Ralf Tappert
Michelle C. Tappert

Diamonds in Nature

A Guide to Rough Diamonds

Springer

Diamonds in Nature

Ralf Tappert
Michelle C. Tappert

Diamonds in Nature

A Guide to Rough Diamonds

Springer

Ralf Tappert
Department of Earth
and Atmospheric Sciences
University of Alberta
Edmonton, Alberta, Canada
rtappert@ualberta.net

Michelle C. Tappert
Department of Earth
and Atmospheric Sciences
University of Alberta
Edmonton, Alberta, Canada
michelle.tappert@ualberta.ca

ISBN 978-3-642-12571-3 e-ISBN 978-3-642-12572-0
DOI 10.1007/ 978-3-642-12572-0
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2011924333

All photos were taken by Ralf Tappert unless otherwise stated.

Editing and index: Michelle Tappert

Book design: Susan Hunter

Cover design: deblik, Berlin

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Table of Contents

Preface

Diamond is undoubtedly one of the most well-recognized and sought-after materials. The use of diamond as a gemstone is deeply ingrained in many cultures, and a range of attributes are associated with diamond, such as it being the symbol of wealth and love. Despite their popularity as a gemstone, relatively little attention is paid to the mineral diamond in its naturally occurring form.

In this book we focus exclusively on natural, uncut diamonds and their characteristic features, such as their crystal morphologies, their colors, their surface textures, and the types of inclusion they contain. We elucidate how these features not only provide insights into the growth processes of diamonds, but also into the workings of our planet's interior.

A number of popular books have been written about diamonds, but few of these discuss the unique features of natural diamonds in any detail. More information can be found in the scientific literature, but this literature is scattered over many disciplines, including physics, geology, mineralogy, gemology, and material science. Due to the vast number of scientific articles that have been published about diamonds, it is difficult to provide a comprehensive overview of the literature. The references provided throughout this book, therefore, should only be regarded as a starting point from which the interested reader can delve deeper into the world of diamonds in nature.

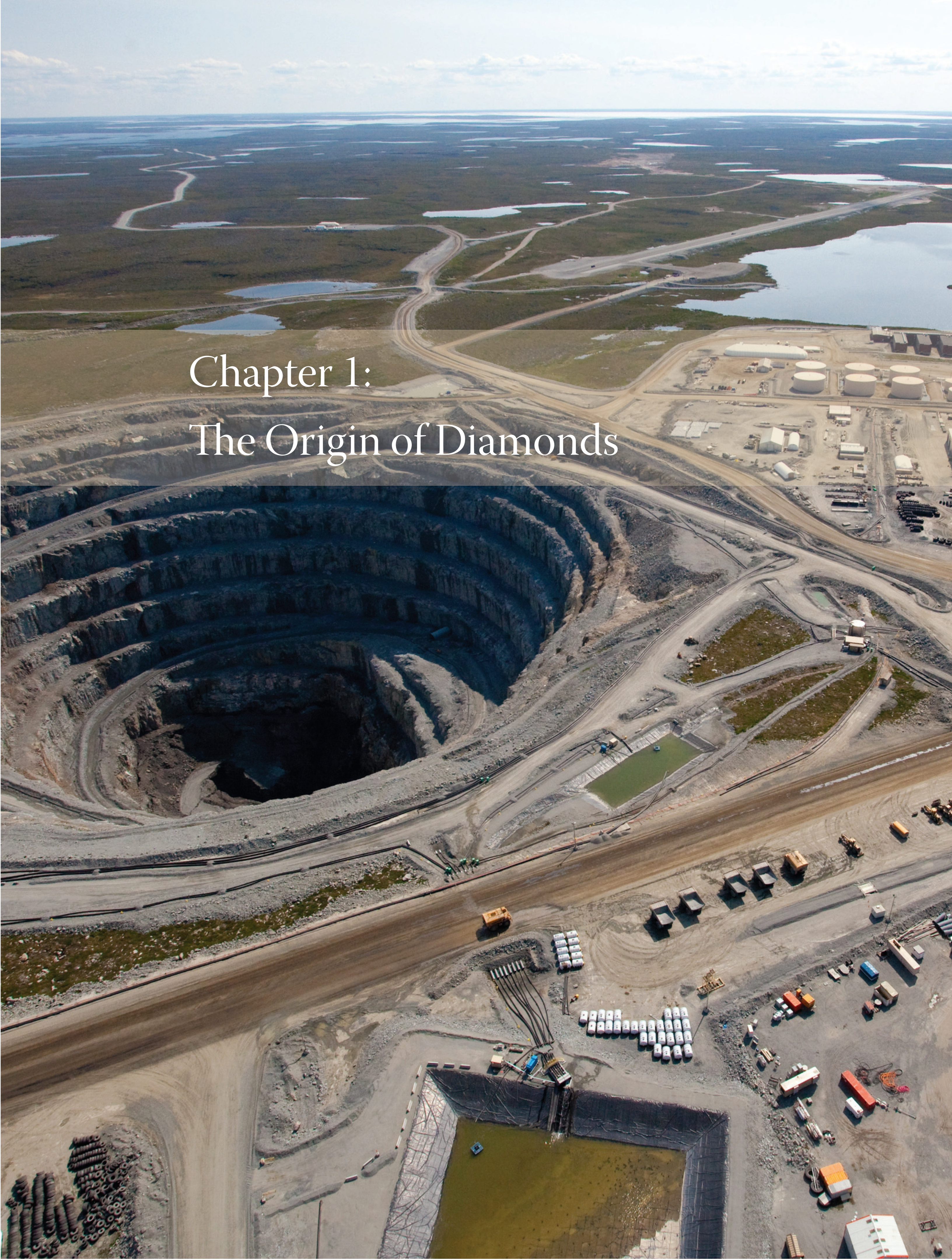
Acknowledgments

Most of the diamonds shown in this book are museum or research specimens. Among those, a large proportion are on display in the Mineralogy and Petrology Museum at the University of Alberta in Edmonton, Canada. The diamonds for this exhibit were graciously donated by DeBeers through the Diamond Trading Company (DTC) and by Jeff Harris. Additional diamond specimens photographed for this book came from the mineral collection of the South Australian Museum in Adelaide, Australia. We thank Allan Pring for providing us with access to these diamonds. A detailed list of the diamond and rock specimens from these collections can be found at the back of this book. The diamonds from Boa Vista, Canastra, Arenapolis (Brazil), and from Jagersfontein (South Africa) were generously provided by Jeff Harris and DeBeers as research specimens. Additional diamonds came from Flinders Mines through Kevin Wills and John Foden; from Pascal Grundler; and from Thomas Stachel, who also gave us access to his research laboratory, microscope, and photography equipment.

We are also grateful to Petra Diamonds for providing us with the photographs of their exceptional diamonds, and to Ekati Diamond Mine and Argyle Diamond Mine who provided us with aerial photographs of their mining operations. Additional photographs came from Stephen Creighton and Graham Janson. Help and support with various aspects of imaging and photography were provided by Donald Chan, Anetta Banas, Heidi Höfer, Angus Netting, Peter Self, John Terlet, and Ryan McKellar. Comments on earlier versions of the manuscript by Shannon Zurevinski, Pascal Grundler, Jason French, Gerhard Brey, Karlis Muehlenbachs, Thomas Stachel, and Jeff Harris are gratefully acknowledged.

Chris Bendall handled the editorial aspects and encouraged us to pursue this project. For doing an excellent job in designing this book, we thank Susan Hunter.

Chapter 1:
The Origin of Diamonds



Previous page –
Koala pit, Northwest
Territories, Canada.
Photo courtesy of BHP Billiton
EKATI Diamond Mine.

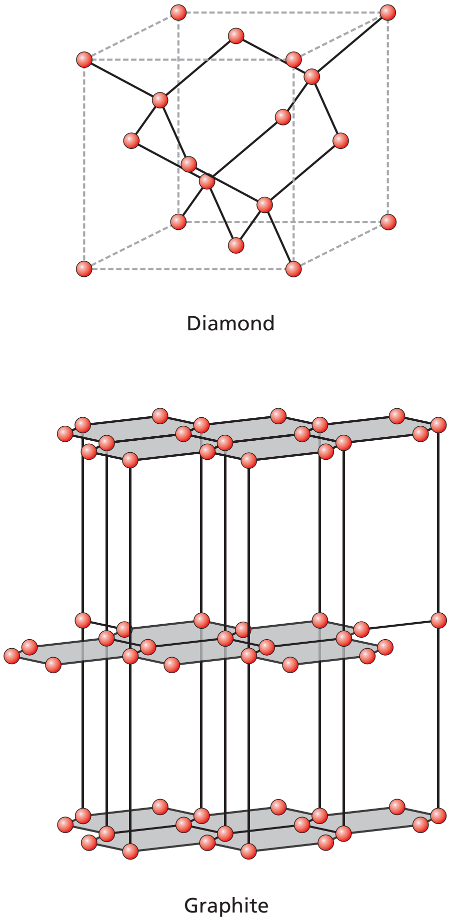
Chapter 1:
The Origin of Diamonds

Diamond, by definition, is a mineral composed exclusively of the element carbon. The carbon atoms in diamond are arranged in a dense cubic crystal structure (Fig. 1-01), and it is this crystal structure that gives diamond its unusual physical and chemical properties. Diamond is the hardest known naturally occurring mineral (Moh's hardness 10), but despite this extreme hardness, it is also a brittle material that can fracture in response to severe force. Another unusual property of diamond is its resistance to reactions with most chemical agents, which makes diamond virtually inert. Diamond, however, can be oxidized, but the oxidation of diamond is generally restricted to high temperatures. The hardness and chemical resistance of diamond and its potential to be oxidized at high temperatures strongly influence the presence of diamonds in nature.

Diamond has a range of additional properties that make it an appealing and sought after mineral. Its high refractive index (2.4), for example, gives it an outstanding luster and makes it an attractive and extremely valuable gemstone. Diamond also has a high thermal conductivity, making it a valuable component in a wide range of technological applications.[314]

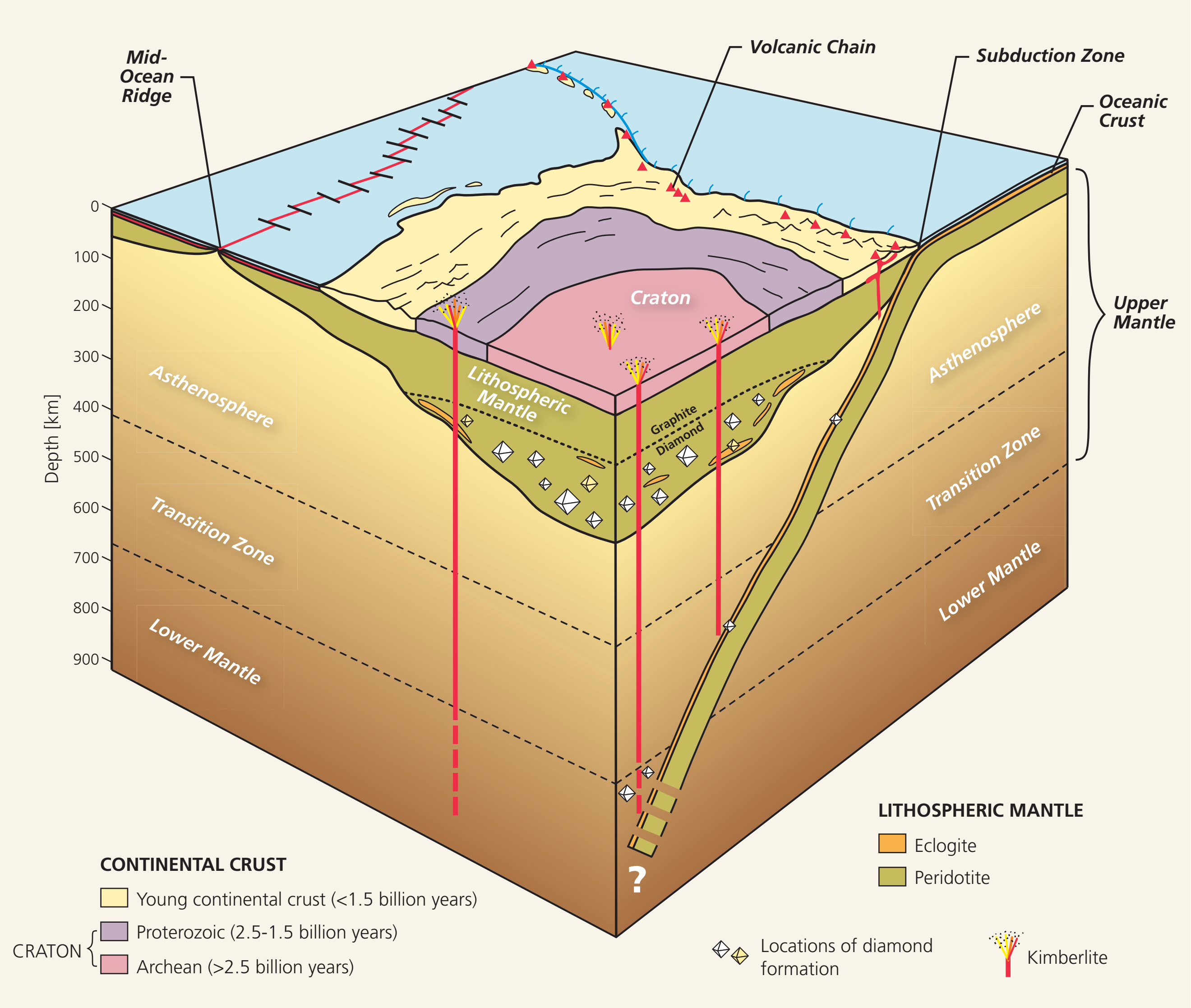
In nature, carbon atoms only crystallize with the crystal structure of diamond at pressures exceeding several tens of thousands of bars.[153] At lower pressures, graphite is the stable form of carbon. Unlike diamond, graphite consists of layers of carbon atoms that are weakly bound to each other (Fig. 1-01). This crystal structure causes graphite to be one of the softest minerals in nature.

Even though diamond only forms at high pressures, it can survive in a low-pressure environment without converting to graphite. Pressures high enough to stabilize the crystal structure of diamond do not exist anywhere near the Earth's surface or even in the deeper parts of the Earth's crust. This means that the formation of diamonds in nature is always linked to very unique geological processes that involve high pressures.



1-01: Crystal structures of diamond and graphite illustrating the different arrangements of carbon atoms in the crystal lattices of the two minerals. Drawn to scale.

R. Tappert and M.C. Tappert, *Diamonds in Nature: A Guide to Rough Diamonds*,
DOI 10.1007/978-3-642-12572-0_1, © Springer-Verlag Berlin Heidelberg 2011



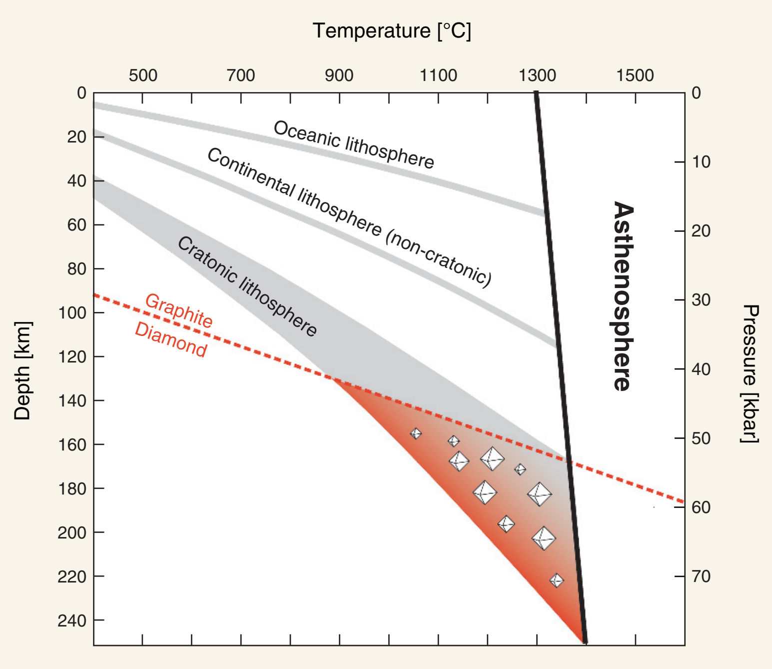
Artwork by Jason French and Ralf Tappert.

1-02: Cross-section of the crust and mantle showing the main locations of diamond formation in the Earth's interior.

The origin of diamonds in the Earth's mantle

The vast majority of natural diamonds, including all gemstone diamonds, formed in the Earth's mantle at depths of more than 140 kilometers.[10, 98, 193] Within the mantle, diamonds form primarily in the rigid part of the upper mantle, which is referred to as the lithospheric mantle (Fig. 1-02). The lithospheric mantle and the overlying crust constitute the tectonic plates that drift on the convecting asthenosphere. Unlike the lithospheric mantle, the typical asthenosphere does not appear to be favorable for diamond formation.[272]

In addition to high pressures, diamond formation is favored by relatively low temperatures. In nature, these conditions restrict diamond formation to regions with a very low geothermal gradient. Regions with such low geothermal gradients are generally confined to the geologically old parts of continents, which are referred to as cratons (Fig. 1-03).[136, 242] Cratons are composed of crustal basement rocks, such as granites and gneisses that are more than ~1.5 billion years old. The lithospheric mantle roots beneath cratons can extend to depths of more than 250 kilometers, and due to their relatively low temperatures and extreme thicknesses, they



1-03: Pressure-temperature-depth diagram outlining the stability fields of diamond and graphite. Geothermal gradients for typical oceanic, continental, and cratonic lithospheres are shaded grey. Diamonds are only stable in cratonic settings at pressures greater than ~40 kilobars, which corresponds to depth of more than ~140 kilometers.

are the main locations of diamond formation in the Earth's mantle (Fig.1-02).[275] Diamonds are believed to crystallize primarily from carbon-rich fluids that percolate through these lithospheric roots.[158, 276]

Throughout Earth's history, magmas originating from deep within the mantle passed through the lithospheric roots. During their ascent, the magmas incorporated various minerals (xenocrysts) and rock fragments (xenoliths) from the surrounding mantle. The most common type of mantle rock is peridotite, which primarily consists of olivine and variable amounts of orthopyroxene, clinopyroxene, garnet, and/or spinel (chromite) (Fig. 1-04). A less common constituent of the mantle is eclogite,

1-04: A piece of the lithospheric mantle: peridotite xenolith from the Bultfontein mine, Kimberley, South Africa (Ø: ~30 cm), which consists mainly of olivine (dark green), garnet (purplish-red), Cr-diopside (bright green), and orthopyroxene (light brown).

1-05: Eclogite xenolith from the Roberts Victor mine, South Africa (Ø: ~30 cm), which consists mainly of garnet (reddish-brown), and clinopyroxene (greyish-green). Eclogites are a minor constituent of the lithospheric mantle, but they can be important diamond source rocks.

which is a rock that is mainly composed of iron-rich garnet and chromium-poor clinopyroxene (Fig. 1-05). Both of these mantle rocks can host diamonds (Fig. 1-06).[210, 222]

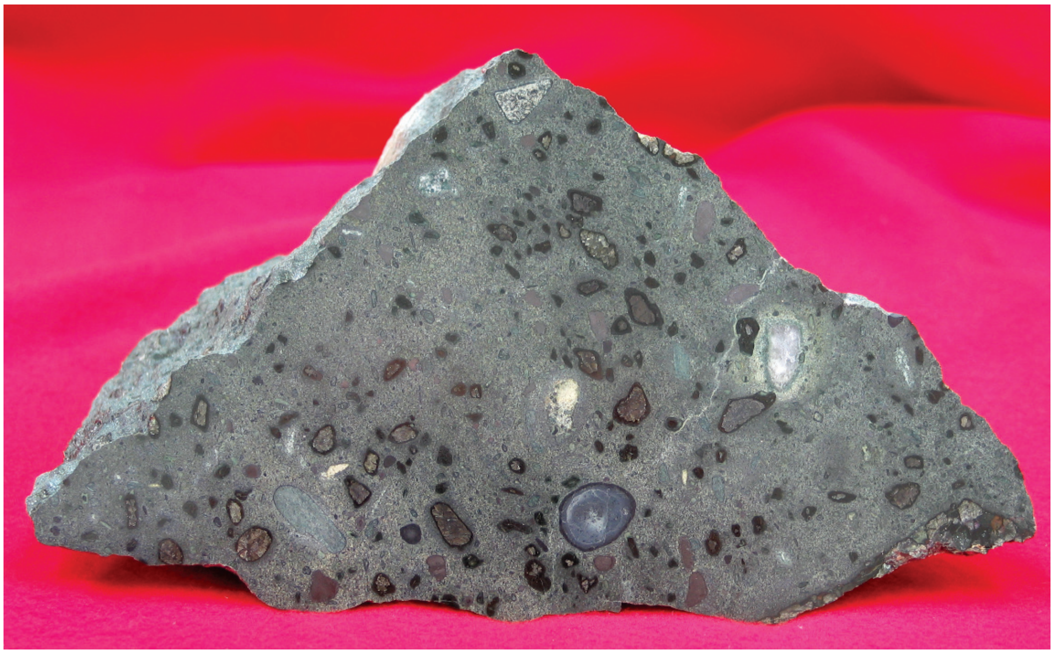
Once incorporated into the ascending magma, many of the xenoliths disintegrate, and their mineral components, which can include diamonds, are dispersed into the magma. Xenoliths that reach the Earth's surface intact can occasionally contain large quantities of diamonds.[43, 181, 253, 305] Once the magmas reach the Earth's surface, they cause violent but small scale volcanic eruptions that form small craters rarely larger than a few hundred meters in diameter. The volcanic structures underlying these craters are commonly referred to as pipes.[78, 120, 211]

1-06: Diamond in a peridotite xenolith from the Diavik mine, Northwest Territories, Canada. Field of view is ~1 cm.

