novel show that he read some background on diamonds in *The Encyclopaedia Britannica* (8th ed., 1855) and the work of King (1865); his knowledge of the British in India profited from the work of Hook (1832) and Wheeler (1867–71) (Lonoff, 1982, p. 176).

[11] Bruton (1978), p. 458. Among those stolen during the French Revolution, the diamond was recovered 15 months later in a garret of a house in France.

[12] King (1865), p. 36.

[13] Bruton (1978), p. 456.

[14] Gardner and MacKenzie (1967), p. 106.

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Diamond Treasures
of Russia

INNA D. KOSTINA AND GEORGE E. HARLOW
RUSSIAN TRANSLATED BY VALERIO 888

The ceremonial and decorative use of diamonds during the period of the Russian tsars demonstrates Russia's distinctive esthetic sensibility and Orthodox religious heritage, as well as its proximity to Asian cultures. The craftsmanship in metalwork and the cutting of the stones show strong French and German influences, but the objects do not. Early Russian regalia clearly shows Russian heritage and geographical location, as shown in the cap crown of Peter the Great. The newer scepter, orb, and crown follow the form of other European monarchies, but the split crown is unique. The ornamentation on gospel covers, icons, and panagias (priests' pendants) exhibits Byzantine characteristics that are not commonly seen in western European objects.

Many of the historic diamond objects in Russia are housed in the Kremlin museums, a complex comprising several historic and cultural institutions. The miniature replica of the imperial regalia created by the House of Fabergé in 1899 is in the Hermitage State Museum in St. Petersburg. The Armory is the most famous museum in the Kremlin Museum historical and cultural complex. One of Russia's oldest museums, it is closely linked to the history of the Kremlin.

The Armory has its origins in the tsar's treasury, which is believed to date from 1508. In 1806, this storehouse of valuable historic and artistic objects became a museum housing richly wrought weapons, ceremonial trappings for horses, old state regalia, ceremonial uniforms, artistic moldings and other artifacts produced in the Armory (hence the name of the museum), the Golden Chamber, the Silver Chamber, the Tsarina's Chamber, and the workshops of the Kremlin Stables, by the best armorers, jewelers, and icon-painters from every corner of Old Russia.

The Armory also houses western European and eastern art, carefully preserved for centuries, from the richest cloth and silver objects to a unique collection of carriages. Received as ambassadorial gifts or purchased, many are masterpieces. The museum's collection continues to grow, with a number of twentieth-century additions. The Armory exhibition is located in a building constructed for it in 1851 by the architect Konstantin Ton; its facade, designed in the Russian style of the seventeenth century, exactly matches the architecture of the rest of the Kremlin.

THE IMPERIAL REGALIA
AND THE ARMORY
TREASURES

The Exposition Universelle of 1900 in Paris – a great world's fair – was a supreme event for countries to present themselves in pavilions filled with fashionable or techno-

The Fabergé Replica was made in St. Petersburg in 1899. Gold, silver, platinum, diamonds, spinel, pearls, sapphires, velvet, rhodonite. Great Crown. 7.3 cm high and 5.4 cm across. (Courtesy of State Hermitage Museum; inventory no. ERO-4745.)

logical products and cultural heritage. The House of Fabergé, a foremost vendor of objets d'art, took the opportunity to display its creativity, from its fabled Easter eggs and carvings to jewels and silver, including pieces from the Imperial Treasury. Presenting the imperial regalia, crafted at the time of Catherine the Great, was legally impossible, but Fabergé asked the tsar for permission to re-create the regalia at 1/10th true size, thereby providing the chance to add the Fabergé imprimatur to the regalia's public image (or vice versa). The replica's jeweled regalia were probably crafted in the workshop of August Holmström, and Julius Rappoport created the silver bases and rhodonite column. The Great Crown contains 1,083 brilliant diamonds and 245 rose cuts; the Small Crown contains 180 brilliants and 1,204 rose cuts; the Orb has 65 brilliants and 654 rose cuts; and the Scepter a replica of the Orlov diamond and 125 rose cuts. After the exposition Nicholas II bought the replica, and it has been exhibited in the Hermitage since 1911.

The diamond crown of Tsar Peter I the Great was one of a pair made in Moscow in the Kremlin workshops, 1682–1684. Gold, silver, diamonds, emeralds, rubies, tourmaline, sable; casting, chasing, carving, enamel; 28.3 cm high and 65 cm around. (Courtesy of Kremlin Museum; inventory No. R-9.)
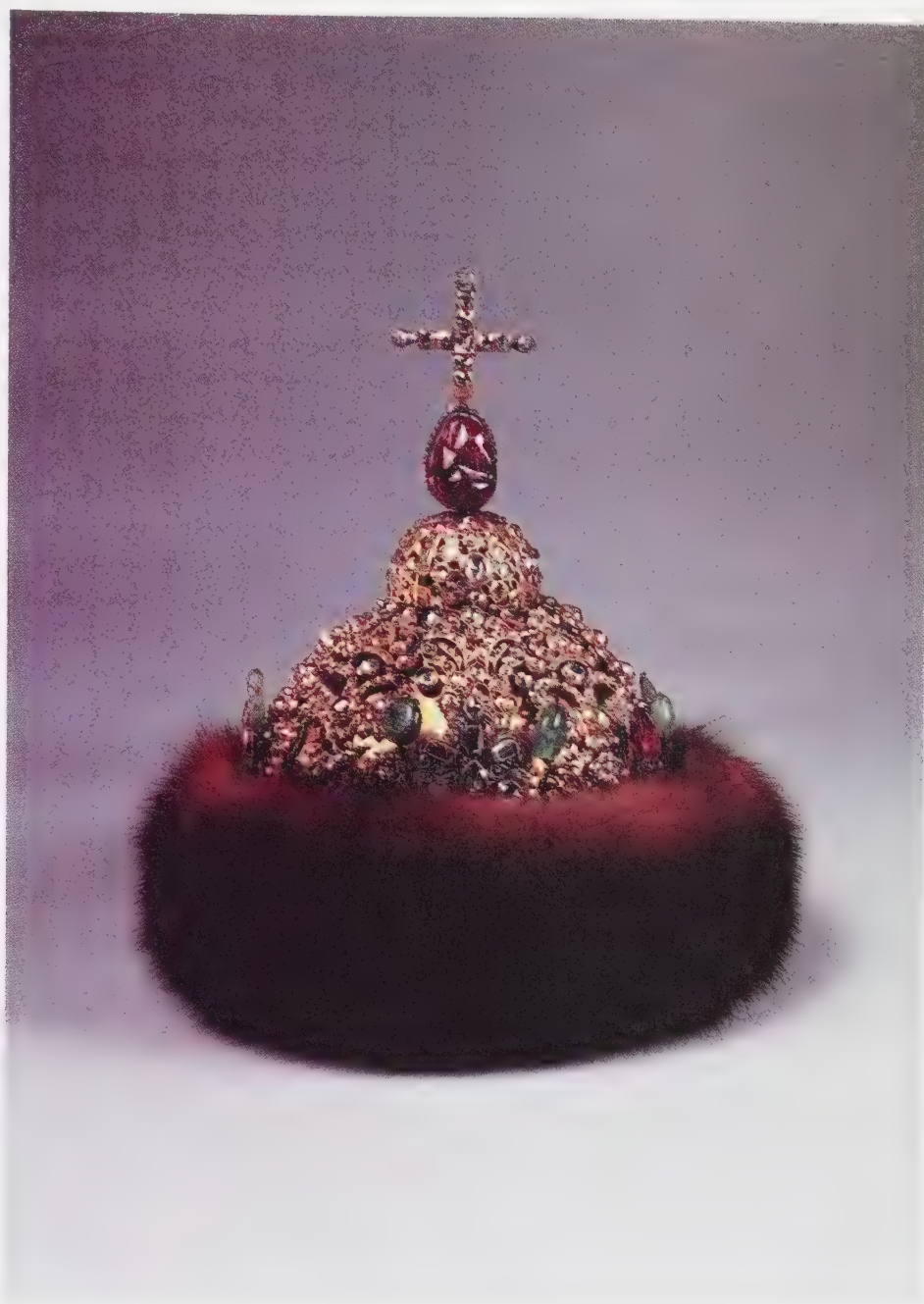
At the death of Tsar Fyodor Alekseyevich in 1682 the succession to the throne posed problems. In order to avoid disturbances it was decided that the two sons of Tsar Aleksei Mikhailovich by different wives would be crowned at the same time. The new tsars were the fifteen-year-old Ivan V (1667–1696) and his younger half-brother Peter I (1672–1725). The Kremlin craftsmen made them ceremonial crowns, which, following the medieval Russian tradition, were conical and trimmed with fur. Each crown was set with about 800 diamonds, so the pair were called the diamond crowns. The crown of Peter I is decorated with gold in the shape of the Russian emblem, a two-headed eagle, beneath a crown and rosettes of flowers. Above the fur trimmings, attached to the high central part of the crowns are large uncut emeralds and rubies. Beneath the diamond cross is a large tourmaline. This cap crown style was succeeded by larger double-hemispherical crowns of the imperial Russian regalia shown in the Fabergé replica.

The panagia was worn by a church official. St. Petersburg, mid-eighteenth century. Gold, silver, brilliants, rubies; molding, engraving, enamel, gilding; 22 3 13.5 cm, length of chain, 124 cm. (Acquired in 1928 from Sergievo-Posadsky Museum. Courtesy of Kremlin Museum; inventory no. MR-838/I-2.)

The panagia was a pectoral symbol worn by the representatives of the highest Russian priesthood. In sixteenth and seventeenth century Russian art, there was a tradition of mounting these miniature icons with precious stones. In the mid-eighteenth century, the diamond brilliant became the most fashionable stone in wealthy social circles, as can be seen even in the jewelled decoration of numerous panagias.

Perhaps the most impressive panagia in the Armory collection, this two-sided panagia with an enamel image of the Savior and the Mother of God belonged to Plato, the metropolitan or primate, of Moscow. It is decorated with 485 brilliants and 130 rubies on the panagia and 180 small brilliants on the chain. The biggest stone weighs 5.5 carats. On the reverse side is a portrait of the Empress Elizabeta Petrovna, daughter of Peter I, who probably gave it to the metropolitan.

In the sixteenth and seventeenth centuries, saddles, horse-cloths and harnesses covered with pearls and precious stones adorned the horses on the tsar's ceremonial rides. Most of these were made in the workshops of the Kremlin.

In the eighteenth century the Russian way of life changed, but artifacts for horses continued to be kept as works of art and exchanged as expensive gifts. In 1775, to commemorate the signing of the peace agreement of Küchük-Kainardzhisky, Turkish sultan Abdülhamid I gave Catherine the Great a beautiful riding costume decorated with precious stones and enamel. Of particular value was the extraordinarily beautiful and delicate "Sultan Feather" to decorate the horse's head. Made of interwoven stalks, leaves, buds, and flowers, it is embellished with more than a thousand glittering colorless stones of various sizes that serve as an intricate setting for the central topaz.

This elaborate gospel with frame was published in Moscow in 1698. The frame was made in St. Petersburg in 1794. Paper, wood, cloth; typography. Gold, silver, diamonds, rubies, sapphires, emeralds, amethysts, aquamarines, almandines; castings, engravings, pictorial enamel, gilding, 53 3 38.5 3 10.5 cm. Stamps of the craftsman – Unger, Municipal – two crossed anchors and scepter (dated 1794), and the assay-master – Nikifor Moshchalkin. (Courtesy of Kremlin Museum; inventory no. KN-5.)

This Gospel, unique for its craftsmanship and splendor, was placed in the Alexander Nevsky monastery in St. Petersburg by Empress Catherine II. It is decorated with more than two thousand gems including 554 diamonds. Many of them are concentrated in clusters which resemble panagias.

The latticework of diamonds, aquamarines, and amethysts overlays a silver and gold background. Large amethysts are set at the edges of the upper cover of the book. The clasp is engraved with the figures of the Apostles Peter and Paul. The setting was completed in the workshop of the famous St.

Petersburg silversmith Hermann Gottlieb Unger (1759– 1807).

The Gospel was received at the Armory in the 1920s, from the Alexander Nevsky monastery.

A treasure of the Armory, this chalice was made in Moscow in 1789. Gold, silver, diamonds; filigree, castings, engraving, pictorial enamel, engraved enamel; 29.5 × 17 × 17 cm. Stamps of craftsman – C.M., Municipal – St. George, and assay – 84. (Acquired in 1938 from the Sergievo-Posadsky Museum. Courtesy of Kremlin Museum; inventory no. MR-847.)

This golden chalice, one of the master-pieces of the Armory, is notable for its elegant shape, its fine decoration, and its supreme workmanship. The bowl is set in a surround of azure filigree made up of small four-petaled rosettes. On the bowl are two enamel medal-lions depicting the Savior and the Last Sup-per. The titles are set against a blue back-ground and written in the gray-brown tones popular during the second half of the eigh-teenth century. The medallions are framed with brilliants and visually connected by small stones in six horizontal rows. Overall, 206 brilliants decorate the chalice.

The chalice was made on the order of Metropolitan Plato of Moscow and Kaluga. The gift cost 8,000 rubles, an enormous sum, of which 2,029 rubles were paid to the jew-eler Carl Müller. For this reason, the base bears an engraved inscription.

8

Diamond Jewelry for Everyone

JANET ZAPATA

TWO important events in the late nineteenth century changed the subsequent history of diamonds. First, diamonds were discovered in South Africa in such abundance that their production by the 1870s eclipsed the Brazilian output and, soon, the output by the rest of the world, making ample quantities of diamonds available. Second, in 1887, the French crown jewels were sold, with many pieces going to buyers in the United States. The new supply of diamonds and a new market eager for luxury goods in the United States paved the way for the mining companies to increase their production and ushered in a new era in which diamond jewelry would be accessible to almost everyone.

The fall of Napoleon III in 1871 confronted the Third Republic in France with a dilemma: what to do with the crown jewels, those ostentatious reminders of the monarchy. The jewels were part of the collection that Empress Eugénie had ordered redesigned in the fashionable Louis style, a revival of the opulent designs favored during the reigns of Louis XIV, XV, and XVI. After much debate and criticism by Parisian jewelers, the bulk of the collection was sold at auction, with only a few items retained for the state. Buyers from all over the world attended the sale, including such important Parisian jewelers as Frédéric Boucheron and Paul Bapst, who had earlier remounted many of those very stones. In the end, the American firm Tiffany & Co. bought the major share: 24 lots for $480,000, a sum greater than the combined purchases of the next nine largest buyers. That unexpected development served notice that Americans would be in the vanguard of the new moneyed class.

Among the jewelry that Tiffany purchased were pieces from Empress Eugénie's great girdle, which Tiffany sold in specially designed boxes, and a currant-leaf corsage ornament (Figure 1), which went to Cornelia Bradley Martin.[1] Some of the stones that Tiffany purchased became part of its display

Figure 1 (opposite). This currant-leaf corsage ornament, once part of the collection of Empress Eugénie, was divided into sections and sold at the auction of the French crown jewels in 1887. This section was presented to the Metropolitan Opera diva Lucrezia Bori at her last performance. Upon her death, Bori bequeathed the brooch to the Metropolitan Opera. (David Behl /courtesy of Metropolitan Opera Guild.)

Figure 2. Paulding Farnham is credited with designing all the jewelry in the Tiffany & Co. display at the 1889 Exposition Universelle in Paris, including this corsage garniture, set with over 2,000 diamonds mounted in platinum. For its exhibit, Tiffany was awarded a gold medal; Farnham received a silver medal. (Courtesy of Tiffany & Co.)

at the 1889 Exposition Universelle in Paris. One diamond of slightly more than 25 carats was the center stone in a pendant, suspended from a necklace, based on the American hazelnut; the diamond was valued at $45,000, and the necklace at $150,000.[2] A diamond fantasy piece – a corsage garniture imitating lace and embroidery that was made up of more than 2,000 diamonds mounted in platinum (Figure 2) – dazzled viewers at the exposition. Approximately 3 feet long and from 3 to 7 inches wide, it followed the line of the figure and was attached by three rosettes beginning at the right shoulder, cascading to the bodice, and ending at the waist. A reviewer from the London *Art Journal* considered it "probably the best piece of diamond work of the size that has ever been executed!"[3]

In the New World, the economy continued to boom, and newly affluent entrepreneurs in the United States were clamoring for visible means to show off their great wealth. Diamonds, with their historical links to royalty, offered the perfect vehicle. The select Four Hundred of New York society (400 was the number of guests Mrs. Caroline Astor claimed she could accommodate in her ballroom) entertained on a scale not previously seen in private homes in the Americas. Dressed in the latest Parisian fashions and adorned with an abundance of diamond jewelry, the women seemed to sparkle in the evening candlelight to such an extent that the first tier of boxes at New York's Metropolitan Opera was dubbed the Diamond Circle. Tiffany & Co. continued to offer what it did best, exquisitely designed jewelry set with superb diamonds, as exemplified by the corsage ornament shown in Figure 3, probably once part of a tiara, in the reigning Edwardian style. T. B. Starr and other jewelers working in that style often incorporated fancy colored diamonds into their designs. The two matched pear-shaped blue diamonds shown in Figure 4, set in a brooch in the form of an elegant masked-ball eyepiece, reflect the period's emphasis on counterbalancing colorless and deeper-hued gemstones. Other notable emerging American jewelers of that period included E. M. Gattle & Co., Udall & Ballou, Charlton & Co., and Dreicer & Co., who attempted to keep abreast of Parisian fashions and introduce the latest diamond cuts. New York City became a mecca for the affluent, prompting Cartier to open a branch in 1909, hoping to capitalize on the interest in European fashion.

As the Edwardian era drew to a close, it was replaced by a rectilinear style, based on motifs drawn from the fine arts and architectural forms. Gone were the ribbons, bowknots, tassels, and floral sprays set into lace-like settings, replaced by geometric patterns and bright colors. That style, given the name art deco, after the 1925 Exposition Internationale des Arts Décoratifs et Industriels in Paris, was characterized by the use of squares, rectangles, circles, and triangles, often juxtaposed to create complex linear configurations. For the first half of the 1920s, uniformly sized diamonds were featured in integral designs, either set into narrow bar pins or forming a single row of stones set into flexible bracelets. By the middle of the decade, larger jewelry, massed with diamonds,
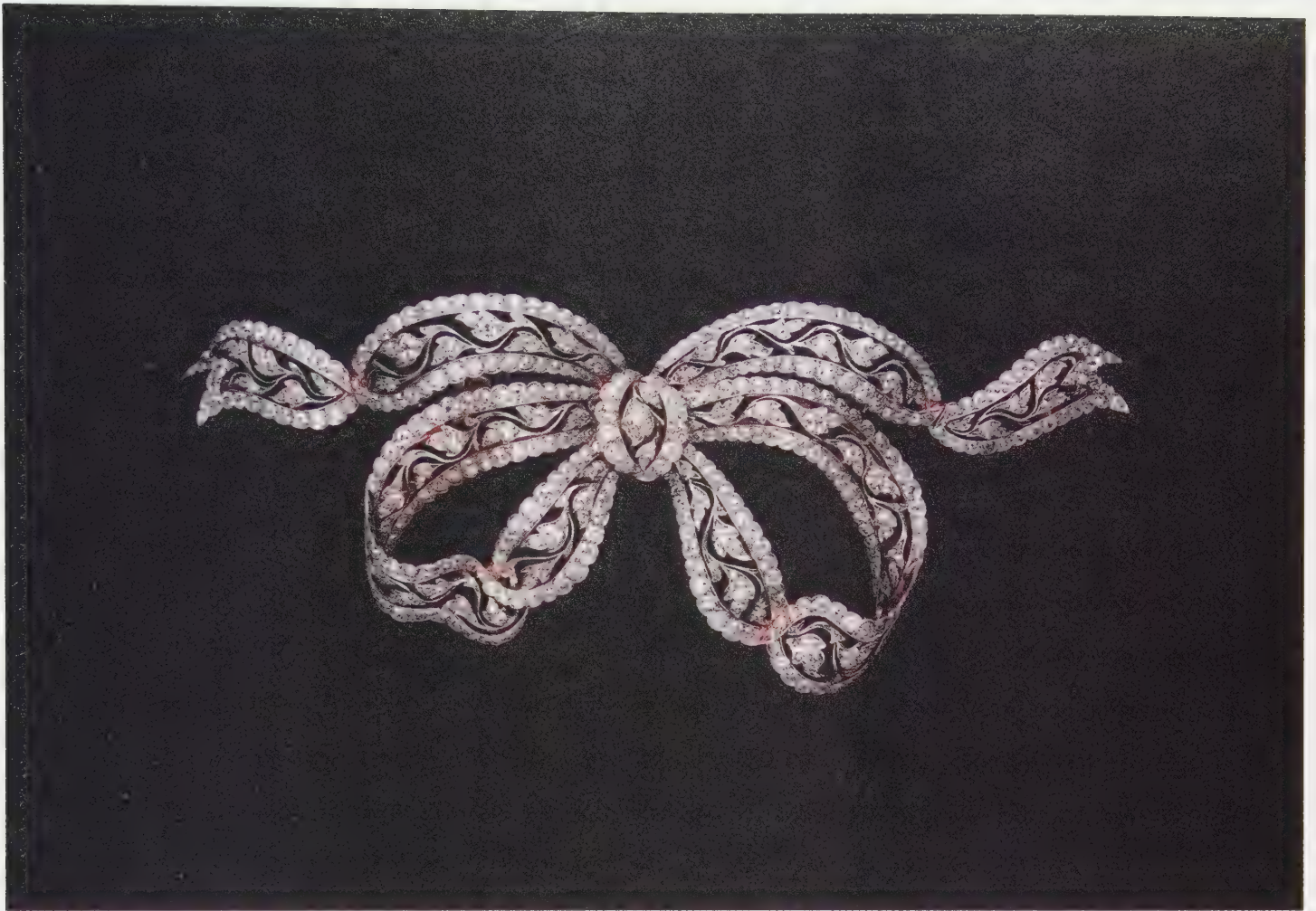
Figure 3. Tiffany & Co. created elaborate diamond jewelry in the popular Edwardian style. This corsage ornament in the form of a bowknot with laurel leaves epitomizes the elegant lines characteristic of the style. The diamonds are set into a platinum mounting backed with gold. Dating from 1900 to 1905, it is 6 inches (15.3 cm.) in length. (Tino Hammid/courtesy of Collection of Neil Lane)

Figure 4. In the late nineteenth and early twentieth centuries, the U.S. firm of Theodore B. Starr created exquisite jewelry, often set with colored diamonds. This understated brooch in the form of an elegant masked-ball lunette is set with two very rare and much-coveted matched blue diamonds weighing 2.66 and 2.98 carats. It was created around 1905. (Courtesy of Christie's Images.)

Figure 5. Raymond Yard maintained an up-stairs salon in New York City. News of his high-quality jewelry was spread by word of mouth only. This bracelet in the Art Deco style was worn by Joan Crawford. It dates from around 1925. (David Behl.)

was the standard. By the end of the 1920s, several new fancy shapes for diamonds had been introduced, based on geometric forms, including the baguette, trapezium, kite, pentagon, octagon, and square cut. Those cuts spawned a new era in ring design, with such innovations as baguettes set upright to emphasize the diamonds. The stones dictated the design of a piece of jewelry.

Cartier was regarded as the home for the true masters of the jeweled arts during the art deco period, transforming jewelry into small works of art. Diamonds accented opaque stones such as onyx, jade, carnelian, and other semiprecious gems, or they might be paved across an entire piece of jewelry. Enameled vanity cases with decorative panels, often made from mother-of-pearl and hard stones, were outlined with diamonds; Cartier in Paris and Black, Starr & Frost in New York created superb examples of that type. Toward the end of the 1920s, color disappeared from jewelry, replaced by the all-white look of diamonds. Wider bracelets, often divided into panels, were worn in multiples on the exposed arm. The bracelet shown in Figure 5, by Raymond Yard, a prominent jeweler in New York, epitomizes that style, featuring baguette, epaulette, and marquise shapes. Chaumet, who often designed for royalty, not only provided princely crowns for that elite clientele but also designed an updated version of the bandeau, a narrow band encircling the forehead that originated during the Middle Ages.

Until the latter part of the 1920s, jewelry designers in the United States followed European styles. In 1927, the editor of *The Jewelers' Circular* commented that "the American designer . . . has come into his own," and "Paris no longer dominates American jewelry design as it may have done in the past."[4] That certainly was true of designers such as Paul Flato, Seaman Schepps, Verdura, and, later, Jean Schlumberger, who together forged a distinctive American style.

During the Great Depression of the 1930s, many jewelers were forced out of business, but some innovative designers were able to survive and even flourish, in part because they had the courage to break with tradition and create new styles for new markets. Their clients included not only those whose wealth had survived the stock-market crash but also the emerging stage and movie personalities, who wore their jewelry both on and off the screen. Promotion of the diamond's mystique continued in a variety of forms, such as the credit roll at the end of a movie, and fashion magazines, such as *Vogue* and *Harper's Bazaar*, which were quick to illustrate the latest styles.

As the 1930s progressed, the machine-age aesthetic began to dominate jewelry design, with its reliance on spirals, domes, and scrolls shaped into large gold mountings and accented with diamonds. That style was counterbalanced by a return to naturalism, a trend that occurred simultaneously in France, with such jewelers as Boivin, and in the United States, with a few talented designers.

In 1938, Paul Flato opened a branch in Los Angeles, providing fanciful, often humorous, jewelry for that aspiring new capital of glamour, where dia-

monds became almost required apparel. Jewelry was being conceived in innovative forms, such as Flato's diamond feather necklace that was open at the front, which was worn by Paulette Goddard, wife of Charlie Chaplin.[5] She also owned a diamond-fringe scroll necklace by Trabert & Hoeffer–Mauboussin set with round, baguette, octagonal, and cushion-cut diamonds.[6] Early in the 1930s, that firm introduced a new line, "Reflections – Your Personality in a Jewel," in which jewelry elements could be assembled by the client. For the first time, virtually any reasonably well heeled customer could afford diamond jewelry designed to individual specifications.

Before opening his own salon in 1939, Fulco di Verdura worked as a designer for Paul Flato. For Verdura, design was paramount, so diamonds highlighted but never dominated his jewelry. He would accent an object with diamonds to serve a pictorial function, as on the lion's-paw shell clip shown in Figure 6, where diamonds imitate sea foam. Seaman Schepps, like Verdura, incorporated unusual objects into his designs. Branched coral, wood, rock crystal, lapis lazuli, and ivory were juxtaposed with diamonds, forming unusual contrasts.

Jean Schlumberger is perhaps the quintessential designer, creating fabulous pieces of jewelry, often with diamonds providing color. Emigrating to the United States from France, he maintained a salon in New York City before beginning his long association with Tiffany & Co. in 1956. Schlumberger turned to everyday objects and nature for inspiration, creating such exquisite pieces as a necklace in the guise of a cowboy's bandanna in which marquise diamonds made up the fringe.[7] Round diamonds make up the scales on the Schlumberger brooch shown in Figure 7, which became known as the Iguana

Brooch after Richard Burton presented it to Elizabeth Taylor to wear at the opening of *The Night of the Iguana* in 1964.

Jeanne Toussaint at Cartier made cats her design motif in the late 1940s, starting with a panther, its fur made of round diamonds and onyx, followed by a tiger, with canary diamonds representing its yellow fur. Perhaps the most famous of her cat jewelry was the panther astride a cabochon sapphire, weighing 152.35 carats, designed for the duchess of Windsor.

Shortly after Van Cleef & Arpels opened its New York office in 1939, its Parisian supplier, Rubel Frères, followed. Five years later, that affiliation was dissolved, and the firm of John Rubel & Co. began producing noteworthy jewelry: baguette diamond necklaces and jewels of fantasy that included

Figure 8. Set with 2,473 diamonds, this diamond necklace in the form of a snake was designed in 1968 by Gabriel Raton at Cartier for the Mexican actress Maria Felix. The necklace is reversible, with an enameled underside. (David Behl.)

flowers, fairies, and the popular series of ballerinas, often entirely covered with diamonds.

The animal motif was championed in New York by David Webb, who designed a host of jewelry with frogs, elephants, horses, cows, and fish (his most popular), often as articulated bangles that combined enamel and diamonds. "Big" and "bold" describe Webb's jewelry from the 1960s. The snake necklace shown in Figure 8, designed by Gabriel Raton under Jeanne Toussaint's direction at Cartier, was made for the Mexican film star Maria Felix and was set with a hoard of diamonds.