Photo courtesy of Steven Creighton.

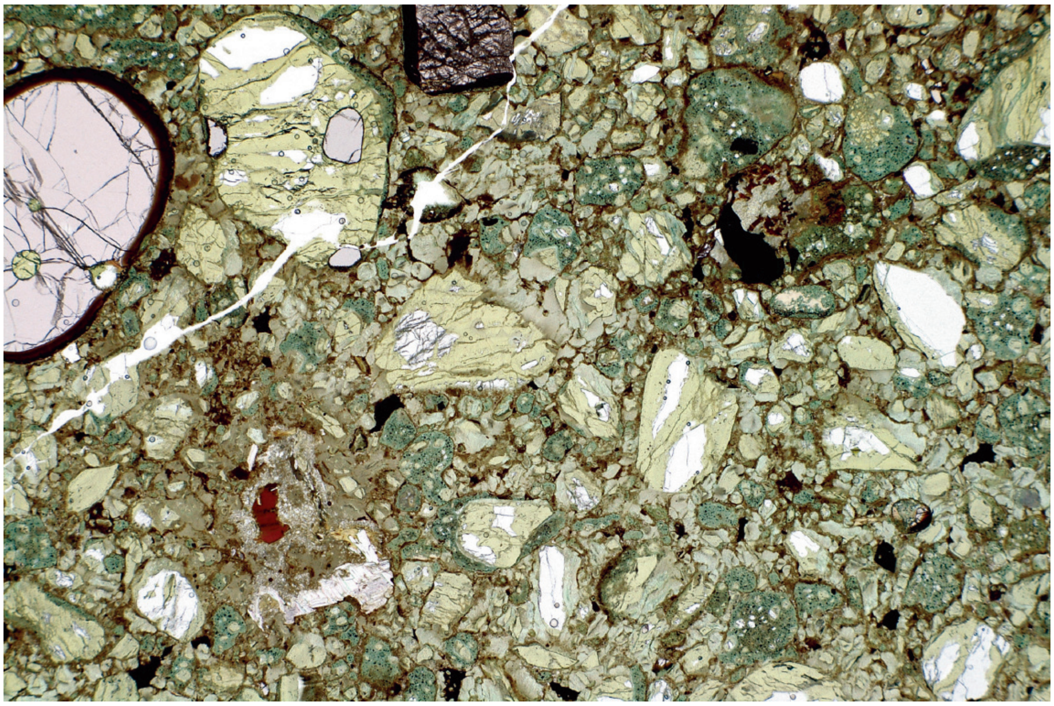
1-07: Rounded peridotite xenolith with alteration crust in kimberlite. Kelsey Lake mine, State Line District, Colorado, USA. Hand lens ~8cm.

After the eruption, the magmas cool and form volcanic rocks (Fig. 1-07). The most common type of diamond-bearing volcanic rocks is kimberlite, which was named after the town of Kimberley in South Africa where it was first discovered. Due to the high abundance of minerals and rock fragments incorporated into the magma during the ascent to the Earth's surface, kimberlites can be quite heterogeneous and variable in their appearance (Fig. 1-08, Fig. 1-09, Fig. 1-10).[36, 255, 256] In addition to kimberlites, several other types of volcanic rocks are known to host mantle-

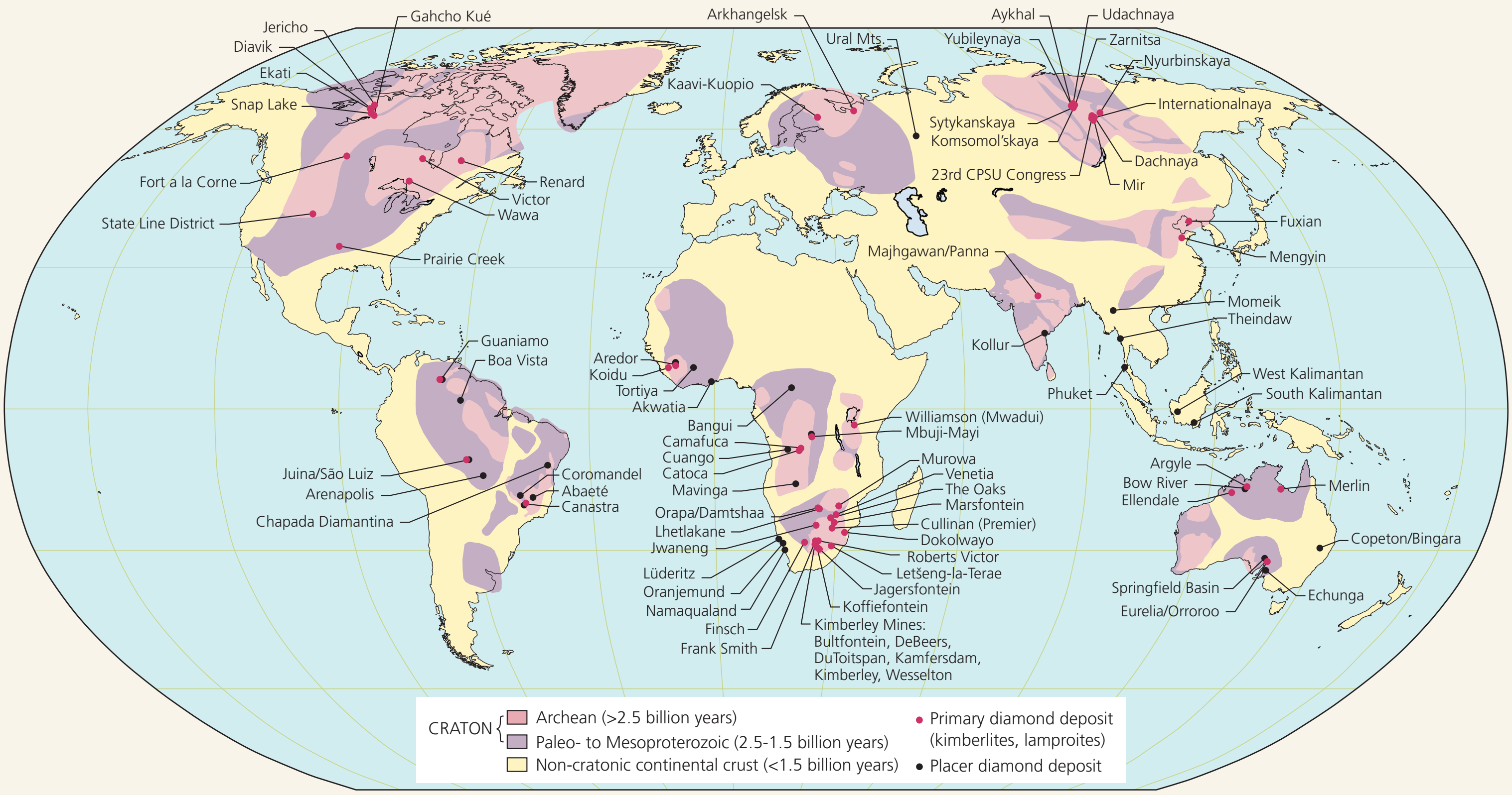


1-08: Kimberlite sample from the Monastery mine, South Africa (Ø: ~25 cm), containing numerous rounded and angular xenocrysts and xenoliths in a fine-grained matrix.

1-09: Kimberlite sample from the Panda kimberlite pipe, Ekati mine, Northwest Territories, Canada (Ø: ~20 cm). The kimberlite sample contains xenoliths of granite (white) and shale (dark grey) from the surrounding craton, along with abundant mantle-derived olivine crystals (green).



1-10: Photomicrograph of a thin section of kimberlite from the Panda kimberlite pipe, Ekati mine, Northwest Territories, Canada, showing numerous rock and mineral fragments that were fused together during the emplacement of the kimberlite. Photo taken under plane polarized light. Field of view is ~3 cm.



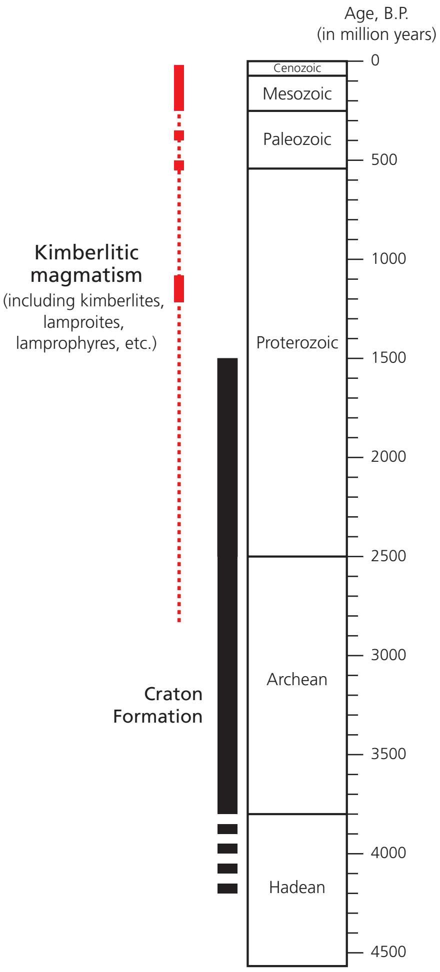
1-11: Map of the world's cratons and the locations of diamond deposits.

derived diamonds, including lamproites, lamprophyres, and even some komatiites.[21, 138, 169, 250, 285] Among those, only lamproites occasionally contain diamonds in economic quantities, for example, at the Argyle and Ellendale mines in Western Australia.[139] For simplicity, all diamond-bearing volcanic rocks will hereafter be referred to as kimberlites.

Diamondiferous kimberlites most frequently occur in the geologically most ancient parts of cratons (Fig. 1-11), which are those that formed in the Archean eon, 3.8 to 2.5 billion years ago. Only a small proportion of diamond-bearing kimberlites are present in younger parts of cratons, which are those that formed in the Proterozoic eon, 2.5 to 1.5 billion years ago. These younger, Proterozoic parts of cratons are sometimes referred to as mobile belts. Continental crust that is younger than 1.5 billion years usually does not host diamondiferous kimberlites.[37] The lithospheric roots beneath non-cratonic continental crust (e.g. the roots beneath central and southern Europe) generally have high geothermal gradients and are limited to depths of less than 100 kilometers, which is not deep enough for diamond formation (Fig. 1-03). However, the extent and the age of a craton is not always easy to determine, particularly in areas where cratonic basement rocks are buried beneath younger sedimentary rocks (e.g. the Amazon Basin) or beneath ice sheets (e.g. Antarctica).

The kimberlitic magmatism that carries diamonds from the mantle to the Earth's surface is generally much younger than the cratons. Even though the oldest known diamond-bearing volcanic rocks are Late-Archean in age and are more than 2.6 billion years old,[169] most of the kimberlitic magmatism occurred in the last 1.2 billion years (Fig. 1-12). Kimberlitic magmatism appears to be episodic, and one of the most active times of magmatism was the relatively recent period from 250 to 20 million years. During this time, many of the diamond-bearing kimberlites and lamproites in southern Africa, Canada, Australia, and other parts of the world were emplaced.[101, 121] Since the end of that period, the diamond-producing magmatism seems to have ceased worldwide.

Only a small proportion (~10%) of the more than 5000 known kimberlites are diamond bearing. Among those, only a small percentage (<1%) contain diamonds in sufficient quantities to permit large scale industrial mining (Fig. 1-13, Fig. 1-14, Fig. 1-15). These few diamond-rich kimberlites, however, supply the bulk of the world's natural diamonds, which on an annual basis equals around 30 metric tons, which is equivalent to around 150 million carats.[137, 230]



1-12: Geological time scale showing the time intervals of craton formation and global kimberlitic magmatism. The thick red lines mark major episodes of diamond-producing kimberlitic magmatism.

Photo courtesy of BHP Billiton EKATI Diamond Mine.

1-13: Aerial view of an open pit (Fox kimberlite pipe) at the Ekati mine, Northwest Territories, Canada. The flat landscape surrounding the pit is typical for Archean cratons.

Photo courtesy of Steven Creighton.

Photo courtesy of Argyle Diamond Mine.

1-14: Aerial view of an open pit (A-154 kimberlite pipe) at the Diavik mine, Northwest Territories, Canada, in the early stages of development. The kimberlite is exposed in the central part of the pit.

1-15: Aerial view of the Argyle diamond mine, Western Australia, showing the processing plant, tailings piles, and tilted sedimentary rocks of Proterozoic age, which form the wall rocks of the mine.

1-16: Geologists examining an outcrop of diamond-bearing sandstones and conglomerates in the Springfield Basin, South Australia, which contain rare diamonds of lower mantle origin.

Diamonds in placer deposits

Kimberlites that are exposed on the Earth's surface after their emplacement often erode, and their diamonds and other mantle-derived minerals are dispersed. As a result of their extreme hardness and resistance to chemical weathering, diamonds can endure long transport distances that may be hundreds or even thousands of kilometers long. Diamonds have a high density (3.5 g/m^3), and during transport they can be concentrated in placers along with other heavy minerals. Placer diamonds occasionally reach economic quantities and produce placer deposits. These placer deposits can contain diamonds from more than one kimberlitic source and form in different geological environments. Most frequently, diamonds are concentrated in riverbeds where they form alluvial deposits. Other depositional environments include marine and beach settings. As a result, placer diamonds are often found in sandstones or conglomerates (Fig. 1-16). Diamonds are less commonly concentrated by wind to form aeolian placers.

Diamonds can also be distributed by glaciers. Although glaciers in modern times are limited in their extent, they were much more widespread during certain periods in Earth's history. For example, the extensive glaciations during the Late Carboniferous to Early Permian periods—around 300-270 million years ago—likely caused the dispersion of diamonds throughout large parts of the former supercontinent Gondwana.[197, 200, 299] The subsequent break-up of Gondwana and the rifting of its fragments distributed the diamonds onto continents that are now widely separated. As a result, some placer diamonds in southern Africa, Australia, and South America may be derived from common sources.[48, 92, 291]

Placer diamond deposits that form close to a kimberlite usually contain a high abundance of mantle-derived minerals that are associated with the diamonds. These mantle-derived minerals are compositionally distinct and are generally much more abundant than the diamonds themselves. As a result, these minerals are often used to locate kimberlite sources and are, therefore, referred to as indicator minerals.[79] The abundance of indicator

1-17: Mineral separation plant used for processing small-scale placer diamond deposits. Terowie, South Australia.

minerals declines with increasing distance from the kimberlite source. Therefore, diamond placer deposits that formed far from the original source may not contain any of the mantle-derived minerals. In these cases, it is much more difficult to locate the primary kimberlitic sources, and they often remain unknown.[258, 283, 289]

Placer deposits themselves can also be subjected to erosion, causing the diamonds to be dispersed again. In some cases, diamonds within a placer deposit may have gone through multiple cycles of erosion and deposition.[61] Placer deposits can also be subjected to thermal metamorphism, which may destroy or alter the minerals that were originally associated with the diamonds.

Placer deposits were the main sources of gemstone diamonds until the discovery of the diamondiferous kimberlites at Kimberley, South Africa, in the early 1870s. Diamonds have been mined from placer deposits since prehistoric times, but the mining was initially restricted to a few deposits mainly located in India. It was not until the 1730s that extensive placer deposits in Brazil were discovered, and these provided the bulk of the diamonds for around 150 years. A placer deposit in Brazil was also the source of the world's largest placer diamond, which was named Presidente Vargas and weighed 726.6 carats.[14]

The largest modern placer mining district is located along the west coast of southern Africa (e.g. Namaqualand, Oranjemund, and Lüderitz), where diamonds are recovered from beach and marine sediments, as well as from riverbeds.[99, 308, 315] The majority of the diamonds in these deposits are probably derived from eroded kimberlites that were located in the interior of southern Africa.[307]

Diamond placer deposits also exist in many other parts of the world (Fig. 1-11), but most of the placer diamond mining operations are on a small scale (Fig. 1-17).[3, 178] The combined placer diamond production, therefore, is much smaller than from primary kimberlitic deposits. Diamonds in placer deposits, however, are often of high quality because the transport has reduced the number of stones with imperfections.[279]

Diamonds from other sources

Outside the Earth's mantle, natural diamonds can form in a variety of ways. In all cases, their formation is due to unusually high pressure conditions. So far, none of the diamonds from such sources are of large enough size or of high enough quality to be of economic importance.

Metamorphic and other crustal diamonds

Diamonds have been identified as accessory components in metamorphic rocks from localities in central Asia, such as the Kokchetav massif in Kazakhstan and the Dabie Shan-Sulu terrain in China.[265, 319] The diamonds in these areas occur in crustal rocks, such as gneisses and crustal eclogites. It is believed that these diamonds formed as a result of continental plate collision that caused the rocks to undergo short-lived, high-pressure metamorphism. The resulting metamorphic diamonds are generally very small, in most cases only fractions of a millimeter in size. Subsequently, metamorphic diamonds were found in other parts of the world, including the Western Gneiss region of Norway and in the Erzgebirge in Germany.[62, 180]

In addition to their presence in metamorphic rocks, diamonds have recently been identified as minute (~ 1µm) inclusions in detrital zircon crystals from the Jack Hills, Western Australia.[186, 209] The host zircons are among the oldest known minerals, with ages of up to 4.2 billion years. Although it is not known how the enclosed diamonds formed, they are the oldest known terrestrial diamonds.

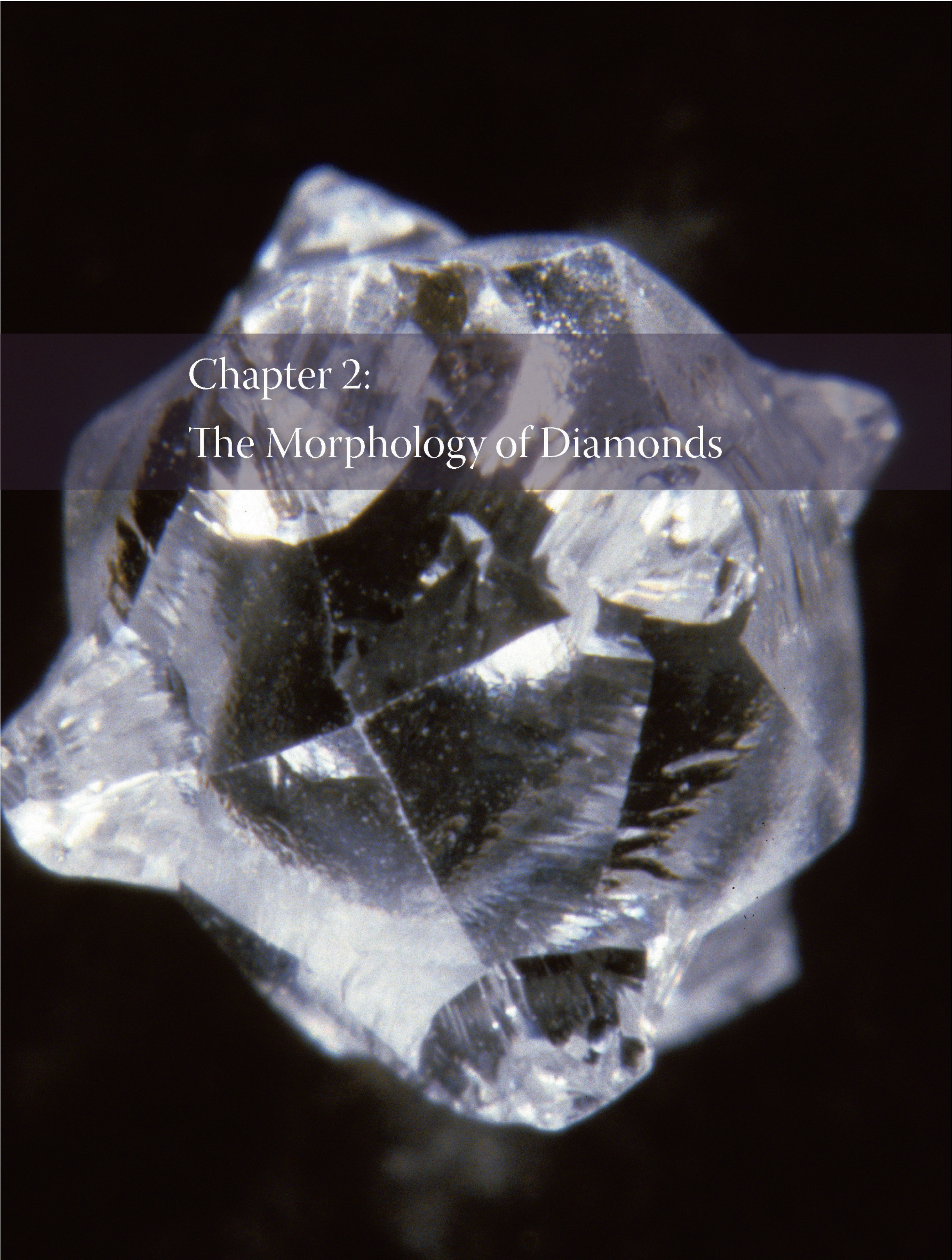
Meteoritic and impact diamonds

Diamonds have also formed as a result of meteorite impacts on the Earth's surface. The shock waves from a large meteorite impact can cause the pressures at an impact site to be temporarily high enough to allow diamonds to crystallize. As a result, carbonaceous matter at the impact site instantaneously converts to diamond. Diamonds that formed by meteorite impacts have been discovered at the Popigai impact structure in Russia, at the Nördlinger Ries in Germany, at the Sudbury impact structure in Canada, and at other localities.[65, 164, 179, 254] The presence of impact diamonds is generally restricted to the impact sites of larger meteorites. The diamonds that formed through meteorite impacts are generally small. Most of the diamonds are only fractions of a millimeter in size; however, some polycrystalline diamond aggregates linked to meteorite impacts can be larger than a centimeter.[145]

Diamonds are also known to be rare components of the meteorites themselves.[151] The diamonds in some types of meteorites, such as iron meteorites and ureilites, probably formed during collisions between meteorite parent bodies in space, and not during the impact on Earth.[35, 171] Similar to terrestrial impact diamonds, these diamonds are very small.