In the twentieth century it became clear that the key to continuing increases in diamond sales lay in educating the public to appreciate the beautiful stone. To that end, many diamond importers and retailers published booklets on diamonds to be given out at retail stores. In the first decade of the twentieth century, two diamond merchants, John Kay & Co., from Detroit, and Sidney Holt, from Newark, New Jersey, published *The Diamond: Its History, Importance and Value* and *The Diamond: A Short and Snappy Account of Its Occurrence, Characters and Applications in Jewelry*, respectively. Other publications included *The Diamond* (1924), by Justin Wood, *The Story of the Diamond* (1937), part of a series of gemstone books distributed by Marcus & Co., and *A Diamond Primer* (1958), by Black, Starr & Gorham. In the late 1940s, De Beers, the world's chief diamond supplier, held annual design competitions in the United States to encourage interest in diamonds, both within the jewelry industry and among the wider public. By the late 1950s, De Beers was also holding international contests, whose winners included Pierre Sterle, Jean Schlumberger, Seaman Schepps, and Julius Cohen.

Cohen worked at the Harry Winston firm before opening his own business in 1955. While with Winston, Cohen escorted "The Court of Jewels" exhibit to major cities around the United States. That exhibition featured important diamonds that Winston had cut, as well as jewelry pieces of historical importance, and it was the first time that such a large segment of the public had had an opportunity to see gems and jewelry of that quality. The name Winston has become almost synonymous with diamonds, for a variety of reasons: the cutting of several famous stones (including the Jonker, the Lesotho, the Star of Sierra Leone, and the Vargas), the introduction of the flexible wire setting that would hold stones in place but would not overpower them, and the donation of some important diamonds to the Smithsonian Institution (the Hope, the Portuguese, and the Oppenheimer).

Like Harry Winston, the London diamond dealer Lawrence Graff specialized in important diamonds, designing his jewelry with the simplest of settings, thus allowing the natural beauty of the stones to dominate. Such stones as the Idol's Eye, the Emperor Maximilian, the Porter Rhodes, and the Windsor Yellows passed through his hands. In 1973 he became the first jeweler to receive the Queen's Award to Industry.
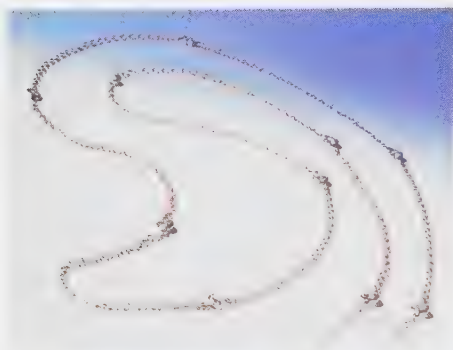
Figure 9. Elsa Peretti's "Diamonds by the Yard" created a sensation when introduced at Tiffany's in 1974. (Courtesy of Tiffany & Co.)

Figure 10. Daniel Brush's bunny bangle is molded out of Bakelite, with pink diamonds set into pink gold prongs. Graduated shades of pink diamonds make up the bunny's ears and head, simulating shadows. (David Behl /courtesy of Harry N. Abrams, Inc.)

Figure 11 (opposite). "Whimsical" is a word often used to describe the designs of Rachelle Epstein of Shelle. This is an apt description of her 1989 clock necklace, in which two rows of baguette-cut white diamonds border pavé-set pink diamond roman numerals.(David Behl/courtesy of Harry N. Abrams, Inc.)

The 1970s brought a dramatic change in the way diamonds were used in jewelry. That period was dominated by Italian designers who sold their jewelry predominantly in New York. Gone were the large confections, replaced by minimalist designs that could be worn during the day and into the evening. In 1971, Bulgari opened a salon in New York City, offering updated art deco motifs in hard stones accented with diamonds, as well as jewelry incorporating antique Roman coins and intaglios with pavé-set (set close together, forming a pavement) diamonds on bezel mounts and gold-link chains. Elsa Peretti began her association with Tiffany & Co. in 1974, creating her famous "Diamonds by the Yard" promotion (Figure 9), in which diamonds were set into gold mountings at intervals on a gold-link chain. The price varies, depending on the number of stones. Her simplicity-of-form theme continued, with diamonds sprinkled on her open-heart and bean pendants. This diamond jewelry was available to a wide audience.

The dominant position of white diamonds was challenged by the 1979 discovery of pinks at the Argyle mine in Western Australia, a source that has yielded a small but reliable supply of pink stones of less than half a carat. The jeweler Ralph Esmerian, a specialist in colored stones, was one of the first to see their potential, creating a bow necklace set with Australian pinks from which a 5.57-carat pear-shaped Brazilian pink diamond was suspended. Artist Daniel Brush designed the imaginative bunny bangle (Figure 10), in which the animal's head is superimposed onto the shell of a bangle made of Bakelite, an unusual material for jewelry. Christopher Walling used the Argyle stones to paint the pink quince blossoms on a pair of ear clips, and Rachelle Epstein of Shelle paved the numerals on her clock necklace in pink (Figure 11). Perhaps the most spectacular example of pink-diamond jewelry is the unsigned double flamingo brooch shown in Figure 12.

The 1990s have brought something like a repetition of the direction that jewelry design took at the end of the nineteenth century. Just as the use of platinum ushered in a new era of jewelry design in the 1890s, technological advances in the 1990s hint of interesting developments in the twenty-first century. In the mid-1990s, Bulgari created a thin collar necklace with letters of the alphabet spelled out in diamonds that had been cut by a laser, a process that allows the diamond cutter to shape stones in any direction.[8] The solitaire diamonds that for the past century had been mounted in the pronged Tiffany setting are now being mounted into a tension setting in which the diamond is suspended in the middle of the shank. In Belgium, Emmanuel Guillaume's recent experimentation with titanium alloys has produced a very light mounting suitable for the jewelry that his wife, Sophie, designs. These featherweight pieces are excellent for wearing on today's lightweight fabrics.

Some prominent designers of the 1990s have been looking at jewelry through new eyes. Henry Dunay has turned to current issues, designing for the American Foundation for AIDS Research (AmFAR) a diamond mask with a

Figure 12. Pink diamonds make up the bodies of two flamingoes standing in a marsh of demantoid garnets. Their beaks are formed from faceted black diamonds, and their eyes from cabochon rubies. The birds can be worn together or separately. It was made by the prestigious firm of Carvin French. (David Behl.)

Figure 13. Designed in 1991 by Henry Dunay, this "Lachrymosa" mask commissioned by AmFAR symbolizes the pain and sorrow of AIDS. A single gold tear falls from the left eye. Set with 136 carats of diamonds, the mask has diamonds provided by William Goldberg, platinum by the Platinum Guild International, and gold by the World Gold Council. (Courtesy of Christie's Images.)
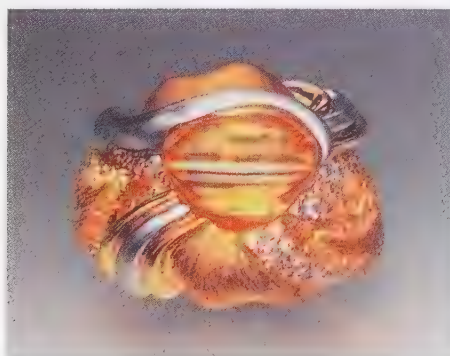
Figure 14. Henry Dunay designed a ring set with the 4.23-carat uncut Kahn canary diamond owned by Stanley Kahn and found in a state park in Arkansas. Hillary Rodham Clinton wore it to Bill Clinton's gubernatorial and to both his presidential inaugurations. (Courtesy of Stanley Kahn.)

tear to symbolize the tragedy of the AIDS epidemic (Figure 13). He also created a ring based on the topography of Arkansas and set with the Kahn uncut canary diamond that Hillary Rodham Clinton wore to the 1992 and 1996 presidential inaugurations (Figure 14). Joel Arthur Rosenthal, owner of the Parisian salon JAR, has reinterpreted the past in a contemporary style, modernizing the insect motif of the Victorian period (Figure 15).

Since the late nineteenth century, the ownership of diamonds has passed from royalty to the wealthy and, since the 1920s, to the general public – diamonds for everyone. This transformation and the evolution of diamond jewelry are examined in *Diamonds: A Century of Spectacular Jewels* by Penny Proddow and Marion Fasel (1996). Catchy advertising slogans may have helped popularize diamonds, but diamonds are desirable primarily because they are beautiful, almost mesmerizing. Anyone who has gazed into a flawless diamond at close range knows the power of its beauty.

NOTES

1 For illustration of a brooch incorporating diamonds, emeralds, and pearls taken from Empress
   Eugénie's great girdle, see Loring (1987), p. 83. For more information and a listing of the jewelry
   at that sale, see Bernard Morel (1988), pp. 365–81. For an illustration of Cornelia Bradley Martin
   wearing the jewelry from the French crown jewels, see Proddow and Fasel (1996), p. 23.
2 For illustration, see Zapata (1991), pp. 556–67.
3 As quoted in September 1889 (clipping in Scrapbook IVB, p. 234), Tiffany Archives.
4 *The Jewelers' Circular*, February 2, 1927, p. 169.
5 An illustration of the drawing for the diamond feather necklace appears in the Christie's catalogue
   Important Jewels, December 6, 1994, lot no. 59.
6 For an illustration of this necklace, see Proddow et al. (1992), p. 101. The prestigious French
   house Mauboussin had opened a salon in New York City in 1929, but because of the stock-market
   crash it closed, selling its stock and the right to use the name to Trabert & Hoeffer.
   For illustration, see Snowman (1990), p. 182.
8 Proddow and Fasel (1996), p. 160.
9 For illustration, see Proddow and Fasel (1996), p. 164.

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9

Hollywood Loves Diamonds

MAURA SPIEGEL

WATCHING the rise of the movie industry, with its tremendous impact on popular taste and fashion trends, diamond merchants like Harry Winston, Paul Flato, and Trabert & Hoeffer must have imagined the silver screen as a giant traveling display window. Beginning in the 1930s, jewelers began to place their diamonds in movies, lending them to studios free of charge. Several jewelers opened branches in Hollywood to attract new customers among the rich, glamorous, publicity-seeking parade of stars – the American "royalty."

Breathtaking diamond necklaces, rings, cuffs, brooches, clips, earrings, and hair ornaments became regular and expected accessories in movies. Like couturier dresses, hairstyles, and furs, the jewels were attributed to their suppliers in the film's credits. Every moviegoing American would get to know the names Cartier, Tiffany, and Van Cleef & Arpels.

But beyond the fashion influence and name recognition, movies would promote diamond sales in far more subtle ways, by advancing the symbolic and ritual functions of the gems. In the movies, occasions for which diamonds were the perfect gift multiplied – as their promoters urged, "A diamond for every romantic rite of passage." A familiar movie scene shows a man shopping for diamonds in order to surprise a lucky woman. It has been speculated that this particular formula – the surprise factor – was created as the diamond industry's insurance against the possibility that, if consulted, a woman might veto so extravagant and impractical a purchase. Anyway, in the thrill that lucky lady expresses as she opens the velvet box seems, at last, to be the answer to that eternal question: What do women want?

Consumer volume did increase as the diamond in movies began to replace other jewels (most notably the emerald and the pearl) as the gem of choice, as the badge of feminine triumph, and as the measure of a man's romantic or mar-

Figure 1. Poised and alert, Elizabeth Taylor as Maggie the Cat in Cat on a Hot Tin Roof *contends with the stifled passion of her husband, Brick, played by Paul Newman. Her single diamond collet necklace advanced a new style, inviting younger women to wear diamonds without ostentation. (Courtesy of Film Still Archives, Museum of Modern Art.)*

ital investment. Along with a Hollywood-linked upscale advertising campaign in magazines, that elaborate product placement helped to raise the diamond industry in the United States to the $10-billion-plus business it is today.

Indeed, while Hollywood helped promote diamonds, diamonds helped promote Hollywood. The prestige and glamour surrounding the gems and their merchants were carefully cultivated. The great salesman-cum-showman, Harry Winston, who, for security reasons, never allowed his face to be photographed, referred to his opulent Fifth Avenue store as a *salon* and counted among his clientele international royalty as well as American celebrities. The diamonds shed their radiance on Hollywood and its stars; the stars brought their own luster to the gems.

Yet no marketing strategy can explain the role that diamonds have had in the movies and the hold they have had on the public imagination. Not for women only, diamonds become the objects of male ambition and desire in countless heist films and adventure quests to exotic lands in search of forbidden or curse-carrying stones and in the kinky glitter-world of James Bond. As the most concentrated and portable form of wealth, we have seen them smuggled in war and peace, hidden in hats and dolls and coat linings, and even ingested or stuffed inside human bodies. And we have seen them traded in exchanges that often thrill us by their incomprehensible inequity: when Tallulah Bankhead, in *Lifeboat* (1944), uses her diamond bracelet as fish bait; when Linda Fiorentino, in *The Moderns* (1988), tosses a diamond earring on a cafe table in exchange for a glass of whiskey; when Rita Hayworth, in *Gilda* (1946), includes her diamond necklace in her reckless striptease to "Put the Blame on Mame"; or, at the other extreme, when Greta Garbo, as a Soviet envoy in *Ninotchka* (1939), comes to Paris to sell a diamond tiara confiscated from a grand duchess to pay for grain to feed her starving nation for the winter; when Dustin Hoffman, in *Marathon Man* (1976), tosses handfuls of diamonds at Laurence Olivier, who plays a former Nazi concentration-camp officer, saying that he can keep as many as he can eat; and when Liam Neeson, as Oskar Schindler in *Schindler's List* (1993), pours a glittering mound of diamonds on the SS commandant's desk in payment for a trainload of doomed Jews.

The camera itself seems to love diamonds, especially in black and white. To create the magical luminism of films of the 1930s and 1940s, cinematographers and designers used gauze and reduced-contrast lighting to create a world of gossamer and moonlight. Tiny glints and sparkles of light were effects sought in every scene to enhance the enchantment. Diamonds, radiant and warm in such lighting, appeared ethereal, almost alive. The camera would linger on them, and rarely were they pictured in a subjective shot. For the shallow-focus close-up of a star bedecked in diamonds, time almost stopped, as the camera seemed to absorb the luminescence.

In the conventional practice of using real diamonds instead of paste imitations in the land of make-believe we see more than simple name-credited prod-

uct placement. The genuineness of the diamonds, the knowledge that those were real stones, had a complicated secondary resonance for moviegoers. It confirmed the metaphor of Hollywood that writers like F. Scott Fitzgerald and Nathanael West understood so well, that the message of the movies went far beyond the contents of the films. The genuineness of the diamonds breaks through the illusion, opening up a second order of fantasy – our *real* fantasies, one might say.
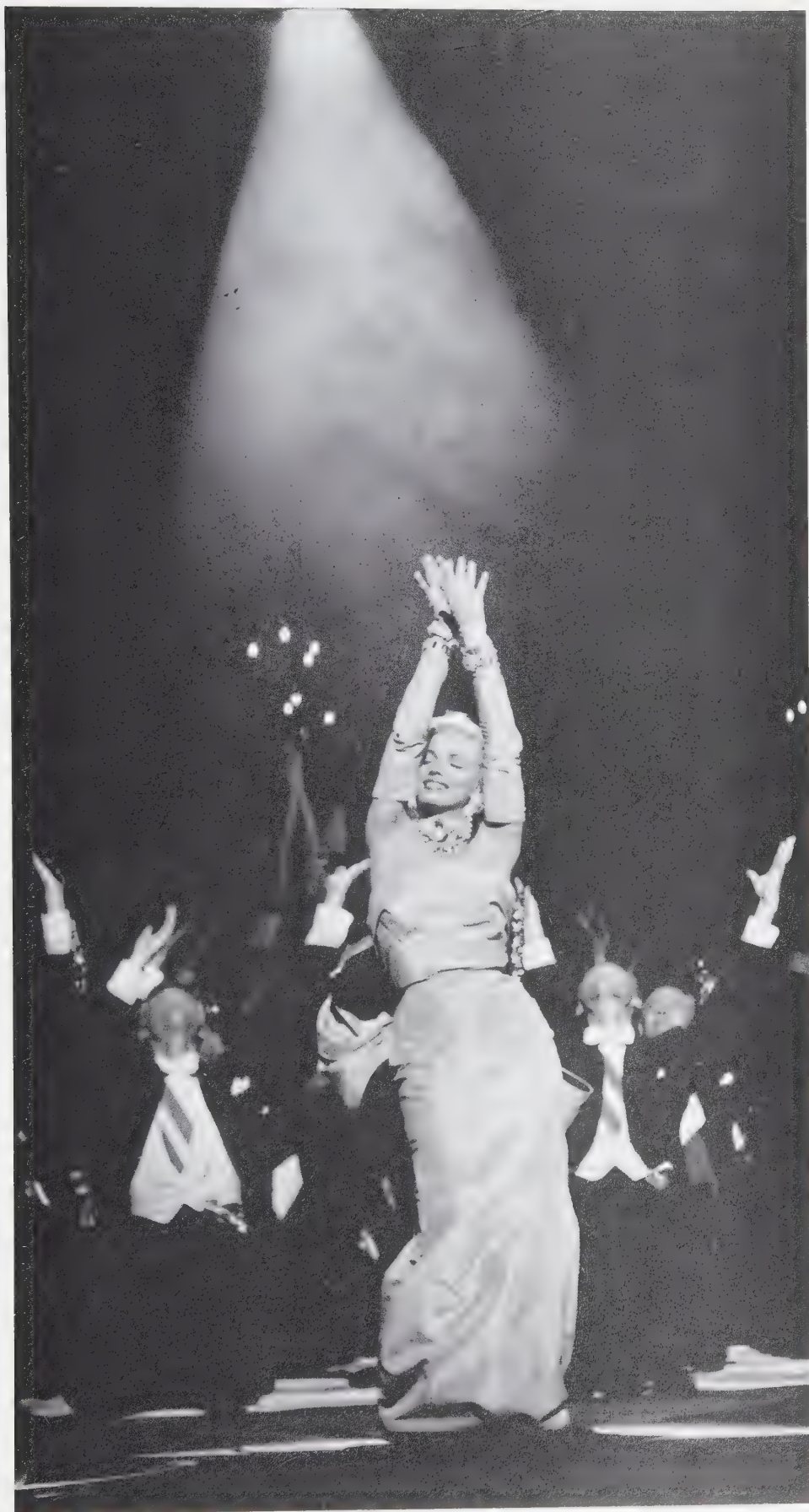
The genuineness of the diamonds – and their continuity with real life – is highlighted again in the practice of movie stars like Mae West, Marlene Dietrich, Barbara Stanwyck, and Lana Turner, to name a few, who seldom appeared in public without their eyecatching diamonds and who often wore the very same gems in their movies. Details about the stars' jewelry collections and appearances of specific pieces in films would be passed along to the public through wide-circulation movie magazines. Stars welcomed the publicity generated by their diamonds, and the diamonds themselves seemed to confirm their glittering stardom, as well as their box-office success.

But the stones, radiant as they are, don't automatically confer glamour – it's all in how they are worn. In the way she carries those rocks, a woman communicates an attitude about herself, about money and men, and about how she feels about being looked at. In short, in adorning herself with diamonds, a woman expresses her feelings about how best to deploy her feminine powers.

Claudette Colbert wears her diamonds with urbane femininity, blithely but never without consciousness of their value; Katharine Hepburn wears them as if they aren't important. For Garbo, wearing them is almost bondage – the gems become shackles – while Dietrich seems warmed by their radiance. Joan Crawford wears hers with the defiant pride of someone who's earned them at great cost to herself; Margaret Dumont wears her jewels with a stately comportment that is only vestigially feminine; Mae West parades hers with a swagger; Marilyn Monroe displays her diamonds along with the rest of her dazzling body with a tender generosity; and Elizabeth Taylor wears her diamonds with a queenly modesty that acknowledges that these gems are loving tributes to her beauty. The great stars express themselves through their diamonds.

And in some of the most lighthearted of romantic comedies, diamonds have illuminated feminine, even feminist, themes, about financial independence, inequality in marriage, male infidelity, and the double standard that Marilyn Monroe, as Lorelei Lee, articulates in *Gentlemen Prefer Blondes* (1953). Her prospective father-in-law asks her if she will admit that all she's after is his son's money. She responds: "No, I don't. Aren't you funny. Don't you know that a man being rich is like a girl being pretty? You might not marry a girl just because she's pretty, but my goodness, doesn't it help?"

In *Gentlemen Prefer Blondes*, the diamonds are placed at the intersection of love and money. They represent a tried-and-true feminine distrust of men and their urges. And who should know better about male urges than Marilyn Mon-

Figure 3. This publicity shot of The Gangster and The Lady for Public Enemy *is certainly worth a thousand words. Jean Harlow's diamond and platinum jewelry and diamond-studded cigarette-holder seem to contrast with and intensify the malignant image of James Cagney, seated with the gun. (Courtesy of Film Still Archives, Museum of Modern Art.)*

roe's Lorelei Lee? If men are fickle and untrustworthy and take what they can get when an attractive woman catches their eye, why shouldn't a woman take what she can get in return? Diamonds, in contrast to men, are reliable. And a girl, according to Lorelei, being a practical person, has to plan for the future. If she will eventually lose her allure, her diamonds – square-cut or pear-shaped – will never lose theirs. The arrangement appears to be fair and reciprocal: Men desire women, and women desire diamonds.

But this setup, this exchange system between men and women, is no recipe for love, marriage, or a happy ending. In fact, Lorelei is frequently misunderstood to be a simple gold-digger. This assessment of her character is corrected, and the plot wonderfully resolved, by the fact that Lorelei just happens to genuinely love the millionaire she has managed to snare. When Marilyn flashes her

enormous diamond ring triumphantly during her marriage ceremony, we understand that her triumph is the marriage, not the diamond. In the end, the movie resolves, more valuable than diamonds is a real piece of the rock: matrimony. But in that last look of understanding between Lorelei and her friend Dorothy Shaw, played by Jane Russell, they acknowledge a mischievous secret that marriage is in fact another game in which a woman had better keep her advantage.

Like Lorelei, Mae West's Diamond Lou in *She Done Him Wrong* (1933) is interested in a fair exchange. Diamond Lou is a Bowery saloon singer, famous for her beauty, her generosity, and the diamonds her many beaux have given her. When Pearl, her maid, is helping her off with her jewels, she remarks: "Miss Lou . . . *you* never been in the circumstances where the wolf came to your door." And Lou responds, "Never had the wolf at my door? Why the wolf came into my room and had pups." Her diamonds are her unemployment insurance and her pension plan – and her joy.

Because the men in the tough, 1890s Bowery world she inhabits are basically incompetent criminals – with the important exception of the austerely virile Captain Cummings, played by Cary Grant – a woman *has* to look after herself. But it's not only their incompetence, as Lou explains to the unworldly Sally, who has been betrayed by a married man, "Men's all alike, married or single. It's their game. I happen to be smart enough to play it their way." Playing it their way means not being sentimental, not tying your heart to one man, and not being squeamish about using and enhancing all your assets – and even some you don't have – to take whatever you can get.

In this film, West's desirability is unmistakably linked not to the goodness and beauty the movie celebrates in her, but to the desire of many men. Her current beau, Gus Jordan, remarks, "It ain't bad having a girl all the men are after. It shows I must be pretty good." Lou wears her diamonds as tokens of male desire, past and present; they enhance demand so that she can name her price. And for Mae West, who makes the surplus of male desire a comic theme in all her films, this economy can always be turned to a woman's favor.

The movie closes with Diamond Lou on her way to reform, forced by Cummings, her missionary-fiancé, to forfeit her diamonds, her men, and her independence, all for marriage. When he places the tiniest of diamond rings on her finger, beside her chunky rocks, we see a kind of miniature handcuff. "You're my prisoner," Grant-as-Cummings says to her, and shorn of her portable, man-catching wealth, we can believe she is losing her autonomy – maybe entering a sucker's game.

Marilyn Monroe, Mae West, and Jane Russell all seem to embody an extravagant and uninhibited principle of feminine excess, to which the diamonds contribute. A contrasting feminine type and plot, however, are also associated with diamonds. This female is all fire-and-ice, remote, impenetrable, and rich, and her passion, existing under the pressure of tremendous self-

Figure 4. In this scene from She Done Him Wrong, *Cary Grant (Captain Cummings) has taken up Mae West's (Diamond Lou's) invitation to "come up and see her sometime." As a missionary, Cummings expresses concern for Lou's moral well-being: "I'm sorry you think more of your diamonds than you do of your soul." And she responds with trademark innuendo, "I'm sorry you don't think more of my diamonds than you do of my soul." (Courtesy of Archive Photos.)*

repression, has achieved a diamond-like intensity. Unsurprisingly, she often turns up as the target of a diamond heist. (Diamonds are not simply objects to be stolen, but to be stolen from women.) In the great 1963 comedy *The Pink Panther*, we find David Niven in the familiar cat-burglar/lady-killer combination. As Sir Charles Litton (a.k.a. the Phantom), Niven is in hot pursuit of the eponymous gem, which belongs to the aloof and virginal Princess Darla, played by Claudia Cardinale. In a memorable scene, Niven attempts to seduce the princess as she lies sipping champagne on a tiger-skin rug. (Here the princess is distinctly associated with the pink panther, the diamond itself.) Not only does the infallible seducer Niven fail in his efforts, but in fact he finds himself seduced by her kittenish charm in its startling contrast to her customary stern self-control. The hilarious bedroom antics of Peter Sellers as Inspector Clouseau comically mirror Niven's failures, as Sellers is repeatedly foiled in his efforts to make love to his glamorous wife, who is secretly the mistress of Niven.

In the movie's marvelous final twist, Peter Sellers is set up by his wife and the princess to take the rap for Niven. Now perceived to be the notorious jewel thief, Sellers leaves the courthouse only to be mobbed by a crowd of adoring women for whom the diamond burglar possesses Beatles-like sexual allure.

In Hitchcock's comedy-mystery *To Catch a Thief* (1955), Grace Kelly fits the bill as the wealthy, elegant, hot-and-cold beauty, while Cary Grant, as Robie (a.k.a. the Cat), is a *reformed* cat-burglar, not the current talent who is plundering the French Riviera, where the movie is so lusciously set. In this

story, the heroine is doubly associated with the traits of diamonds, not only as cold yet alluring and exceedingly costly but also as genuine versus fake.

Grace Kelly as Francie, the daughter of a newly minted American oil-millionairess, is the recent product of finishing school. Unlike her mother, a diamond in the rough, Francie is thoroughly polished. Kelly is herself the diamond, requiring no adornment; in fact, she wears no diamonds or jewelry at all except in one scene. Despite her obvious charms, she remains doubtful that she is herself the real thing (perhaps this film is a distant heir to Henry James's *Daisy Miller*). Unsure of herself, she fears that men desire her only for her money. Cary Grant, whom she believes to be the cat-burglar, holds out a strange challenge for her. She plays at being his seductress because she wants to avoid being his victim. At the same time, she genuinely longs to seduce him, to possess the European-style connoisseur, Robie, a man who can distinguish between the real and the fake, in diamonds and in women.

Diamonds and Hollywood movies are made for each other. In recent years, of course, the role of diamonds has largely shifted from feminine ornament to plot device. Is it because movie characters no longer wear top hats and tails, Dior gowns and tiaras, as they once did? Or are women now earning their way in many markets besides men and marriage? Is feminine glamour now defined not by the cut of a gown or the sparkle of a diamond, but by the muscle tone of a luminescent, nude female body, often treated to the same careful lighting and adoring camerawork that diamonds once were? (Diamonds, like a well-toned body, seem automatically to reference the perishability of feminine beauty, while the films themselves preserve that beauty in a "crystal of time," as the French theorist Gilles Deleuze put it.) For many movie stars today it is more urgent to get to the gym than to a jeweler. Diamonds, like women, are stock ingredients for Hollywood's single most significant product: desire.

FILMOGRAPHY

Diamonds Are Forever, director Guy Hamilton, 1971
Gentlemen Prefer Blondes, director Howard Hawks, 1953
Gilda, director Charles Vidor, 1946
Lifeboat, director Alfred Hitchcock, 1944
Marathon Man, director John Schlesinger, 1976
The Moderns, director Alan Rudolph, 1988
Ninotchka, director Ernst Lubitsch, 1939
The Pink Panther, director Blake Edwards, 1963
Schindler's List, director Steven Spielberg, 1993
She Done Him Wrong, director Lowell Sherman, 1933
To Catch a Thief, director Alfred Hitchcock, 1955

Figure 5 (opposite). Grace Kelly (Francie) looks almost too good to be true in this scene from Hitchcock's To Catch a Thief. *Hitchcock plays her flawless beauty against the perfection of the diamonds, at one point completely obscuring her face in favor of the necklace. (Courtesy of Archive Photos.)*

10

Diamonds in the Twentieth Century

GEORGE E. HARLOW

I N THE TWENTIETH CENTURY diamonds have been trans-
formed from baubles for rulers and badges of royalty to adornments for
virtually everyone. The gem of mystery has become a common symbol of
material wealth; the legend has become a tangible object. These dramatic
changes began in the 1860s with the discovery of vast new diamond deposits in
South Africa. The new abundance of diamonds, coinciding with the end of the
Civil War in the United States, changed the public perception of diamonds,
particularly in regard to who would own and wear them. In the United States,
it seemed that everyone from the small entrepreneur to the railroad magnate
was growing wealthy, and the Civil War greatly accelerated prosperity in the
northern cities, particularly New York City. The New World had a persistent
itch to show Europe that wealth could also be found west of the Atlantic
Ocean, and even cultural sophistication could flower. Thus, there was a fortu-
itous match between the newly increased supply of diamonds and the vora-
cious appetite of a young, boisterous people, perhaps figuratively consum-
mated when Tiffany & Co. purchased many of the crown jewels of Empress
Eugénie at the "fire sale" held in 1887 by the new French government, thus set-
ting the stage for a binge of conspicuous consumption by a new leisure class.

The first three decades of the twentieth century in the United States must
have been heady times indeed. The British empire was in decline, and the star
of the United States seemed to be ascendant: These were people who recog-
nized no limits, people who could fly, as the Wright brothers demonstrated
beginning in 1903. These were people so full of themselves that they ordered
the European nations to stay out of the New World, but who at various times
during those years cavalierly sent U.S. troops into Cuba, the Dominican
Republic, Panama, Nicaragua, and Mexico to "restore order" or impose their
will. Teddy Roosevelt sent the U.S. Navy around the world to flex American

muscle and cow other nations. These were people who thought themselves a dandy lot, who believed in their manifest destiny. Not waiting for the historians, they wrote the story of the battle before the smoke cleared – virtually erecting statues to themselves.

Small wonder that diamonds, the ultimate in beauty and hardness among gems, should find a home among these hard people of such unabashed self-promotion. During the period from the Gay Nineties to the 1930s, there were many colorful figures in the United States who loved to flaunt their new wealth before a wider audience, though a few preferred to confine their displays of opulence to fashionable parlors or the Diamond Circle boxes at the Metropolitan Opera. "Diamond Jim" Brady (d. 1917), a New York financier, made his fortune in the late nineteenth century selling supplies to the rapidly expanding railway lines. He had a taste for lavish living and routinely wore diamonds, particularly stickpins. One of his companions in pursuit of the good life was Lillian Russell (born Helen Louise Leonard), the beautiful and flamboyant singer and actress, a diva of light opera who well knew the value and uses of diamonds. As a result of her many romances, including her relationship with Diamond Jim, her jewelry collection was continually expanded by tokens of affection from her admirers, including the elusive adamantine stones. The movie *She Done Him Wrong*, featuring Mae West, was based in part on the popular reports, real and fictional, that swirled around Russell. Such ostentatious displays of wealth in the United States helped to launch diamonds into a wider public arena.
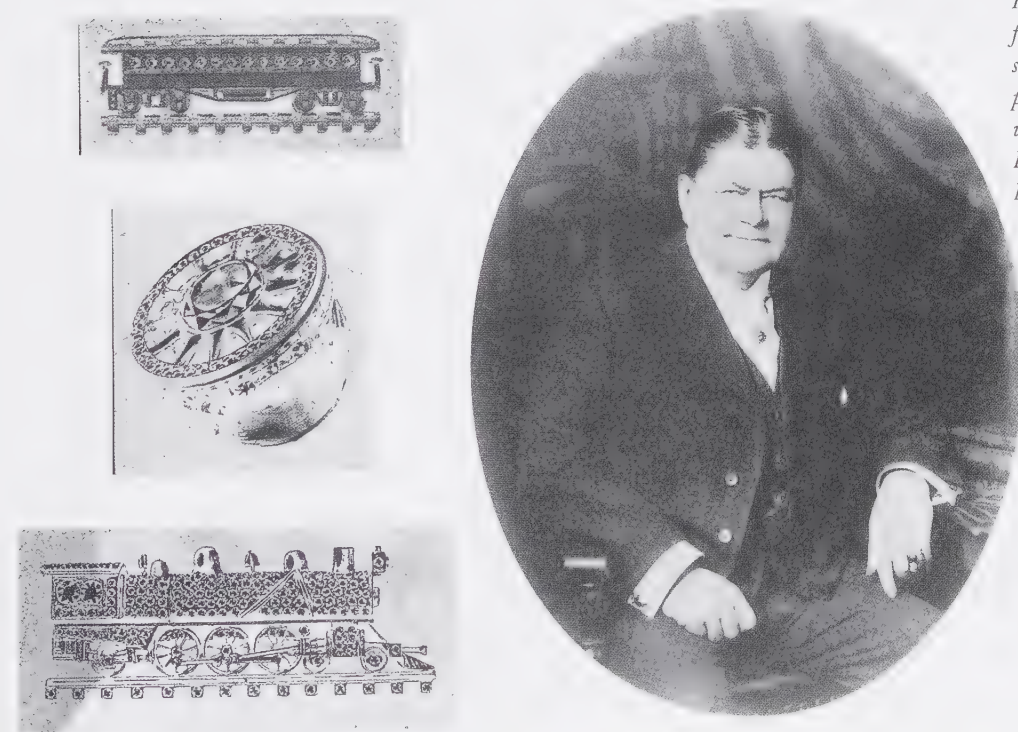
Figure 1. "Diamond Jim" Brady had a great fondness for stickpins, cufflinks and other accessories in the form of his transportation enterprises accented with diamonds; these pieces were sold from his estate. (Courtesy of Astor, Lenox and Tilden Foundations, New York Public Library.)

Improvements in telegraphy and shipping had increased the speed of com-
munications around the world, bringing all sorts of new knowledge to the gen-
eral public. Relatively fresh stories from South Africa about the diamond fields
and the competition between the rival entrepreneurs Cecil Rhodes and Barney
Barnato were daily fare in newspapers around the world, sometimes with
pictures.

With diamonds being so frequently and widely seen in the apparel of
wealthy New Yorkers, even the general public had knowledge, if not experi-
ence, of diamonds. So widespread was the interest in the mystique of dia-
monds that the short-story writer O. Henry could easily incorporate that motif
into his tales. In "The Diamond of Kali," a former military man, a retired gen-
eral, from a family whose members ordinarily did not "advertise," was seeking
publicity for the acting debut of his niece, and he took advantage of the pub-

List of Boxholders for the Opera Season.
PARTERRE BOXES.

1 Mrs. Cornelius Vanderbilt, Jr., Mondays and odd matinees
General Samuel Thomas, other performances
3 R. T. Wilson, Mondays and odd matinees
W. Emlen Roosevelt and Mrs. E. Reeve-Merritt, Wednesdays
Mrs. Orme Wilson, Fridays
Mrs. H. Mortimer Brooks, even matinees
5 C. M. Hyde and John Notman, odd nights and even matinees
Anson Phelps Stokes, even Mondays, Wednesdays and odd matinees
E. Rollins Morse, even Fridays
7 Mrs. Astor, odd nights and even matinees
John Jacob Astor, even nights and odd matinees
9 Stanford White, Mondays
Charles T. Barney, Wednesdays and matinees
George C. Clark, Fridays
11 Perry Belmont, Mondays, Fridays and odd matinees
Egerton L. Winthrop, Wednesdays
Mrs Edwin Gould, odd Fridays
W. C. Oakman, even matinees
13 Edward Cooper, } alternately
H. A. C. Taylor, }
15 Adrian Iselin, Mondays and odd matinees
James Stillman, other perform ances
17 W. D. Sloane, } alternately
H. McK. Twombly, }
19 Mrs. H. I. Barbey, Mondays and odd matinees
H. F. Dimock, Wednesdays
George Crocker, Fridays
Mrs. C. D. Dickey, even matinees
21 Pembroke Jones, Mondays
Gerald L. Hoyt, Wednesdays
Mrs. J. Hood Wright, Fridays
John Hobart Warren, matinees
23 Elbridge T. Gerry, Mondays and matinees
E. J. Berwind, Wednesdays
O. G. Jennings, Fridays
25 G. G. Haven, odd Mondays and matinees; even Wednesdays
John E. Parsons, even Mondays and matinees; odd Wednesdays
John Sloane, Fridays
27 George S. Bowdoin, Mondays
Charles Lanier, Wednesdays
J. M. Bowers and F. S. Wetherbee, Fridays
Mr. Bowdoin and Mr. Lanier, matinees
29 Mrs. Gambrill, Mondays and even matinees
Dallas B. Pratt, Wednesdays
Mrs. Van Nest, Fridays and odd matinees
31 Mrs. Vanderbilt
33 Thomas Hitchcock Mondays and odd matinees
Joseph Stickley, Wednesdays
J. J. Wysong, Fridays
Mrs. Frederick Pearson, even matinees
35 J Pierpont Morgan

2 A. D. Juilliard, odd Mondays and matinees; even Fridays
Miss Leary, Wednesdays
Geo. E. Dodge, even Mondays and matinees; odd Fridays
4 James Speyer, odd Mondays and even Fridays
George S. Scott, first and even Wednesdays
August Belmont, other perform ances
6 W. K. Vanderbilt, Mondays
C. W. Morse, Wednesdays
W. K. Vanderbilt, Jr., Fridays
Miss Jennings, matinees
8 C. N. Bliss, Mondays
M. C. D. Borden, Wednesdays
John Claflin, Fridays
Mr. Bliss and Mr. Borden, matinees
10 George F. Baker, Mondays
H. C. Fahnestock, Wednesdays
E. Francis Hyde, Fridays
Mr. Baker and Mr. Fahnestock matinees
12 Henry Clews, } alternately
George Gould, }
14 George Henry Warren, Mondays and odd matinees
George L. Rives, Wednesdays
S. B. French, Fridays and even matinees
16 L. P. Morton, Mondays and odd matinees
Mrs. George Bliss, Wednesdays and even matinees
Edward R. Thomas, Fridays
18 Charles B. Alexander, odd Mondays and matinees; even Fridays
Edward R. Bacon, even Mondays
Herbert L. Terrel, Wednesdays and even matinees
J. J. Emery, odd Fridays
20 D. O. Mills, } in
Ogden Mills and family, } rotation
Whitelaw Reid " }
22 W. Seward Webb, Mondays, Wed nesdays, Fridays and even matinees
W. G. Oakman, odd matinees
24 Mrs. Robert Goelet
26 S. D. Babcock, Mondays and matinees
D. S. Lamont, Wednesdays
H. Fairfield Osborn, Fridays
28 W. Bayard Cutting, odd nights and even matinees
Mrs. Mackay, even nights and odd matinees
30 W. C. Whitney, Mondays, Wed nesdays and matinees
J. B. Haggin, Fridays
32 Jas. A Burden, Mondays and even matinees
Miss Gurnee, Wednesdays
Mrs. Bradish Johnson, Fridays
John Sloane, odd matinees
34 Heber R. Bishop, Mondays and matinees
E. H. Harriman, Wednesdays
A. Iselin, Jr., Fridays

lic's interest in diamonds to get it. He managed to get a newspaper reporter to print the information that the young lady "will appear on the stage next season. . . . Her diamonds are said to be extremely valuable and of much historic interest." No doubt the fact that he thought that the diamonds would be a better draw than his niece's acting skills did little for her confidence. In "The Making of a New Yorker," O. Henry wrote autobiographically that in New York he had found a city "as cold, glittering, serene, impossible as a four-carat diamond in a window to a lover outside fingering damply in his pocket his ribbon-counter salary."

In addition to carrying out such symbolic tasks in literature, diamonds admirably performed their more tangible function of showing off wealth, a

Figure 4. A magazine advertisement layout from De Beers/N.W. Ayer in the early 1950s captures a special moment symbolized both by the blossom bearing the diamond and by the eclipse of the Sun. (Courtesy of Diamond Information Center.)

demonstration made all the more palpable by the newly increased abundance and availability of diamonds and their increasing notoriety.

Magazines also helped to thrust diamonds to center stage, greatly assisted by the jewelry industry and the diamond syndicate. Advertisements by the jewelry houses helped to promote the seductive brilliance of diamonds, but such simple strategies were left in the dust by the marketing tour de force engineered by De Beers, N. W. Ayer, and the Diamond Information Center. In 1938, Harry Oppenheimer, representing De Beers, met with Gerold Lauck of the advertising agency N. W. Ayer to discuss a marketing campaign to stimulate the sale of finer diamonds for engagement rings in the United States. A thorough study of the U.S. diamond market led to a campaign to insinuate the diamond into the middle of the romance/courtship/marriage cycle. Because

Figure 5. A story-board for a De Beers television advertisement from 1996. The casual but comfortable visit to the beach is punctuated by the sole presence of color in the diamond ring to mark the moment when he pops the question. (Courtesy of Diamond Information Center.)

De Beers

"Beach" :30
ERDB 5303

young men bought more than 90 percent of all engagement rings, it would be crucial to indoctrinate them in the idea that the diamond was the ultimate expression of love: "the larger and finer the diamond, the greater the expression of love."[1] The success of that campaign was undeniable: By 1941, sales of diamonds in the United States had increased by 55 percent. Then the advertising team came up with a memorable slogan: "A diamond is forever." That was followed by an offer from the Diamond Information Center, a resource group set up within N. W. Ayer, to provide authoritative information on diamonds.

Perhaps the greatest achievement of the diamond team was the creation of a market for diamonds in a country that previously had had little use for jewelry: Japan. By the mid-1960s the world market for diamonds was not as good as the world economy would seem to have warranted. Japan was becoming an economic superpower, but the Shinto esthetic made no provision for jewelry, and marriages normally were arranged, rather than being left to the vicissitudes of young romantics. To meet that challenge, J. Walter Thompson, an advertising agency with worldwide reach, launched a magazine campaign to promote a modern, Western look for young couples, including, of course, a diamond ring on the woman's finger. In 1967, some 5 percent of prospective Japanese brides had diamond engagement rings; by 1972 the figure was 27 percent, and by 1981, 60 percent. Japan has become the second largest market for diamonds, after the United States.

Since the 1930s, many people have complained bitterly about the state of the world diamond market and the virtual monopoly of the diamond syndicate. De Beers has done a remarkable job of maintaining the upper hand with the diamond producers. Each decade has brought a challenge from a new diamond producer attempting to crack the market open, but there is little indication that those producers have the leverage to realign the diamond market.

NOTE

[1] Epstein, E. J. (1982). Have you ever tried to sell a diamond? *Atlantic Monthly* 249:23–34.

11

From the Earth to Fashioned Objects: Processing Diamond

GEORGE E. HARLOW

THE TRANSFORMATION OF DIAMOND from a rough crystal to a polished gem or a more mundane but highly important abrasive tool requires many steps (Figure 1). First, diamond deposits must be located, evaluated, and then, if they show economic potential, developed. Development is a continually evolving technological enterprise, the feasibility of which must be assessed by balancing the value of the diamonds expected to be produced against the costs and difficulties of mining and of environmental protection, as well as consideration of societal values and national interests. The raw diamonds produced must be sorted and distributed through the closely controlled trade practices of the diamond cartel. After sorting industrial and gem diamonds, a distinction that is somewhat variable, the distribution system puts diamonds into the hands of fabricators, who transform crystals to gems or to other products.

EXPLORATION

The search for diamonds is focused on continents or continental fragments whose underlying basement rocks are older than 1.5 billion years. That means exploring the "archons" and "protons," terms coined in 1966 by geologist T. N. Clifford, who noted that diamondiferous kimberlites were restricted to those kinds of old deposits. As in the search for most resources, the easily accessed areas of the Earth have already been surveyed or exploited, so exploration is aimed at remote areas, poorly exposed or covered-over deposits, and areas previously discounted as unpromising for diamond production. Such remote areas

Figure 1. Rarely are diamonds exposed in kimberlite like this 25-carat rounded octahedron from Kimberley, South Africa. The search for and extraction of diamonds are complicated processes. (Rick Sheridan/courtesy of American Museum of Natural History.)

include the Arctic and Antarctic regions, which have not been well explored, largely because of inhospitable climate and inaccessibility. Because exploitation of Antarctica is restricted by international law, there has been no exploration for diamonds. However, the Arctic regions of Canada, Siberia, Scandinavia, and Greenland and the Arkhangel'sk region in Russia are all being carefully searched, as discussed in Chapter 4. Uninhabited deserts and the scab-lands of Africa and Australia are still being explored. In North America, the less promising protons continue to be scrutinized, and a vast area that includes the northern Rocky Mountain states, the western Canadian provinces, the northern Midwestern states, and Ontario awaits the development of technologies that can provide indications of what lies under perhaps 1,000 meters (m) of sedimentary cover. Finally, after the recognition in the mid-1970s that diamonds could be found in lamproites (abundantly in the Argyle lamproite) and the 1980s discoveries of metamorphic diamonds in the Kokchetav Massif in Kazakhstan, reevaluations of diamond origins and the "elevator mechanisms" that bring them to the surface have occupied academic and economic geologists (Figure 2).

Figure 2. Geologist Melissa Kirkley looking at overburden at a drill-hole test site in South America. (Melissa Kirkley/courtesy of BHP Minerals.)

Because kimberlite and lamproite pipes have small "footprints" (outcrops), many exploration and prospecting strategies look for trails of the "indicator minerals" that are more abundant than diamonds in the pipes. All known kimberlites and lamproites are sufficiently old (more than 50 million years old, and most more than 100 million years old) that weathering has disseminated the

Figure 3. A rogues' gallery of the indicator minerals from the Rietfontein kimberlite in South Africa, showing a mix at the bottom and top reading clockwise: ilmenite, orangey eclogitic garnet, chromian pyrope, clino-pyroxene (both chromian diopside and pale omphacite). (Rory O. Moore.)

pipe minerals over wide areas and down stream channels for many miles, altering the minerals to soil-like clays that are no longer specific indicators of kimberlites. However, some minerals distinctive of rocks from the upper mantle are more resistant to weathering and are more dense than quartz sand, and they concentrate in the channel bottoms. These dense indicator minerals from kimberlites are, in order of decreasing significance in exploration, garnet, chromite/ilmenite, clinopyroxene, olivine, and zircon, whereas the order of decreasing persistence in streams is zircon, ilmenite/chromite, garnet, chromian diopside/olivine. Diamond itself is a most important indicator.

The utility of indicator minerals, particularly garnet, ilmenite, and clinopyroxene, was recognized soon after the discovery of diamonds in South Africa (Figure 3). Since the 1970s, a major effort has been under way to identify characteristics specific to these minerals that would indicate not only a kimberlite or lamproite source, but also one with diamonds. Garnets are relatively common and are associated with most kimberlites and lamproites, so identification of a characteristic type or types is needed. Those garnets associated with peridotites, particularly garnet harzburgite, which is known to host diamond in the mantle, are a pinkish to purplish pyrope-almandine (mineral nomenclature is given in Chapter 3), unusually low in calcium and rich in magnesium and chromium; they are sometimes referred to as G10 garnets, based on a classification developed in the 1970s.[1] Orangey red garnets that are higher in calcium and iron than the pink garnets are typical of eclogites, another diamond host.[2] One more highly useful indicator of a peridotitic diamond source is magnesian ilmenite (or picroilmenite). Emerald-green chromium-rich diopsides (one of the clinopyroxenes) also are found in peridotites and are important indicators. Clinopyroxene is not well preserved in alluvial sediments, but it can be very helpful in the early evaluation of a newly discovered pipe. Finally, the shapes of the indicator minerals can also be revealing: While experiencing the same ascent that rounds diamonds, the indicator minerals can become rounded, disk-shaped, and etched, characteristics that are unusual for these minerals from other sources.

Most commonly the indicator minerals are recovered from deposits laid down by rivers that drain archons and protons, but other sampling strategies can also work. In areas with moderate (or greater) rainfall, the river deposits can be sampled every 3–15 kilometers (km), with larger samples being required to detect sources farther away. For example, a sample of 10–20 kilograms (kg) may be adequate to assess a source 50 km away, but if the source is farther away, or if diamonds themselves are being sought, several cubic meters of sample (several metric tons of sand and gravel) will be required. In locations in which there is poor drainage, the soils themselves can be sampled, but that requires a fairly close spacing of samples so as not to miss a pipe. In much of Botswana, the Kalahari Craton (archon) is covered by up to 100 meters (m) of sand from the Kalahari Desert, but in the 1960s De Beers geologist Gavin

Lamont took advantage of an observation about termite mounds: Ancient Egyptians had located gold by examining the "anthills" for traces of the precious metal that the insects had excavated while burrowing to the water table at bedrock level. Lamont found that the Botswanan termite mounds yielded indicator minerals over the Orapa pipe (Figure 4).

In North America, Pleistocene glaciation uncovered the ancient craton of Canada and piled up the alluvial debris in discordant deposits called moraines. Diamonds have been known from some glacial deposits in Wisconsin for more than a century, but the diamond source, other than being somewhere to the north, has remained a mystery. The trail of indicator minerals from glacial deposits back to sources around the Lac de Gras area in the Northwest Territories in the late 1980s led to the first major diamond-mining ventures in the potentially rich Canadian Shield.

Indirect geophysical techniques of exploration have revolutionized practices in the mineral industries over the past 50 years; however, their application to diamond exploration has yielded mixed results. Geophysical measurements, which sometimes can be made remotely, detect differences in properties such as density, magnetic susceptibility, electrical conductivity, and radioactivity. Moreover, the spacing of sampling points must be proportional to the size of the structures being investigated. Airborne measurements of the magnetic field, which is affected by the magnetic susceptibility (the magnetization of a material per unit of applied field) of the underlying strata, have located kimberlites in the barren lands of Siberia, because the moderately susceptible kimberlites occur in nonsusceptible sedimentary rocks, and the terrain is flat, permitting low-altitude traverses. In most cratons the average rock is as magnetically susceptible as kimberlite, or more so, and thus aeromagnetic surveys have not been productive. Kimberlites and lamproites are variable in density (2.8–3.2) and usually do not have values greatly different from those for most country rocks, and their sizes are relatively small so they are not readily detected by airborne measurements of gravity that locate density discontinuities in the ground. Electrical conductivity or impedance measurements have largely been used in ground surveys to define the perimeters of pipes. Pipes are not sources of uranium or thorium, but lamproites usually contain some radioactive elements and have been surveyed by airborne radiometers, concurrently with magnetic surveys, primarily in Russia, Australia, and Canada.

Figure 4. Termites scavenge subsurface minerals while tunneling to the water table and leave these minerals at the surface in or near their nests. Examinations of the grains for diamond indicators have led to the discovery of diamond pipes. This is a typical termite hill in Karamouth, Zaire. (Herbert Lang/courtesy of American Museum of Natural History.)

EVALUATION AND MINING OF DIAMOND DEPOSITS

Diamond mining is among the top 10 mineral-extraction enterprises worldwide in terms of the value of annual production, but it is unique among

the top 10 in that the product is valued in terms of individual pieces rather than aggregate mass. The differences in the values of diamonds can range over orders of magnitude, from dollar-per-carat industrials to pinks or water-clear stones that go for many thousands of dollars per carat. Consequently, to evaluate a pipe or marine deposit, one must know not only the concentration (carats per ton of ore removed) and size of the deposit but also the sizes and quality of the diamonds. A recent worldwide review of mining output reported the average per-carat value of gem-quality stones to be about 10 times that for near-gem stones (a term referring to smaller, off-color, or lower-clarity stones that, depending on market demand, may or may not be used as gems), with near-gem stones having 10 times the value of industrial stones.[3] The enormous range of the relationship between quality and quantity is a feature that makes the diamond industry extraordinary in terms of the mining strategies required and the sizes of the operations undertaken. Different evaluation strategies and mining processes are used for primary, alluvial, and marine deposits; each will be treated separately.

Primary Deposits

When a kimberlite or lamproite pipe is found, samples at the top of the pipe must be collected and processed to determine if there are diamonds; such sampling may involve tons of rock. If diamonds are present, the perimeter of the pipe must be determined; drilling and petrological examinations will reveal both the extent of the deposit and more information about the diamond content. To fully evaluate a deposit, at least 5,000–10,000 carats of diamonds are needed, which, at concentrations ranging from 0.05 to 17 carats per metric ton, requires the processing of hundreds to thousands of cubic meters of pipe rock; some evaluations have involved 30,000 m³.[4] Moreover, the sampling must encompass a representative portion of the upper volume of the pipe. Such an evaluation can reveal the distribution of diamond sizes and quality, used to assess the feasibility of mining the pipe and to select a development strategy, such as whether to use only surface excavation or to plan for underground mining, which is generally much more expensive.

Figure 5. Explosion of multiple charges at the bottom of the Udachnaya kimberlite in Sakha releases diamond ore for removal to a processing plant; bench steps are about 20 m. (Courtesy of Almazy Rosii-Sakha Co., Ltd.)

Open-pit Mining

Most modern mining is carried out by excavating a pit, basically conical in shape. Called open-pit or open-cast mining, the excavation begins with removal of the loose overburden using large hydraulic shovels and ore trucks; that and all subsequent material will be processed for diamonds. Once hard rock is reached, holes for explosives are drilled into the pipe, and it is blasted with a low-velocity explosive to try to avoid shattering the diamonds. The material blasted free is removed by shovels and trucks (Figure 5). The open pit will develop as a steadily deepening cone with stepped sides, the average steep-

ness being about 30–40°, with a spiral roadway climbing up the perimeter of the pit for the ore trucks to bring material out of the hole. To achieve economies of scale, there are giant hydraulic shovels that can lift 40 tons of rock in a single scoop and ore trucks capable of holding it. Trucks take the rock to a crusher to commence the recovery of diamonds. The depth to which a pit is excavated is determined primarily by the cost of excavating more and more of the surrounding material (pipes have steep sides, so the conical pit that must be excavated will eventually intersect the surrounding country rock) compared with the diamond yield, or the cost of using underground methods. The Premier mine reached a depth of about 180 m (600 ft), and the Finsch mine about 430 m (1,410 ft), before underground mining commenced. The Argyle open-pit mine in Western Australia will reach 300 m (980 ft), and underground mining appears feasible. Essentially all of the material removed is waste and, after processing, will be piled into heaps called tailings. More and more countries are requiring that waste material be returned to some semblance of its original placement (i.e., filling the hole), with consideration for environmental quality. In the case of mined kimberlite and lamproite, the rock does not contain toxic minerals or by-products and poses only limited problems for reclamation and restoration. However, those additional costs at the end of the life of a mine must be factored in.