Another type of meteoritic diamonds has been recovered from some un-metamorphosed chondritic meteorites. The carbon isotope composition of these diamonds—which are only few nanometers in size—is very distinct from any other known carbon source. This indicates that the diamonds did not form within our solar system. These diamonds are considered to be presolar dust grains of interstellar origin that were incorporated into the chondritic meteorites as exotic mineral components.[2] These unusual diamonds possibly formed billions of years before our solar system and are some of the oldest minerals known.

Chapter 2:
The Morphology of Diamonds



Previous page –
Diamond from the
Diavik mine, Northwest
Territories, Canada.

Chapter 2:

The Morphology of Diamonds

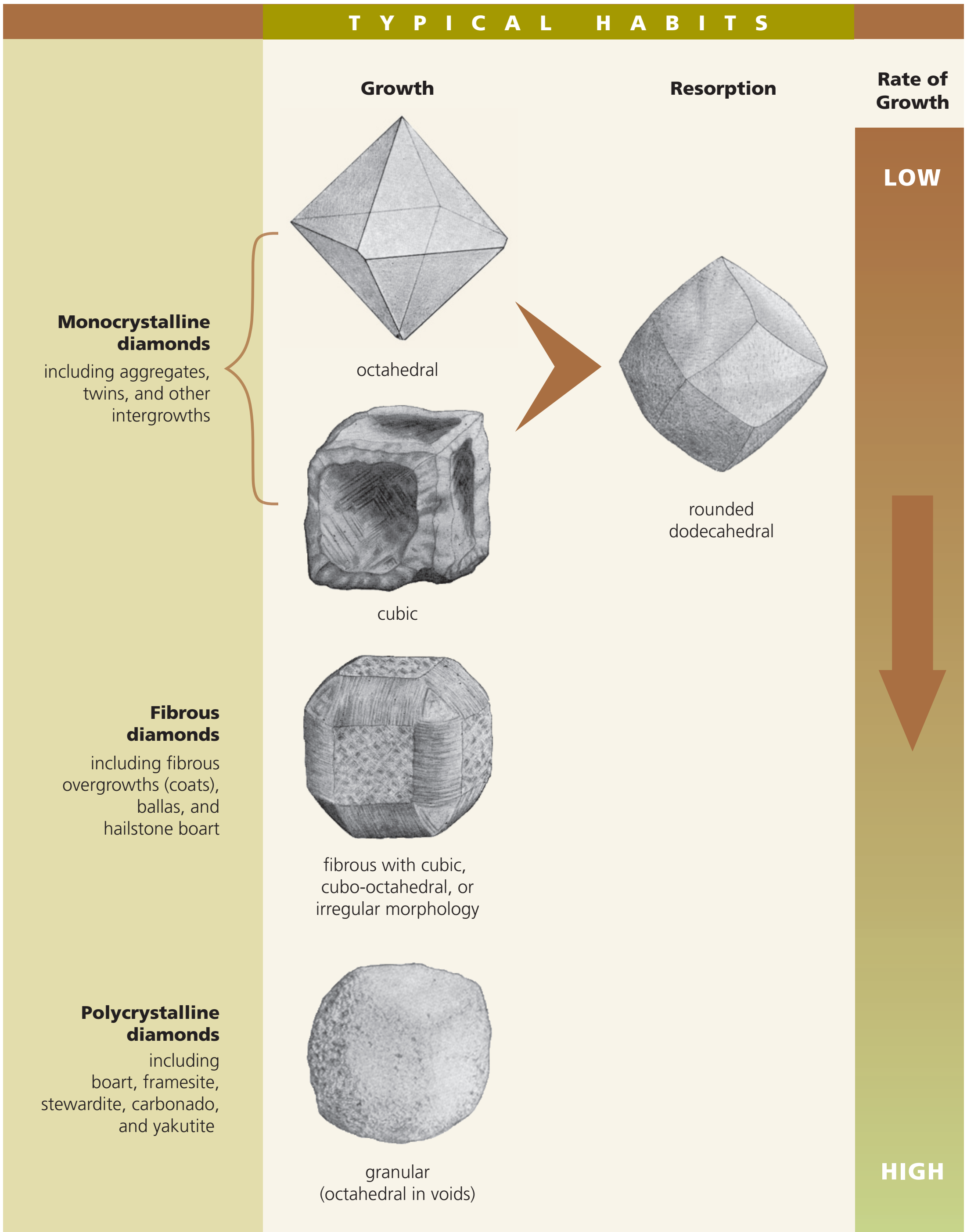
Natural diamonds occur as single crystals, as aggregates of a few crystals, or as clusters of countless small crystallites. The different morphologies (i.e. shape, size, number of crystals, etc.) reflect the growth conditions and provide valuable information about the processes that led to the diamond formation.

The classification and interpretation of the morphologies of diamonds has been a matter of debate for more than a century. Initial studies of diamonds were mostly descriptive, and they often focused on diamonds from a specific deposit or region.[76, 281, 315] More comprehensive diamond classifications were subsequently developed. The classification scheme of Orlov (1977), for example, distinguishes eleven types of diamonds (varieties I-XI) based on differences in their morphology.[214, 215] Other, more generalized diamond classification schemes emphasize the growth mechanisms (i.e. single crystal growth, fibrous growth, etc.) that produce the different morphological types of diamonds.[277, 278, 314]

Based on differences in morphology and growth mechanisms, three principle types of diamond are distinguished in this text: monocrystalline diamonds, fibrous diamonds, and polycrystalline diamonds (Fig. 2-01).

- **Monocrystalline diamonds** consist of single diamond crystals, but some aggregates, twins, and other intergrowths also belong to this type. In any case, the number of individual crystals is small.
- **Fibrous diamonds** are composed of numerous elongated fibers of microscopic size. The overall morphologies of fibrous diamonds, however, can resemble those of some monocrystalline diamonds. Fibrous diamonds can also occur as fibrous overgrowths (coats) around other types of diamonds.
- **Polycrystalline diamonds** consist of countless small diamond crystallites, and they usually occur as indistinct masses.

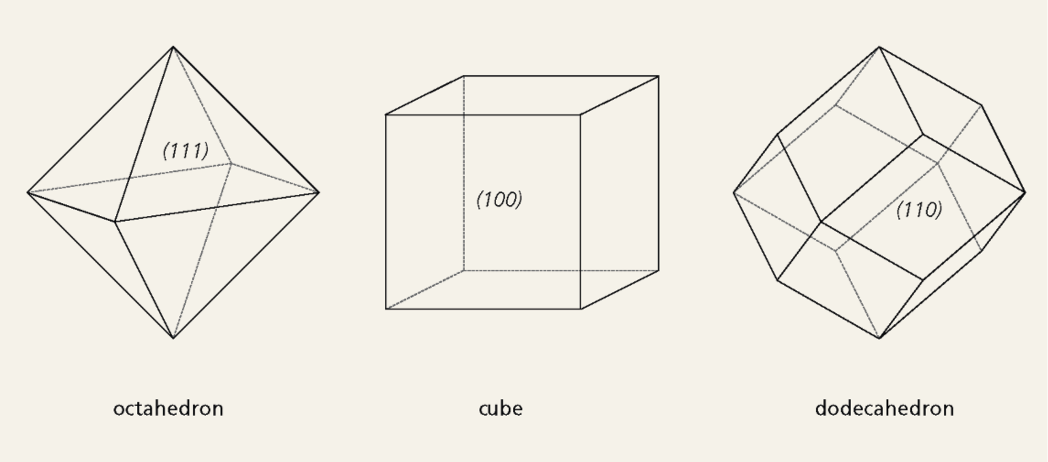
R. Tappert and M.C. Tappert, *Diamonds in Nature: A Guide to Rough Diamonds*,
DOI 10.1007/978-3-642-12572-0_2, © Springer-Verlag Berlin Heidelberg 2011



2-01: Classification of diamonds based on morphological characteristics and growth mechanisms. Drawings by Fersmann and Goldschmidt (1911).

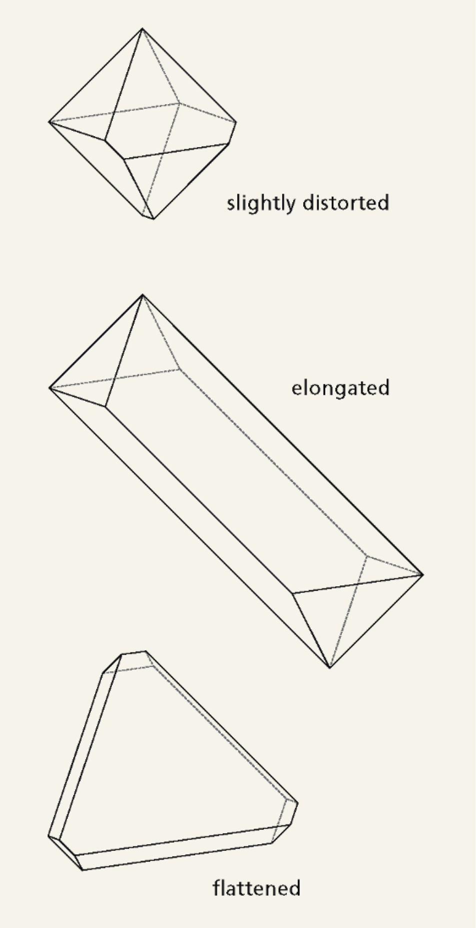
Monocrystalline diamonds

The external shape (habit) of most naturally occurring monocrystalline diamonds is restricted to three basic geometric forms: the octahedron, the cube, and the rhombic dodecahedron (Fig. 2-02). Only the octahedral and the cubic habit, however, represent genuine growth habits of monocrystalline diamonds. The dodecahedral habit is generally the result of resorption.[76, 202] Even though kimberlites and placer deposits usually contain diamonds with a wide range of habits, these variations are solely the result of these three basic geometric forms being modified.



2-02: Basic geometric forms that underlie the crystal habits of monocrystalline diamonds. Miller indices denote the principle crystal faces.

2-03: Diamond octahedron with minor resorption at the crystal edges (1.08 ct). The crystal faces exhibit several triangular etch pits (trigons).



2-04: Distorted octahedral habits.

Octahedral diamonds

The octahedral habit is the most common growth habit of natural diamonds (Fig. 2-03). The ideal octahedron consists of eight equally-sized triangular faces. Very few diamonds, however, approximate the ideal octahedron; instead, most are distorted. This distortion occurs when one growth direction is favored over another. A distorted octahedral diamond can have additional edges instead of pointed corners and/or edges of unequal lengths. A high degree of distortion can result in an elongated or flattened diamond (Fig. 2-04). In addition, the development of numerous growth layers can produce a stepped appearance (Fig. 2-05). Whether ideal or distorted, the development of an octahedral habit indicates that the diamond grew slowly, typically layer-by-layer, under relatively stable conditions.[115, 251, 277]

2-05: Stepped, octahedral diamond with slightly rounded crystal edges (0.96 ct).

The majority of octahedral diamonds show signs of modification caused by resorption that took place after their growth. The resorption is usually linked to the exposure of the diamond to the kimberlitic magma during transport to the Earth's surface. Kimberlitic magmas can contain high concentrations of oxidizing agents, namely CO_2 and H_2O. At high temperatures, these oxidizing agents are detrimental to the diamond and can partially or completely resorb an octahedral diamond. It is notable that diamonds found enclosed in xenoliths are often sharp-edged octahedral diamonds because they were protected by the xenoliths from direct exposure to the kimberlitic magma (Fig. 1-06).[253, 267]

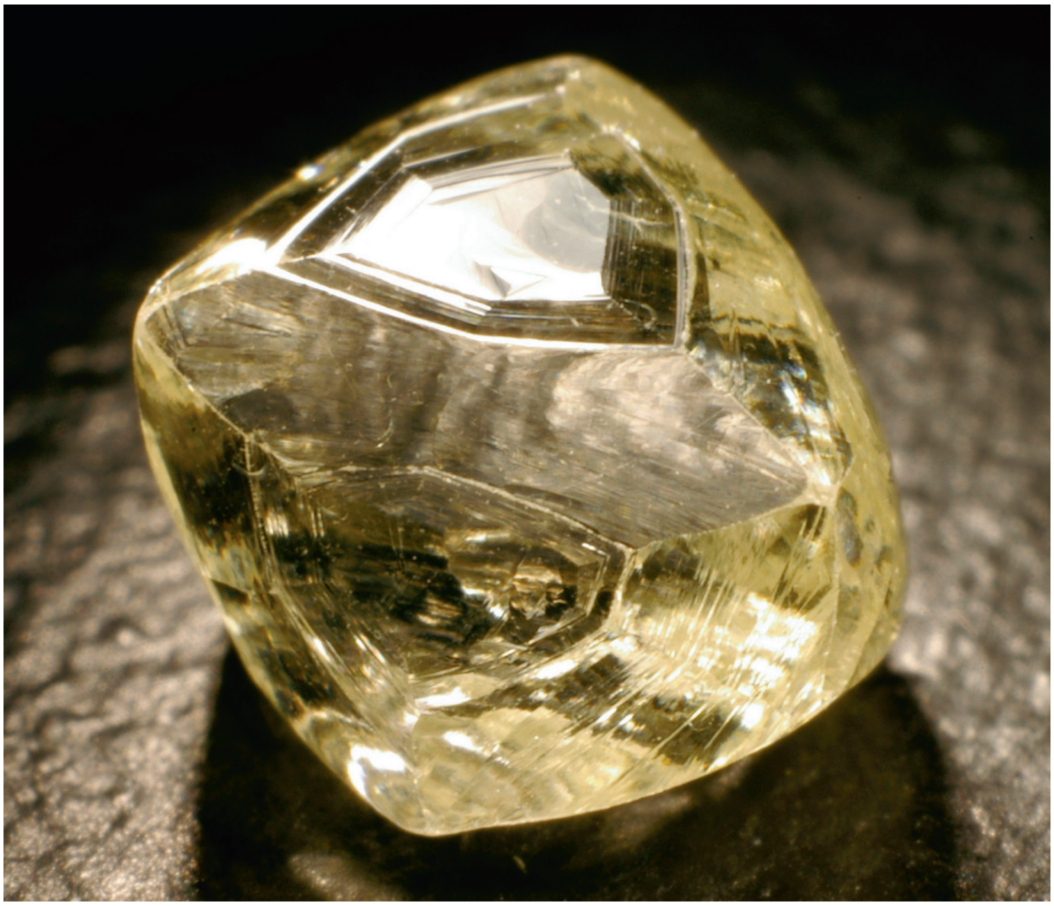
For an octahedral diamond, the start of resorption is marked by the development of rounded corners and edges. In this initial stage, the resorption only affects the most protruding features, such as pointed corners and sharp edges (Fig. 2-06). The less protruding features, including the crystal faces, are affected as resorption progresses (Fig. 2-07, Fig. 2-08, Fig. 2-09). Resorption continues until entire octahedral crystal faces disappear. The complete loss of octahedral crystal faces results in a rounded dodecahedral habit (Fig. 2-10). The transition from an octahedral to a dodecahedral habit is associated with a considerable loss of the diamond's original volume (Fig. 2-11).

2-06: Octahedral diamond with resorbed crystal edges and corners (0.96 ct). Numerous triangular etch pits (trigons) indicate that the octahedral crystal faces were also affected by the resorption.

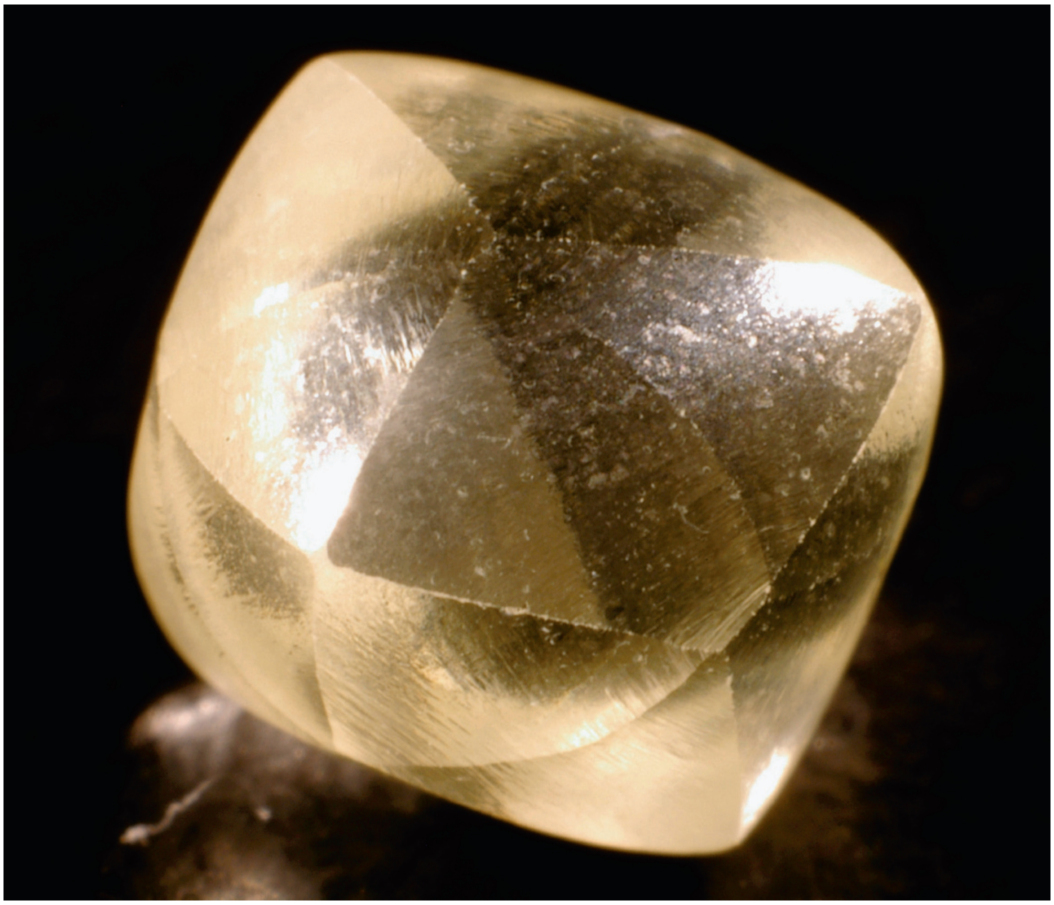
2-07: Partially resorbed (~20%), pale yellow diamond with a habit transitional between octahedron and dodecahedron (1.05 ct). The crystal edges and corners are extensively rounded, and the octahedral crystal faces are reduced in size.