Underground Mining

When an open pit becomes so deep that the expense involved exceeds the return, but the deeper fertile pipe is still economically valuable, the mining goes underground, with shafts and drifts (lateral tunnels). Vertical shafts are sunk in the stable rock adjacent to the pipe to raise and lower personnel and equipment and to provide ventilation, drainage, and other services (Figure 6). A headframe is set over the working shaft to handle the workers and ore cars; a winch and cables raise and lower those elevator-like cars for vertical transportation. Lateral drifts are tunneled out into the pipe, where several different techniques have been used to extract kimberlite (currently there are no underground lamproite mines). *Chambering*, a technique no longer widely used, involves horizontal excavation of parallel drifts about 14 m (40 ft) apart, at equivalent vertical intervals, with each level being staggered so that each drift is overlain by the solid wall or pillar between the drifts above. The tunneled material is hauled out, and the ceiling is blasted to collapse the pillar above; after breaking it into sizes to fit into ore skips, kimberlite is carried out in a downward progression of collapsing chambers. That technique has been replaced by *block caving* because it is more mechanized and more efficient and requires a smaller work force. Concrete-lined tunnels are placed as for chambering, but under a large section, perhaps 140–180 m (400–600 ft) of kimberlite. At 5-m intervals along the tunnels are *draw points* or openings in the concrete casing where kimberlite is drilled upward and blasted to cave in a section

Figure 6. The headframe at Frank Smith mine in South Africa stands above the vertical access shaft to underground workings and controls the cable and cars moving in the shaft. (George E. Harlow.)
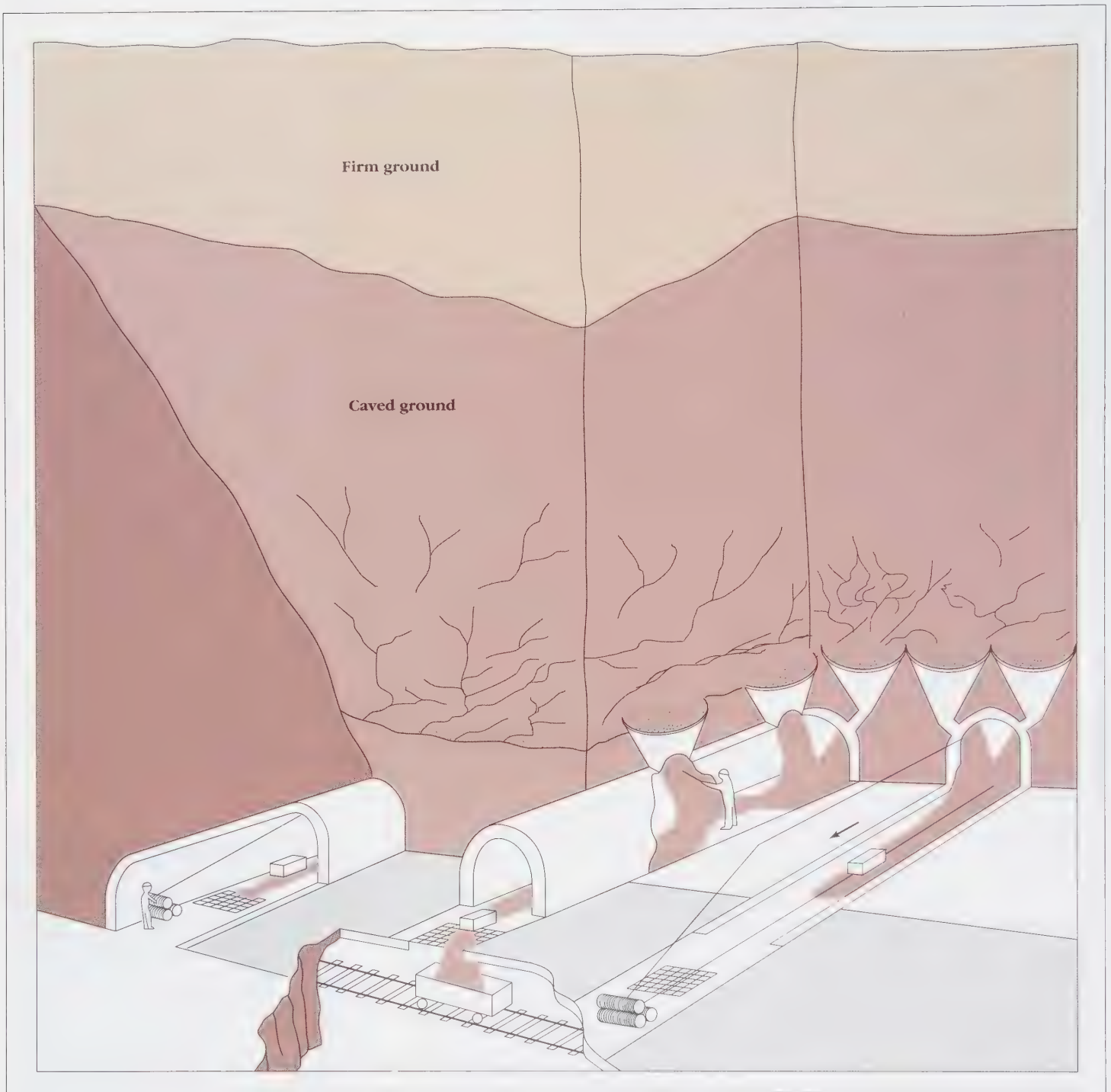
Figure 7. In block caving, parallel tunnels are bored into the kimberlite, lined with concrete, and perforated with access chutes or draw points. Blasting above the draw point produces a controlled collapse of broken kimberlite into the tunnel. Scraper buckets operating on a long cable drag the broken kimberlite out of the tunnel, over and through a grate, and into an ore car below. (Adapted from Legrand, 1980.)

or cone about 9 m above the tunnel (Figure 7). Broken kimberlite falls through the draw points and is scraped out of the tunnel with a drag or scraper bucket attached to a cable and winch, working much like a clothesline on a pulley used to draw clothing to a window. The kimberlite roof above the tunnels falls
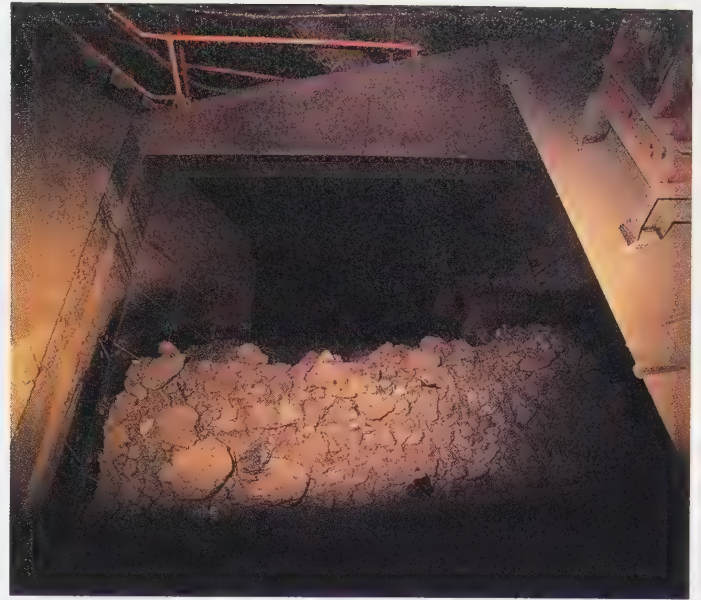
Figure 8. Broken kimberlite at the Finsch mine is dumped from an ore car into the crusher or sizer (above) that reduces the ore to lumps less than 15 cm (6 inches); then the ore is moved by conveyor, on the right of the tunnel (left) to ore skips that lift the material to the surface for processing. (Courtesy of De Beers.)

under its own weight and leads to a slow continuous caving of ground that is drawn off from points on alternate tunnels, with the help of occasional kicks of explosive to loosen the flow or break up blocks stuck in the draw points. The scraped kimberlite blocks are loaded into cars on an electric train that dumps the mixed blocks into a crusher underground. The crushed ore is carried by conveyors to skips that carry the ore up the vertical shaft for further processing (Figure 8).

Two other techniques are also employed in underground kimberlite mining: *sub-level caving* and *vertical crater retreat*. The former is sort of a cross between chambering and block caving, involving independent vehicles that drill cave-in draw points to ore from successive levels of tunnels and movement of kimberlite ore via load-haul dump vehicles to the underground crusher. The latter uses large vertical drill holes to funnel ore to a lower scraper level and blasting of craters adjacent to the hole to send broken kimberlite down to the scraper and haulers. All variations of such methods are attempts to decrease the amount of manpower needed for mining, increase the use of vehicles, develop ore-flow systems that will minimize blasting and interruptions to the mining process, and minimize the exposure of mining crews to the risk of accident or death. Modern mines are increasingly aware of safety concerns and the problems of downtime resulting from injuries (Figure 9).

Figure 9. Mining operations, such as this one at the Kimberley mines, conspicuously post their goals and numbers of on-the-job injuries. Safety is important and valuable. (Willard Whitson.)
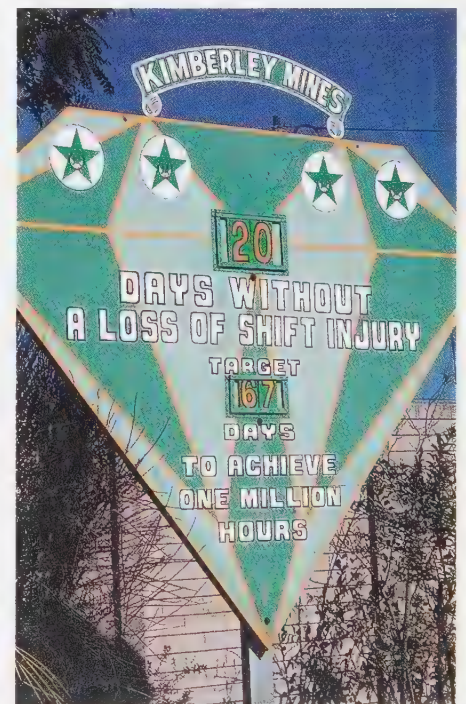
Figure 10. A 4-foot rotary washing pan. The gears drive the star-shaped support for vanes that push gravel along the base of the pan. When the pan is filled with "puddle" and gravel, heavy minerals, including diamonds, move to outer wall while waste washes out the center hole. (George E. Harlow.)

Diamond Recovery from Primary Deposits

The kimberlite or lamproite rocks extracted from a primary deposit must be reduced in size to release the diamonds. Diamonds are hard and tough, so the rock will break before they do, but ultimately the crushing process limits the maximum size of rock or diamond that can pass through. The smaller diamonds will flow through the process and be extracted; the larger ones will be crushed. The size cutoff in an underground mine is about 150 millimeters (mm), and in an aboveground plant it usually is between 25 and 50 mm (1–2 inches), which means that a Cullinan-size diamond 100 mm (3.9 inches) would be shattered if not spotted before it entered the second crusher. As an incentive to avoid such losses, virtually every mine operation has a reward program for recovery of larger diamonds before the ore goes through the crushers, and certainly there are disincentives for anyone with sticky fingers. Every visitor to the mines keeps an eye open for loose diamonds in the ore stream.

Crushed ore is processed by various means to concentrate the heavier minerals, including diamond, at a density of 3.52 grams per cubic centimeter. An older but still practical method features the *washing pan*, a circular pan 4–12 feet in diameter: Crushed ore is mixed with a muddy-water suspension (density about 1.3), called the *puddle*, and the mix is stirred in the pan by angled rotating blades (Figure 10). Heavier minerals settle to the bottom and are pushed toward an exit point, whereas lighter waste rises to the top and overflows as a separate stream of material. Usually the waste is crushed to a smaller dimension, ultimately to 0.5-mm cutoff size, and reprocessed in one or more other pans. The bottom concentrate, which represents just a small percentage of the original kimberlite, is drawn off with an Archimedes screw. In

Figure 11. Diamonds are separated from concentrate with a dense suspension of ferrosilicon in water that fills the cone (left) and cyclone (right). A feed of concentrate containing diamonds enters both at the top. In the cone, rotational mixing permits lighter minerals to float to the top and run out an overflow, while diamonds and dense minerals sink to the bottom and are sucked out with a compressed air siphon. In the cyclone, fast rotation of the suspension drives heavy minerals to the conical wall, where they sink to the bottom and are extracted, while float waste minerals are sucked from the center of the vortex. (Adapted from Bruton, 1978.)
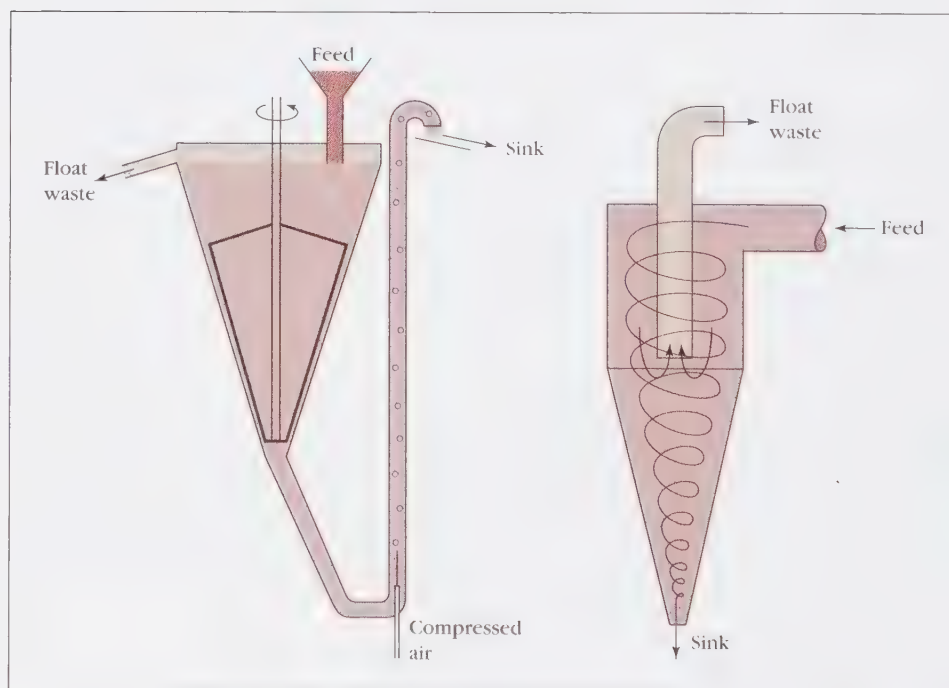
large operations the concentrate is processed further with what is called heavy-media separation: basically, mixing with a fluid near the density of diamond, and density separation assisted by centrifuge-style equipment. Powdered ferrosilicon, an alloy of iron and silicon, is suspended in water to form the dense fluid to which the ore concentrate is added. Separation occurs in cones or "cyclones" that swirl the mixture at low and high velocities, respectively, forcing the diamonds and other dense minerals to the walls and bottom of the container, while waste rises at the center, to be sucked out and screened to remove the waste particles (Figure 11). That process yields an even more dense concentrate at about 1 part in 100,000, by weight, just 0.001 percent, from the ore that was input.

Finally, to separate the diamonds from the concentrate, either a grease belt (or table) or an x-ray fluorescence separator is used; both take advantage of the special properties of diamond. The surface of diamond resists being wetted by water, but sticks readily to grease. To take advantage of that property, concentrate is wetted and passed with water over moving belts coated with grease (Figure 12). Diamonds stick to the grease, whereas wetted garnets or ilmenites tumble across the belt into a waste stream; diamonds are scraped off the grease belt with a hot blade and separated by melting the grease. The other technique takes advantage of the fact that diamond will emit light (fluoresce) when struck by an x-ray beam: A thin stream of particles from the concentrate is accelerated off a moving belt into the air, where it encounters an intense beam of x-rays. When a diamond fluoresces, that activates a photodetector that triggers a jet of air, which strikes the diamond in its trajectory. The air blast deflects the diamond into a collector box (Figure 13). The material recovered from both processes contains a high proportion of diamonds, which then must be sorted by hand.

Figure 12. A working grease table at Longlands, Cape Province, South Africa. Wet gravel washes across three inclined surfaces covered with beeswax and paraffin, while the concession partner routinely scrapes the material that adheres to the table with a trowel. Diamonds would be separated from the grease melting pot if not picked off the table by hand. (George E. Harlow.)
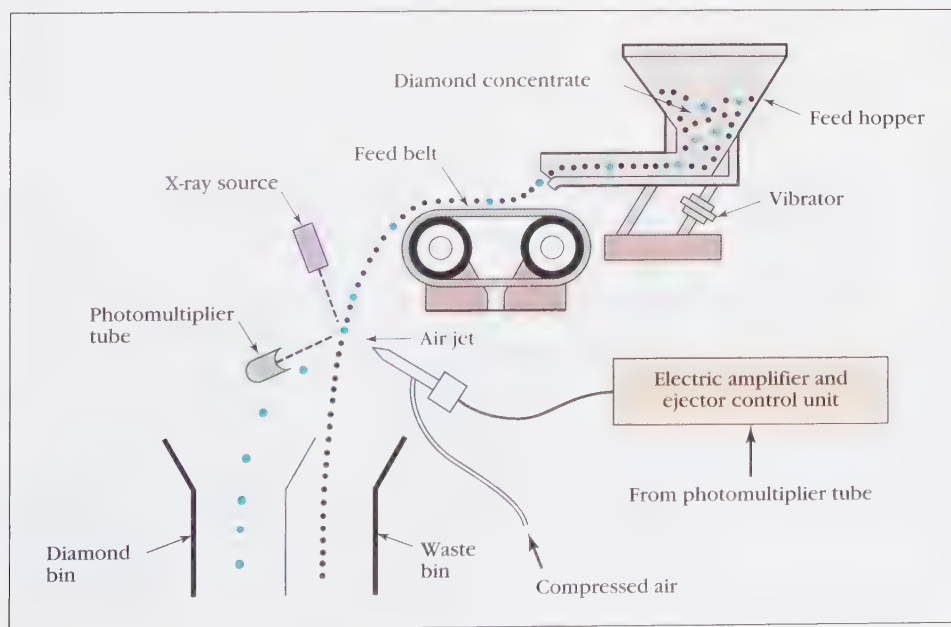
Figure 13. The x-ray separation system uses x-ray fluorescence to "see" the diamonds via a photomultiplier tube that triggers a compressed air jet to blow diamonds (blue) into a bin from a stream of diamond concentrate. (Adapted from Bruton, 1978.)

Alluvial Mining

Most of the diamond deposits that were first mined were alluvials – concentrations in the beds of streams or rivers. Those deposits are no longer as productive as they once were, but they are still actively exploited in many ways, from the most primitive to the highly sophisticated. The large firms still operate alluvial works, and individuals and small groups also persist in their pursuit of instant wealth. The goal is relatively simple: Find a location where diamonds, eroded from a primary source, were deposited at the bottom of a water channel, possibly in a pocket or cleft. Because rivers meander, and drainage can change, fossilizing a once-active river, the search for an alluvial concentration of diamonds requires some geological knowledge of an area plus a lot of luck.

The primary process in alluvial mining is straightforward: Remove the overlying barren ground, dig up the bearing ground, extract the diamonds, and, nowadays, restore the landscape when finished. The approaches to that task are diverse. In the most basic, individual operations, such as in Sierra Leone or Angola, the technology features shovel and pan, with some hand sloshing to gravitate diamond to the bottom of a pan, the eye being the ultimate sorting device. Mom-and-pop operations in South Africa work small claims and involve limited technology (shovels, buckets, jury-rigged cranes powered by small vehicles, and the like) to load a small washing pan (Figure 14). The concentrate is sieved into several size ranges, and each fraction is dumped onto a picking table, usually a table in the shade with blue carpeting, where one partner scrapes the gravel and checks by eye for diamonds (Figure 15). In the bigger operations, large earth-moving equipment transports the alluvium, and the processing approaches that at the primary mines: coarse sieving, then rotary sieving in what is called a trommel, before loading into the washing pan (Figure 16). The final processing includes concentrate sieving, a picking table, and usually a grease table. In alluvial mining, no crushing is required, and sieving removes all pieces larger than 30–50 mm (1.25–2 inches) as unreprocessed waste.

Figure 14. Basic alluvial operations along the Vaal River near Gong Gong in South Africa. At left, a team operation moves red gravel close to a lifting arm, and, on the right, are their basic trommel and washing pan. (George E. Harlow.)

Figure 15 (above). One of the family members at a modern alluvial works examines concentrate from a washing pan that has been sieved and washed. Blue carpet is judged the best surface on which to visually pick out a diamond. (George E. Harlow.)

Figure 16 (above left). Modern alluvial facilities set up at Longlands, 30 km northwest of Kimberley, South Africa. (George E. Harlow.)
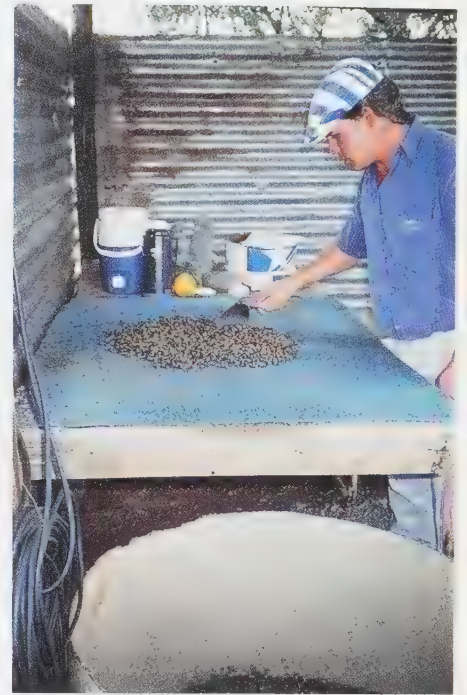
Marine Deposits

The diamond deposits along the Atlantic coast of southern Africa are mixtures of alluvial and beach deposits, and they contain the largest known stores of gem-quality diamonds. There are more than 3,000 kimberlite pipes (many not bearing diamonds, of course) in the parts of southern Africa that are drained by tributaries to the Orange and other rivers that end at the Atlantic coast. Over the past 100 million years, up to 1,400 m have been stripped off the top of the Kalahari Craton, releasing billions of carats of diamonds. The estimate for diamonds eroded from the Kimberley mine alone is 500,000 carats.[5] Only 10 percent of the eroded diamonds are believed to remain in the alluvial deposits, but 90–95 percent of the marine diamonds are of gem quality! The powerful ocean waves have tended to break the poorer-quality diamonds, while not affecting the finer stones. The littoral zone, the area of wave action on the coast where diamonds accumulate, has moved in and out with changes in sea level, which was lower by at least 500 m 25 million years ago, and has been 300 m higher within the past 10 million years. Strand lines were constant over long periods, creating wave-cut terraces that were long-term barriers and channels for diamond concentration in hollows and crevices. Those terraces are preserved both above and below sea level and are the focus of mining activity. Another factor in the distribution is the along-shore drift, the process of sand moving in a particular direction along the coast in the littoral zone; the along-shore drift is northward on the Atlantic coast of southern Africa because powerful northerly waves emanate from storms in the cold southern Atlantic. Diamonds are pushed north from their river sources or their earlier entrapments, their sizes decreasing with distance from the source because the smaller, lighter ones are more easily transported. Thus, the Orange

River and the proto-Orange, with its mouth at what is now the Olifants River, are two southern termini for exploration. With diamonds distributed over such a large area and varied terrains, the methods of mining diamonds from those marine deposits vary: modified alluvial methods, shallow-water operations with divers, and deep-sea automated processing from large mining ships. Finally, although the African marine deposits are the only ones being exploited today, marine deposits may exist on the shores of the Arctic Ocean near the Lena River in Siberia or along Coronation Gulf in the Northwest Territories, Canada.

On shore, the work is like a large-scale alluvial operation, except for two features. First, in the surf zone, large earthen dams are built to hold back the water and allow recovery from deposits as much as 20 m (65 ft) below sea level. Second, the pounding action of the surf can actually force diamonds into crevices so that special extraction techniques are needed. When the overlying sand and gravel have been removed and sent for processing, workers come in with tools like brooms, prying tools, and compressed air jets to clean the underlying bedrock surface to find diamonds – literally an "on hands and knees" operation (Figure 17).

In water less than 15 m deep, divers do the work in South Africa. The method usually involves a suction pump, housed on shore or in a boat and attached to a long hose controlled by a weighted diver, that sucks water and gravel off the ocean floor. The diver pays attention to scour holes and crevices where diamonds may have accumulated. Because the surf is always driving sand and gravel along the coast, divers will regularly revisit the same traps that have produced diamonds before. The Atlantic waters off South Africa are so cold that divers need insulated suits or suits heated with hot water pumped from the facility that houses the suction pump. Gravel from the pump is

Figure 17. After removal of many meters of Kalahari sands from the bedrock surface on Namibia's west coast, workers scour exposed crevices and crannies for diamonds. (Rory O. Moore.)

sieved, and sometimes even concentrated by one of the methods described earlier, with the finer fractions or concentrate being sent to a recovery plant ashore (Figure 18).

In deeper water, the problems increase, as does the need for exploratory investigation. Initially, detailed mapping of the ocean floor is required. Boats make sonar traverses that can detect details of a few centimeters (if there is no wave action), and the data are transformed into a map via computer software, with positions determined from the global positioning system (GPS). The GPS is based on the U.S. military satellite positioning system, which permits locating a receiver to within a few meters of its exact longitude and latitude and has allowed the construction of remarkably accurate and detailed maps with relatively inexpensive technology. These new maps can identify small gullies, basins, and ridges, and the GPS allows a boat to return to the exact mapped coordinates (Figure 19). Divers wearing heated suits and using vacuum hoses can work to depths of about 40 m, although a diver cannot spend much time on the ocean
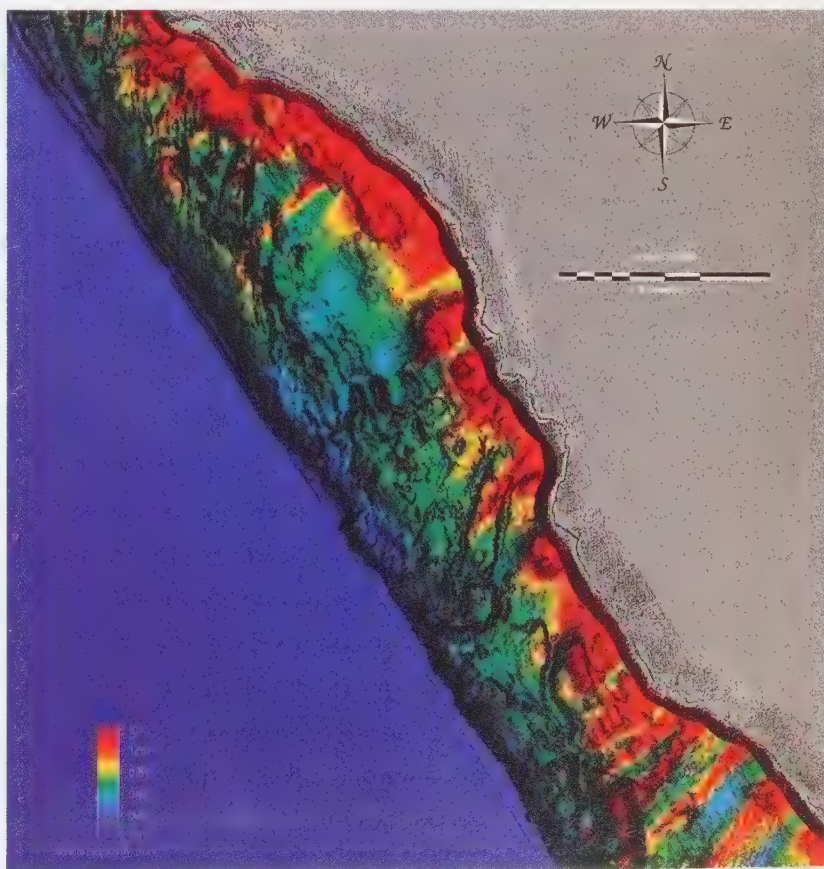
floor at such depths, and that makes such an operation expensive. Automated crawlers with suction devices are being developed to reduce the risks to humans and to improve efficiency.

At depths greater than 40 m, large recovery ships, which are still evolving, are used. De Beers Marine has several large ships, some equipped with robotic crawlers for locations that have little sediment covering the diamond-bearing horizons, and some with large-diameter borers that can dig through thick over-lying sediment to reach the diamond-bearing zone. Such vessels carry all of the processing and recovery equipment necessary to extract and sort any diamonds encountered.

SORTING AND DISTRIBUTING DIAMONDS

Sorting or grading is the fairly straightforward but important task of sepa-rating the stones into gem-quality, near-gem-quality, and industrial-grade dia-monds. The distribution process is the primary marketing step, which is and has long been controlled by De Beers Consolidated Mines, Ltd., through its majority control of the Central Selling Organization (CSO), which handles about three quarters of all diamond mine sales.

Grading by Color, Clarity, and Size

Sorting is carried out at every level of the marketing process, from the mine to the jeweler. At the mine, the sorting depends on the sophistication of the operation and the volume of the production, but it is based on grouping stones of like type. The size groups for diamonds are called "sizes," "smalls," and "sand," with the breakpoints at about 1 carat (though the actual weight will vary with the market) and 0.1 carat. Diamonds larger than about 15 carats are handled individually.

The shape groups include "stones," "shapes," "cleavages," "macles," and "flats" (Figure 20). There are at least 10 different grades of quality. Classi-fications according to clarity or freedom from flaws and inclusions focus as much on the location of a flaw as on its presence, because a flaw near the sur-face, particularly at the corner of an octahedron, is likely to be removed during cutting, without loss of weight to the finished gem.

Color also plays an important role; water-clear stones or diamonds with fancy colors are far more desirable than off-yellow or muddy colors. The pur-pose of classifications is to estimate an asking price for the rough diamonds. About 75 percent of all mine sales go through the Diamond Producers' Associ-ation of the CSO.

Figure 20 (opposite). Sorting small diamonds in a Botswanan operation. (Courtesy of Lazare Kaplan Botswana.)

The CSO

Beginning in 1889, when Cecil John Rhodes consolidated his holdings in Kimberley, South Africa, efforts have been made to stabilize the diamond market. That worked for Rhodes, who died in 1902, so long as the main diamond sources in South Africa were controlled by De Beers, but that situation did not last. Discoveries in other parts of Africa led to strong competition, and prices fluctuated considerably with any changes in supply or demand. In 1929, on the eve of the Great Depression, Sir Ernest Oppenheimer became chairman of De Beers Consolidated Mines, after gaining control via his interests in Consolidated Diamond Mines of Southwest Africa and Anglo-American Corporation, the conglomerate he created to mine the gold of the Witwatersrand. By the early 1930s the demand for diamonds had declined, forcing the mines to close down. Faced with that disaster, Oppenheimer convinced the other diamond producers to form the Diamond Producers' Association to try to control the supply of diamonds and maintain a stable market. The Diamond Trading Corporation (DTC) was set up in 1934 to handle the actual sales of diamonds, and those two units make up the nucleus of the CSO, which is basically a group of marketing companies. The CSO stabilizes the prices in hard times and raises them in accord with inflation and demand during good times. It needs considerable wealth and stockpiles of diamonds to maintain that position, but that single-channel marketing system has been an effective cartel. In the United States, cartels are illegal under the federal antitrust laws, so De Beers cannot operate there. De Beers interests are represented there by an advertising agency, the Diamond Information Center, managed at this writing by J. Walter Thompson, and indirectly by the diamond dealers and jewelers.

CSO: A DELICATE BALANCE

A cartel is considered to be a fading business model as the world adjusts to an increasingly global marketplace, so the diamond system deserves inspection. De Beers argues that the diamond market is a fragile luxury enterprise rather than a market for a commodity or an essential good or service that should be open to unfettered competition. It provides stability and gives the roughly 2.5 million people employed in the diamond industries a bit of security. The CSO primarily stabilizes for the diamond producers and the mine owners, buffering the retail market and preventing depreciation of diamonds. In order to maintain a war chest to protect the market and fight breakaway producers, the CSO levies a service charge on all its sales. Those unwilling to play by the cartel's rules are frozen out of the CSO system and risk being frozen out of the marketplace should independent suppliers run out of diamonds or join the CSO system. Roughly 20–25 percent of the market is independent of the CSO, and that tends to work toward higher prices for sellers and lower prices for buyers. Overall, market stability is still maintained by the CSO. The risk to the CSO is that large players might sink the system by withdrawing and significantly expanding the non-CSO portion of the market. Should someone break the back (or bank) of De Beers, there could be a wild reorganization of the market to some new but unstable set of prices. Many suppliers and buyers would like to have individual freedom from the CSO, but do not want to see the entire edifice collapse. Large producers like Russia are more interested in a bigger piece of the economic pie and leverage at the bargaining table with De Beers than collapsing the cartel.

The mines sell their diamonds to the Diamond Producers' Association, which sells them to the Diamond Trading Company (DTC). The DTC also buys diamonds from the independent producers, such as in west Africa, and on the open market in Antwerp. All of the DTC diamonds are weighed and graded again in special facilities, often with daylight from windows facing north in London, using calibrated sets of stones to grade for color and clarity. Those diamonds are then divided into parcels for sale or storage, depending upon the demands of the market.

The CSO markets rough diamonds through the DTC at 10 sales each year. The DTC prepares parcels of diamonds, totaling many millions of carats, for its regular buyers, who are invited to attend those sales, known as "sights," for they are the clients' first sight of the diamonds being offered. Those regular buyers, called "sight holders," number around 165; they make their needs known to brokers who represent their interests to the CSO. Once the DTC knows the size, quality, and color ranges that buyers are seeking, it prepares parcels as a compromise between the buyers' needs and the diamonds it has and/or needs to sell.

Buyers are mostly large dealers who sell both rough and finished products. The buyer views the parcel but has no choice about the contents or the price, except when there is mutual agreement that an evaluation has been inappropriate for some portion of the parcel. The buyer can refuse the parcel. What the buyer obtains in a parcel but does not need, he or she must sell. Most of the sales are carried out in London, but there are also sights in Lucerne and Johannesburg. Industrial diamonds are sold at a fixed price per carat, depending on a particular quality, through an arm of the CSO: De Beers Industrial Diamonds, Ltd.

The next stage in the selling of gem-quality diamonds is handled primarily through the diamond clubs and bourses of the major trading centers in London, Antwerp, New York, Tel Aviv, Bombay, Singapore, and Bangkok (Figure 21). Those club organizations belong to the World Federation of Diamond Bourses, and their members must accept and meet standards of operation that permit a trustworthy and safe system of transactions. The business in those facilities, in both rough and cut diamonds, is carried out between individuals who scrutinize the stones and each other, confirm a deal, or perhaps consult an original seller if the sale is being handled by a broker. If a given deal is not consummated immediately, the diamonds are sealed in gem-paper envelopes and held in the club office until approved. Payments are arranged in advance, and trust is an important component in the trading. Each of those clubs functions as a safe haven and a social facility, providing an environment in which buyers can see a wide variety of goods to fill orders for matched sets or graded suites of diamonds for the members' clients. There are also many transactions that take place in private offices or at the offices of large dealers.

FASHIONING GEMS

The transformation of a rough diamond into one or more faceted gems is a mixture of art and engineering that begins with careful examination. The first step is to determine the crystallographic orientation and "grain" of the diamond. The orientation of an octahedron or other crystal form is obvious, so the master cutter knows exactly the direction of cleavage (along the four planes that parallel the octahedral faces, as discussed in Chapter 1) and of the grain (lines of intersection of the cleavage with any other surface). Irregular diamonds are more difficult to orient, but usually the grain is revealed by subtle lines on the surface or in the interior. Knowing these orientations is vital to shaping a diamond. The next step is to locate inclusions or imperfections. The cutting should be planned so that they will be positioned either outside the finished gem(s), there to be removed during faceting, or at the perimeter of the stone, where they will be least visible. In order to determine how to fashion a rough diamond, the cutter must visualize the crystal from within as it is turned in the hand and examined with a loupe (magnifying glass). The most important consideration is to determine how to cut the crystal so as to preserve the largest gem that will have proportions close to the ideal. The "break" weights at which the values of diamonds increase are the multiples of the carat, such as 1.0 carat, 2.0 carats, 3.0 carats (± 0.1 carat); so designing such a stone from the rough is important. Once the design decision is made, lines will be drawn on the stone with ink if it is to be cleaved or cut; otherwise a dot or dots will be placed for orientation (Figure 22).

Although the shaping of a diamond is referred to as cutting, that is only one of the four fundamental processes: cleaving, cutting, bruting, and grinding and polishing (the last two are basically a single process). Most of the techniques were developed early in the history of diamond fashioning, as well described by Benvenuto Cellini in 1568, so that only the mechanisms, refinements, and degrees of automation have changed. The major improvement has been the use of lasers. *Cleaving,* the most efficient means of dividing a diamond, is the act of splitting the diamond along one of its four planes of weakness. Cleaving requires great skill, because an accident will result in a crushed diamond. The ink-marked diamond must be notched so that a steel cleaving blade can be placed in the notch (Figure 23). The notch traditionally is made with a sharp fragment of another diamond, dragged carefully along the direction of cleavage near a corner. Alternatively, the diamond can be moved back and forth through the beam of a laser. The diamond usually is cemented to a wooden holder for both notching and cleaving, placed so that the force of the cleaving blow will drive the diamond downward into the holder. The cleaving blade is placed in the notch and rapped with a metal bar, which forces the cleaving blade to spread the notch and cleave the diamond.

Figure 23. A diamond being notched (top) *and cleaved* (middle), *with the two halves after cleaving. (Courtesy of De Beers.)*
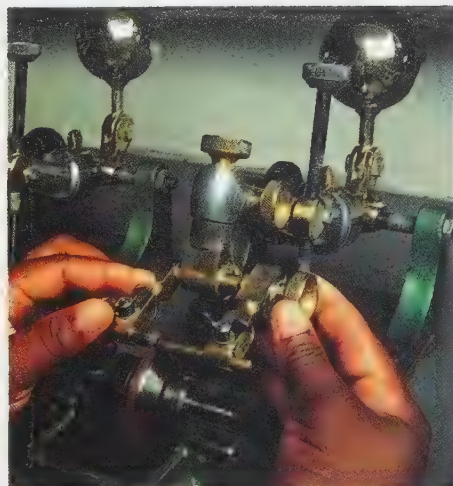
Figure 24. Sawing a diamond. (Courtesy of Lazare Kaplan Botswana.)

Cutting is used to divide a diamond or remove a large portion when the direction selected for the division is not parallel to the cleavage. That involves sawing across the grain, such as truncating an octahedron to make a brilliant stone or separating an octahedron to form two brilliants (Figure 24). Cutting results in loss of diamond weight because of the thickness or kerf of the blade, so the blades are kept as thin as possible. The diamond must be fastened securely to a hinged holder that will move the diamond smoothly parallel to the blade. The blade usually is made of a special bronze and either has diamond abrasive embedded within it or is "charged" with diamond grit and oil prior to cutting; the diamond particles actually get stuck in the bronze and scratch their way through the large diamond being cut. In large, automated facilities, lasers can be used to slice through diamonds.

Bruting is literally the brute-force means of shaping a diamond by forcing a tool diamond against the one being fashioned to round its corners and create part of the outline of the gem envisioned. The diamond to be bruted is cemented to a drop or holder (the cutting or bruting diamond used as the tool is held likewise), and great force must be exerted to scrape the two diamonds past one another (Figure 25). Lathe-like devices are used today, but when bruting was done by hand, craftsmen often suffered long-term damage to their hands and wrists from the strain of forcing the diamonds together.

To create the precise orientation of the facets that will constitute a cut diamond, it must be fixed firmly in a holder (the dop) and held precisely against the polishing lap. In the classic method, the diamond was partially embedded in plumber's solder in a cup attached to a copper shaft, the whole dop assembly looking like an acorn. The solder was softened with a torch or charcoal fire, but the temperature was well below that at which diamond would burn in air. That technique has been replaced by the use of dops with mechanical clamps (Figure 26). The dop is mounted in a holder, called a tang, which has two legs that rest on the table adjacent to the lapping wheel; that allows the tang to maintain the alignment of the dopped diamond with the lap. In the past, the dop shaft was bent to the orientation required to position a facet flat to the lap, but now most dops are adjustable or are indexed to permit easy and accurate alignments. The diamond must be removed and reset in the dop several times in order to grind and polish the entire gem. The table facet, the face of a gem, is normally polished first, which takes the longest time, followed by two crown facets to orient the stone, then remounting to polish some pavilion facets and onward to complete the gem. A skilled craftsman can fashion a stone to an accuracy of less than 1° of error by gauging sizes and examining the reflections and the corners of intersecting facets.

Figure 25. The bruting of two diamonds captured in stroboscopic light, which permits more rapid and accurate shaping. (Courtesy of De Beers.)

The final step in fashioning involves the slow process of grinding and polishing the diamond to its finished dimensions on a diamond-charged cast-iron wheel, called a lap or scaife. The lap must be charged regularly with diamond paste (a mixture of crushed diamond and oil) toward its center, and as it rotates

it grinds the diamond in the middle section of the lap and polishes or brillianteers the diamond at the outer edge of the lap (Figure 27). The dop and tang are rotated to orient the grain of the diamond across the direction of wheel rotation; the diamond is relatively softer when abraded across the grain, so this orientation is necessary in polishing diamond with diamond.[6] The tang rests against a post adjacent to the lap to keep the tang and diamond at a fixed spot on the rotating lap, and there is room for up to four diamonds on a lap at one time. A lap will slowly develop grooves and notches over a period of a month or so, though it can be remachined to a flat surface many times. Modern laps are powered by electric motors, following an evolution from the original manual power to horse power to steam power. For the hand-powered system, a drive wheel with an eccentric lever was pushed back and forth, usually by the diamond cutter's wife or children; the drive wheel was connected to the lap shaft via a pulley system.

Although the faceting of diamonds (Figure 28) has been facilitated somewhat by technological developments, most of the work is still done manually in the major cutting centers: Antwerp, the diamond-cutting capital; New York, a cutting center for large diamonds; Tel Aviv, the technology center; Bombay, a representative center for the 800,000 diamond cutters of mostly smaller stones in India; and the growing centers in Singapore and Bangkok. Companies in Tel Aviv have been developing computer-controlled devices to automate much of the process, including the examination of diamonds, bruting, laser cutting, and faceting. Their goal is to maximize stone size and lower the costs of diamond fashioning in order to compete economically with India and the developing countries, where labor costs are lower.

Figure 26. A diamond held in a mechanical dop and being polished on a diamond lap. (Courtesy of Argyle Diamonds.)

INDUSTRIAL PRODUCTS

Eighty percent of the natural diamonds produced plus five times that volume from synthetic production are used in industry. Because diamond is the hardest substance, it is used to fashion a host of other hard substances, ranging from its technological synthetic cousin, tungsten carbide, to other gems.

The most basic and most widespread use of diamond is as an ultrahard cutting tool, either as the tool itself or as an abrasive. Diamond is chosen for such uses when its strength and resistance to abrasion (having a long working life and fast cutting action) outweigh its costs. There are three classes of uses: diamond (either individual crystals or polycrystalline diamond, PCD)[7] as a cutting tool, diamond-embedded material as a tool or abrasive, and diamond powder or paste for grinding and polishing. Diamond as a machining tool for turning, milling, and boring is preferred where finely finished surfaces of high precision are needed. Its resistance to wear is also important in automated

Figure 27. A cutter adjusting the tang for polishing a diamond on a lap or scaife at the Kimberley Mining Museum. (Willard Whitson.)

processes that need to turn out many copies of a product without replacement of the cutting tool. Diamond is used for machining a wide variety of plastics, glasses, and metals, yielding products such as the drums for laser printers, polygon mirrors in laser printers, and aluminum-alloy pistons for automobile engines. However, diamond cannot be used for machining ferrous and similar alloys. Under intense machining conditions, diamond will abrade very quickly against some materials, apparently because as a diamond tool heats it reacts with metals like iron, nickel, molybdenum, and titanium to form carbides. Those either break away or are much harder than the metal itself, in either case wearing the diamond cutting edge at unacceptably fast rates.

The cutting and abrading tools that use diamond vary widely. For machining, individual diamonds can be attached to a metal tool using brazing compounds of copper, tin, or silver, plus a small amount of titanium or tantalum to help form the critical bonding to the diamond's surface. Such tools are used much like a standard machine tool, being held as the work (the material to be machined) turns against it, or as the tool is turned against the work. For grinding, diamonds are embedded in a metal carrier, usually bronze, but sometimes steel or carbides, by sintering the metal powder with small diamond grains whose grit diameters range from 5 to 125 micrometers (μm; 0.0002–0.005 inch). The bonded grinding material typically consists of less than 25 percent diamond by mass and forms a thin layer on a metal grinding wheel or some other moving surface. For less intensive applications, where fast cutting or accuracy is desired, diamonds can be bonded into phenolic or polyimide resins to make grinding and polishing materials, particularly grinding and polishing drums and disks. All of these are used widely in the ceramics, stone, and lapidary industries to grind and polish surfaces smooth. For sawing and drilling, slightly larger diamonds, 150–1,000 μm, are similarly bonded or embedded in bronze or cobalt and attached to steel saw blades or cylindrical coring drills for myriad applications: cutting rocks, concrete, bricks, and ceramics, coring holes in buildings, streets, and runways. Large circular blades up to 3 m (10 ft) in diameter are used to cut building stones (Figure 29), and 75-mm (3-inch) blades are used for slicing gems. Some interesting devices for cutting stone and concrete include chain saws with bonded diamond abrasive on the chains for making deep piercing cuts and wire saws that can cut large blocks out of quarries or cut buildings in two.

The oil industry and deep-drilling projects are in particular need of diamonds to make holes deep into the Earth. Diamond crystals or PCD are bonded to the cutting edge of drill bits. The drill bit is turned either by twisting the entire drill stem (the assembly of pipes connected to the bit) or by a turbine just behind the bit; heavy drilling mud is pumped down the pipe to carry out the cuttings, to lubricate and cool the bit, and to power a turbine if one is being used. Because such holes can reach depths of 5,000 m or more, and the entire drill stem must be pulled and disassembled to change a drill bit,

Figure 28 (opposite). The fashioning of a round brilliant: (top left) – a diamond octahedron; (top right) – the octahedron has been sawn into two pieces; (middle) – one half has been bruted round to shape the girdle of the stone; (bottom left) – the table has been polished and eight facets have been polished on the pavilion, or bottom, and 16 facets on the crown, or top; (bottom right) – brillianteering has finished the 58 facets of the gem. (Courtesy of Lazare Kaplan.)

Figure 29. Diamond abrasives are critical to cutting and drilling stone and masonry. The image at top shows circular blades, a wire saw, and a coring drill, all imbedded with diamond; left below shows a mobile circular saw cut concrete; and right below a wire saw cuts through a block of granite. (Courtesy of GE Superabrasives.)
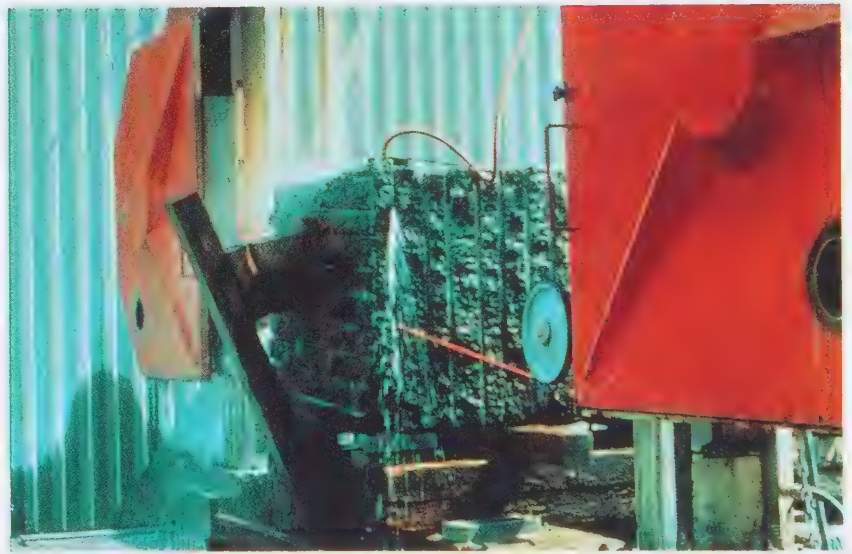
the durability of a diamond drill bit makes it well worth the considerable investment (Figure 30). At the opposite end of the size spectrum, most of us are aware of another diamond drill – the dental drill. Modern dental drills are coated with a layer of diamond abrasive that will maximize a drill's rate of cutting through tooth enamel while minimizing the painful buildup of heat.

Diamond is the ultimate polishing abrasive. The diamond paste described earlier is used for polishing of other gems, glass, rock, and ceramics. It is particularly useful for fast cutting and producing smooth surfaces on composites of materials with different hardnesses. I routinely use diamond to polish the products of mineral-synthesis experiments that consist of mixtures of hard aluminum oxide (the same substance as sapphire), medium-hard silicate minerals, and soft carbonate minerals, because only diamond will polish aluminum oxide as easily as it polishes carbonate and produce a flat surface.

An important industrial application that utilizes the extreme hardness of diamond is the drawing of wires (though not ferrous wires, as mentioned earlier). Wires are formed by drawing metal billets through ever-smaller holes in a hard block called a die. Diamond is an ideal substance because it is hard and does not deform, has a low-friction surface so that the metal pulls through relatively easily, and will last for many kilometers of pulled wire. Every television, telephone, computer, and CD player utilizes wire drawn through diamond dies. In the past it was difficult to drill a hole a couple of millimeters or less (only a few hundredths of an inch) in diameter through a near-gem-quality diamond, because it entailed the slow process of a diamond boring through another diamond. Since the 1960s, pulsed lasers[8] have been used to drill the initial hole in a diamond, greatly speeding up the process. Such a hole is polished to its final hole size and taper with a steel mandrel and diamond abrasive powder (Figure 31).

Figure 30. A drill bit armed with polycrystalline diamond (PCD) teeth used in petroleum exploration. The long life of the diamond edges reduces the frequency of removing the entire drill assembly (perhaps several thousand meters) and, thereby, reduces the cost. (Courtesy of GE Superabrasives.)

SPECIALTY PRODUCTS

There are several applications of diamonds that fall into the realm of consumer or specialty applications. Formerly well known, but now used only by hard-core audiophiles, is the diamond stylus for playing vinyl phonograph records: Conical or elliptical diamonds measuring about 1 mm by 0.5 mm, with a tip only about 20 μm (0.0008 inch) in radius, rode the grooves of almost every phonograph record for more than 30 years; the diamond's long life and low friction made it the ideal phonograph needle. That application was adapted in an attempt to make video-disk players but has now been superseded by magnetic tapes and laser disks. Diamond styli are used in devices for looking at the smoothness of surfaces and in the ultimate surface-examining instrument, the atomic-force microscope, which can "feel" the individual bumps of an atom on a crystal surface.

Diamonds can be fashioned to form ultrahard and smooth-cutting knives and scalpels. A supremely polished diamond knife has very low drag and deformation when it cuts, making it excellent as a scalpel for slicing delicate tissue, such as in eye surgery (Figure 32). Fine cuts in coronary arteries are sometimes

Figure 31. Wires are shaped with drawing dies that squeeze large wires to successively smaller diameters; wire is reduced in diameter in the "approach" section and polished in the "bearing." Dies made from an individual diamond crystal or PCD (the hatched cylinder) have very long working lives compared with those made of other materials. Virtually all the copper wire used in electronics is drawn through diamond dies. (Adapted from Blakey, 1977.)
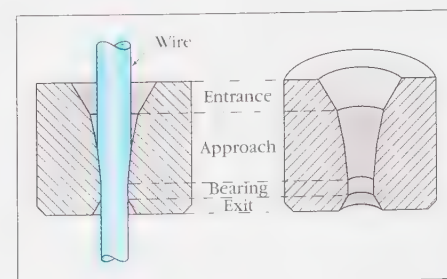
Figure 32. Small scalpel blades are fashioned from single diamonds and used for surgery where the extreme hardness and sharpness of a diamond scalpel lessens the risk of tearing delicate tissues, such as of the eye or internal organs. The diamond blade is 1 mm across. (George E. Harlow/courtesy of Lunzer, Inc.)

carried out with special diamond blades. Diamond microtome blades are used in medical biopsy and research for making ultrathin slivers of frozen or impregnated tissues. The sharpness and the nonwetting (hydrophobic) surface of diamond yield undamaged slivers of wet materials. Diamond microtome blades are also useful for sectioning composite materials consisting of substances of different hardnesses, because diamond will not readily adhere to and drag a harder material into an adjacent softer material. An example is asbestos in lung tissue. Those same attributes make diamond useful for installing the fiber-optic cables used in telecommunications: Diamond blades are used to make clean, smooth cuts in the 100-μm-diameter fibers in flexible sheaths, sometimes with the aid of ultrasonic vibration to make the glassy fibers break smoothly.

The applications cited are only a sampling of the uses diamond finds in industry. The electronic, thermal, and optical applications are described in Chapter 13. Diamond is used in so many technologies that are important to modern life that it should be no surprise that the demand for diamond in industry exceeds that for ornamentation.

NOTES

[1] G10 refers to a grouping via cluster analysis, as defined by Dawson and Stephens (1975) and modified by Meyer (1968), Dawson (1980), Sobolev et al. (1984), and Gurney (1984).

[2] The Na-rich varieties described by McCandless and Gurney (1989) fall into the range of G3 Mg-almandines described by Dawson and Stevens (1975).

[3] See Levinson et al. (1992) for a brief review and sources.

[4] Compare the estimates of Atkinson (1989) and Levinson et al. (1992).

[5] Gurney et al. (1991), p. 210.

[6] The optimal direction is either perpendicular to or diagonally across the traces of the octahedral face, but the polishing rate changes with even subtle changes in direction or angle. See Wilks and Wilks (1995), p. 234.

[7] PCD is a synthetic diamond product made by sintering many small synthetic diamond crystals into a solid (centimeter size or larger), like a better version of carbonado.

[8] Both carbon dioxide and neodymium-doped yttrium-aluminum-garnet (Nd-YAG) lasers are used, and pulsing is necessary to allow air to reach the heated diamond and to limit heating to the surface that needs to be removed.

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12

Diamonds as Gemstones

JAMES E. SHIGLEY AND
THOMAS MOSES

ALTHOUGH DIAMONDS have an enormous variety of industrial applications, they are most often thought of as the most important gemstone (Figure 1). In this chapter, the gemology of diamonds will be discussed: identifying gem diamonds, grading them for quality, and examining them for possible laboratory treatments and enhancements.

Diamonds suitable for use in jewelry are mined in many countries. Before being fashioned as gemstones, rough diamond crystals typically are found in the shape of an octahedron, a dodecahedron, or a macle (the twinned form of an octahedron). These crystal shapes often have rounded surfaces because of partial dissolution of the diamond while being transported in the kimberlite or lamproite pipe or because of abrasion during transport in a stream or river away from the source pipe. Broken fragments and imperfectly formed crystals are also common. Most diamond crystals weigh less than 1 carat (0.2 gram), although much larger ones (as much as 100 carats or more) suitable for fashioning as gemstones are occasionally found. The majority of diamonds are nearly colorless to pale yellow or brown. The rare colored diamonds, such as vivid yellow, green, blue, or pink, are currently much sought after.

Once they are fashioned for jewelry use, gem diamonds must be valued for sale in the retail jewelry marketplace. Such valuation involves two steps, both of which require careful examination by a qualified gemologist or jeweler:

> *identification,* to ensure that the stone is actually a diamond, that it is a diamond of natural origin, and that it has not been artificially treated
> *grading,* to assess quality with respect to color and clarity.

For each of those steps there is a grading system internationally accepted in the jewelry industry. The quality of the gem cut (its proportions and the fashioned shape) is also evaluated, but there is no accepted grading system. The

preferences for different gem proportions vary with the local market, thus making standards difficult. Nevertheless, the cut style, proportions, and finishing quality have an important impact on the perceived value of a diamond.

Gemology plays a crucial role in supporting the international industry in gem diamonds because there are laws stating that the identity and quality grade of a polished diamond must be disclosed by the jeweler to the customer at the time of sale.

DIAMOND IMITATIONS

The first step that a jeweler or gemologist must take is an examination to ensure that the gemstone is a diamond. A number of inexpensive colorless materials, also called "diamond simulants," with optical properties approaching those of diamond have been used in jewelry. The one most commonly encountered today is cubic zirconia, which is the cubic form of the material zirconium oxide. They have distinct gemological properties and are easily identified. Cubic zirconia and other diamond simulants can be quickly recognized by a jeweler using a simple and inexpensive testing device known as a diamond probe, which measures thermal (i.e., heat) conductivity. Diamond is superbly conductive, whereas all simulants on the market today are much poorer thermal conductors; the diamond probe readily detects the difference, usually with an electronic display. This instrument can be used to check both loose as well as mounted gemstones. It can distinguish all simulant materials except for colorless synthetic moissanite (silicon carbide), which has only recently been introduced. (As moissanite is hexagonal, it is not optically isotropic and can be easily distinguished by simple optical tests. However, the cubic form of silicon carbide will require very careful examination to distinguish it from diamond.)

SYNTHETIC DIAMONDS

The first synthesis of diamond was achieved in 1955. That was a valuable scientific and technological development because of the many industrial uses of diamond. In 1995, more than 400 million carats (80 metric tons) of synthetic diamonds were produced, roughly four times the production of natural diamonds. Synthetic diamonds are mostly tiny crystals used as abrasives in the manufacture of machining tools and for grinding powders and even for polishing natural diamonds. In 1970, General Electric announced the production of 1-carat synthetic diamond crystals that were of a quality suitable for jewelry use. Both colorless and colored (yellow and blue) synthetics were produced at

Figure 1. Eighteenth-century brilliant-cut diamonds in garniture from the Grünes Gewölbe in Dresden, including a jewel from an Order of the Golden Fleece, diamond studs (left), and cuff links (bottom). (Courtesy of State Art Galleries, Dresden.)

Figure 2. Gem-quality synthetic diamonds, both crystals and faceted pieces, produced on an experimental basis by the General Electric Company. The largest crystal weighs 0.73 carat, and the faceted pieces weigh between 0.3 and 0.4 carat. (Tino Hammid/courtesy of Gemological Institute of America.)