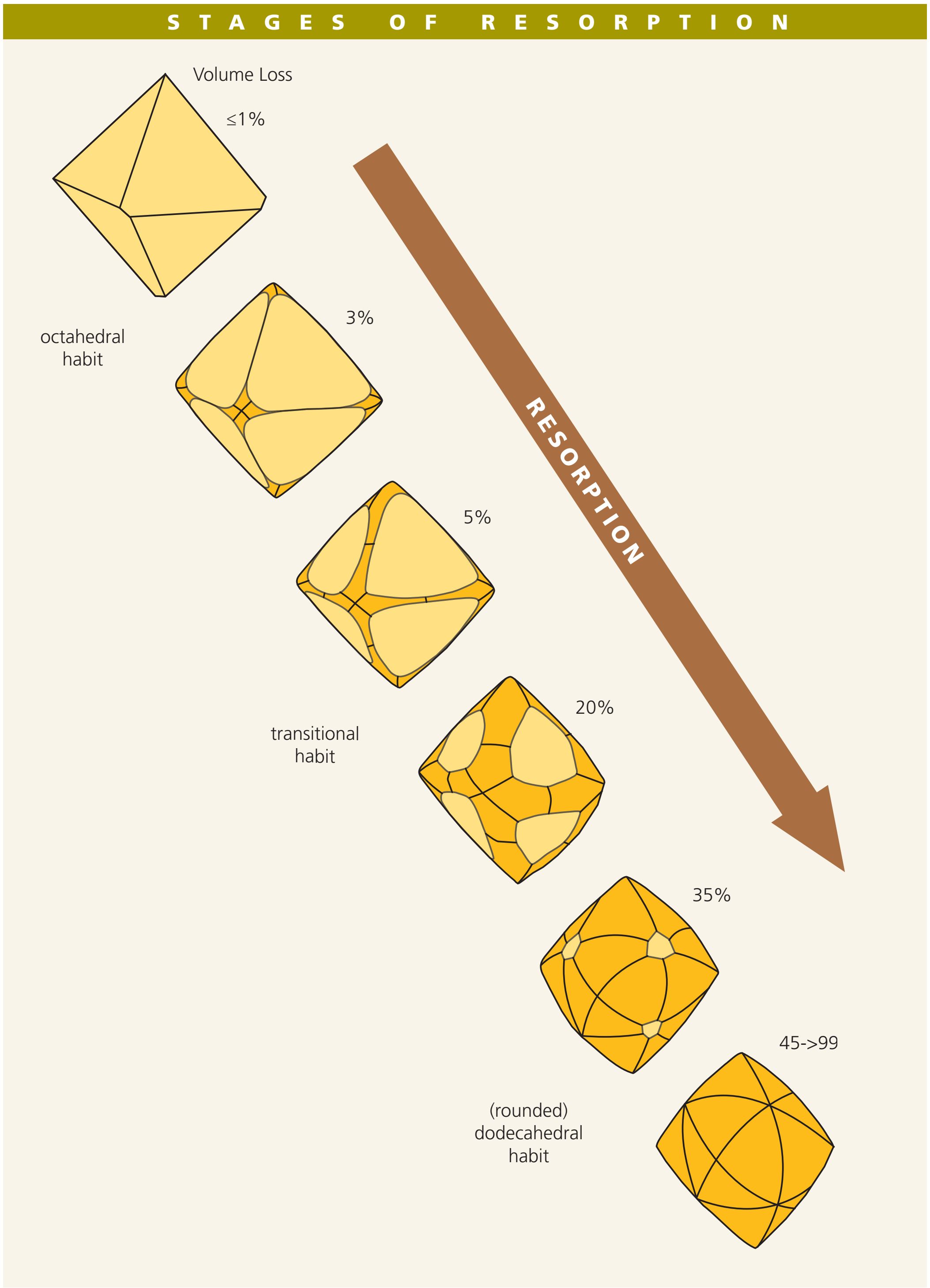
2-08: Diamond with a transparent green surface color exhibiting a habit transitional between octahedron and dodecahedron (0.92 ct).

2-09: Yellow diamond with a habit transitional between octahedron and dodecahedron (0.99 ct).



2-10: Diamond with fully developed rounded dodecahedral habit (1.20 ct).

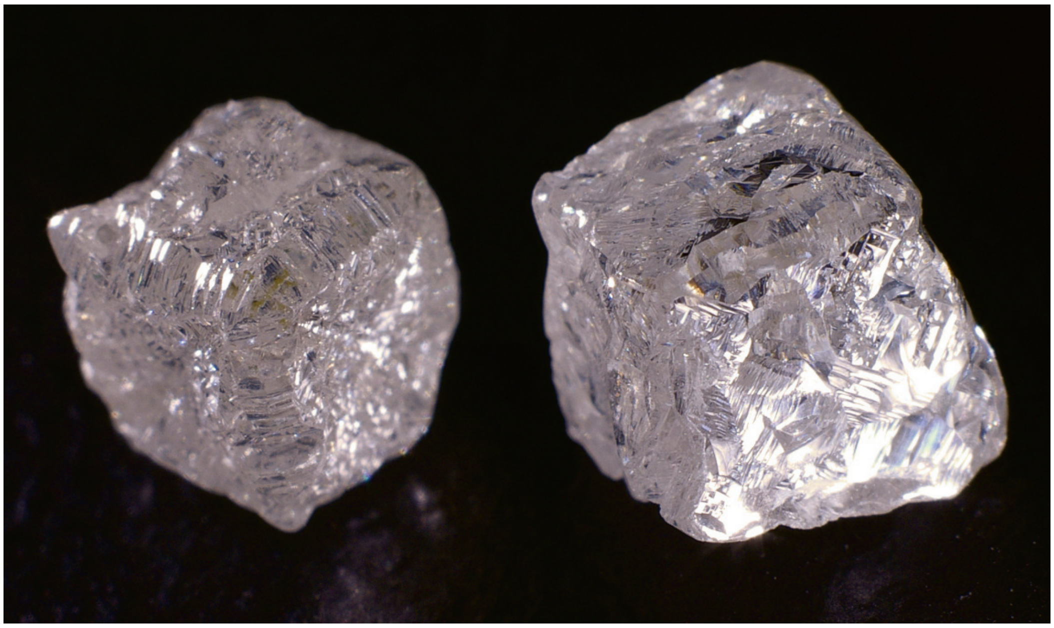




2-11: The stages of resorption for an octahedral diamond. Modified from McCallum et al. (1994).

Although the degree of resorption varies from crystal to crystal, diamond populations within each deposit usually have distinctive resorption attributes.[42, 111, 315, 324] In other words, each deposit contains diamonds with a characteristic distribution of resorbed and un-resorbed crystals. The distribution can vary as a function of crystal size or other physical properties of the diamonds.[109]

Deposits that produce a high percentage of sharp-edged octahedral diamonds are located in Russia (e.g. Mir, Udachnaya),[214, 325] Canada (e.g. Ekati, Diavik),[100, 160] China,[113] and Sierra Leone (e.g. Koidu).[91]



2-12: Monocrystalline diamond cubes with characteristic rugged crystal faces (each ~1.0 ct). The transparency of these monocrystalline diamond cubes contrasts with the cloudiness of fibrous diamond cubes.

Diamond cubes

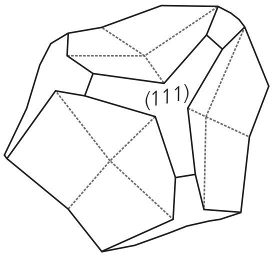
A small number of monocrystalline diamonds exhibit a distinctive cubic habit. These diamonds always have conspicuously rugged crystal faces and rounded edges (Fig. 2-12). In addition to being rugged, the crystal faces of diamond cubes are often curved, either towards the inside (re-entrant) or the outside (salient) (Fig. 2-13). In some cases, the inward curvature is so extreme that the diamond develops a skeletal appearance. These diamonds are referred to as re-entrant cubes (Fig. 2-14, Fig. 2-15).[282] Diamond cubes with crystal faces that have a strong outward curvature can develop a rounded form that resembles a tetrakis-hexahedron (Fig. 2-16). Because they lack flat, crystallographically bound crystal faces, diamond cubes are sometimes referred to as cuboids.

Although the cubic habit is rare among monocrystalline diamonds, it is very common among fibrous diamonds. Compared to typical transparent and clear monocrystalline diamonds, fibrous diamond cubes are generally non-transparent and have a dull appearance. Fibrous diamond cubes, however, may not always be visually distinguishable from monocrystalline diamond cubes.

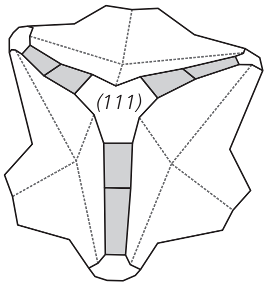
Studies of the zoning patterns of monocrystalline diamond cubes have shown that their internal structures can be quite complex and that the cubic growth was frequently disturbed by octahedral growth episodes.[168, 201, 251] In comparison, some octahedral diamonds show evidence that their development was interrupted by cubic growth episodes.[115]

Although octahedral growth can occur in combination or alternating with cubic growth, it is rare to find natural monocrystalline diamonds with a distinct cubo-octahedral habit. Synthetic diamonds, in contrast, can be produced as flat-faced and sharp-edged, cubo-octahedra (Fig. 3-11).[77] The growth habit of synthetic diamonds depends largely on the temperature conditions.[321] At relatively high temperatures, synthetic diamonds crystallize as octahedra, whereas cube and cubo-octahedral habits develop at lower temperatures (Fig. 2-17). This relationship, however, is not directly applicable to natural diamonds because the growth mechanisms between synthetic and natural diamonds differ considerably.

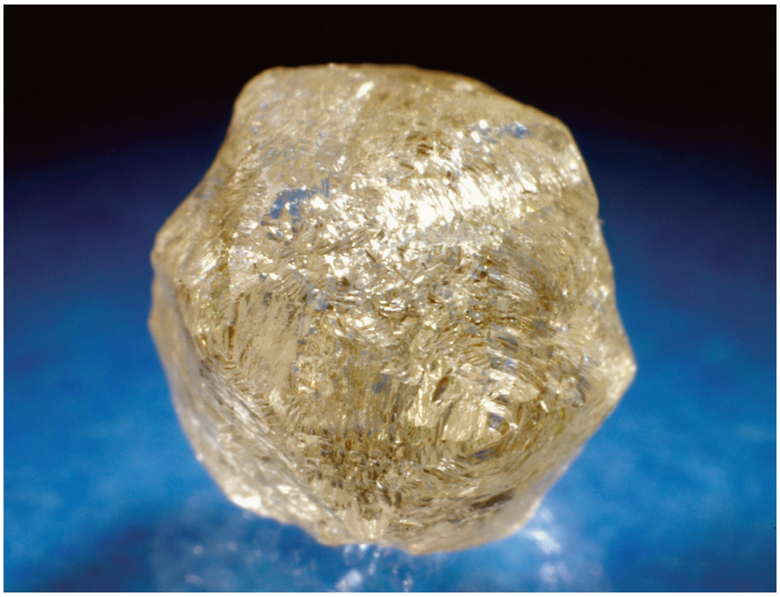
2-13: Diamond cubes with different types of surface development. Drawings from Fersmann and Goldschmidt (1911).



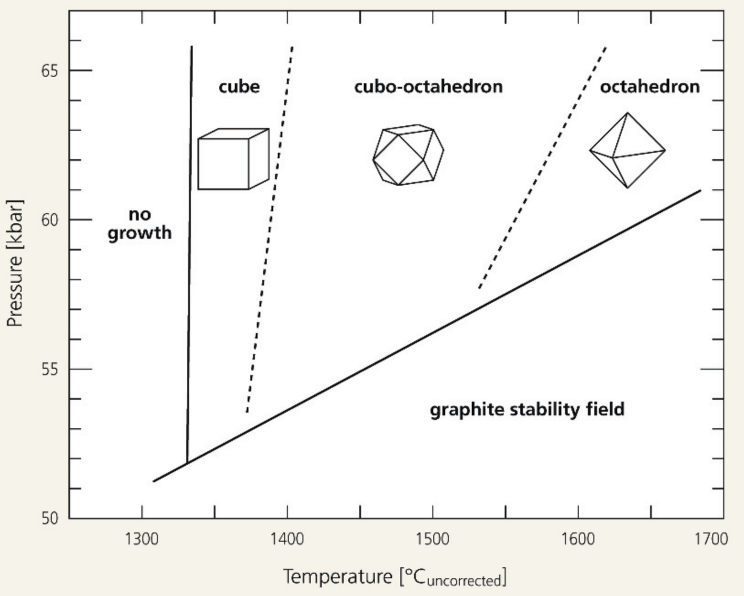
2-14: *Left,* Re-entrant diamond cube (1.19 ct). The strongly concave crystal faces result in a skeletal appearance. *Above,* Simplified representation of the crystal faces. Miller indices mark subordinate octahedral crystal faces.



2-15: *Left,* Re-entrant diamond cube with re-entrant facets along the crystal edges (1.03 ct). *Above,* Simplified representation of the crystal faces. The re-entrant facets along the crystal edges are marked in grey.



2-16: Diamond cube with strongly convex crystal faces that result in a rounded appearance (1.00 ct).



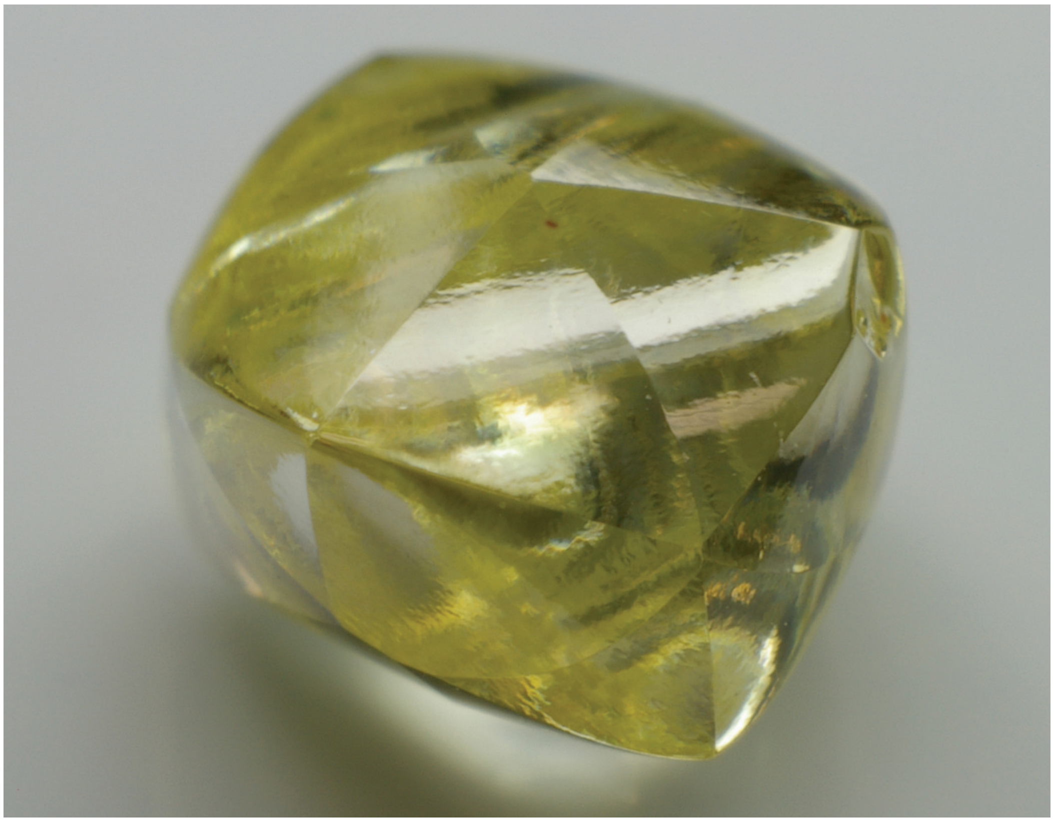
2-17: Pressure-temperature diagram outlining the fields of different growth shapes for synthetic diamonds. Modified from Yamaoka et al. (1977).

In nature, other factors, such as the degree of carbon oversaturation in the diamond-forming fluids (i.e. carbon availability), are likely to have an important influence on the growth habit of the diamond.[277] Diamond cubes are likely to form under slightly higher carbon supersaturation conditions and to grow more rapidly compared to octahedral diamonds.

Monocrystalline diamond cubes are generally rare, and only a small number of diamond deposits produce significant quantities, including the Diavik and Ekati mines in Canada,[100] the Jwaneng and Orapa mines in Botswana,[312] and the Udachnaya mine in Russia.[325]

Diamond cubes can also show signs of resorption. Similar to octahedral diamonds, resorption causes rounding of the corners and edges (Fig. 2-18). The original edges and crystal faces disappear as the resorption progresses, and the diamond develops a dodecahedral or texahexahedral habit.

2-18: Unusual, knobbed diamond from the Diavik mine, Northwest Territories, Canada (Ø: ~5 mm). This diamond may represent a strongly resorbed re-entrant diamond cube. In this case, the conspicuous knobs mark the position of former octahedral crystal faces.

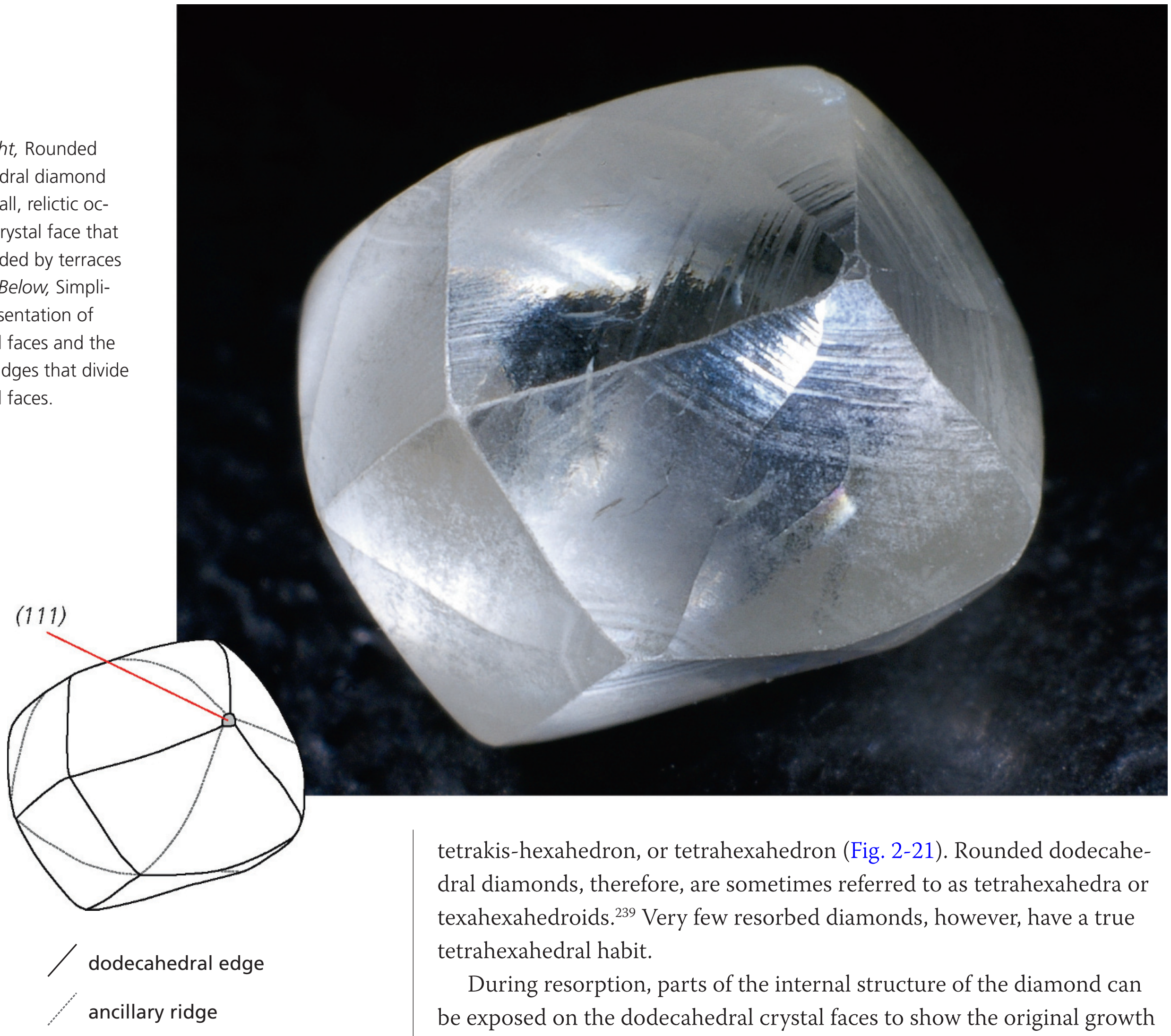


2-19: Slightly flattened, rounded dodecahedral diamond from Echunga, South Australia (0.46 ct).

Dodecahedral diamonds

The dodecahedral habit of natural diamonds is always the result of resorption.[76, 202] The resorption can take place while the diamonds reside in the mantle or during exposure of the diamond to a kimberlitic magma. Two factors influence the habit of a dodecahedral diamond: the original growth habit and the extent of resorption. Resorption usually starts at the corners and the edges, and it gradually transforms a diamond with an octahedral or cubic growth habit into a diamond with a dodecahedral habit (Fig. 2-19).[239] The transition from a growth habit to a dodecahedral resorption habit is linked to a significant loss of volume (Fig. 2-11). A non-distorted diamond with an octahedral habit loses at least 45% of its volume when transformed into a rounded dodecahedron without relictic octahedral faces.[182] Remnants of the original crystal faces may still exist on dodecahedral diamonds that have undergone only weak or moderate resorption (Fig. 2-20).