DIAMOND PROPERTIES VS. SUBSTITUTES

	Diamond	Cubic zirconia[a]	Sapphire	Silicon carbide[b]
Composition	C	ZrO_2	Al_2O_3	SiC
Crystal system	Cubic	Cubic	Trigonal	Hexagonal or cubic
Hardness (Mohs scale)	10	8¼	9	9–9½
Cleavage	Excellent on (111)	None	None	None
Density (g/cm³)	3.515	6.0	4.00	3.2
Refractive index[c]	2.42	2.15–2.18	1.77	2.65
Dispersion	0.044	0.058–0.066	0.018	>0.08
Thermal conductivity[d]	5–25	0.1	0.4	0.9

[a]CZ, usually containing Y_2O_3 or CaO as stabilizers or HfO_2 to enhance optics.
[b]Also called synthetic moissanite.
[c]Measured in yellow sodium light.
[d]In watts per centimeter per degree Celsius (at 300K).

that time (Figure 2). Since then, a small number of high-technology companies have refined the methods to synthesize gem-size diamond crystals for industrial applications or experimental purposes. Most large synthetic-diamond crystals weigh 1 carat or less; faceting for jewelry purposes would yield stones of 0.5 carat or less.

The types of laboratory apparatus used to grow gem-quality diamonds are expensive to construct, to operate, and to maintain and thus far have been used by relatively few companies and laboratories. Thus, the potential for synthetic diamonds in quantity for use in jewelry is still remote. By 1996, very few instances of the use of gem-quality synthetic diamonds had been reported in the jewelry industry. If synthetic diamonds were encountered by a gemological laboratory, a report on their quality grading (for color and clarity) likely would not be issued; they are not considered part of the gem market. Detection of synthetic diamonds is nonetheless a necessary capability in professional gemology.

Although synthetic diamonds do not have the imprimatur of nature in their formation, they are the same material and thus are far more difficult to detect than the simulants. The absence of nature's signature is the key to identification of synthetic diamonds. The larger synthetic diamonds must be grown at higher temperatures and pressures than those in which natural diamonds crystallize, and they grow in a much shorter time in a chemical environment that is vastly different from that in the Earth's mantle. One result is that laboratory-grown crystals typically have a shape that differs from that of natural diamonds. Rather than octahedra being most common, cuboctahedra are the norm (see Figure 5 in Chapter 1); that form is lost in the fashioning, but it can leave its fingerprint in color zoning and other internal features.

A useful distinguishing feature is the color of synthetic diamonds, the majority being brownish yellow, a result of nitrogen contamination from the air and other sources that is difficult to avoid in industrial production. It is possible to treat these yellow crystals with irradiation and heating to produce colors of orange to purplish red. Blue synthetic diamonds can be grown by suppressing nitrogen and adding boron to the growth mixture. These colored synthetic diamonds have several distinctive characteristics. First, they frequently exhibit internal color zoning that is very different in appearance from the color zoning occasionally seen in natural diamonds (Figure 3). Most colored natural diamonds have even coloration, but if it is uneven, it tends to be blotchy, striped, or irregular in distribution. In contrast, most colored synthetic diamonds have uneven coloration, with distinct colored and less-colored (or colorless) zones marking the internal growth sectors related to the crystal form (cube, octahedron, dodecahedron, etc.).

Another distinctive feature of synthetic diamonds is the occurrence of tiny metal inclusions, which often become trapped during the growth of the synthetic crystals from a molten-metal solution (see Chapter 13 for more details). Such inclusions can contain iron, nickel, cobalt, or their alloys, making the

Figure 3. Distinct color zoning, as seen in this faceted blue synthetic diamond, is a good identification feature for colored synthetic diamonds. This kind of color zoning results from the conditions of diamond growth used in the laboratory. (Courtesy of Gemological Institute of America.)
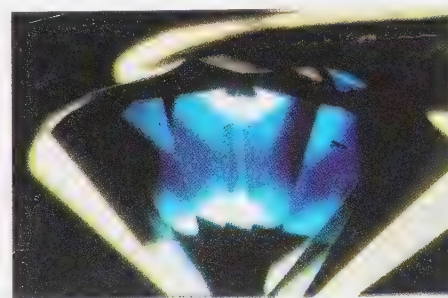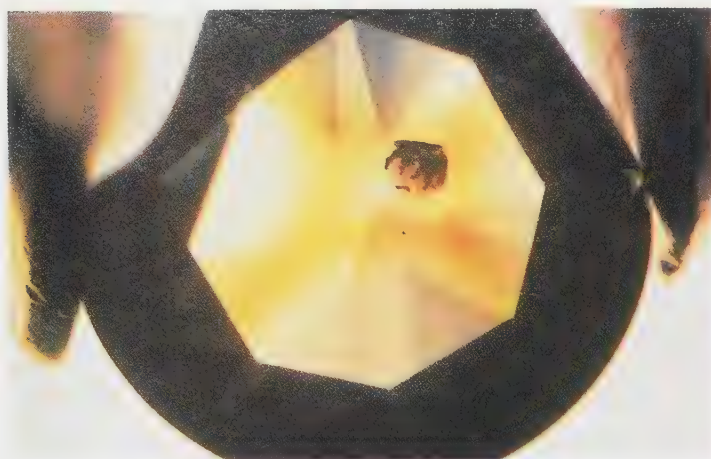
Figure 4 (left). This yellow synthetic diamond, seen immersed in a liquid to minimize distracting surface reflections from the facets, has a large inclusion of metal (which appears black in this lighting) near its center. Such metallic inclusions originate from the molten metal alloy and become entrapped in the synthetic diamond during growth. Similar metallic inclusions are not found in natural diamonds. This synthetic diamond also exhibits unusual color zoning that appears as narrow areas of yellow color. (John I. Koivula/courtesy of Gemological Institute of America.)

Figure 5 (above, right). Because of their internal structure, synthetic diamonds often exhibit fluorescence (to an ultraviolet lamp) in an uneven, cross-like pattern. The center region of this yellow synthetic diamond is not fluorescing and appears dark, whereas the surrounding regions are fluorescing with a yellowish green color. This kind of fluorescence pattern is not encountered in natural diamonds and is another indication of synthetic origin. The image is 2.3 mm across. (John I. Koivula/courtesy of Gemological Institute of America.)

synthetic diamonds slightly magnetic, and some will be noticeably attracted by a magnet (Figure 4). Such metallic inclusions have not been reported in natural diamonds. Finally, synthetic diamonds can display what are called internal grain lines in the form of intersecting patterns. Both the metallic inclusions and the grain lines can be seen with a standard gemological microscope.

Another distinctive feature of synthetic diamonds is a characteristic fluorescence when exposed to radiation from a standard ultraviolet lamp. Many natural diamonds exhibit ultraviolet fluorescence, usually in colors such as blue or yellow, and less commonly as orange or green, with more intense fluorescence to a long-wave than to a short-wave ultraviolet lamp. Synthetic diamonds behave differently. Their typical fluorescence color is yellow or yellow-green, and often it is more intense to a short-wave ultraviolet lamp. In addition, the fluorescence frequently can be seen to be unevenly distributed and is emitted from only certain growth sectors (Figure 5). That ultraviolet fluorescence pattern is one of the more distinctive features of synthetic diamonds, and it can be checked for in a number of diamonds at the same time.

Synthetic diamonds that are colorless lack such color zoning and grain lines. They frequently contain metallic inclusions, but their most distinctive characteristic is their ultraviolet fluorescence. Colorless synthetic diamonds fluoresce yellow, with an intensity that varies from moderate to weak in strength. When viewed in a darkened room as the ultraviolet lamp is turned off, synthetic diamonds frequently will continue to glow (phosphoresce) a yellow color that can persist for as much as 60 seconds or more, a characteristic feature that distinguishes them from most colorless natural diamonds.

TREATED NATURAL DIAMONDS

Some lower-quality natural diamonds are treated by various laboratory processes to alter their color or appearance, so as a result they can potentially

be more salable. Treated diamonds can have a more attractive color, because the color has been changed, or they can have better apparent quality (or clarity or appearance), because they seem to have fewer internal flaws. Laboratory treatments for diamonds can be divided into processes that change either color or clarity. In both cases, their identification can present much more of a challenge to a jeweler than does the recognition of simulant materials such as CZ.

Some treatments are similar to the geologic processes that affect diamonds in the Earth, such as exposure to a source of natural radiation (uranium- or thorium-bearing minerals), which can yield a similar color. This fact greatly complicates the identification procedure. Whereas the gemologist can tell that the diamond has been exposed to radiation, it is not always possible, without elaborate testing, to determine whether that exposure took place in nature or in the laboratory. Nonetheless, whether the color is due to a natural or laboratory process, the result can be a very great difference in the commercial value of the stone. Treatments with no counterpart in nature are more easily recognized.

Color Treatments

Color-changing processes can be divided into those involving *surface coatings* and those involving *radiation exposure*, often followed by *heating*. Coated diamonds are rarely seen; irradiated colored diamonds are more common.

Surface Coatings

A thin coating of a foreign material can be placed on the polished surfaces of a faceted diamond either to produce a different color or to hide an undesirable inherent color. Several coating materials have been used for this purpose, but none is as resistant to abrasion as the diamond itself. A gemologist can check for the presence of a surface coating by carefully examining the individual polished facets of the diamond using a binocular microscope and reflected lighting, looking for features such as an uneven surface covering, the presence of scratches or other evidence of surface damage to the coating, and an uneven or unnatural-appearing coloration (Figure 6). Diamonds treated with a surface coating are rarely encountered in the jewelry trade.

Irradiation and Heat Treatment

Untreated colored diamonds can owe their coloration to various causes (see Chapter 2 for a complete discussion). Color can result from trace impurities in the diamond (such as nitrogen, which gives rise to a yellow color, or boron for a blue collar, and possibly hydrogen for some yellow, violet, and gray colors). Color in diamond can also be due to structural defects at the atomic level (e.g., a missing atom), called "color centers." Color centers can also be formed by slight deformation of the diamond crystal by geologic forces within the Earth, or they can originate from natural radiation exposure and damage, as men-

Figure 6. This faceted yellow diamond has had a surface coating of an unknown pink-colored material applied to some of the facets to give the diamond a more orange-pink coloration. As can be seen, the surface coating is unevenly distributed on the facet surfaces. This feature identifies this diamond as having been treated to change its appearance. The image is 0.56 mm across. (Courtesy of Gemological Institute of America.)
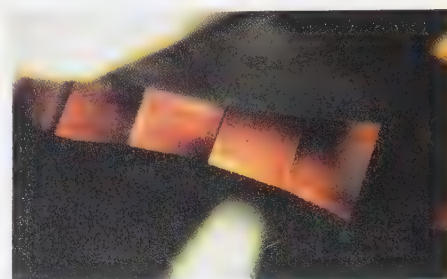
tioned earlier. Radiation exposure gives rise to a green or blue color in an oth-
erwise near-colorless (i.e., very light yellow or brown) or colorless diamond. If
laboratory irradiation is followed by heating in nonoxidizing conditions (to
prevent the diamond from burning), yellow, orange, purple, or pink colors can
be produced (Figure 7). As noted earlier, the treatments mimic nature; both
irradiation and subsequent heating can take place in nature as well. Thus it is
the task of the jeweler or gemologist to determine the origin of the color in a
colored diamond. Natural colored diamonds can be worth many times, per-
haps orders of magnitude, more than laboratory-enhanced colored diamonds.

There are several techniques for irradiating diamonds. They can be placed
in a nuclear reactor, in a charged-particle accelerator (such as a cyclotron or a
linear accelerator or linac), or in close proximity to a radioactive isotope such
as cobalt 60 (used commercially to sterilize medical instruments). A treatment
method rarely used today is to embed a diamond in a radioactive substance
such as radium bromide or americium oxide. The first two groups of treatment
processes (nuclear reactor and linac) are most commonly used for gem treat-
ment. In the Earth, diamonds can be exposed over long periods of geologic
time to radiation given off by naturally radioactive isotopes of elements such as
uranium, thorium, and potassium. Distinguishing a radiation-treated and pos-
sibly heat-treated colored diamond from an untreated colored diamond
requires testing with basic gemological equipment and often with more sophis-
ticated scientific instrumentation as well. In rare instances a conclusive origin-
of-color determination for a diamond cannot be made.

The determination whether or not a diamond color has been produced by
laboratory treatment requires the gemologist to consider the variety of data
mentioned earlier: the color, the distribution of color within the diamond

observed with magnification, fluorescence to ultraviolet light, and the visible and infrared absorption spectra.

Although the color is normally distributed evenly within a laboratory-irradiated diamond, in some instances there is an uneven coloration that can be seen (using a hand-held magnifying lens or a binocular microscope) to be directly related to the faceted shape of the diamond (Figure 8). Such uneven or zoned coloration, which results from the radiation exposure, is most often seen as a band of darker blue, green, or yellow color that parallels the outer faceted shape of the diamond, or a band of color that forms a star-shaped pattern around the pointed culet of the diamond. By comparison, the zoning in naturally irradiated diamond crystals usually is limited to spotty green coloration (referred to as radiation stains) near the crystal surfaces; these stains can easily be seen with a low-power (×10) binocular microscope or magnifier. These green radiation stains are normally removed during the polishing process and thus are rarely seen in cut stones. Only very rarely does exposure to natural radiation produce a green or blue color, usually as cloud-like regions of color visible within the diamond (Figure 9).

There can also be features in the diamond's absorption spectrum, as seen with a hand-held spectroscope, that will provide evidence of laboratory treatment or natural coloration. Confirmation of laboratory irradiation can come from the visible and infrared absorption spectra recorded with a spectrophotometer. On rare occasions, a diamond irradiated in a nuclear reactor may be very slightly radioactive, which again is proof of laboratory treatment, as measured by γ-ray spectroscopy.

In general, the determination of color treatment is based on the complete data for the diamond being tested in comparison with the data base previously obtained for natural colors and treated colors. Thus, the profile provides the determination, rather than a single piece of evidence.

Treatment to Change Appearance

One treatment process to improve the clarity appearance of a fashioned diamond has become quite widespread in recent years: *fracture filling*.

Many natural diamond crystals have small fractures, or narrow open breaks, that usually extend inward from the outer surface, even after they are polished as gemstones. Such fractures can form during the diamond's crystallization or can result from mechanical damage to the crystal during transport in a river or stream. Fractures vary in size and visibility and can be located anywhere within the faceted diamond. When present, they tend to reflect light and hence often are visible in the gemstone with magnification, and possibly even to the unaided eye. Because they are easily seen and detract from the appearance of the faceted stone, open fractures will lower the clarity grade of a diamond. Since the 1980s, a process has been developed to improve the
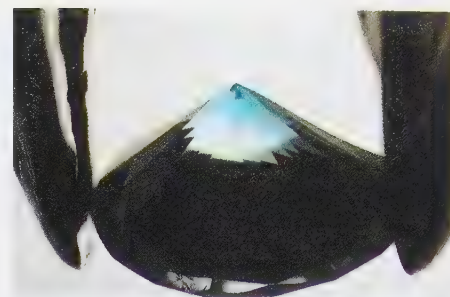
Figure 8. Treated diamonds that have been irradiated to change their color sometimes show uneven color zoning. This treated diamond exhibits a blue color when viewed face-up. When examined with a microscope, the blue color is actually seen to appear only at the culet of the diamond. This type of color zonation is a good indication of laboratory treatment, for it has not been observed in untreated, naturally colored diamonds. The stone's girdle is 3 mm in diameter. (Shane Elen/courtesy of Gemological Institute of America.)

Figure 9. In rare cases diamonds can be exposed to radiation in the Earth, and as a result they can take on a light green or light blue-green color. (Maha DeMaggio/courtesy of Gemological Institute of America.)
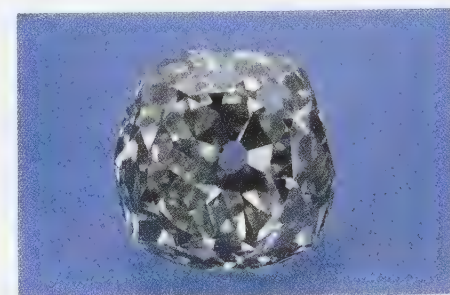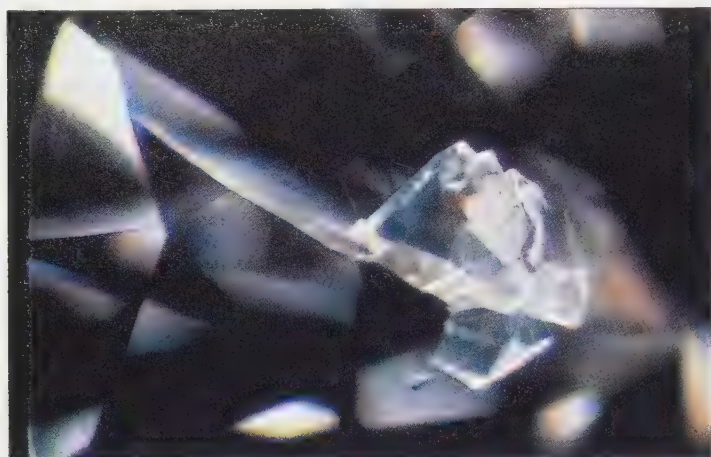
Figure 10 (above left). This untreated diamond has a large open fracture located beneath the table facet. The image is 1.75 mm across. (John I. Koivula/courtesy of Gemological Institute of America.)
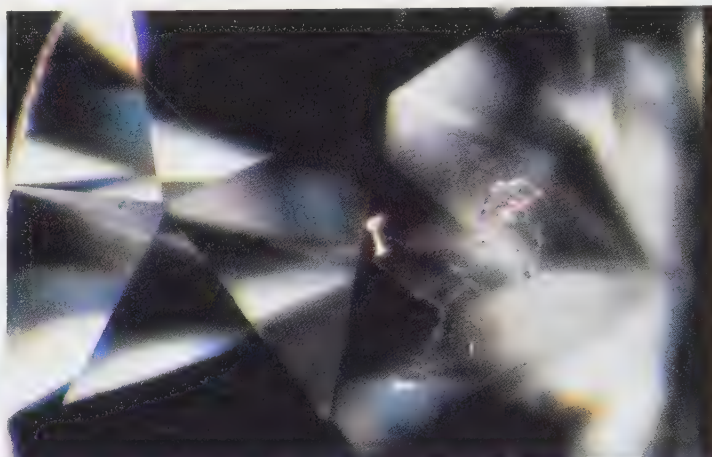
Figure 11 (above right). This is the same diamond as in Figure 10. However, it has now been treated by fracture filling to change its clarity and appearance. (John I. Koivula/courtesy of Gemological Institute of America.)

appearance of a polished diamond containing fractures. The process involves injecting a glass-like material into the open fractures so that the air in the fractures is replaced by the material. The filled fractures are then much less visible. The fractures are still present in the diamond, but they are much less apparent (Figures 10 and 11).

That treatment reportedly is used to treat many thousands of diamonds each year. We have encountered fracture-filled polished diamonds larger than 10 carats and as small as 0.03 carat. The process is most often used for near-colorless diamonds that previously would not have been deemed gems by jewelers because they had been laboratory-treated. Their increasing availability in the market means that jewelers and gemologists must be aware of the practical ways they can be recognized.

Another treatment to change appearance is the removal of inclusions by laser evaporation. A carbon dioxide laser will effectively heat a diamond to a temperature where it will react with oxygen in the air and form carbon dioxide. A small-aperture laser can thus be used to drill or cut diamonds, a technique that has only recently been used in the manufacturing process. Likewise, the laser can be used to bore a tiny hole in a diamond with an unsightly inclusion; when the laser reaches the inclusion, it will literally evaporate, leaving a hole behind. The fracture-filling process is sometimes used to fill the void and hole. As the technique requires time and expertise, it is limited to larger stones of otherwise high quality and is not as commonly encountered as fracture filling.

There are two important reasons for identifying diamonds treated by fracture filling. First, disclosure to a customer that a diamond has been fracture-filled is required by both the law and jewelry-industry standards. Second, the treatment modifies the properties of the gem and its long-term durability. The glass-like filling material has physical properties different from those of diamond, which means the material will not behave as diamond does to changes in conditions, such as temperature. When polished diamonds are set in jewelry, or later when a jewelry piece requires some repair service, the diamonds may be

subjected to very high temperatures from a jeweler's torch, to attack by various chemicals, or to cleaning by chemical solutions or high-pressure steam. In testing fracture-filled diamonds supplied by several vendors by exposing them to the conditions likely to be encountered in jewelry-repair situations, we have found that the fracture-filling material can be damaged to such an extent that the damage is visible to the eye. An apparently high-clarity, treated diamond that once looked fracture-free is then seen in its true condition as a poorer-quality, lower-clarity stone with very visible fractures. If a piece of jewelry with a fracture-filled diamond is given to a jeweler for repair, but is not recognized as such, the diamond could be damaged during repair. That could pose a public-relations problem that could undermine the credibility on which the jewelry business depends.

Fracture-filled diamonds have several features that allow them to be identified by a jeweler or gemologist, the most obvious being "flash-effect" colors: bright color flashes, usually blue or yellow, resulting from an optical effect produced as light passes from the diamond through the filled fracture.[1] They are best seen when viewing the diamond with magnification using an intense, narrow beam of light and looking in a direction nearly parallel to the plane of the filled fracture (Figures 12 and 13). It has been our experience that even if the polished diamond is small in size (<0.1 carat), and even if the filled fracture is not extensive, these flash-effect colors can be seen with magnification.

GRADING GEM-QUALITY DIAMONDS

Grading the quality of a polished diamond requires a trained jeweler or gemologist to evaluate it in terms of the four Cs: carat weight, color, clarity, and cut.

Carat Weight

The carat weight of a diamond (1 carat = 0.2 gram) is easily measured with an electronic balance. If the diamond is polished in the shape of a round brilliant, its weight can be estimated quite accurately merely by measuring, or judging by eye, the diameter of the stone.

Color

The color of a diamond is assessed in terms of a color grade. As mentioned earlier, a few diamonds are colored (yellow, green, pink, blue, etc.), and a very few are completely colorless. However, most diamonds are slightly colored, mostly light yellow, and some pale brown or gray, so in the 1950s, the Gemological Institute of America (GIA) introduced to its gemology students and the gem trade a simple grading system for colorless-to-light-yellow diamonds – D
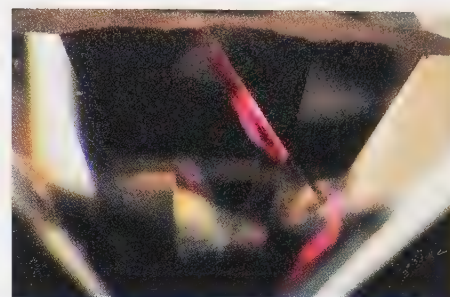
Figure 12. The large fracture in this diamond extends into the stone from the girdle. The filled fracture exhibits a purplish pink flash effect when viewed in dark-field illumination. (Courtesy of Gemological Institute of America.)
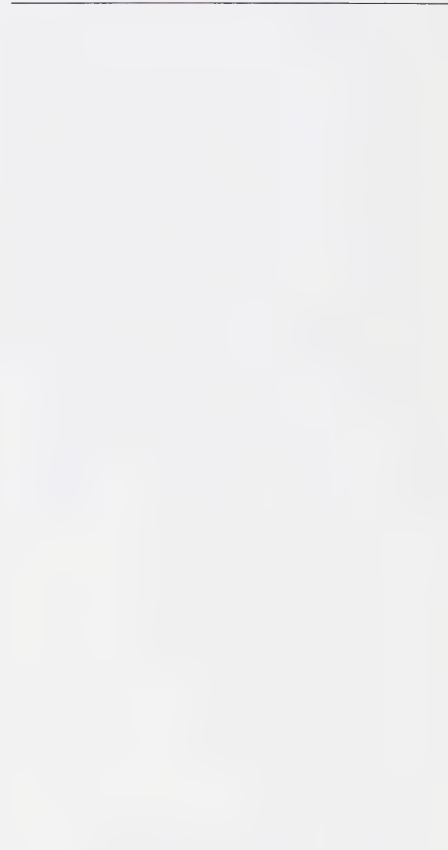
Figure 13. The same diamond as in Figure 12 shows a yellowish green flash effect when viewed in transmitted light. (Courtesy of Gemological Institute of America.)
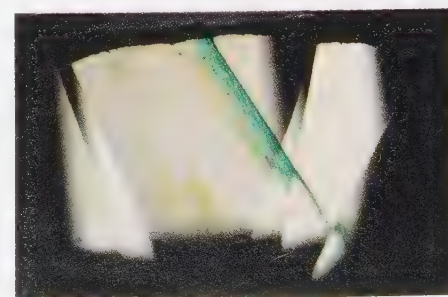
TABLE 1

Color grades for colorless to light-yellow faceted diamonds

D E F	Colorless
G H I J	Near colorless
K L M	Faint yellow
N O P Q R	Very light yellow
S T U V W X Y Z	Light yellow

to Z color grading (Table 1). A series of polished diamonds in the colorless-to-light-yellow range were selected to be representative masterstones used to grade other diamonds by visual comparison of their colors under controlled lighting and viewing conditions. The system was intended to replace the use of other color terms in the jewelry trade that either were not appropriately descriptive of the color appearance or were simply misleading and thus were prohibited by the U.S. Federal Trade Commission (e.g., the term "blue-white"). The grading system in Table 1 has now been adopted internationally. Following its introduction, other jewelry-trade organizations have adopted the GIA grading systems for other features, such as clarity, or have developed similar systems based on the same ideas.

A jeweler or gemologist grades the color of a diamond by examining it in a specially designed viewing box illuminated with a standard fluorescent lamp. The diamond is placed in a white plastic tray and is viewed, with the table facet down, through the pavilion facets, where distracting light reflections are minimized (Figure 14). The goal is to judge the "colorlessness" of (or the absence of yellow color in) a polished diamond by comparing it with a series of diamond masterstones positioned in sequence by color grade. The diamond being graded is placed first on one side and then on the other of a masterstone, and a visual judgment is made as to whether the diamond being graded is more or less colored than the masterstone. Then it is compared to the next masterstone in the sequence, and that continues until the color is bracketed by the colors of two adjacent masterstones. Using this process, the color grade can be quite accurately determined by visual means (with experience, within one color grade). At a gemological laboratory, such color grading involves the expert opinions of several experienced gemologists. Efforts have been made to develop instruments to measure diamond color and then relate the resulting numerical value to the visually established color (i.e., letter) grade, but such methods have not been widely accepted in the jewelry trade. Most gem diamonds available commercially fall into the near-colorless to faint-yellow grades.

The color grading of colored diamonds (darker yellow, and also green, blue, pink, etc.) is based on a slightly different procedure. The color is determined visually by examining the diamond (again under controlled lighting and viewing conditions) face-up through the table and crown facets. That step is performed because what is being judged is the relative presence of color (rather than the absence of yellow color, as in the D–Z grading). In addition, the whole spectrum of colors must be considered, so along with diamond masterstones there is more use of other color references for comparison purposes. However, an attempt is again made to bracket the color of the diamond being examined (by comparison with other colored objects), to locate that color in the color spectrum, and then to assign one or more word terms to describe the color. In the jewelry trade, these more strongly colored diamonds are described with the term "fancy" – such as a fancy blue, or fancy intense yellow diamond (Figure 15).

Figure 14. Four diamonds with different color grades, ranging from grade E on the left to Z on the right, illustrate the range of color appearance. During grading, the diamonds would be examined face-down, as shown here. (Tino Hammid/courtesy of Gemological Institute of America.)

Clarity

Clarity grades were introduced by the GIA at the same time as the D–Z color grades. They are used for polished diamonds as a simple means of describing how free the diamond is of flaws and imperfections that would affect its faceted appearance.

Almost all natural diamond crystals contain characteristics that can affect their appearance when polished. Such characteristics typically consist of fractures or inclusions of foreign material that vary in terms of size, visibility, loca-
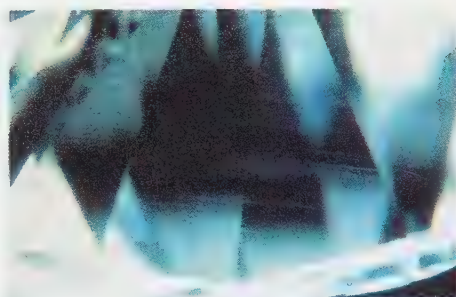
Figure 16. Faceted natural diamonds can exhibit a variety of inclusions and other internal features created during their crystallization. This diamond has a series of faint linear bands running across the stone. (Courtesy of Gemological Institute of America.)

tion, and number (Figure 16). During manufacturing, the diamond cutter attempts either to remove those features or to minimize their visibility by the cutting style chosen and the placement of the polished facets on the finished gemstone. The effort to achieve a diamond free of inclusions, or containing as few inclusions as possible, requires considerable skill.

During grading, a diamond is examined by a gemologist or jeweler at ×10 magnification using a gemological microscope or hand-held magnifier (loupe), looking in all directions to determine the types of inclusions and fractures present. In many cases, a diagram or sketch will be made, showing the locations and extents of the characteristics by means of colored symbols. Such a diagram is a permanent record of the diamond's "fingerprint." The gemologist determines the diamond's clarity grade by assessing the nature, number, size, and visibility of the features observed in the gemstone. The clarity grade is expressed in terms of the deviation from flawless, coded or abbreviated with letters and numbers (Table 2). Typically, comparison masterstones are not used to establish the clarity grade. Rather, accepted rules on the visibility of features govern the clarity grade assigned. Beyond the use of the microscope, there are no instrumental means of determining the clarity grade.

Cut

The shape description for a polished diamond typically is that of its outline as viewed from the top. To bring out the most return of light (its "brilliancy") and reflected color flashes (its "dispersion" or "fire"), flat polished surfaces (facets) are created on the diamond crystal during the manufacturing process. The arrangement of polished facets is referred to as the cutting style or "cut." There are several standard cutting styles for diamonds, but the most common and best-known style is the "round brilliant" (Figures 17 and 18).

Although there are some well-accepted arrangements of facets, there is no standard grading system for cutting styles. Preferences for various proportional relationships of facet size and angle vary from one individual to another and from one diamond market to the next, precluding international agreement on a grading system for cuts. However, deviations from symmetrical placement of facets (such as a round brilliant diamond that is not entirely round in shape) and poor quality in the polishing are noted during the evaluation process.

Gemologists have taken the lead in developing practical systems for identifying diamonds and grading their quality that have been crucial to the expansion of the jewelry industry and to continued consumer confidence in the value of diamonds. Gemological laboratories worldwide provide such systems as services to the diamond industry. There are ongoing efforts to improve the identification and grading procedures for diamonds: Natural diamonds must be quickly and accurately differentiated from simulants, synthetics, and laboratory-treated stones, and the grading procedures must provide clear measures of gem quality for natural diamonds.

TABLE 2

Clarity grades used for faceted diamonds (based on ×10 magnification)

FL	Flawless: no exterior blemishes or internal inclusions
IF	Internally flawless: no inclusions, and only insignificant blemishes
VVS_1	Very very slightly included (1): minute inclusions are very difficult to see
VVS_2	Very very slightly included (2): minute inclusions are difficult to see
VS_1	Very slightly included (1): minor inclusions are difficult to see
VS_2	Very slightly included (2): minor inclusions somewhat easy to see
SI_1	Slightly included (1): noticeable inclusions easy to see
SI_2	Slightly included (2): noticeable inclusions very easy to see
I_1	Included (1): obvious inclusions easy to see
I_2	Included (2): obvious inclusions very easy to see
I_3	Included (3): obvious inclusions can be seen by eye

PEAR-SHAPED BRILLIANT CUT

OVAL BRILLIANT CUT

MARQUISE OR
NAVETTE BRILLIANT CUT

HEART-SHAPED BRILLIANT CUT

EMERALD CUT

BAGUETTE CUT

FACET ARRANGEMENT OF STANDARD ROUND BRILLIANT

Crown (or Bezel)

Girdle

Pavilion

Table	1
Bezel	8
Star	8
Upper Girdle	16
Crown total	33

Lower Girdle	16
Pavilion Main	8
Culet	1
Pavilion total	25
total	58

(culet enlarged)
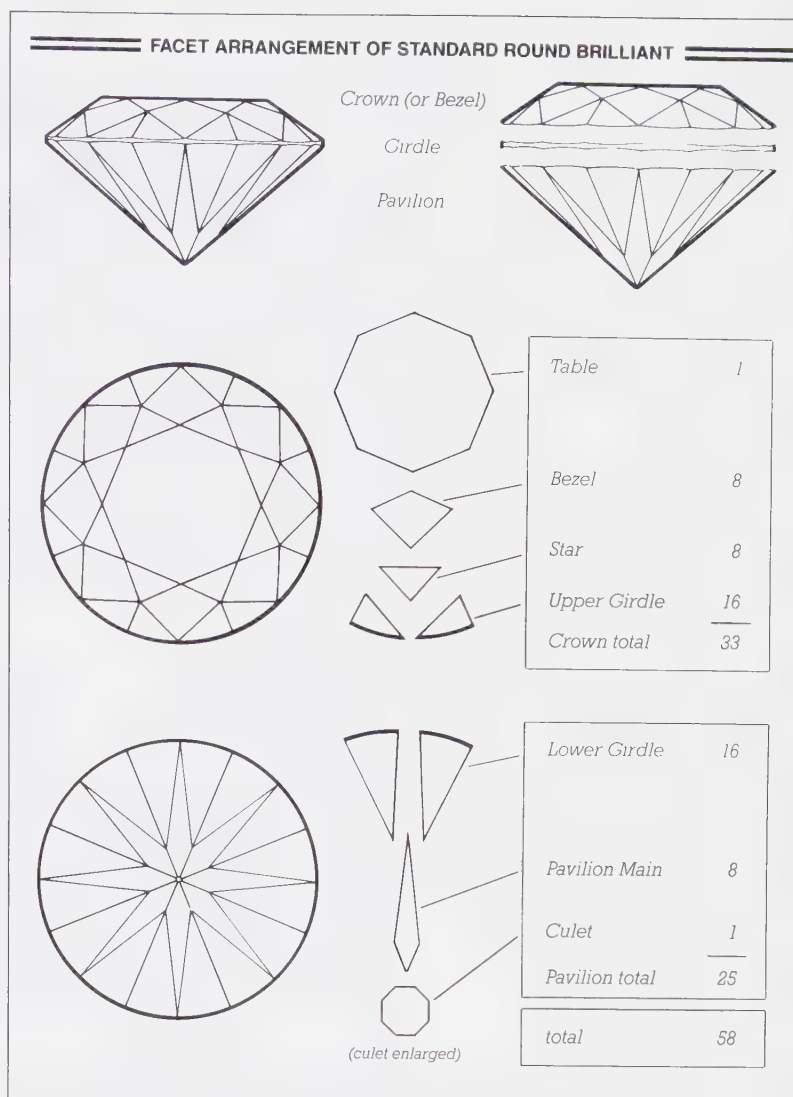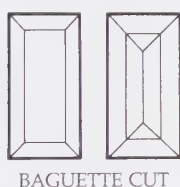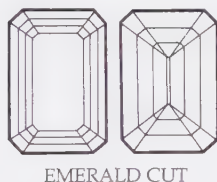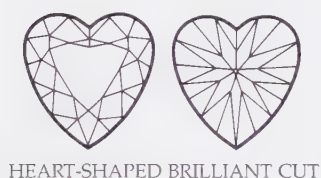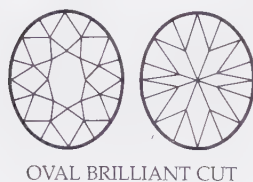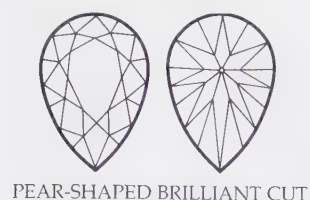
Figures 17 and 18. Popular gem cuts showing the crown (top of the stone) at left and pavilion (bottom) at right. (Courtesy of Gemological Institute of America.)

GEMOLOGICAL EQUIPMENT USED TO STUDY DIAMONDS

Binocular microscope: The most frequently used tool for a gemologist, providing magnified views of inclusions and other internal features in a gemstone that are important for identification and quality grading.

Spectroscope: An instrument for viewing a gem's absorption spectrum in visible light.

Spectrophotometer: A device like a spectroscope, but more sophisticated, in that it records the spectrum and quantifies both the absorption and wavelength of light; spectrophotometers also can operate at infrared wavelengths.

Polariscope: A simple device for viewing a gem between two crossed polarizing filters. It is useful for identification and provides a visual indication of strain within a diamond.

Thermal-conductivity meter: An instrument for measuring thermal conductivity at the surface of a gem. Because of the superb thermal conductivity of diamond, this device allows easy detection of imitation materials.

Ultraviolet (UV) lamp: A lamp that emits invisible UV radiation at two fundamental wavelengths (253.7 nanometers, referred to as short-wave UV, and 366 nanometers, long-wave UV). It is used to examine the fluorescence of a gemstone as an aid to identification.

NOTES

[1] The flash is considered an internal reflection affected by the dispersion of the filler. As the critical angle for internal reflection varies with the difference in refractive index between the diamond and filler, a specific colored flash is observed.

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13

Diamonds in Modern Technology: Synthesis and Applications

ALAN T. COLLINS

THE superlative physical properties of diamond make it not only the king of gems but also an important strategic material in a wide range of industries where its extreme hardness and toughness are exploited. More than 100 tons (500 million carats) of diamonds are produced each year. Around 80 percent of that total production is not mined but is manufactured in the form of grit products by high-pressure, high-temperature synthesis. Of the mined production of 100 million carats per annum, approximately 25 million carats are used in the gem trade. In addition, research on the production of diamonds by chemical-vapor deposition has now reached the stage where wafers of polycrystalline diamond more than 150 millimeters (mm) in diameter and up to 1 mm or more in thickness can be produced on a routine basis, and exciting new applications for such material should open up in the near future. This chapter will briefly review the development of the method for manufacturing diamonds and some of the ways in which the synthetic material complements and extends the industrial applications of natural diamonds.[1] It will also describe the use of diamond to achieve pressures comparable to those at the center of the Earth.

EARLY ATTEMPTS AT
DIAMOND SYNTHESIS

In 1772 the eminent French scientist Antoine Lavoisier, who laid the foundation for modern chemistry, showed that the gas produced when diamond was burned was similar to that produced when charcoal was burned. He did that by sealing a diamond in a glass jar filled with oxygen and focusing the sun

on it with a powerful lens. The diamond burned totally to produce carbon dioxide. In 1797, Smithson Tennant carried out further combustion experiments. He showed that when *identical weights* of diamond and charcoal were burned, they produced the *same volumes* of carbon dioxide. From those observations he concluded that diamond "consists entirely of charcoal, differing from the usual state of that substance only by its crystallized form." Almost a century earlier, two Italian scientists, G. Alverani and C. A. Targioni, had shown that diamond could be burned completely without leaving an ash, but they did not trap or identify the gases produced. Following Tennant's work, a number of chemists, including Humphry Davy (perhaps best known for his invention of the miners' safety lamp) recognized that diamond was simply one of the possible forms of carbon, two other common varieties being graphite and amorphous carbon (not a mineral, by the way).

Those discoveries fueled the quest to manufacture diamonds in the laboratory from one of the other, less valuable forms of carbon, and over the following 150 years at least 30 claims were advanced by scientists who believed that they had been successful.[2] Of those, the attempts by the Scottish chemist James Ballantyne Hannay and the French chemist Frédéric-Henri Moissan probably are the best known. In 1866 or 1867, natural diamonds were discovered in South Africa. The South African diamonds were traced to a primary source in what we now call kimberlite, which was determined to be of volcanic origin. That suggested that diamonds were formed deep in the Earth at high temperatures and high pressures. When Hannay and Moissan began their attempts to produce diamonds in the laboratory, they concluded that because natural diamonds probably were produced under geologic conditions of high temperature and high pressure, such conditions would be necessary to manufacture diamonds in the laboratory, but the two researchers adopted very different techniques.

Moissan dissolved carbon in molten iron, using an electric-arc furnace capable of reaching temperatures around 3,000°C (almost 5,500°F), and then rapidly quenched the iron in water. He believed that the solidification of the iron from the outside would exert enormous pressure on the solution of carbon in the still-liquid core and cause the carbon to crystallize as diamond. Although Moissan recovered a number of small, hard crystals from his apparatus and believed that they were diamonds, later attempts to reproduce his experiments suggested that the crystals were in fact silicon carbide. The silicon may have been present as an impurity or may have dissolved into the iron from the refractory walls of the furnace, and then combined with the added carbon. Moissan's experiments may not have succeeded in growing diamond, but they provided a source of inspiration for the scientists who made the final breakthrough in the 1950s.

Hannay's method was to heat a mixture of bone oil, paraffin, and lithium in sealed iron tubes 4 inches (10 cm) in diameter, with a 0.5-inch (12.5-mm)

bore. At red heat the paraffin "cracked," producing carbon and hydrogen, the latter causing enormous pressure to build up. Hannay hoped that the carbon would be deposited as diamond under those conditions. His experiments were particularly hazardous: On many occasions the iron tubes exploded, and at least twice the furnace was completely demolished and had to be rebuilt. Nevertheless, Hannay persevered with his experiments and eventually claimed success in 3 of more than 80 attempts. The diamonds were recovered from the residue inside the tubes by dissolving them out with acid.

Hannay sent some of the tiny crystals to Professor Nevil Story-Maskelyne of the British Museum mineralogical department for identification. There were three criteria that Story-Maskelyne could apply to identify Hannay's samples: Diamond, being the hardest known mineral, would scratch sapphire. Being carbon, as the early investigators had noted, diamonds would burn if heated to about 1,000°C in oxygen, leaving no residue. Finally, the angle between the cleavage faces for a diamond was known to be close to 70.5°. Using those criteria, Story-Maskelyne positively identified Hannay's samples as diamond and announced that fact in a letter to *The Times* (London) on February 20, 1880.

The Hannay diamonds shown in Figure 1 are unique in that they are the only known surviving examples from any of the early experiments to synthesize diamonds. The nine remaining specimens, each only a few tenths of a millimeter across, are still held by the Natural History section of the British Museum. Many investigators have examined those crystals, and though there is no doubt that they are indeed diamond, all the tests indicate that they are fragments of natural diamond. It is a matter of conjecture whether Hannay's equipment became accidentally contaminated with diamond (Hannay almost certainly would have had specimens of natural diamond in his laboratory) or whether his claim was fraudulent. One plausible suggestion is that one of Hannay's workmen, tired of the continual explosions, planted the diamonds, hoping that apparent success would bring an end to the hazardous series of experiments.

It is generally accepted that none of the early attempts to produce diamond was successful, but the two methods briefly described provide some interesting insights.

FIRST SYNTHESIS

By the 1940s the conditions of temperature and pressure under which diamond is the stable phase of carbon were being established experimentally, and in 1938 Frederick Rossini and Ralph Jessup produced the first "phase diagram" for carbon,

Figure 1. The nine remaining Hannay diamonds. Not all of the specimens are clearly in focus, and some have foreign material clinging to them. The surface markings to which Story-Maskelyne drew attention are clearly visible on some crystals. (From Collins, 1975.)

1·0 mm
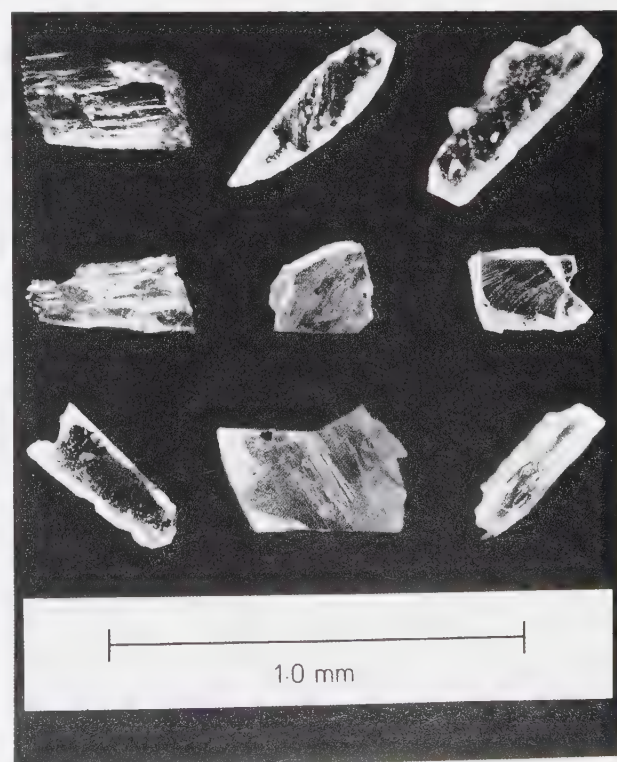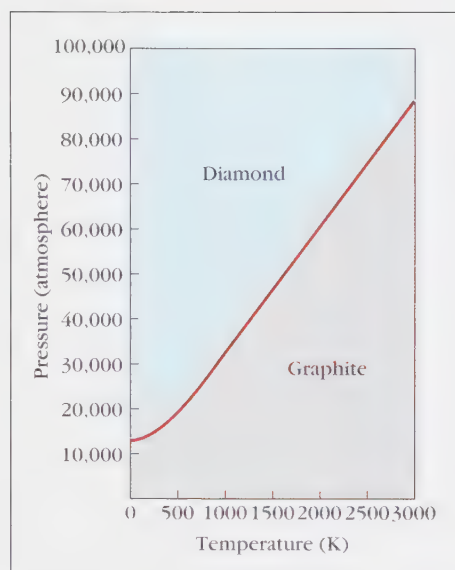
Figure 2. Simplified diagram showing the Berman-Simon line, which indicates the regions of pressure and temperature where diamond is the stable phase. Temperatures are in Kelvin; subtract 273 to convert to degrees Celsius. (Adapted from Wilks and Wilks, 1995.)

showing the regions of temperature and pressure in which either diamond or graphite was the stable phase. Those calculations were extended by Robbie Berman and Sir Francis Simon in 1955, and the Berman-Simon curve is the one generally referred to today. The curve illustrated in Figure 2 shows that diamond is not, in fact, stable at normal temperatures and pressures. Fortunately, the rate of transformation of diamond to graphite is negligible at room temperature, but if a diamond is heated to about 1,800°C it will rapidly convert to graphite, swelling up in the process, because graphite is less dense than diamond.

Percy Bridgman, the father of high-pressure technology, carried out a number of experiments in which graphite was taken to pressures and temperatures where diamond is the stable phase, but the graphite stubbornly refused to convert to diamond. Bridgman carried out most of his research in an extraordinary laboratory at Harvard University. In the early experiments, pressures were limited to about 20,000 atmospheres (atm), but in the 1930s an extremely tough material became available: tungsten carbide. Bridgman constructed a pressure cell using tapered tungsten carbide anvils that had shrink-fit rings of steel surrounding them for added strength. In one of the early cells, Bridgman was able to achieve pressures of 70,000 atm. Later he was able to achieve pressures above 400,000 atm at room temperature. No diamond was formed in any of the room-temperature experiments on graphite. The strength of tungsten carbide decreases rapidly with increasing temperature, and for work at high temperatures a careful design of the capsule containing the graphite is necessary to minimize the heat transferred to the anvils. In some of his experiments Bridgman was able to subject graphite to pressures of 30,000 atm at 3,000°C. Although those were extreme conditions, diamonds refused to form; Bridgman could not sustain sufficiently high pressure and high temperature simultaneously. Following those failures, Bridgman commented that "graphite is Nature's best spring." The problem was kinetic: A large amount of energy has to be supplied in order to convert the graphite structure to diamond.

That problem was first solved by a team of scientists working at the Allmänna Svenska Elektriska Aktiebolaget (ASEA) laboratory in Stockholm in 1953, but that early success was not publicized until after the announcement, on February 15, 1955, by the General Electric team of Francis Bundy, Tracy Hall, Herbert Strong, and Robert Wentorf, that they had transformed graphite to diamond (Figure 3). It is interesting that both teams used a molten metal to dissolve the graphite. As more and more graphite is dissolved, the metal becomes saturated, and soon small crystals nucleate and begin to grow; because the temperature and pressure are maintained in the region where diamond is the stable phase, the growing crystals are diamond. (That was the approach Moissan had tried 60 years earlier, but he had been unable to reach the conditions where diamond is stable. However, it is almost certain that the General Electric scientists had Moissan's ideas in mind when they tried, after many pre-

vious failures, the technique of dissolving the graphite in the molten metal.) It is still a matter of debate whether the metal acts solely as a solvent or whether there is also some catalytic action, and the description "solvent-catalyst" is generally used. The transition metals cobalt, nickel, and iron work well as solvent-catalysts, and these metals or their alloys are used in most commercial systems. Typical values of temperature and pressure used in commercial synthesis are 1,400°C and 55,000 atm. It is difficult to envisage the enormous pressures being used; 55,000 atm is equal to 800,000 pounds per square inch, or 2.3 million kilograms per square centimeter. The weight of the Eiffel Tower standing on a one-cent piece is an analogy sometimes cited.

There are two approaches to growing synthetic diamonds, depending on the final size required. To produce diamond grit, with grain sizes up to about 1 mm, graphite and the solvent (for simplicity, I will refer to the metal as the "solvent" from here on) are mixed together and placed in the growth capsule, which has electrically insulating walls. When the pressure has been applied, an electric current is passed through the mixture to raise the temperature above the melting point of the metal (this is referred to as "direct heating"). Once nucleation occurs, carbon flux is transported across a thin film of molten solvent between the graphite and the growing diamond. After a few tens of minutes, a substantial fraction of the graphite is converted to diamond.
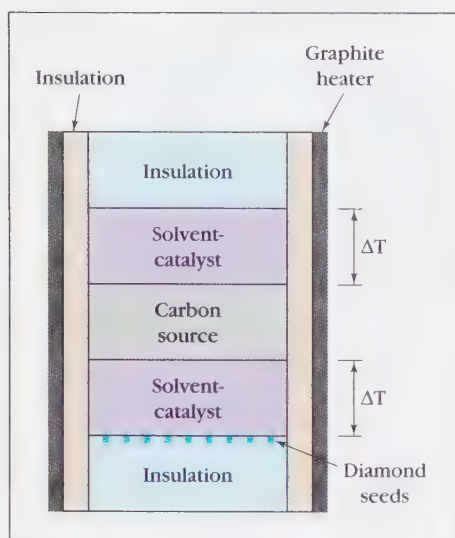
Figure 4. Schematic diagram showing the geometry of the growth capsule for growing large diamonds by the temperature gradient method. There is a temperature difference ΔT of about 30°C between the center of the capsule and the seed pad.

A different technique is used to grow larger specimens: the temperature-gradient method, illustrated in Figure 4. Here the carbon source is at the center of the growth capsule, and a substantial layer of the solvent metal separates the carbon source and the small diamond seeds at the bottom of the cell. The temperature of the reaction volume is raised by a graphite heater sleeve surrounding the growth capsule (this is referred to as "indirect heating"). A small temperature gradient exists between the center of the cell and the seed pad, and that is the driving force for the process in which carbon is dissolved in the solvent at the center of the cell and precipitated on the seeds at the bottom. The process is sometimes described as the "reconstitution method," because often the carbon source is synthetic diamond grit. If graphite is used, there is a substantial reduction in volume as the graphite is converted to diamond; however, if diamond grit is converted to large diamond crystals, there is no change in the volume of the growth capsule, and the conditions necessary for high-quality growth are much easier to control and maintain. Crystals several millimeters across can be grown in a few days with this technique (Figure 5). The reasons for the different colors of diamonds are discussed in Chapter 2.

The two major applications of these relatively large synthetic crystals are as wire-drawing dies and as heat spreaders, often wrongly called "heat sinks." At and slightly above room temperature the thermal conductivity of pure diamond is higher than that of copper by a factor of 3–5. Some electronic devices, particularly laser diodes, function much more efficiently at high power densities; however, that is possible only if some means can be found for removing the heat generated. The active region of a typical device has dimensions around

Figure 5. De Beers diamonds grown by the temperature-gradient method. The yellow diamonds were grown from a cobalt solvent with a small concentration of titanium to act as a nitrogen getter. The residual nitrogen concentration was about 20 ppm. The nearly colorless and blue stones were grown from an iron solvent, with aluminum added as a nitrogen getter; for the blue crystals a small quantity of boron was added to the growth capsule. The weights of the diamonds range from 1 to 3 carats, and they were grown for experimental purposes. (Courtesy of De Beers.)

100 micrometers (μm; 1 μm is one millionth of a meter, or one thousandth of a millimeter). If such a device is bonded to a diamond heat spreader with dimensions around 0.5 mm square and 250 μm thick, and the diamond in turn is bonded to a copper heat sink, the heat can be extracted from the laser diode far more efficiently than if the diode were directly bonded to the copper heat sink. A schematic diagram of such a device is shown in Figure 6. For many years, specially selected natural diamonds (the so-called type IIa diamonds, which are very pure) have been used for this purpose, but it is also possible to use heat spreaders fabricated from synthetic diamond.

The yellow color of the diamonds in Figure 5 is caused by the presence of nitrogen in the diamonds at concentrations of around 20 parts per million (ppm). It is possible to reduce the incorporation of nitrogen into a diamond by adding elements such as titanium, aluminum, or zirconium to the growth capsule; these metals act as "nitrogen-getters." Without any nitrogen-getters added, the typical concentration of nitrogen in a synthetic diamond is 200–300 ppm, and the crystal will have a deep yellow or brown color. Using a small concentration of nitrogen-getters will yield pale-yellow diamonds, and with larger concentrations of nitrogen-getters the resulting diamonds can be almost colorless (Figure 5). To produce nearly colorless diamonds, it may be advantageous to use iron as the solvent metal, because that also favors low nitrogen concentrations. If a large concentration of nitrogen-getters is used to remove virtually all the nitrogen, and a small quantity of boron is added to the growth capsule, the resulting diamonds will have an attractive blue color (Figure 5) and will be electrical semiconductors.
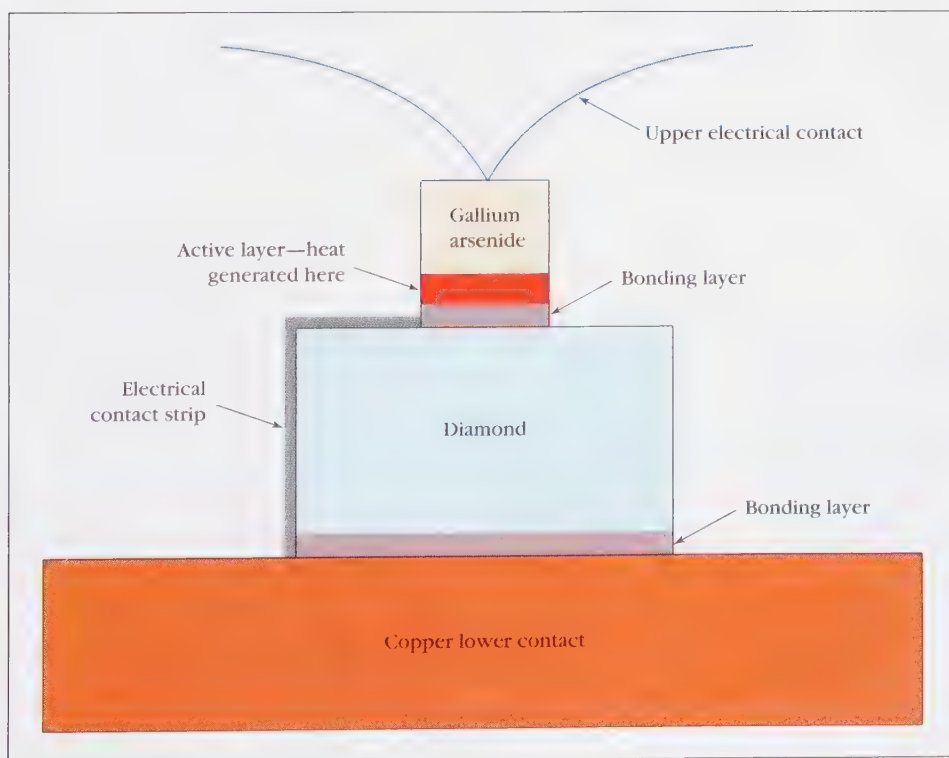
Figure 6. Schematic diagram of a gallium arsenide device mounted on a diamond "heat sink." (Adapted from Caveney, 1979.)

CHEMICAL-VAPOR DEPOSITION

Despite the dramatic developments that have taken place in the production of high-pressure, high-temperature synthetic diamonds, the emphasis in diamond research during the past 15 years has been on diamonds grown by chemical-vapor deposition (CVD). Research into the growth of diamond from the gas phase was in progress in the 1950s, but the growth rates were very slow, and the success of diamond synthesis by the high-pressure route largely eclipsed that pioneering work. John Angus was one of those early pioneers and is now a leading authority on the growth of diamond by CVD techniques.[3] After a period of quiescence, research on the growth of CVD diamond began in 1974 at the National Institute for Research in Inorganic Materials (NIRIM) at Tsukuba, Japan, and an English-language publication from that institute in 1981 was to galvanize activity throughout the world on CVD diamond growth. The technique developed at NIRIM is illustrated in Figure 7.