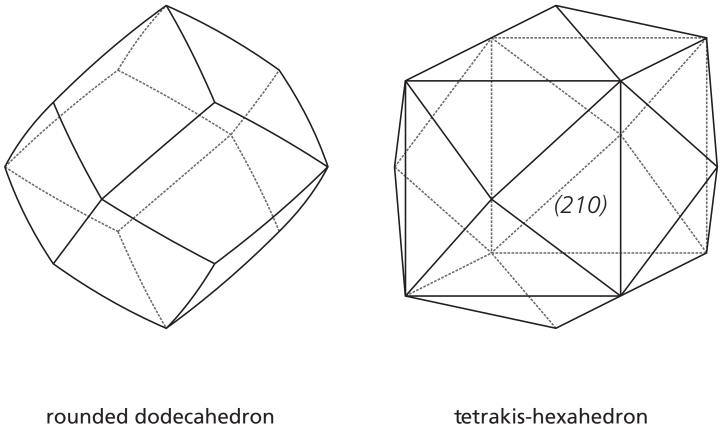
The ideal dodecahedron consists of twelve equally-sized rhombic faces (Fig. 2-02). In contrast to this ideal geometry, the faces of dodecahedral diamonds are always convex, which causes the diamonds to appear rounded. The rounded surfaces are not true crystal faces, and so the dodecahedral habit of diamonds is sometimes described as dodecahedroid.[214] Some dodecahedral diamonds are spherical, but many are flattened, elongated, or distorted in other ways. The crystal faces commonly exhibit an ancillary straight or undulating ridge that connects their shortest diagonals (Fig. 2-20). In most cases, this ridge is a minor feature, but occasionally it is quite prominent. If regarded as a true crystal edge, the presence of this ridge would double the number of crystal faces from twelve to twenty-four. In this case, the idealized polyhedron would be a



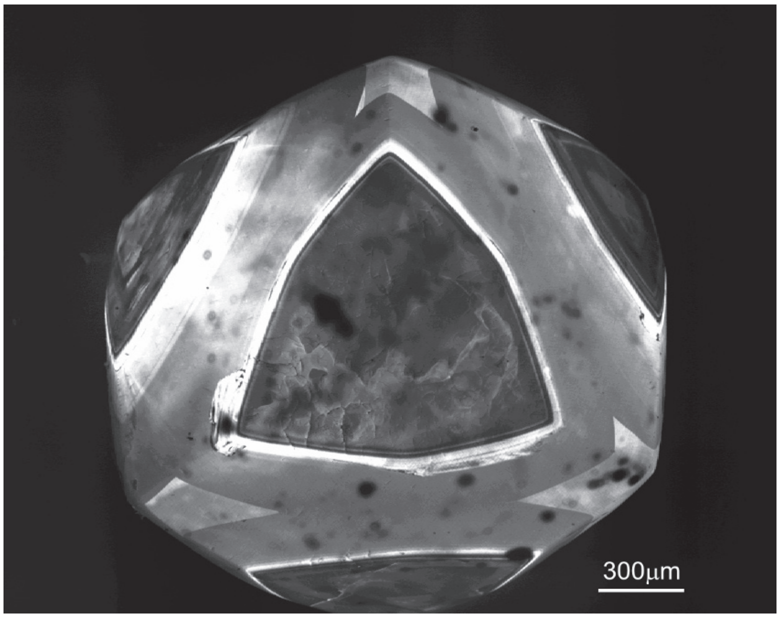
2-20: *Right,* Rounded dodecahedral diamond with a small, relictic octahedral crystal face that is surrounded by terraces (0.92 ct). *Below,* Simplified representation of the crystal faces and the ancillary ridges that divide the crystal faces.

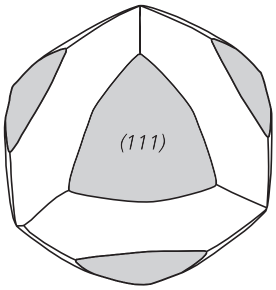
tetrakis-hexahedron, or tetrahexahedron (Fig. 2-21). Rounded dodecahedral diamonds, therefore, are sometimes referred to as tetrahexahedra or texahexahedroids.[239] Very few resorbed diamonds, however, have a true tetrahexahedral habit.

During resorption, parts of the internal structure of the diamond can be exposed on the dodecahedral crystal faces to show the original growth zones. Although these growth zones may not be visible in normal light, they can often be observed using high-energy radiation, such as UV-light or electron beams (Fig. 2-22).



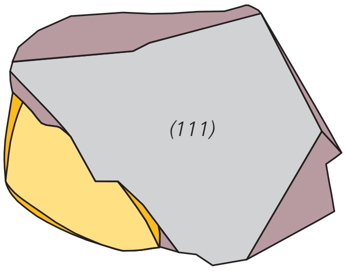
2-21: Comparison between a rounded dodecahedron and a tetrakis-hexahedron.





2-22: *Above,* Cathodoluminescence image of a partially resorbed diamond with a transitional habit from an alluvial deposit at Arenapolis, Mato Grosso, Brazil (0.07 ct). Octahedral growth layers of the diamond, which were exposed by resorption, are visible on dodecahedral crystal faces. Relictic octahedral crystal faces are marked by weak cathodoluminescence (dark tones). Scattered dark round spots are caused by irradiation damage. *Right,* Simplified representation of the external shape. Relictic octahedral crystal faces are grey.

In some cases, only a part of the diamond exhibits a dodecahedral habit while the remaining part retains the octahedral or cubic growth habit. This combination of growth and resorption habits is referred to as pseudohemimorphism (Fig. 2-23). A pseudohemimorphic habit can result from a diamond being partially enclosed in a xenolith during ascent to the Earth's surface. In this case, the enclosed part of the diamond is protected from the kimberlitic magma, and its growth habit is preserved. The parts exposed to the magma undergo resorption and develop a dodecahedral habit.[43, 223, 241]



2-23: *Left,* Pseudohemimorphic diamond from the Springfield Basin, South Australia (0.02 ct). *Above,* Simplified representation of the main crystal faces showing the rounded dodecahedral (bottom left) and octahedral (right) parts.

2-24: A group of irregular diamonds from Santa Elena, Bolivar Province, Venezuela. The largest diamond is ~8 mm in diameter.

Irregular diamonds

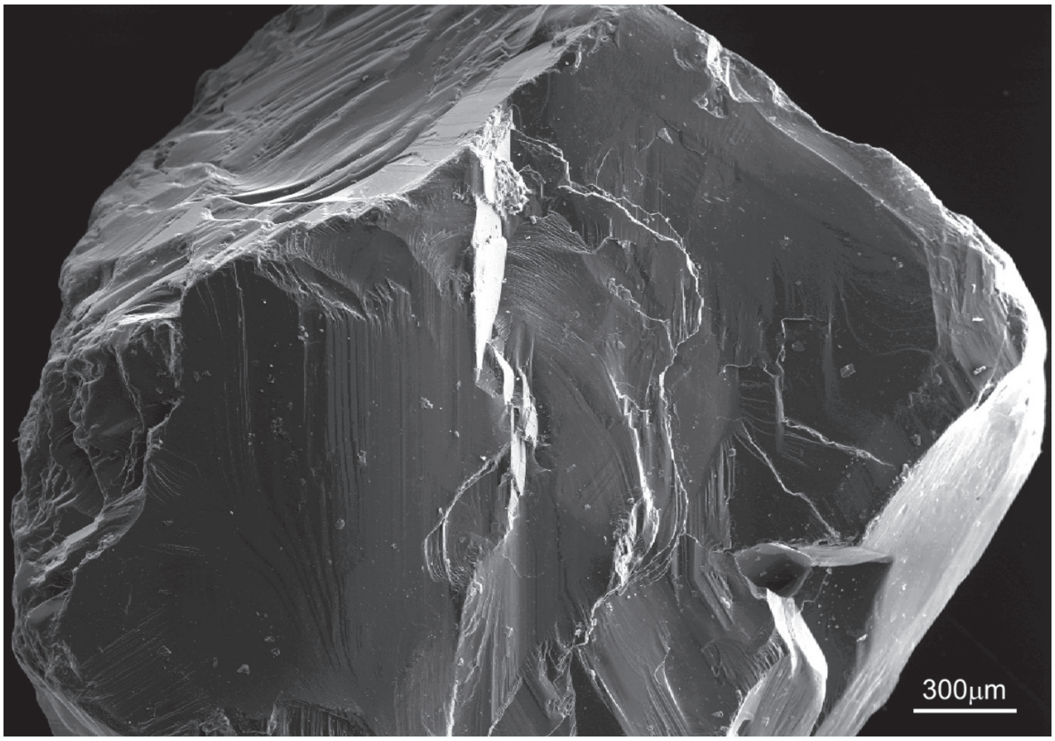
Diamonds are classified as irregular if they do not exhibit an identifiable crystal shape or if their existing shape is largely incomplete (Fig. 2-24). Irregular diamonds occur frequently, and they even represent the majority of diamonds at some deposits.[109] It is notable that irregular diamonds are particularly common among Type II diamonds, and most of the very large diamonds (> 500 carats), such as the Cullinan diamond (3,106 carats), belong in this category.[89, 199] Besides the absence of well-developed crystal faces, these diamonds are generally characterized by distinctly smooth and undulated surfaces (Fig. 2-25, Fig. 2-26).

Photo courtesy of Petra Diamonds.

2-25: Exceptionally large diamond—weighing 507.55 carats—from the Cullinan (formerly Premier) mine, South Africa. Its irregular shape is typical for large diamonds, which are also mostly Type II diamonds. Around 1.5 times its natural size.

2-26: Irregular diamond with a smooth undulated surface and a light brown color (1.19 ct). The appearance of this diamond is typical for Type II diamonds. This diamond also contains several colorless mineral inclusions.

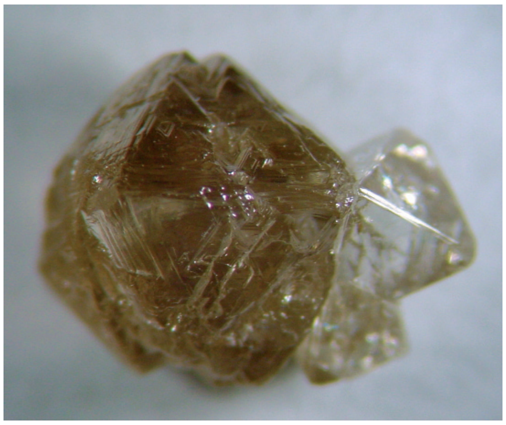
Fragmented diamonds are another type of irregular diamond. Their fracture planes are often flat or slightly conchoidal, and they exhibit conspicuous stepping (Fig. 2-27). The fragmentation of a diamond can occur in the mantle or during its ascent to the surface in a kimberlitic magma. The presence of etched or resorbed fracture surfaces provides evidence that the fragmentation occurred during or before entrainment in the kimberlitic magma. In the case of placer diamonds, the fragmentation can occur during transport in a high energy environment (e.g. in a river). In other cases, fragmentation may be linked to damages that were caused by the mining process.



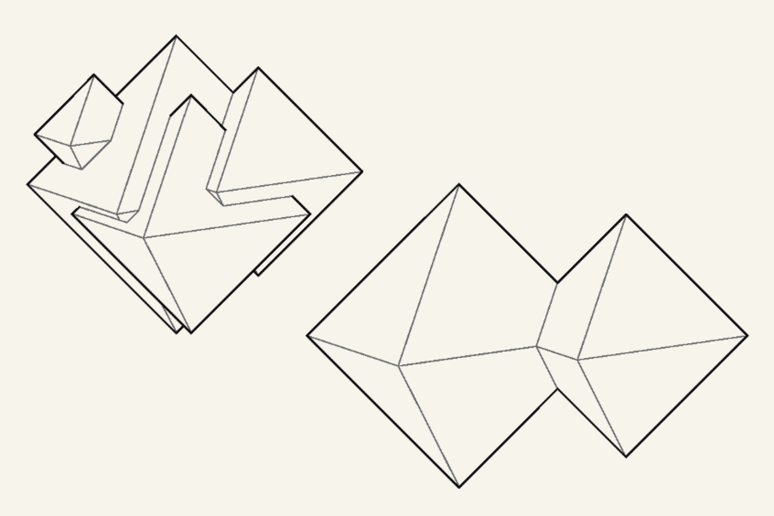
2-27: Scanning electron microscope (SEM) image of a diamond fragment showing the characteristic stepping of fracture planes.

Aggregates, parallel intergrowths, and twins

Aggregates, parallel intergrowths, and twins consist of two or more intergrown diamond crystals. Aggregates are composed of randomly oriented crystals (Fig. 2-28), whereas parallel intergrowths and twins consist of crystals that are aligned along crystallographic planes. In contrast to parallel intergrowths, which consist of crystals that are oriented in the same direction (Fig. 2-29, Fig. 2-30), the individual crystals in twins are oriented in different, yet crystallographically controlled directions.

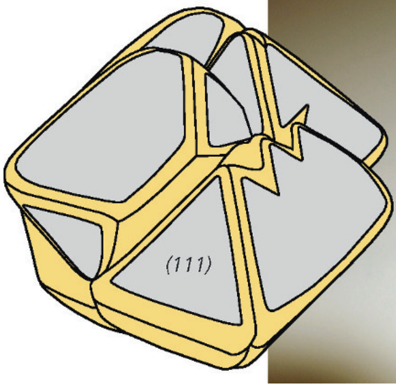


2-28: Aggregate of brown and colorless octahedral diamonds (Ø: ~5 mm).



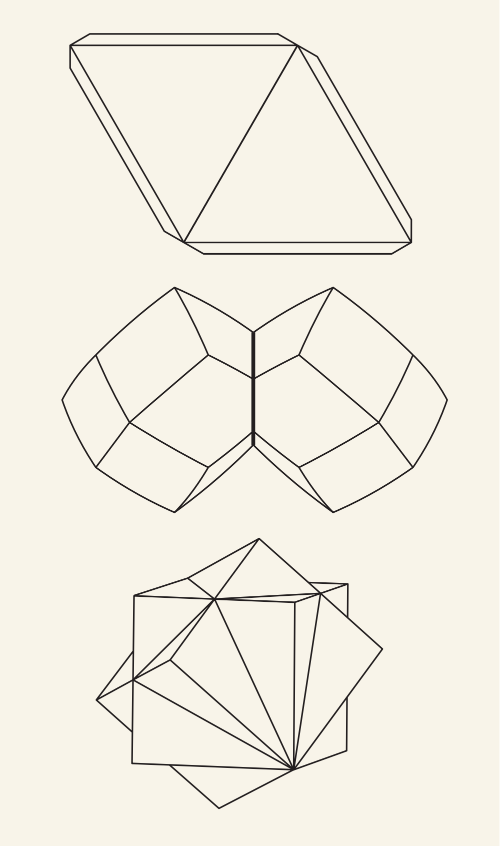
2-29: Examples of parallel intergrowths in diamonds.

2-30: *Right,* Parallel intergrowth of multiple octahedral diamond crystals, which are covered by a thin fibrous coat (0.90 ct). *Below,* Simplified representation of the main crystal faces.



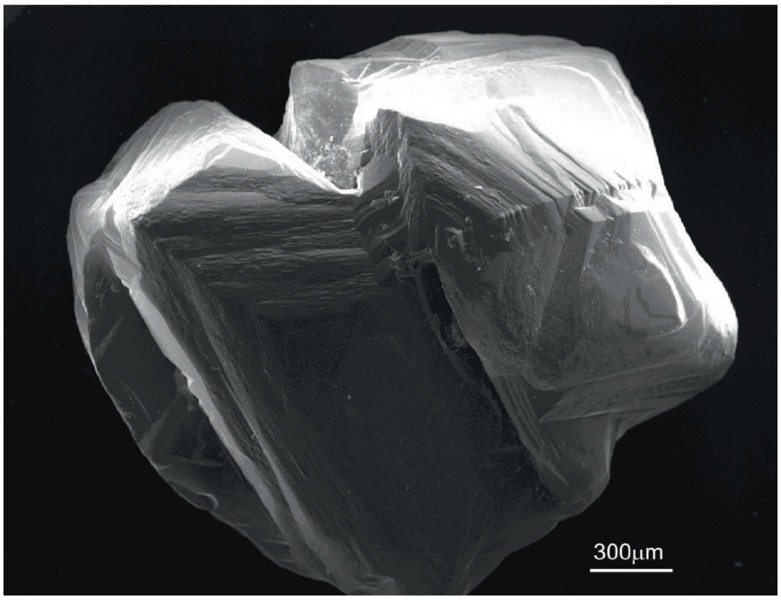
The individual crystals in twinned diamonds can be connected along external crystal faces, in which case they are contact twins. If they are connected along internal planes, they are referred to as interpenetrant twins. Some twinned diamonds exhibit very distinctive morphologies, and these diamonds can be easily identified as twins (Fig. 2-31, Fig. 2-32). In other cases, the twining is more subtle and can be restricted to certain parts of the diamond, for example in lamellar twins (Fig. 2-33).

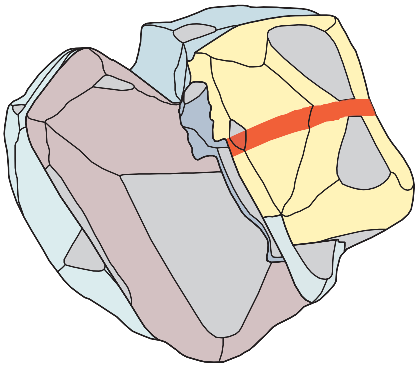
It is often possible to recognize a twinned diamond by the presence of a straight twinning line that marks the contact between the diamond crystals. The twinning line mirrors the crystals on either side. Although diamond twins are common, the twinning might not be obvious, and additional analytical techniques may be required to determine the nature of the twinning within a diamond.[198]



2-31: *Above,* Examples of twinning in diamond. *Top:* "arrowhead" twin. *Middle:* dodecahedral contact twin. *Bottom:* interpenetrant cube.

2-32: Typical flat triangular macles (~1.0 ct each). Macles are common diamond twins that are easily identifiable by their characteristic shape.

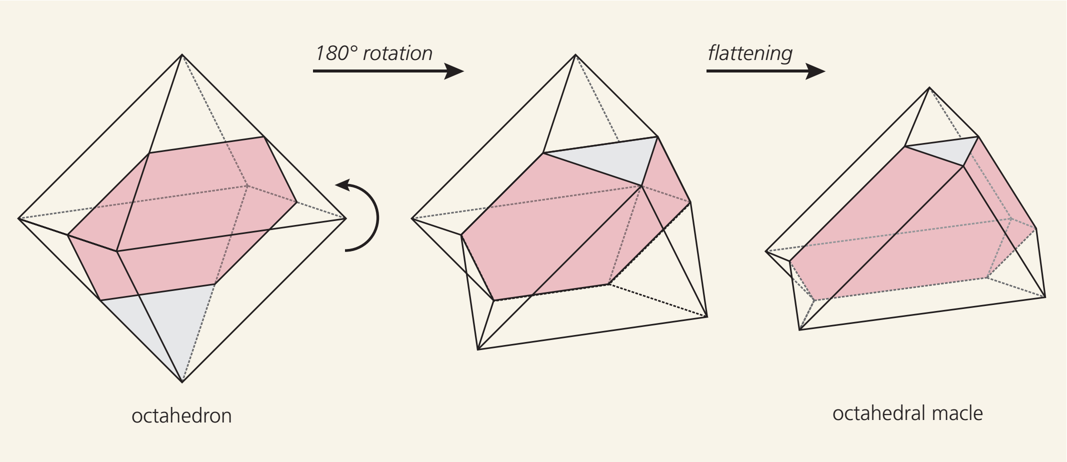




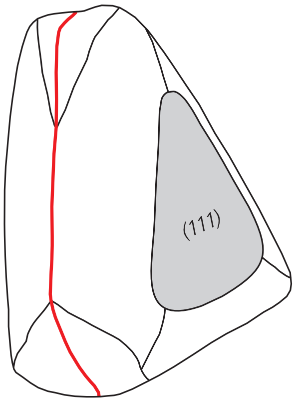
2-33: *Left,* Scanning electron microscope (SEM) image of a complex diamond aggregate. One crystal contains a lamellar twin, which is marked by two twinning lines. *Above,* Simplified representation of the diamond aggregate. Lamellar twin in red.

Contact twins

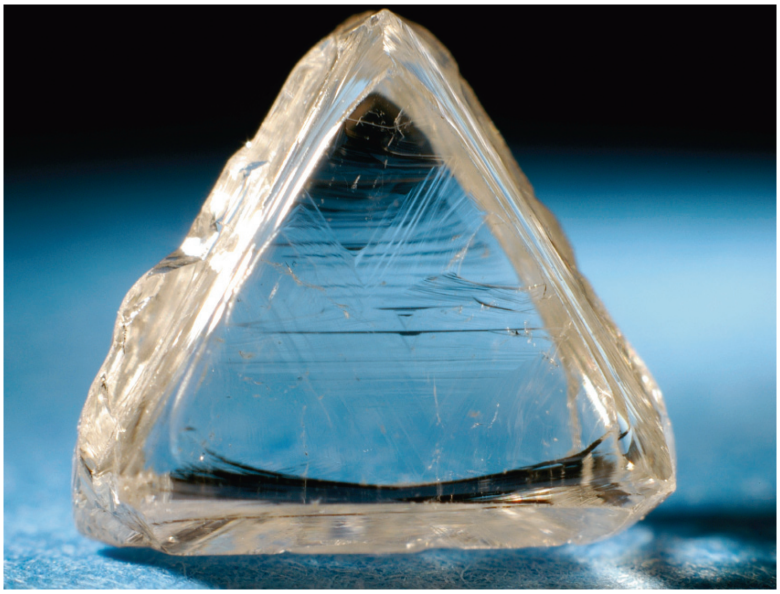
The most distinct type of contact twins is the triangular macle (French for twin) (Fig. 2-32). A macle is an intergrowth of two flattened octahedral crystals that are connected along an octahedral plane, with one of the crystals being oriented in the opposite direction. This orientation can be viewed as one crystal being rotated in the contact plane by 180° with respect to the other crystal (Fig. 2-34).[1, 320] Macles, at first glance, may resemble flattened octahedral diamonds, but the presence of a twinning line distinguishes macles from un-twinned diamonds (Fig. 2-35). As a result of resorption, macles can loose their sharp edges and develop a rounded dodecahedral habit (Fig. 2-36, Fig. 2-37). Ultimately, the resorption can fully convert macles into flattened dodecahedral diamonds that are only distinguishable from their single crystal counterparts by the presence of a twinning line (Fig. 2-38). Macles are quite common and can comprise a considerable fraction of the diamond population within a deposit. At some South African mines, for example, an average of 10-15% of the diamonds are macles.[109, 257]



2-34: Diagram illustrating the geometric relationship between an octahedron and a flattened octahedral macle. A reference plane is shaded grey. The twinning plane is shaded pink.