Methane (CH_4) and hydrogen (H_2) gases are fed into a quartz tube about 50 mm in diameter, and a pump maintains the pressure in the tube to about 5 percent of atmospheric pressure. Microwave power fed to the tube creates a plasma and also heats the substrate to about 800°C. Diamond can be deposited on a wide range of substrate materials, but wafers of silicon are frequently used. Before deposition, the surface of the substrate is mechanically roughened, often by using diamond powder. Initially, small diamond crystals are randomly nucleated on the substrate; then, as growth proceeds, those nuclei become larger and eventually coalesce to form a continuous polycrystalline film. In the pioneering work, the diamond films typically were no more than 25 μm thick and at that thickness generally were brown or completely opaque to visible light.

Figure 7. A view through a window into a working instrument for growing CVD diamond; the blue glow is the microwave plasma region below which a diamond wafer is crystallizing. Schematic diagram of the apparatus used to produce CVD diamond by the microwave technique. (Adapted from Sato and Kamo, 1992/courtesy of Applied Science and Technology, Inc.)
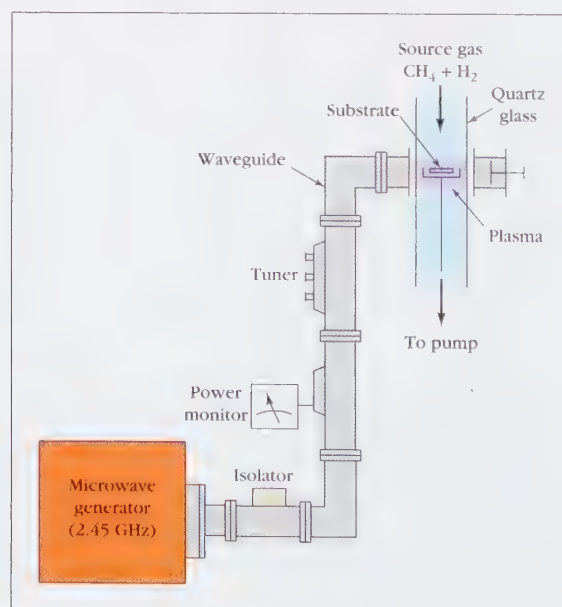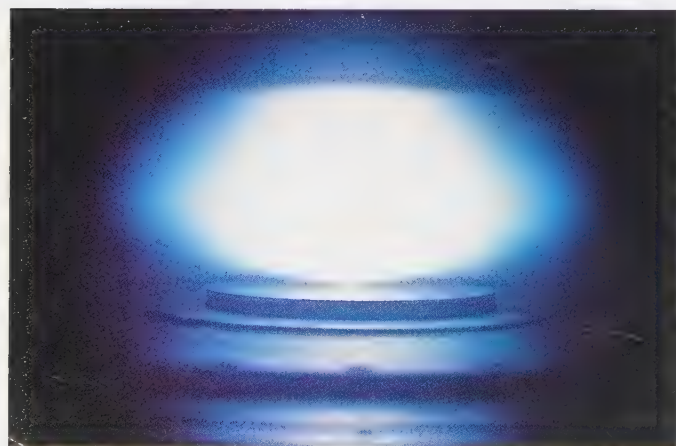
To understand why that work created so much excitement we need to look at some of the physical properties of diamond. Carbon is the first element in group IV of the periodic table of the elements. That group also contains silicon and germanium, the industrially important semiconductors, which have the same crystal structure as diamond. By comparison with silicon and germanium, diamond's carbon atoms are small and very strongly bonded. It is therefore difficult to remove carbon atoms, and consequently diamond is hard and very abrasion-resistant. In the diamond crystal structure, each carbon atom is symmetrically surrounded by four other carbon atoms, and between any two carbon atoms is an electron-pair bond. Those outer (or valence) electrons can be removed if sufficient energy is supplied to the crystal, and those electrons are then available for conducting electricity. It is convenient, when dealing with semiconductors, to represent this process with a diagram (Figure 8) that shows the energy required to transfer an electron from the "valence band" to the "conduction band." For diamond, that energy is 5.5 electron volts (eV), compared with 1.1 eV for silicon and 0.7 eV for germanium. Diamond is therefore referred to as a "wide-band-gap semiconductor."

The light that is detected by the human eye is made up of a stream of photons; it is sometimes convenient to consider the energy that a photon possesses and, for other purposes, to specify its wavelength. The wavelengths in the visible region are several hundred nanometers (1 nm is one millionth of a millimeter). The energies of photons in the visible spectrum range from about 1.8 eV in the red (wavelength 700 nm) to 3.0 eV in the violet (wavelength 400 nm).[4] It is not until wavelengths as short as 225 nm are reached that photons have sufficient energy to excite electrons from the valence band to the conduction band in diamond. Photons with wavelengths shorter than 225 nm are strongly absorbed in this process, but for longer wavelengths diamond has a good transparency (when pure) through to microwave frequencies in the far-infrared spectrum, apart from a small region in the infrared spectrum where the carbon atoms absorb energy because they vibrate at the same frequency as the frequency of the radiation.

Figure 8. Energy level diagrams showing the energy gap of (a) 5.5 eV in diamond and (b) 1.1 eV in silicon. For diamond it is impossible to excite electrons thermally from the valence band to the conduction band at normal temperatures, and so pure diamond is an excellent insulator. Ultraviolet light with a wavelength less than 225 nm has sufficient energy to excite electrons into the conduction band. For silicon there is a slight possibility of thermally exciting electrons into the conduction band at room temperature, and pure silicon therefore exhibits a small amount of electrical conductivity. Wavelengths shorter than 1100 nm (in the near infrared) will produce photoconductivity in silicon.

DIAMOND WINDOWS

The transparency of diamond has led to a large number of scientific applications. For example, in 1978 a diamond window 18.2 mm in diameter and 2.8 mm thick was fitted to one of the Pioneer space probes to Venus. The probe was designed to measure infrared spectra as it descended through the Venusian atmosphere. Diamond was the only material that would be transparent to all the infrared wavelengths of interest and would

Conduction band

5.5 Electron volts

Conduction band

1.1 Electron volts

Valence band

Valence band

(a)

(b)

Figure 9. A wafer of CVD diamond (Diafilm) grown by De Beers, illustrating its exceptional transparency. The wafer is 105 mm in diameter and 630 μm thick (about 4 by 0.025 inches). (Courtesy of De Beers.)

be able to withstand the searing heat and crushing pressure of that planet's atmosphere; the atmospheric pressure on Venus is almost 100 times greater than that on Earth. The window (plus a spare!) was cut from a pure gem-quality diamond; the cost of manufacturing such a window was estimated at 1991 prices to be more than $250,000.

Seventeen years later, De Beers announced the production of Diafilm, polycrystalline diamond grown by the CVD process that has all the desirable properties of the purest natural diamonds. Large-area windows like those shown in Figure 9 can now be readily synthesized.

High-quality CVD polycrystalline diamond is transparent over a wide spectral region, is resistant to abrasion by high-velocity raindrops and dust particles, and is able rapidly to conduct away the heat generated by air resistance. It is thus ideal for imaging applications in airborne systems flying at high Mach numbers. There are, however, still some technical issues to be addressed. Even so, currently that is but a small market, and the major application of CVD diamond in the near future will stem from its thermal properties.

SUPERCOMPUTERS

At present, the major commercial application of CVD diamond is in thermal management. With care, the material can be grown to have thermal conductivity almost as good as that of type IIa natural diamonds and the low-nitrogen, high-pressure synthetic diamonds currently used as heat spreaders. With CVD diamond, many thousands of suitable heat spreaders can be cut from a single wafer of CVD diamond. The availability of large areas of diamond, however, opens up possibilities that are impossible with natural diamond. Perhaps one of the most imaginative is the three-dimensional multichip module, which holds promise for an extremely powerful supercomputer.

In systems using very high frequency digital integrated circuits, the limiting speed of operation is determined by the time the signal takes to travel along the interconnections between the individual "chips." Speed can be increased by packing the bare chips as densely as possible on a multichip module (MCM). Even so, with complex chips, which have dimensions around 1 cm square, the interconnect distances in a two-dimensional array can be substantial when the number of chips is very large. In three-dimensional MCM packaging, use is made of the fact that the chips are thin, allowing a large number of two-dimensional arrays to be packed very close together in the vertical direction. Richard Eden of Norton Diamond Film has shown that whereas in two dimensions,

with chips spaced 1.5 cm apart, each chip has 8 nearest neighbors, in three dimensions, with the layers spaced at 2.5 mm, 116 chips can be reached with the same length of interconnect, allowing substantial increases in system speed. One of the key requirements in implementing such a system is extracting the heat generated by the substantial power dissipation from the large number of high-speed integrated circuits working in a small volume. In the CRAY-3 supercomputer,[5] that is achieved by forcing a spray of coolant droplets in helium carrier gas between the layers. An alternative approach is to mount the semiconductor chips on an electrically insulating substrate that has very high thermal conductivity. Enter CVD diamond. (Pure diamond, of course, is a perfect electrical insulator because of the wide band gap.)

The proposed computer would have a stack of square boards 100 mm ×100 mm, 1 mm thick, each populated with a high density of equal-power-dissipation chips (Figure 10). The diamond substrates would conduct the heat out laterally to heat sinks at opposing faces. The same approach was used at much lower power densities in the CRAY-1 using copper-loaded printed circuit boards. Eden has calculated that even if each board dissipated 500 watts (W), the maximum temperature rise at the center of each board would be only 31°C above the heat-sink temperature. As an example of the power of such a computer, Eden imagines a stack of 40 diamond substrates, spaced at 2.5 mm (as in Figure 10), giving a "cube computer" in which each side would have a length of 10 cm. If each board carried 36 VLSI (very large-scale integration) chips, each 1 cm square, mounted on a 1.5-cm pitch, the entire module would contain 1,440 chips. If they were 10,000-gate GaAs (gallium arsenide) chips optimized for speed, they would dissipate about 10 W each, or 360 W per board, giving a maximum temperature rise at the center of the diamond substrate of 22°C. That compact cube computer would contain 14.4 million gates, almost as many as the CRAY-3 supercomputer. From a performance standpoint it would offer no speed advantage over the approach of the CRAY-3; it would simply allow that same three-dimensional interconnect packaging to be realized in a simple straightforward way at relatively low cost.

In 1995, Norton Diamond Film and AsTex (a company that produces microwave equipment for growing diamonds) succeeded in growing diamond wafers 6 inches (15 cm) in diameter, from which substrates 10 cm square and 1 mm thick were fabricated. In 1997, those substrates were being evaluated for the MCM concept and other large-scale thermal management problems.

Figure 10. Schematic diagram of the multi-chip module that has a stack of 40 substrates, 10 cm square, made from CVD diamond. (Adapted from Eden, 1993.)

DIAMOND ELECTRONIC DEVICES

Because it is a wide-band-gap semiconductor, diamond has, in principle, the potential for applications in high-temperature active electronic devices. Sil-

icon transistors do not work satisfactorily at temperatures above about 200°C, because at those temperatures there is sufficient thermal energy to excite a significant number of electrons from the valence band to the conduction band, producing unwanted leakage currents. Diamond, with an energy gap five times higher than that of silicon, does not run into that problem until temperatures well over 1,000°C. The work at NIRIM showed that diamond, just like silicon, could be grown in wafers, and at the end of the 1980s there was a host of proposals for high-temperature, high-power, high-frequency transistors and lasers made from diamond. In the United States, much of that work was supported by President Reagan's proposed program for a Strategic Defense Initiative (SDI), and many extravagant claims were made to obtain research funding.

Unfortunately, because the carbon atoms in diamond are tightly spaced, boron is the only impurity that can be incorporated to give useful semiconducting behavior. Boron is from group III of the periodic table and therefore produces *p*-type conductivity (in which the current is carried by "positive holes"). Most silicon devices are based on the *p-n* junction, and the *n*-type material (in which the current is carried by negative electrons) is produced by doping with a group V element. For diamond, *n*-type material does not exist, and that limits any devices to MIS-FET-type structures (metal-insulator-semiconductor field-effect transistor). Natural semiconducting diamond, in which boron is the major impurity, does exist, although it is very rare, and it has served as a benchmark for boron-doped CVD diamond. One of the parameters important in semiconductors is "mobility," which is a measure of how quickly the charged carriers (i.e., the electrons or holes) move when an electric field is applied. The higher the mobility, the more suitable the material is for device applications. In the rest of this section, the numerical values for mobility are in units of centimeters squared per volt per second. For the very best natural diamonds, the mobility of the positive carriers is around 2,000 at room temperature. That compares with about 1,500 for *n*-type silicon and about 8,000 for *n*-type gallium arsenide, both of which are widely used in semiconducting devices. Although some single crystals of natural semiconducting diamond have very respectable mobility values, a problem with the large wafers of CVD diamond for device applications is that the material is polycrystalline. The Electronic Materials Center of Kobe Steel USA has been actively involved in evaluating CVD diamond as a device material for several years, and the best mobility value to date is around 280 for polycrystalline material. However, by growing CVD diamond homoepitaxially (i.e., onto a single-crystal diamond substrate), Kobe Steel has produced boron-doped layers with no grain boundaries and mobilities approaching those observed in natural semiconducting diamond. In 1994, Kobe Steel published data for a field-effect transistor (FET) based on homoepitaxial CVD diamond that worked at temperatures up to 500°C and a simple digital-logic circuit that worked at 400°C. More recently, Kobe has constructed an FET using its best polycrystalline material; again, it

exhibited the current–voltage characteristics typical for that sort of device, but, as expected, the current was lower than for the transistor based on homoepitaxial layers.

Despite those successes, the performances of the diamond transistors still are a long way short of what will be required to make them commercially attractive. Far more progress has been made with silicon carbide, another wide-band-gap material. Again, although some light-emitting devices have been made using diamond, their intensities are feeble when compared with those of a material like gallium nitride, and certainly the "powerful lasers" promised in the SDI program are figments of the imagination.

DIAMOND IN THE ATOM SMASHER

Another property of diamond, in addition to its high thermal conductivity, will be exploited in the Large Hadron Collider (LHC) that is to be built at CERN near Geneva.[6] That accelerator will attempt to reproduce the conditions that existed a few nanoseconds after the Big Bang (there are a billion nanoseconds in one second). In a circular tunnel 27 km long, protons will be accelerated until they are moving at almost the speed of light; every 25 nanoseconds they will collide with a similar beam traveling in the opposite direction, producing several hundred particles, most of which will survive for only a very short time before decaying into more stable particles. A few of the particles produced in the collisions may be significant in helping us to answer some of the outstanding questions about the fundamental structure of the universe.

The particle detectors closest to the collision site in the LHC will have to withstand enormous doses of radiation and heat. In previous generations of accelerators, silicon detectors were used, but they do not work well at high temperatures, and in the LHC the intense bombardment by high-energy particles would destroy the detectors in a few months. Diamond can also be used to detect nuclear particles, and compared with silicon it is extremely "radiation-hard" – little deterioration of a diamond detector would be expected over the 10-year working life of the LHC.

Diamond has been investigated as a radiation detector before – in the early 1950s. Only natural diamonds were available then, and as they were very small, variable, and expensive, silicon soon proved superior. The CVD diamond that is now being produced has detector properties comparable to those for some of the best natural diamonds studied and can be crystallized in much larger sheets. The detectors that have been tested thus far in particle beams consist of a slice of CVD diamond 0.2 mm thick, coated with a gold electrode at the back and thin gold-strip electrodes on the front. Each gold strip is con-

nected to a separate amplifier. The particles pass right through the diamond, producing electrical charges that are attracted to the electrodes by a large electric field applied across the detector. By observing which gold strip produces the signal, one can deduce where the particle passed through the detector. Tests show that the signal can be extracted in a few nanoseconds, very much faster than with existing detectors, and fast enough to gather all the data required before the next collision takes place. One drawback with diamond is that the signal produced is about three times smaller than that for silicon, and in early versions of detectors the signal-to-noise ratio (SNR) was too low. However, the SNR was not thought to be a problem in some of the best De Beers material tested at the end of 1996.

DIAMOND PHOTODETECTORS

In addition to detecting nuclear particles, diamond can detect ultraviolet radiation at wavelengths shorter than 225 nm. Researchers investigating that phenomenon believe that there are applications for detectors that can respond to ultraviolet light without being sensitive to visible light. In 1992, Steven Binari and his colleagues at the Naval Research Laboratory (Washington, DC) made a diamond photodetector using a very pure natural diamond that exhibited a quantum efficiency greater than 10 percent over the wavelength range 130–220 nm, with a peak of 29 percent at 210 nm (the quantum efficiency measures the fraction of the incident optical power that is converted to a photocurrent).

The quantum efficiency for CVD diamond grown on a nondiamond substrate was disappointing, at less than 1 percent. CVD diamond prepared in that way is always polycrystalline, and the mobility of the photocarriers is very low because the carriers are slowed down or trapped at the grain boundaries. However, by growing CVD diamond on single-crystal diamond substrates, Maurice Landstrass and his colleagues at Crystallume, in Menlo Park, California, achieved photoconductive mobilities that are comparable to those achieved for the best natural diamonds and photocarrier lifetimes that were only slightly lower (both of those parameters need to be high to achieve good quantum efficiency).

With careful attention to the electrodes applied to the diamond, photoconductive devices can be made to exhibit gain, and quantum efficiencies greater than 100 percent are possible. This effect is well known in other materials, and in 1995 Richard Jackman of University College, London, demonstrated a diamond photodetector based on polycrystalline CVD diamond that exhibited a peak quantum efficiency of 600 percent. That was much higher than the quantum efficiency of ultraviolet-enhanced silicon photodetectors,

which also have the disadvantage (in that context) that they respond to visible and near-infrared radiation. The silicon detectors may, however, have less electrical noise; comparative figures for the crucial quantity, the SNR, apparently have not been published.

FLAT-PANEL DISPLAYS

Another active field in diamond-device technology is the study of the phenomenon of "negative electron affinity." The meaning of this terminology is that if a diamond is placed in a vacuum, and electrons are excited into the conduction band, some of those electrons will be spontaneously emitted into the vacuum. To understand why this might be useful, we need to consider the way in which images are displayed on a television screen or a computer monitor: Electrons are emitted into the vacuum when a suitable filament (or cathode) is heated to incandescence. The electrons are then accelerated toward the screen by a high voltage, where they strike a phosphor to produce red, green, or blue light. One electron beam is used for each color, and the picture is generated by rapidly scanning the three electron beams over the screen.

The problem is that the picture tube (cathode-ray tube) is extremely bulky; it does, however, produce a picture far superior to the displays used in lap-top computers. A technique currently being explored for flat-panel displays that use a phosphor screen (and thus produce a high-quality picture) is to use an electron source for each pixel (picture element) on the screen. That will require about half a million emitters, and obviously it would be impossible to use heated filaments for that. What is required is an array of "cold cathodes" that will emit electrons at room temperature. The negative electron affinity of diamond allows it to be used as a cold cathode, and SI Diamond Technology, in Houston, Texas, has demonstrated prototype flat-panel displays based on diamond emitters. However, numerous problems will have to be overcome before that can become a serious competitor to the cathode-ray tube.

DIAMOND ANVIL CELLS

In the earlier sections of this chapter I have considered some of the high-tech applications for diamond. However, by far the major uses for diamond in industrial applications derive from its extreme hardness. Sawing, grinding, drilling, and wire-drawing applications all use diamond because the rate of abrasion of diamond is so slow compared with the rates for other materials. There is one other property of diamond that makes it invaluable in fundamental research programs that study the behavior of substances under extreme

pressure: Diamond is extremely tough and can be used as the anvil material in high-pressure cells.

The basic principle of the diamond anvil cell is illustrated in Figure 11. Each diamond has a shape similar to that of a brilliant-cut gem, but with a flat culet that forms the anvil tip. The area A_1 of the base is much larger than the area A_2 of the tip. Each diamond is supported with a high-strength material such as steel or even tungsten carbide. The sample is placed between the anvil tips in a small circular hole in a gasket made from a metal foil such as nickel. The use of the gasket ensures that the pressure will be nearly hydrostatic (i.e., uniform throughout the volume). If a gasket is not used, the sample itself provides the seal, but enormous pressure gradients are present. In the design illustrated in Figure 11, the top diamond is mounted in the stationary reaction plate, and the bottom anvil is mounted on the moving piston. The pressure applied to the diamond is amplified by the ratio A_1/A_2. Using a diamond with a base 4 mm in diameter and a tip diameter of 0.4 mm would give a 100-fold pressure enhancement. In order to achieve extremely high pressures, the tip faces of the anvils must be precisely parallel (the simplified diagram in Figure 11 does not show the necessary adjusting mechanism).

An outstanding advantage of diamond, in addition to its strength, is its transparency to ultraviolet, visible, and infrared radiation, as well as to x-rays. A considerable body of research in high-pressure work has involved the study of phase changes using x-ray diffraction.

The concept of producing high pressures by compressing materials between two opposed diamond anvils was developed in 1959 at the National Bureau of Standards, Washington, DC, by Charles Weir and Alvin Van Valk-

Figure 11 (below). Diagram illustrating the principle of the diamond anvil cell, adapted from Seal, 1992; and a photomicrograph of an actual diamond anvil. (Courtesy of Geophysical Laboratory, Carnegie Institution of Washington.)
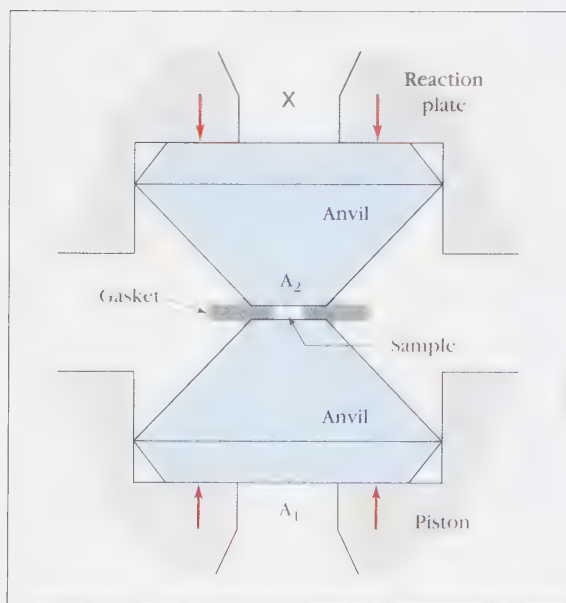
enburg. Van Valkenburg went on to develop the lever-arm diamond anvil cell shown in Figure 12. Pressure is applied to the lower diamond anvil simply by turning the screw, which compresses the spring washers and transmits the force by the lever arm. Van Valkenburg used the lever-arm diamond anvil cell to study alcohol crystals formed at high pressure (Figure 12).

Pressures up to 100 kilobars (kbar) were obtained in early versions of the lever-arm cell, and pressures up to 500 kbar have been reported more recently. [In high-pressure studies, pressures are usually expressed in kilobars, megabars, or giga-Pascals. A pressure of 1 bar is virtually the same as 1 atm of pressure; 1 megabar (Mbar) = 1,000 kbar = 1,000,000 bar; 1 giga-Pascal (GPa) = 10 kbar.]

The cell can easily be incorporated into the specimen stage of an optical microscope to allow visual observation of high-pressure effects, or it can be placed in a spectrometer for measurements of the absorption and scattering of light. The cell can also be used to squeeze a variety of irregular materials into flat, uniform samples suitable for spectroscopic studies, a technique widely used in forensic science.

Scientists are seldom slow to press a new technique to its limit, and new designs for diamond anvil cells have been explored by Peter Bell and Ho-Kwang Mao at the Geophysical Laboratory of the Carnegie Institution, Washington, DC, and Arthur Ruoff at the Cornell University Department of Materials Science and Engineering. Ruoff has also shown that synthetic diamonds can be used to achieve ultrahigh pressures. Extensive work on diamond anvil cells has also been carried out at the National Physical Laboratory in the United Kingdom.
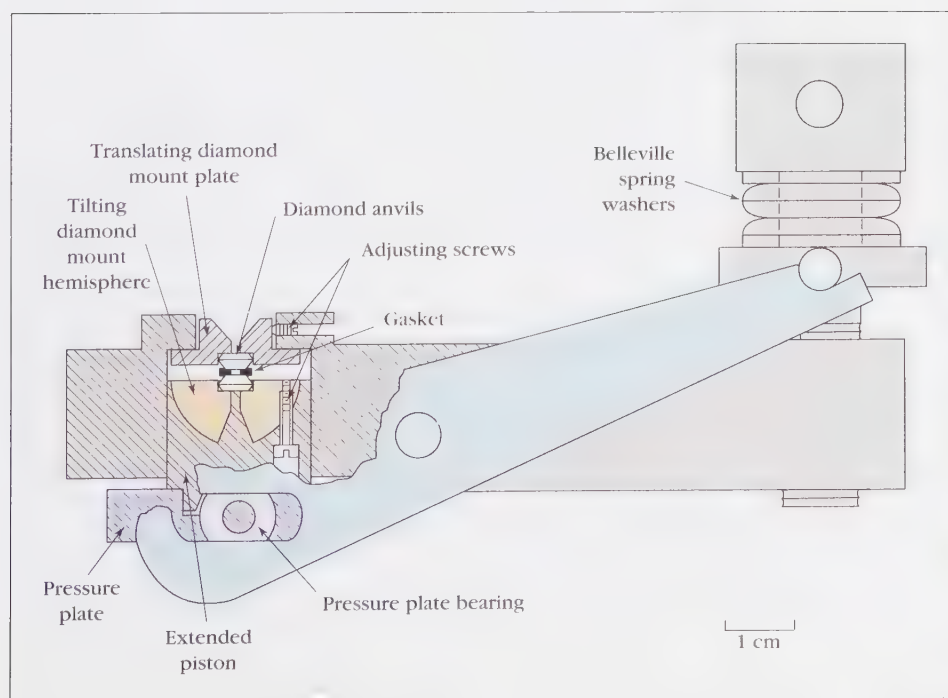
Figure 12. Diagram of lever-arm diamond anvil cell (adapted from Caveney, 1979) and Alvin Van Valkenburg in 1963 using such a device to study materials at high pressure including what he called "gincicles" (bottom) alcohol crystals formed when liquid alcohol is raised to high pressure in the diamond anvil cell. (Courtesy of Geophysical Laboratory, Carnegie Institution of Washington.)

Translating diamond mount plate

Tilting diamond mount hemisphere

Diamond anvils

Adjusting screws

Belleville spring washers

Gasket

Pressure plate

Extended piston

Pressure plate bearing

1 cm

The pressure record for a diamond anvil cell stands at about 4.6 Mbar, slightly greater than the pressure that is estimated to exist at the center of the Earth. It is fitting that diamond, which has emerged from deep below the Earth's crust, is enabling scientists to explore phenomena at any point from the core to the surface.

NOTES

1 A much fuller account of the early history and the events leading up to the successful synthesis of diamond is available (Hazen, 1993). The development and application of the diamond anvil cells to achieve extremely high pressures are also dealt with there.
2 Many of the early claims were mentioned by Mellor (1924).
3 An excellent review of the early work was given by Angus and Hayman (1988).
4 The relationship between energy and wavelength (or frequency) is given by Planck's radiation relationship, whereby the energy change is equal to a constant (h, Planck's constant) times the frequency v ($\Delta E = h \cdot v$), which is also equivalent to the constant divided by the wavelength λ ($\Delta E = h/\lambda$).
5 The CRAY-3 was built only as a prototype. The company went into liquidation before the machine became commercially available.
6 CERN is one of the world's largest scientific laboratories and an outstanding example of international collaboration by its many member states. The acronym CERN comes from the earlier French title: Conseil Européen pour la Recherche Nucléaire.

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The paragon of physical perfection and a sparkling example of Earth's forces at work, the diamond has fascinated all realms of society, from Russian tsars and Hollywood stars to scientists and brides-to-be. *The Nature of Diamonds* is an authoritative and richly illustrated look at nature's most coveted gem.

Leading geologists, gemologists, physicists, and cultural observers cover every facet of the stone, from its formation in the depths of the Earth and its explosive ascent to the surface, to its economic, regal, social, and technological roles. The book takes the reader to cutting-edge research on the frontiers of diamond exploration and exploitation, from Arctic wastes to laboratories that create industrial diamonds for cutting tools that slice through rock. Charting the history of mining from its origins in India and Brazil, the book follows the diamond rush in South Africa to today's high-tech enterprises. It provides a glimpse into the economics of the diamond trade, and an overview of diamond cutting, from the rough uncut stones in early Indian and Roman jewelry to the multifaceted stones we see today. The cultural history of the diamond as both a revered and social symbol is explored, from its early history as the exclusive property of royalty to today's brilliant-laden jewelry as an emblem of wealth and status.

The engaging text is complemented by more than 200 lavish illustrations that span fine art, earth science, and cultural studies and capture the brilliance and beauty of this extraordinary substance.

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Back cover photo: Diamond octahedron. Denis Finnin/courtesy of
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