2-35: *Right,* Side view of a macle from the Bow River alluvial deposit, Western Australia (1.23 ct). The diamond shows the characteristic tabular habit of macles. *Above,* Simplified representation of the main crystal face, and the location of the twinning line (red).

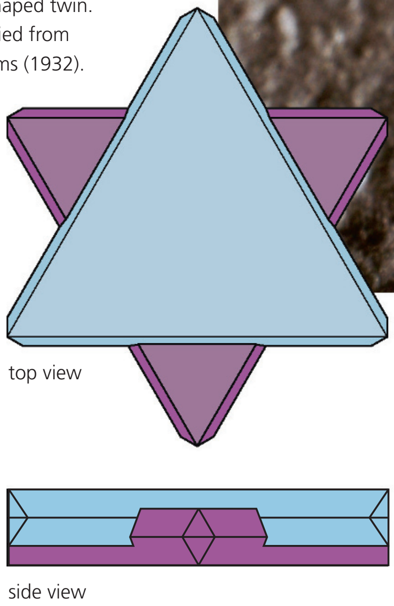


2-36: Octahedral macle with characteristic triangular outline (0.99 ct).

2-37: Resorbed octahedral macle with rounded edges and negative trigons on relictic octahedral crystal face (1.20 ct).

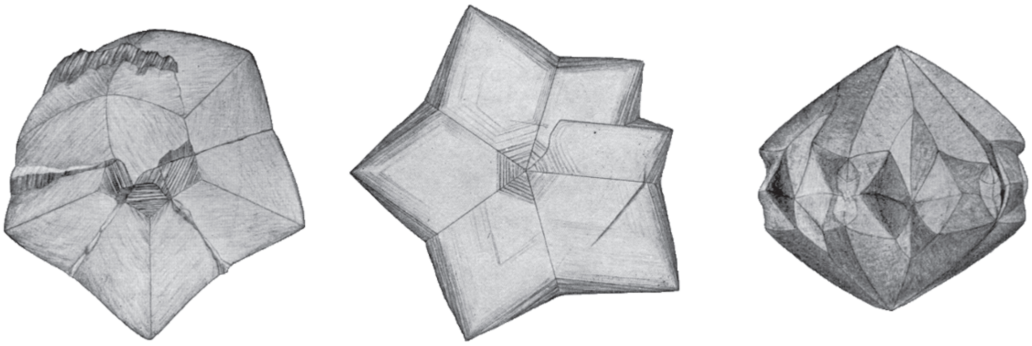
2-38: Strongly rounded and slightly distorted dodecahedral macle (1.13 ct).

2-39: Star-shaped diamond twin, which consists of two triangular macles oriented in opposite directions to each other (0.93 ct).



2-40: Idealized representation of a six-pointed star-shaped twin. Modified from Williams (1932).

Another distinctive type of contact twin resembles a six-pointed star (Star of David twin) (Fig. 2-39). This star-shaped twin represents an intergrowth of two octahedral macles that are oriented in opposite directions (Fig. 2-40). Besides the six-pointed star twin, other star-shaped diamond twins exist. These include cyclic diamond twins, which can have a five-fold symmetry (Fig. 2-41).[29] Just like other diamonds, star-shaped twins can be modified by resorption and develop a rounded dodecahedral habit (Fig. 2-42).

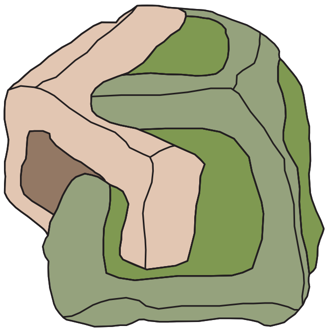


2-41: Cyclic star-shaped diamond twins. Drawings by Fersmann and Goldschmidt (1911).

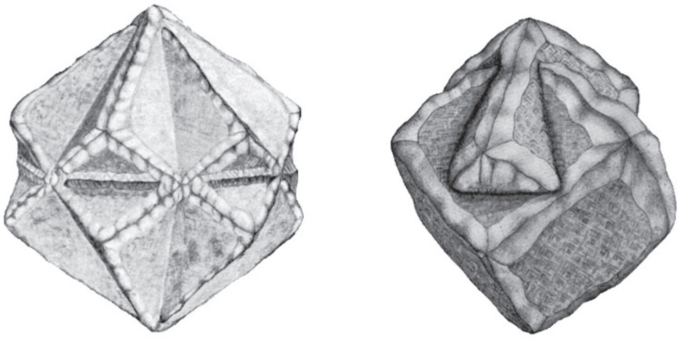
Interpenetrant twins

An interpenetrant twin consists of two or more crystals that have grown in the same space with different orientations. Interpenetrant twins occasionally occur in diamonds with octahedral habit, but they are more common in diamonds with cubic habits (Fig. 2-43).[177] A variety of interpenetrant twins have been documented, and like other types of diamonds, they can be affected by resorption, which results in rounding (Fig. 2-44).[76, 177]

2-42: Strongly resorbed star-shaped diamond twin (0.93 ct).



2-43: *Left,* Interpenetrant diamond twin consisting of two individual diamond cubes (0.95 ct). *Above,* Simplified representation of the individual crystals.



2-44: Interpenetrant diamond twins drawn by Fersmann and Goldschmidt (1911).

2-45: Non-transparent fibrous diamond with cubic habit from the Diavik mine, Northwest Territories, Canada (0.93 ct).

2-46: Polished section through a coated diamond. The diamond consists of a monocrystalline (octahedral) core and a fibrous overgrowth. (Ø: ~7 mm)

Fibrous diamonds and fibrous coats

Some diamonds consist of parallel microscopic fibers that are generally oriented in the direction of diamond growth. Although individual fibers are not usually visible without magnification, most fibrous diamonds can be identified by their distinctive dull appearance. Numerous microscopic inclusions incorporated within the fibers usually cause fibrous diamonds to be non-transparent or completely opaque (Fig. 2-45).

In some cases, the fibrous growth is restricted to the outer layer of monocrystalline diamonds, producing non-transparent fibrous overgrowths (coats).[168] The monocrystalline diamonds enclosed by fibrous coats are often well-crystallized, sharp-edged octahedra (Fig. 2-46).

Fibrous diamonds can grow in concentric layers, and diamonds with very obvious concentric layering are sometimes referred to as hailstones or hailstone boarts (Fig. 2-47).

The habits of fibrous diamonds often resemble those of monocrystalline diamond cubes (Fig. 2-48), but they can also be nondescript (Fig. 2-49). Similar to monocrystalline diamond cubes, fibrous diamond cubes generally have rough surfaces and rounded edges (Fig. 2-45, Fig. 2-48). The visual distinction between monocrystalline and fibrous diamond cubes, therefore, may not always be possible.

Fibrous diamonds with a distinctly spherical habit are referred to as ballas (Fig. 2-50). In ballas, the diamond fibers are usually oriented radially around the center.[59, 175, 301]

The habit of a coated diamond is strongly influenced by the habit of the enclosed diamond and by the thickness of the coat (Fig. 2-51).[176, 214] Octahedral diamonds with a thin fibrous coat are likely to retain an overall octahedral habit (Fig. 2-52), whereas thicker coats can produce cubo-octahedral or cubic habits (Fig. 2-53, Fig. 2-54).

Fibrous diamonds probably formed under considerably different conditions than monocrystalline diamonds. The lack of well-developed crystal faces and the overall flawed appearance of fibrous diamonds is a

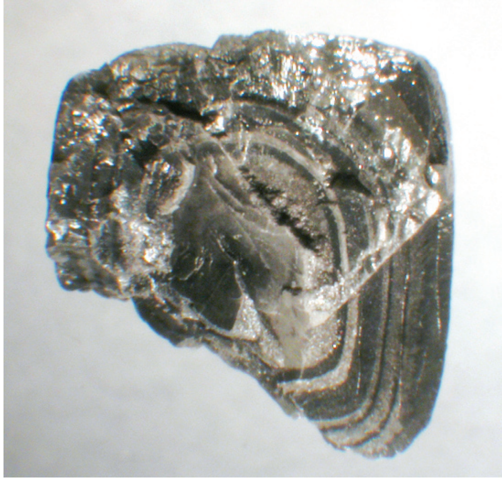
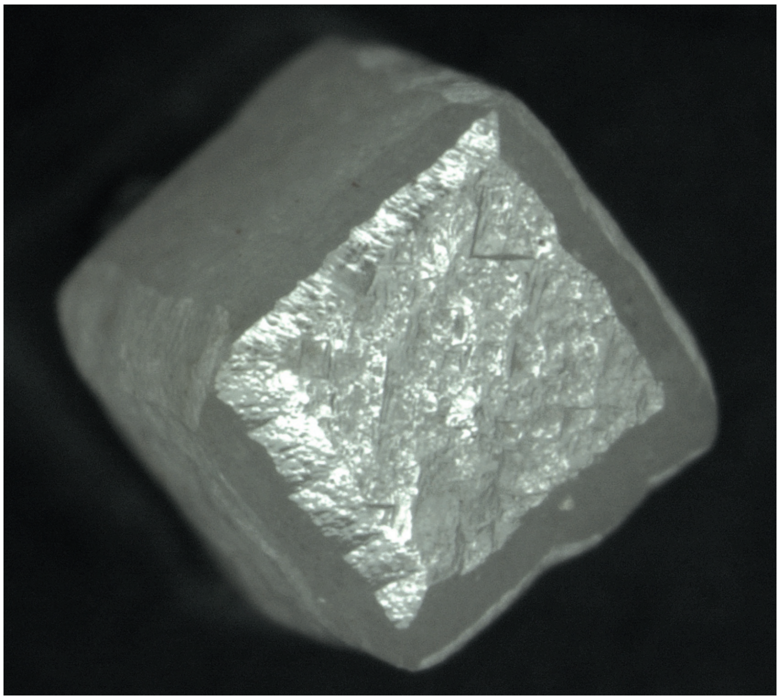


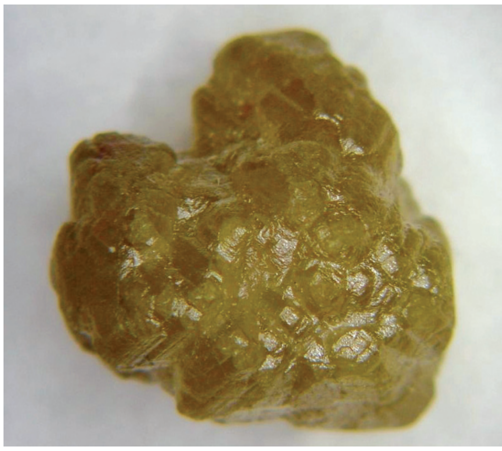
Photo courtesy of Graham Janson.

2-47: Fragment of a hailstone boart from Diavik, Northwest Territories, Canada (Ø: ~8 mm). The concentric layers, which are exposed on a fracture plane, consist of fibrous (grey) and polycrystalline (white) diamond. The habit of the hailstone boart is cubic.

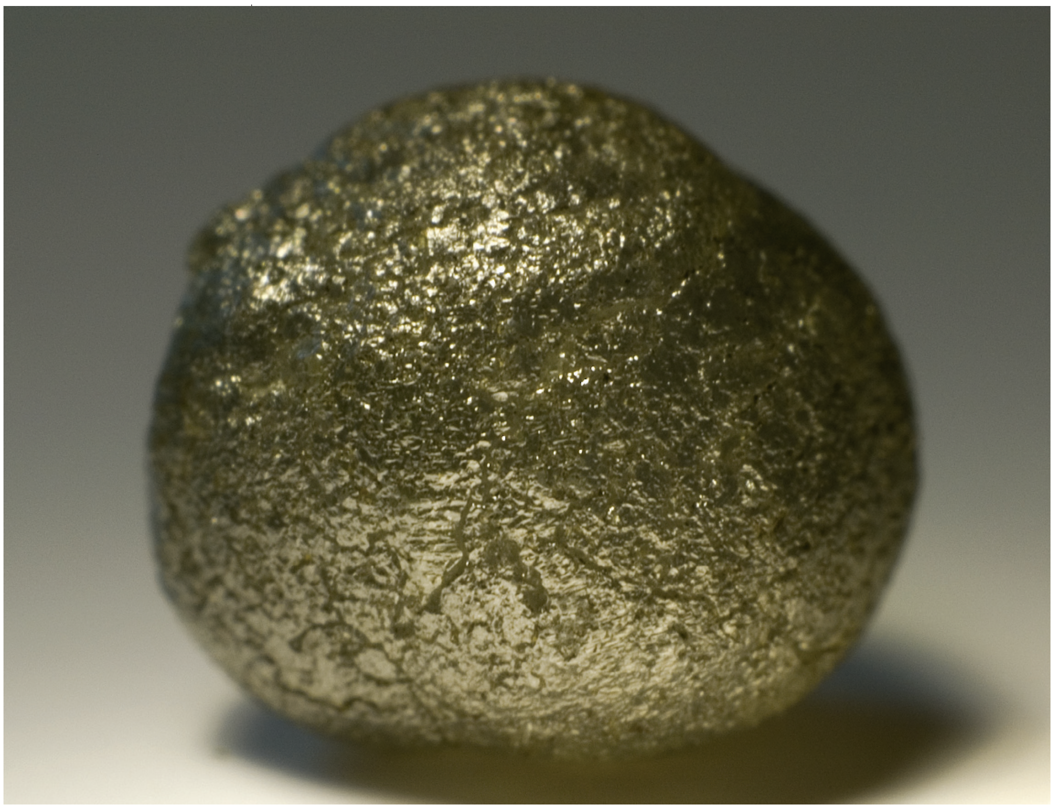


2-48: Fibrous diamond with cubic habit from Brazil (Ø: ~2 mm).

2-49: Fibrous diamond with a nondescript shape (Ø: ~1 cm).



2-50: Ballas: a spherical variety of fibrous diamond. Bahia, Brazil (2.18 ct).



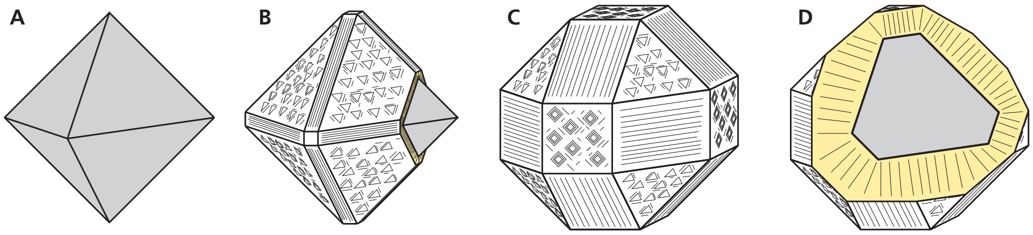
2-51: Relationship between coat thickness and habit of an octahedral diamond with a fibrous coat.

A. uncoated

B. thin coat

C. thick coat

D. section through core and thick coat

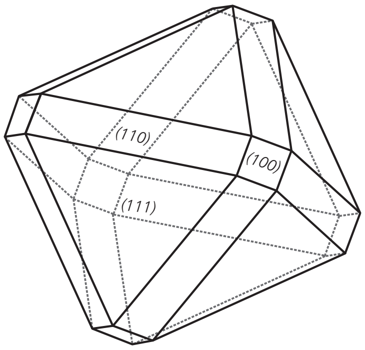


2-52: Octahedral diamond with a thin fibrous coat (1.19 ct). The octahedral crystal faces are marked by numerous trigons.

2-53: Polished section through a sharp-edged octahedral diamond with a thick fibrous coat (Ø: ~7 mm). The fibrous coat exhibits faint concentrical layering.

sign of rapid growth from highly carbon-oversaturated fluids. It has been suggested that the fibrous growth of diamonds may have occurred directly within the kimberlitic magma.[11] In this case, the kimberlitic magma would have been carbon-rich and reducing enough to allow diamonds to grow.

Fibrous diamonds and diamonds with fibrous coats are minor constituents of the diamond populations of many deposits worldwide, but they are completely absent in others. Deposits with a particularly high abundance of fibrous diamonds include Mbuji-Mayi in the DR Congo,[227] and the Aikhal mine in Russia.[214]



2-54: *Left,* Fibrous diamond with a cubo-octahedral habit from Makeni, Sierra Leone (Ø: ~8 mm). *Above,* Simplified representation of the main crystal faces. The diamond is likely to enclose a small monocrystalline core.

2-55: Framesite: a granular variety of polycrystalline diamond (Ø: ~3 cm).

Polycrystalline diamonds

Polycrystalline diamonds are comprised of numerous microcrystalline to cryptocrystalline diamond crystallites. They usually occur as masses without an apparent form. Individual diamond crystals occur as interlocking grains, which often have random orientations and lack discernible shapes. Due to the random orientation of the individual crystals, polycrystalline diamonds are not easily cutable and are generally used as abrasives.

Several varieties of polycrystalline diamonds have been identified. However, the classification of polycrystalline diamonds based on physical properties alone, such as grain size or porosity, has not been proven to be reliable.[142] As a consequence, a generally accepted classification scheme for polycrystalline diamonds has not yet been established. The results of chemical and isotopic analyses confirm that fundamental differences between some varieties of polycrystalline diamonds exist, but the reasons for the differences are not fully understood.

Distinctly granular polycrystalline diamond varieties are generally classified as framesite, but they have also been referred to as bort (boart) (Fig. 2-55). The use of the name bort, however, is ambiguous because it is often used to describe other types of polycrystalline and fibrous diamonds.

Framesites consist of large and sometimes euhedral diamond grains (>100 microns), which are surrounded by a matrix of small grains (<20 microns).[122] Framesites can have some porosity, and the voids are occasionally lined with euhedral diamond crystals. Inclusions and intergrowths of mantle-derived minerals are common. Framesites are found in several kimberlitic diamond deposits and can constitute a large proportion of the diamond production. At the Jwaneng mine in Botswana, for example, around 60% of the diamond production is framesite.[56, 112, 159] Other major sources of framesite are located in Russia, for example, at

2-56: Carbonado: an enigmatic polycrystalline diamond (Ø: 1.5 cm).

the Mir and Aikhal mines.[214, 231] A subvariety of framesite with a strong natural magnetization has been classified as stewardite. The magnetic properties of stewardite are caused by the presence of finely dispersed inclusions or intergrowths of magnetite.[40] Stewardite is a relatively common constituent of the diamond production at the Orapa mine in Botswana.[159]

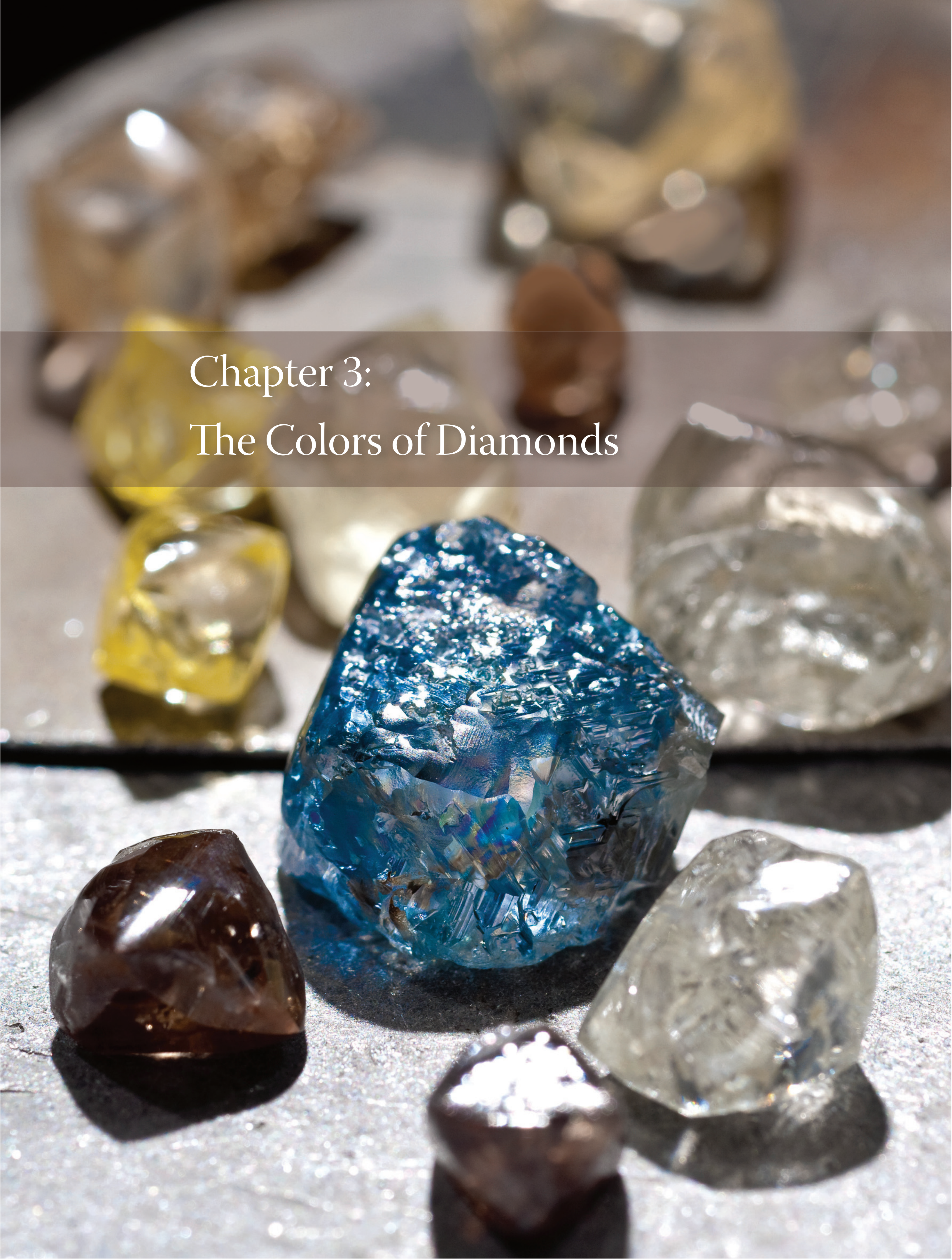
Carbonados are another type of polycrystalline diamond. They have smaller grain sizes and a higher porosity than framesites. Carbonados are commonly black, dark grey, or brown due to the presence of numerous small minerals lining the pore spaces (Fig. 2-56). Minerals associated with carbonados include unusual phases such as florencite, xenotime, zircon, and various native metals and alloys.[51, 294, 300] No typical mantle minerals have been found associated with carbonados. Carbonados are unique because their stable carbon isotope compositions are unusually light ($\delta^{13}C$: -23 to -30‰) when compared to the stable carbon isotope compositions of the other types of polycrystalline diamonds.[150]

The largest diamond mass ever found was a carbonado named Sergio, which weighed 3,167 carats (~ 633 g). Carbonados are restricted to placer deposits in eastern South America, mainly in the state of Bahia, Brazil; and the Central African Republic. In both areas, the carbonados are derived from Mesoproterozoic (1-1.5 billion year old) conglomerates that were deposited when South America and Africa were part of the same continuous land mass. Radiometric age determinations indicate that the carbonados crystallized long before the deposition of the conglomerates—between 2.6 and 3.8 billion years ago.[217, 243]

It is not completely understood how carbonados formed, but they do not seem to be directly associated with kimberlites or other mantle-derived rocks. It has been proposed that carbonados formed as a result of meteorite impacts on Earth that converted carbonaceous matter directly into polycrystalline diamonds.[163, 259] In a more controversial hypothesis, carbonados represent actual fragments of a meteorite that impacted with Earth.[84, 103] In alternative models, the individual diamond crystallites of carbonados formed in the Earth's mantle, and they were welded together by natural irradiation after being emplaced in the crust[144] or by the high temperatures of the magmas that transported the crystallites to the Earth's surface.[28]

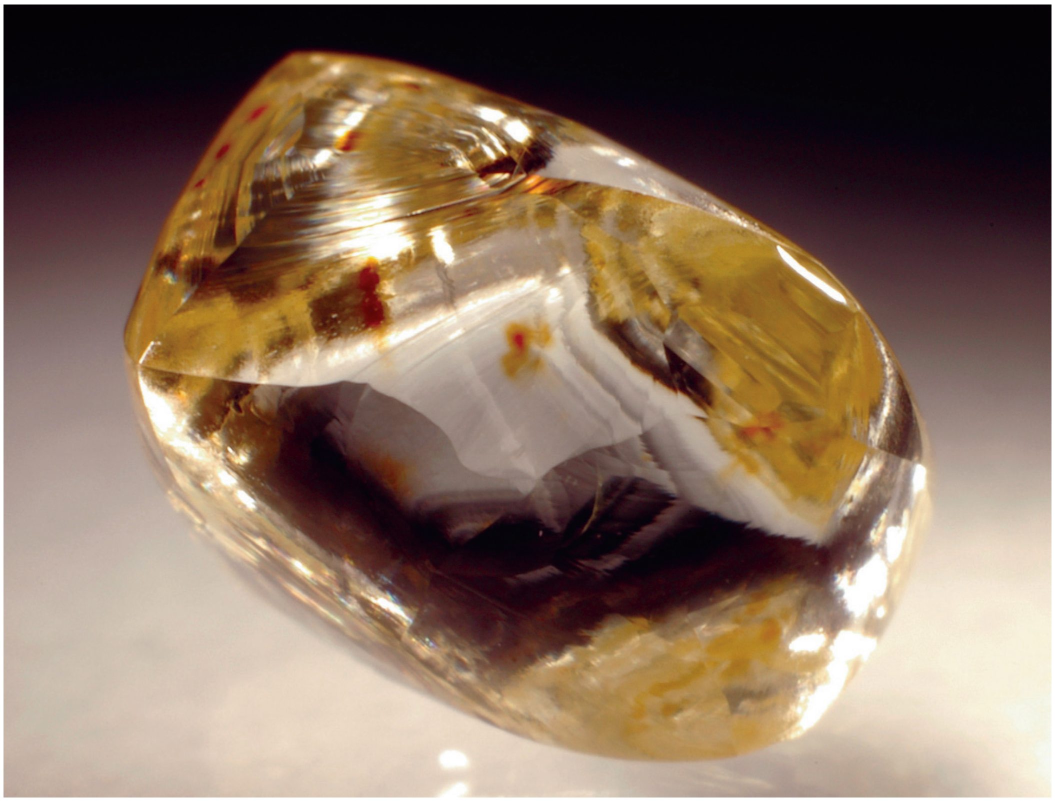
Another type of fine-grained polycrystalline diamond is yakutite, which was discovered in placer deposits in Yakutia, Russia. Yakutites are characterized by a high abundance of the mineral lonsdaleite, which is a hexagonal polymorph of diamond. Lonsdaleite is a characteristic component of meteorites and shock metamorphosed rocks. The high abundance of lonsdaleite, therefore, provides strong evidence that yakutites formed as a result of a meteorite impact. This interpretation is supported by the fact that yakutites have been found in impact metamorphosed rocks.[145, 295]

Chapter 3:
The Colors of Diamonds



Previous page –
Blue diamond (26.58 carats) from the Cullinan mine, South Africa. Photo courtesy of Petra Diamonds.

Chapter 3:
The Colors of Diamonds



3-01: Transparent yellow diamond with dodecahedral habit (1.02 ct). The pale yellow color, or cape yellow, is typical for Type Ia diamonds. The diamond also exhibits brown irradiation spots.

Diamond in its pure form is colorless, but natural diamonds commonly display a range of colors. Transparent colors that affect the entire diamond are usually caused by the presence of atomic or molecular impurities and imperfections (Fig. 3-01). Different body colors are linked to different impurities or imperfections, which form color centers.[38]
The body color of a diamond depends largely on the abundance of color centers and the size of the crystal. A large diamond will generally appear more intensely colored compared to a small diamond. Body colors are also influenced by the source of light. For example, diamonds in natural light may display a slightly different color than in artificial light. Diamonds with

R. Tappert and M.C. Tappert, *Diamonds in Nature: A Guide to Rough Diamonds*,
DOI 10.1007/978-3-642-12572-0_3, © Springer-Verlag Berlin Heidelberg 2011

3-02: Slightly rounded, octahedral diamond with an intense yellow color (1.10 ct). The non-transparent cloudy appearance and rugged surface of this diamond is typical for fibrous diamonds or diamonds with fibrous coats.

3-03: Opaque black diamond cube from Brazil (Ø: ~5 mm). The opaqueness of this diamond is the result of dispersed microscopic inclusions of opaque minerals.

3-04: Rounded octahedral diamond with a strongly abraded surface from the Bow River alluvial deposit, Western Australia (0.42 ct). The abraded surface creates a milky white appearance. Only few relics of the original surface are preserved.

intense and attractive colors are often valuable gemstones, but very few natural diamonds have such colors.

Inclusions of minerals or fluids, or other larger scale imperfections such as fractures, can alter the color and transparency of a diamond. A diamond can appear dull or milky if it contains an abundance of small inclusions and/or imperfections (Fig. 3-02). In extreme cases, inclusions and imperfections might cause a diamond to be completely opaque (Fig. 3-03). Surface textures can also have a strong influence on the perceived color. Colorless diamonds with rough surfaces, for example, may appear whitish (Fig. 3-04).

Many diamonds are compositionally zoned. This means that a single diamond can have zones with different colors, transparencies, or color intensities. Compositional zoning is most apparent on diamonds with fibrous overgrowths (Fig. 2-53).

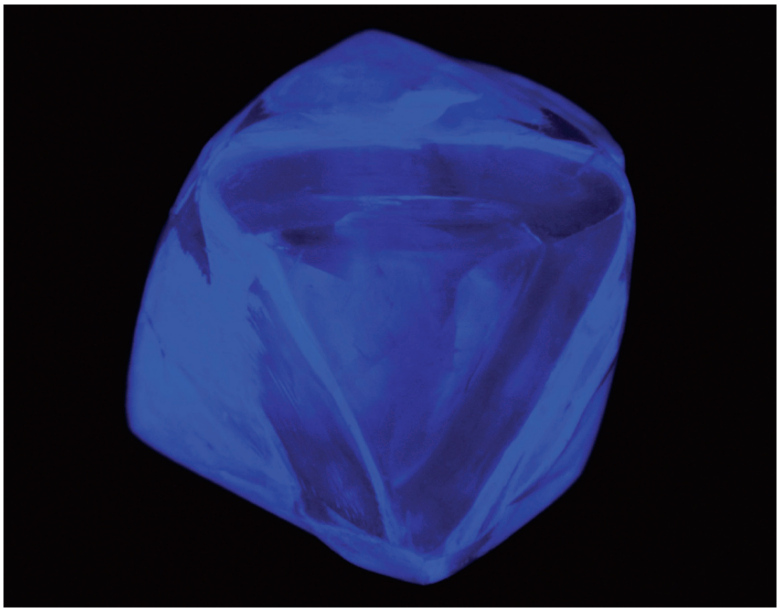
Colorless diamonds

A large proportion of diamonds appear colorless at first glance (Fig. 3-05), but it is common to find that many of these colorless diamonds have faint hues (Fig. 3-06). The various faint hues of colorless diamonds are distinguished in the gem trade, and they can have a strong influence on the value of a diamond. Many colorless diamonds have a bluish hue, which is the result of blue fluorescence.[206]

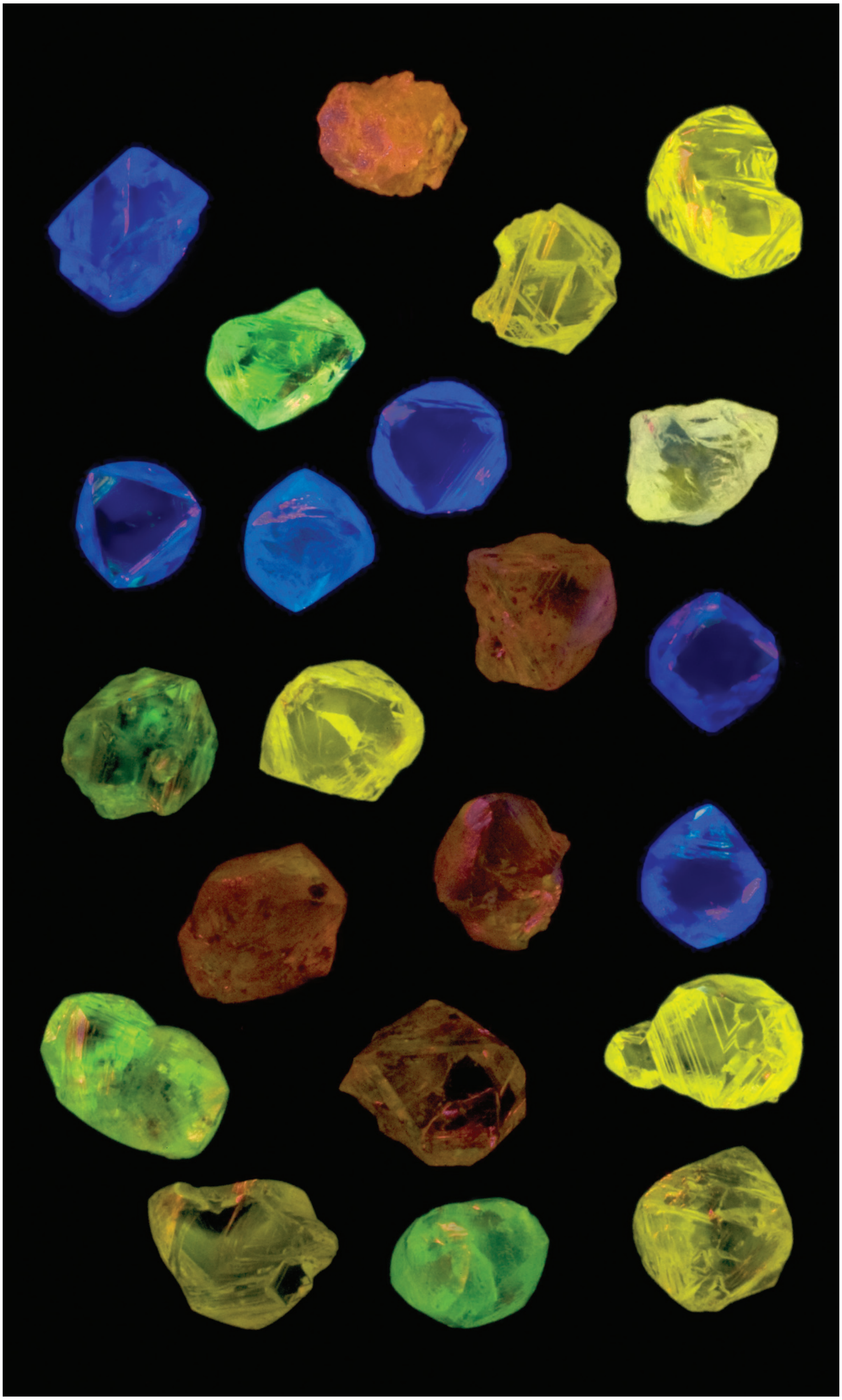
3-05: Colorless transparent dodecahedral diamond from a placer deposit in the Copeton area, New South Wales, Australia (0.73 ct). The diamond surface exhibits numerous green irradiation spots and crescent-shaped percussion marks that extend as fractures into the diamond. These surface features are characteristic for transported placer diamonds.

3-06: Alluvial diamonds with body colors ranging from colorless to pale yellow (Ø: ~3 mm each). The diamonds are strongly resorbed and have distinctly rounded shapes. Copeton area, New South Wales, Australia.

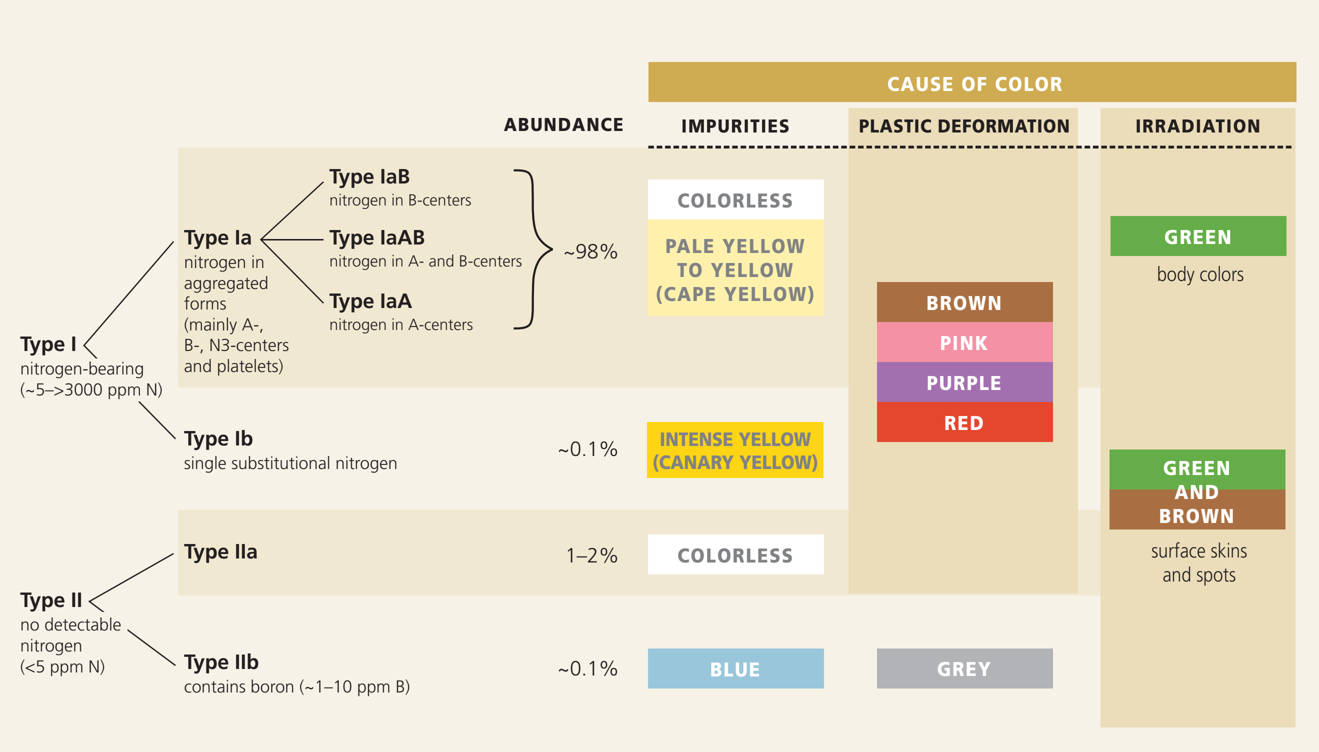
Fluorescence in diamonds is often caused by the interaction of the ultraviolet portion of light with elemental impurities and imperfections. This results in the emission of various faint background colors in the visible spectrum. Fluorescence colors are often diagnostic for specific types of impurities or imperfections. For example, the common blue fluorescence of diamonds (Fig. 3-07) is caused by nitrogen impurities. Other fluorescence colors include yellow, green, orange, and white (Fig. 3-08).



3-07: Image of a faint yellow, slightly rounded octahedral diamond from Echunga, South Australia, under ultraviolet (UV) light (1.00 ct). The UV radiation causes nitrogen impurities in the diamond to emit blue light in the visible part of the spectrum. This blue fluorescence results in a faint blue background color when viewed in visible light.



3-08: Fluorescence colors of diamonds under UV light. (Ø: ~1 mm each)



3-09: Classification of diamonds based on impurities and colors.

Yellow diamonds

Yellow is a common body color in diamonds. The yellow color is generally caused by nitrogen atoms that replace carbon atoms within the crystal structure.[69] Nitrogen is the most common elemental impurity in diamonds, and it can reach concentrations of more than 0.3 weight percent (>3000 ppm).[24, 318] The intensity of a yellow body color depends on the concentration of nitrogen and on the arrangement of the nitrogen atoms. To determine the concentration of nitrogen and their arrangement within an individual diamond, analytical methods—such as infrared spectroscopy—are generally required. The results of these analytical methods are also used to classify diamonds (Fig. 3-09).[12]

Diamonds containing nitrogen are classified as Type I diamonds, and diamonds without detectable nitrogen (< 5 ppm) are classified as Type II diamonds.[238, 280] The majority of mantle-derived diamonds are Type I diamonds, whereas only a small percentage (~2%) are Type II.[314] The proportion of Type II diamonds varies considerably between deposits, and also in relation to crystal size. Type II diamonds, for example, tend to be more common among the very large diamonds.[8, 44]

Type I diamonds are subdivided based on the arrangement of the nitrogen atoms in the crystal structure. In the most basic arrangement, single nitrogen atoms replace single carbon atoms during the growth of the diamond. Diamonds containing such single substitutional nitrogen atoms are classified as Type Ib diamonds.[33] Single substitutional nitrogen atoms are effective color centers, and even small amounts (<100 ppm) cause an intense yellow color that is referred to as canary yellow (Fig. 3-10).[83] Very few mantle-derived diamonds contain single substitutional nitrogen atoms, and if they do, the single substitutional nitrogen usually occurs together with nitrogen in aggregated states. Despite the presence of aggregated nitrogen, diamonds that contain even a small proportion of single

3-10: Distorted dodecahedral Type Ib diamond with intense canary yellow color (1.03 ct).

substitutional nitrogen are generally referred to as Type Ib diamonds.[314]

In response to the high temperatures in the Earth's mantle, single substitutional nitrogen atoms migrate rapidly through the crystal lattice to form more complex nitrogen aggregates.[71, 72] The presence of relictic single substitutional nitrogen atoms in natural diamonds, therefore, is a sign that the diamonds were transported to the Earth's surface shortly after their formation.

Metamorphic and synthetic diamonds are almost exclusively Type Ib.[25, 73] These diamonds have the distinctive intense yellow color of Type Ib diamonds (Fig. 3-11).

Diamonds containing nitrogen in more complex aggregates are classified as Type Ia diamonds. The basic nitrogen aggregate, which consists of a pair of nitrogen atoms, is referred to as an A-center.[47] Through time, A-centers convert to the highly aggregated B-centers, which consist of four nitrogen atoms and a vacancy.[70] Type Ia diamonds are classified depending on the relative abundance of A- and B-centers. Type IaA diamonds mostly contain A-centers, whereas Type IaB mostly contain B-centers. The intermediate Type IaAB diamonds contain a mix of A- and B-centers (Fig. 3-09, Fig. 3-12). A- and B-centers have no effect on the color of a diamond.

Nitrogen can also produce other types of aggregates, such as N3-centers, which consist of three nitrogen atoms.[20] Nitrogen is also present as a

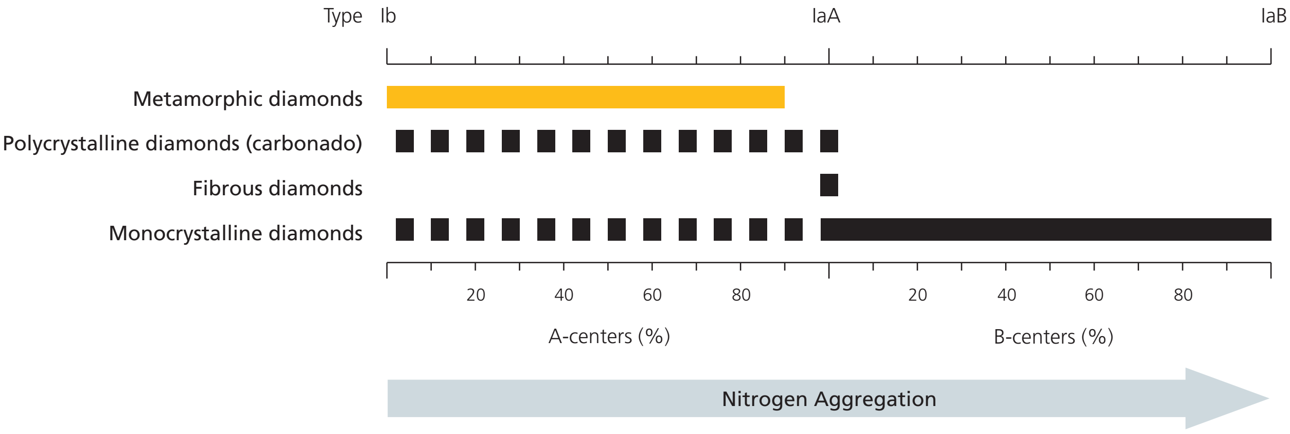
3-11: Synthetic diamonds with cubo-octahedral habit, exhibiting the characteristic yellow color of pure Type Ib diamonds, which is caused by single-substitutional nitrogen impurities. The nitrogen in synthetic diamonds is of atmospheric origin. The field of view is ~1.5 cm.

minor constituent of platelets, which are defect structures that are only a few atomic layers thick but can range in length from a few nanometers to a few micrometers.[68, 318] Like A- and B-centers, platelets have no effect on the diamond color.

It is mainly the presence of N3-centers in natural Type Ia diamonds that causes a straw yellow color that is referred to as cape yellow, named after the Cape Province in South Africa (Fig. 3-13, Fig. 3-14).[83] The color of a diamond can also be influenced by a range of other nitrogen aggregates, many of which are not well understood.[39, 60, 322]

A small number of Type Ia diamonds exhibit a greyish-yellow tinge or a fully grey body color. In these cases, the color has been linked to the presence of hydrogen impurities in the diamond.[83]

3-12: Ranges of nitrogen aggregation for different types of diamonds. Data from Cartigny (2010).



3-13: Slightly elongated dodecahedral diamond with a straw yellow color (cape yellow), which is characteristic for Type Ia diamonds. (1.00 ct).

3-14: Yellow Type Ia diamond with a transitional (octahedral-dodecahedral) habit. (Ø: ~7 mm)

Photo courtesy of Petra Diamonds.

3-15: Large blue (Type IIb) diamond, weighing 26.58 carats, from the Cullinan (formerly Premier) mine, South Africa. The diamond exhibits the characteristic irregular shape of Type II diamonds.

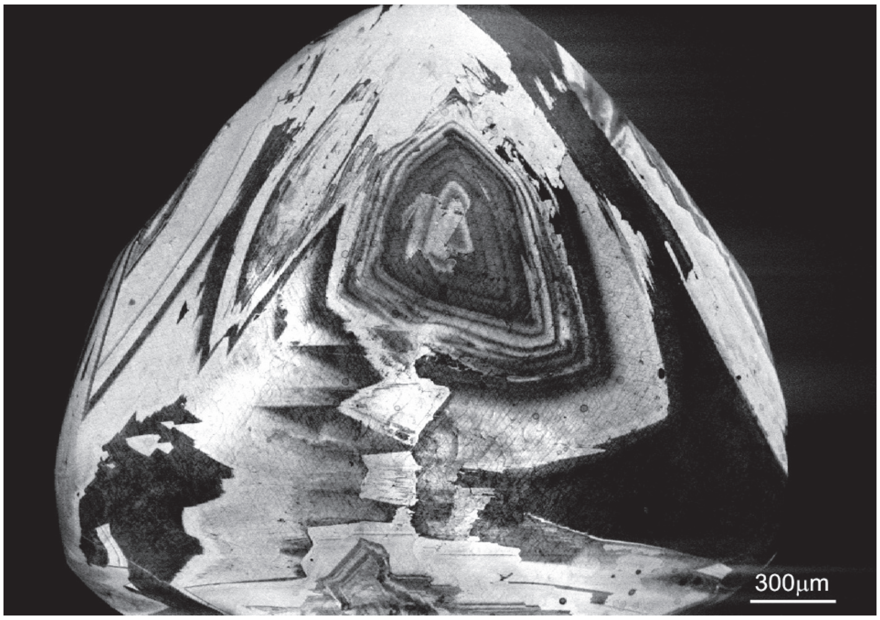
Blue diamonds

Type II diamonds, which are defined by containing no detectable nitrogen (≤ 5 ppm), are often colorless or brown (Fig. 2-26). A small percentage of Type II diamonds have the unusual physical property of being semiconductors, despite that fact that diamonds in general are electrical insulators. These semiconducting Type II diamonds are classified as Type IIb diamonds. They are distinguished from their non-conducting Type II counterparts, which are classified as Type IIa.[45] The electrical conductivity of Type IIb diamonds is caused by trace amounts of boron. Similar to nitrogen, boron replaces carbon atoms in the crystal lattice. The presence of boron is also responsible for the blue body color of some Type IIb diamonds (Fig. 3-15).[155] Boron is a very effective color center, and even small amounts of boron (~1 ppm) can cause an intense blue color. The blue color, however, can only develop if the concentration of nitrogen is very low (< 1 ppm) or if nitrogen is completely absent.[32]

Even though blue diamonds are extremely rare, some large examples of blue Type IIb diamonds exist, including the Hope diamond (45.5 carats) and the Wittelsbach diamond (35.6 carats). Along with others, these two diamonds were originally recovered from placer deposits in the historic Golconda kingdom in eastern India, where diamonds were mined from the sixteenth until the mid-nineteenth century. These deposits include the famous Kollur mine, which was located in the Guntur district of Andhra Pradesh. The deposits of the Golconda kingdom also produced several other famous large diamonds.[14] Blue diamonds have also been recovered from placer deposits in Brazil, western Africa, and Namibia. Several kimberlitic deposits are known to have occasionally produced blue diamonds, including the Jagersfontein, Koffiefontein, and Helam mines in South Africa. The only reliable kimberlitic source of blue diamonds, however, is the Cullinan (formerly Premier) mine in South Africa.[109, 111, 155, 315]

Although most blue diamonds are Type IIb diamonds, there are a few Type I diamonds that have a bluish-grey color. These diamonds are non-conducting, and the blue color is probably caused by hydrogen impurities.[7, 82]

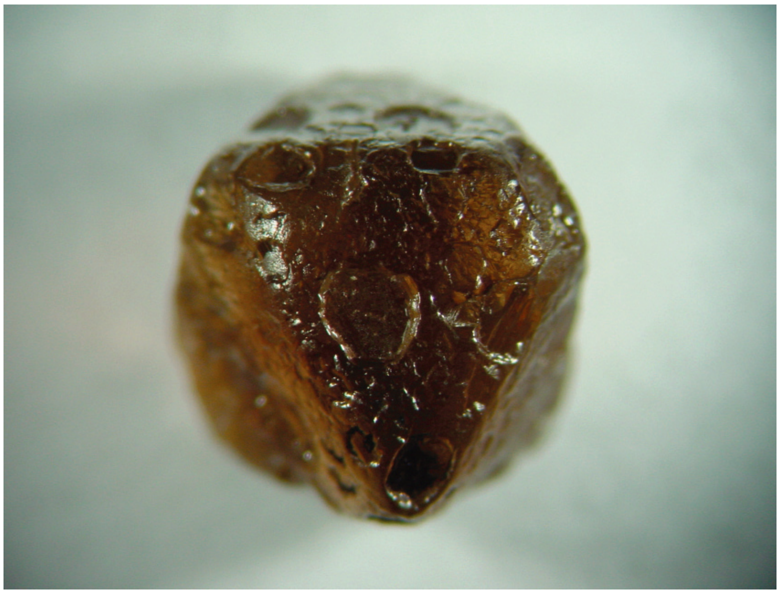
The distinction between Type I and Type II diamonds is not always straightforward because diamonds commonly have a complex growth history that can lead to the development of complex growth zones (Fig. 3-16). The impurity content of individual growth zones can vary considerably, and it is not uncommon that individual diamonds possess nitrogen-bearing (Type I) growth zones alongside nitrogen-free (Type II) growth zones.



3-16: Cathodoluminescence image of a rounded dodecahedral diamond. The complex internal growth zoning of this diamond is visible on the resorbed, dodecahedral crystal faces. Darker tones generally correspond to lower impurity (nitrogen) contents.

3-17: Light brown, strongly resorbed diamond from Guinea (0.50 ct).

3-18: Slightly rounded octahedral diamonds with brown body colors of different intensity. Bow River alluvial deposit, Western Australia (l: 1.80, r: 1.90 ct).



3-19: Dark brown, octahedral diamond from the Argyle mine, Western Australia (Ø: ~5 mm). The surface is covered with deep hexagonal etch pits (hexagons) that are a common feature of diamonds from this deposit.

3-20: Stepped and slightly rounded diamond with deep brown body color (0.95 ct).

Brown, pink, red, and purple diamonds

Brown is the most common diamond color, and the brown color can range in intensity from very faint (Fig. 3-17, Fig. 3-18) to very dark tones (Fig. 3-19, Fig. 3-20). The brown color in diamonds is the result of plastic deformation, which occurred at high temperatures and pressures in the Earth's mantle.[58, 69] Plastic deformation causes the dislocation of atoms and the formation of vacancy clusters in the crystal lattice. These vacancy clusters absorb part of the light causing a brown color.[80, 143] The dislocation of carbon atoms and the formation of vacancies commonly occurs along octahedral planes. Occasionally the brown color is more intense along individual planes, producing a patchy color or color banding within the diamond.

The surfaces of brown diamonds often exhibit parallel lines, which are the surface expressions of the dislocation planes. These lines are referred to as deformation lines.[58] Deformation lines become more accentuated during diamond resorption and are, therefore, more apparent on resorbed dodecahedral surfaces (Fig. 3-21, Fig. 3-22). In general, the proportion of brown colors is higher among the nitrogen-free Type II diamonds compared to the nitrogen-bearing Type I diamonds.[314]

3-21: Brown diamonds with dodecahedral habit from Makeni, Sierra Leone (Ø: 5–6 mm). The diamonds exhibit deformation lines that are a common feature of brown diamonds.

3-22: Dodecahedral diamond with an orange-brown color from Brazil (Ø: ~2 mm).

3-23: Pink dodecahedral diamond from the Bow River alluvial deposit, Western Australia (1.28 ct).

3-24: Patchy, light pink fragment of a strongly resorbed octahedral diamond (0.29 ct).

3-25: Reddish-brown, dodecahedral diamond from Guinea (0.48 ct).

3-26: One half of a slightly rounded octahedral diamond with a reddish-pink color (2.67 ct). Argyle mine, Western Australia.

Pink colors in diamonds, like brown colors, are also caused by plastic deformation (Fig. 3-23). Pink diamonds usually exhibit the same signs of plastic deformation as their brown counterparts, including the presence of deformation lines on the surfaces (Fig. 3-24). Brown and pink colors belong to a color continuum that also includes red and purple (Fig. 3-25). The cause of the difference between these diamond colors has not yet been established.[80]

Plastic deformation may also be responsible for the rare grey color of some Type IIb diamonds. In these cases, the typical blue color of a Type IIb diamond, in combination with plastic deformation, is believed to result in the grey color.[80]

Diamonds with pink, red, or purple colors are extremely rare, and they are restricted to a few localities. The Argyle mine in Western Australia and the associated Bow River alluvial deposit, which are major producers of brown diamonds, are also the main sources of pink and reddish diamonds (Fig. 3-26).[64, 74] Pink, red, and purple diamonds are also found in kimberlites in Russia, particularly in the Mir field, and in southern Africa.[156, 214, 296] Even though most pink diamonds are Type I diamonds, pink Type II diamonds also exist. The Williamson (Mwadui) mine in Tanzania[156] and the Letseng mine in Lesotho,[199] for example, are known producers of pink Type II diamonds.

3-27: Dodecahedral diamonds with intense green surface colors that give the impression of a green body color (0.35–0.50 ct).

Green diamonds

Green body colors

Diamonds with transparent green body colors are extremely rare. Although high concentrations of nitrogen impurities can cause a greenish tinge in some Type Ib diamonds, a green body color is generally the result of natural irradiation. The irradiation is caused by radioactive elements, such as uranium and thorium, that are present in the environment of the diamond. The decay of these elements produces radiation in the form of alpha-, beta-, and gamma-rays that cause carbon atoms in the diamond to be expelled from the crystal lattice, leaving vacancies.[34] These vacancies, which are primarily isolated vacancies, absorb light and cause the green body color. Only gamma-rays have the ability to fully penetrate a diamond. Therefore, they can be considered to be the main cause of transparent green body colors in natural diamonds. Compared to other, more vivid diamond colors, the green body color of naturally irradiated diamonds is rather pale.

It is possible to create green body colors in diamonds artificially using modern high-energy radiation techniques. Irradiating a diamond with neutrons or electrons in a laboratory setting is very effective at producing vacancies in the crystal lattice. In fact, most of the green diamonds used as gemstones owe their color to artificial irradiation.[83] These artificially irradiated diamonds are indistinguishable from naturally irradiated diamonds; therefore, it is difficult to verify the authenticity of a diamond with a natural green body color. However, examples of naturally irradiated diamonds do exist. The largest known naturally formed green diamond is the Dresden Green diamond, which is a Type II diamond that weighs 40.7 carats as a cut stone.[152] The history of this diamond, which was probably found in a placer deposit in India, can be traced back for almost 300 years—long before the development of radiation techniques.

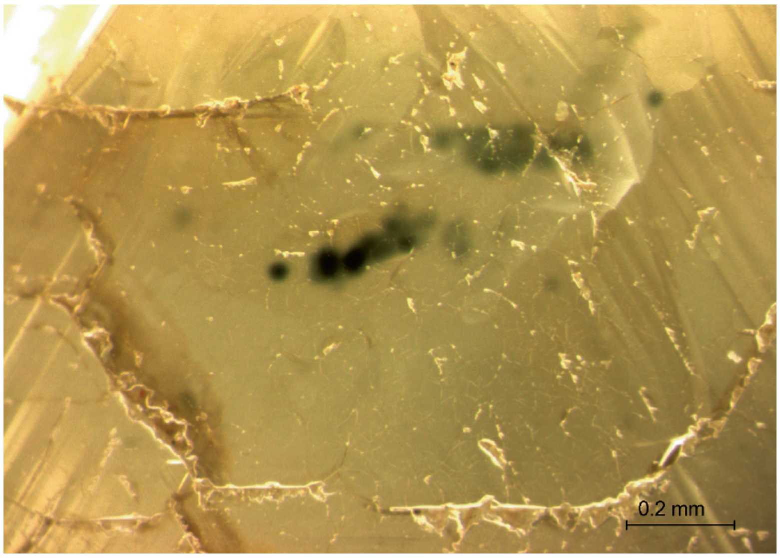
3-28: Strongly resorbed, octahedral diamond with homogeneous pale green surface color (0.93 ct).

Green surface colors

Green skins and spots

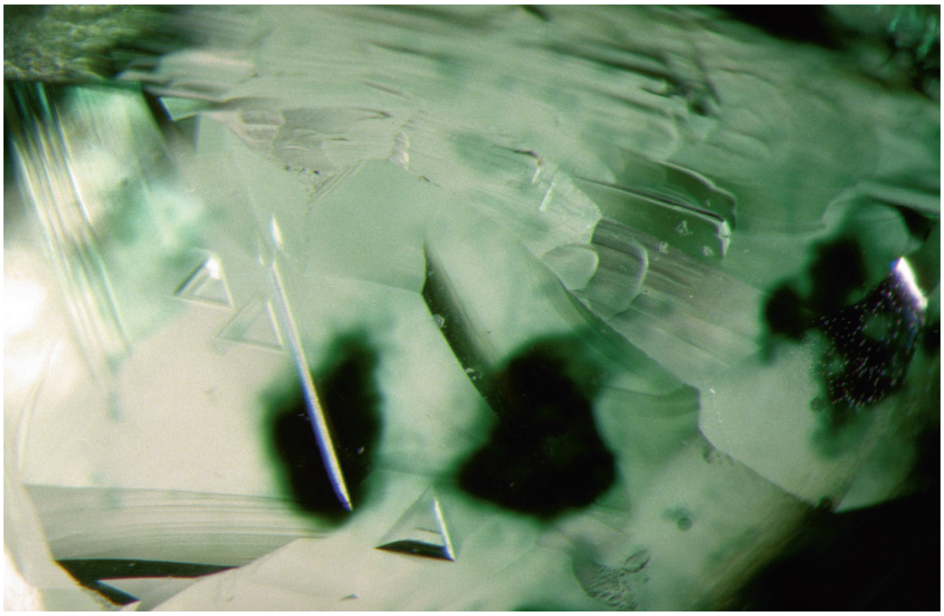
Compared to true body colors, diamonds more commonly have transparent green colors that are restricted to the surface. If the green color is evenly distributed over the entire surface of the diamond as a green surface skin, it can create the impression of a green body color (Fig. 3-27, Fig. 3-28). To determine if a diamond has a true green body color, it may be necessary to remove some of the diamond's surface.

Some diamonds have green surface spots, which can be present as single spots, clusters of multiple spots, or spots that are evenly distributed over the entire diamond surface (Fig. 3-29, Fig. 3-30, Fig. 3-31, Fig 3-32). The color of the surface skins and spots can range from light green to dark green to black.



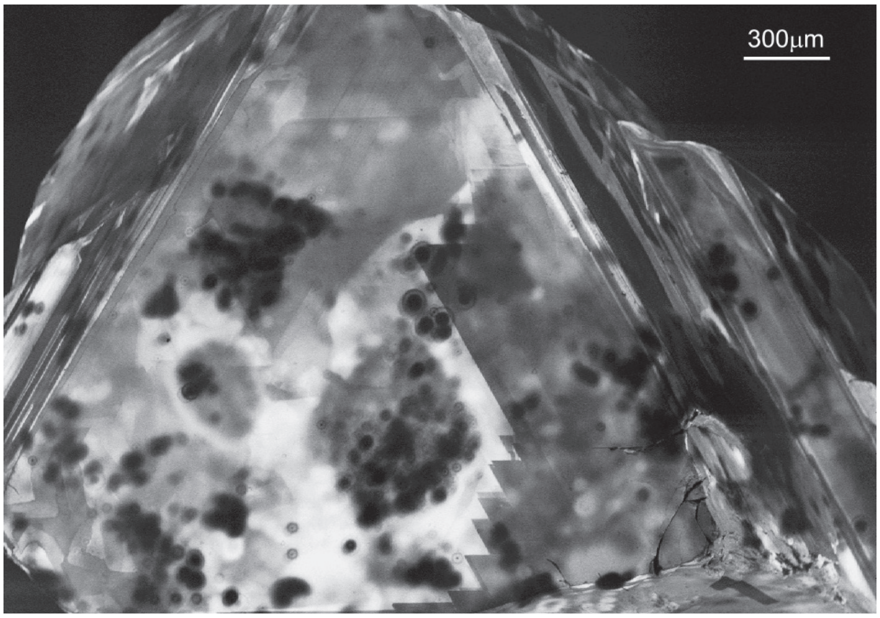
3-29: Green surface spots and percussion marks on an octahedral surface of a diamond from Echunga, South Australia.

3-30: *Right,* Strongly resorbed, octahedral diamond with clusters of dark green surface spots and trigons (0.18 ct). *Below,* Close-up of the dark green spots and trigons. The field of view is ~1.5 mm.



Green surface colors, similar to green body colors, are the result of irradiation damage. In these cases, the irradiation damage is caused by alpha-rays.[187, 303] Unlike gamma-rays, alpha-rays have a very limited penetration depth. Therefore, the damage to the crystal lattice is restricted to the outer few micrometers of the diamond surface. Since alpha-rays are not capable of penetrating deep into minerals, the radiation source must have been in direct contact with the diamond. Green skins and spots generally postdate the surface textures related to resorption and late-stage etching (Fig. 3-30). The irradiation damage, therefore, evidently occurred after the diamonds reached the Earth's surface.

3-31: Octahedral diamond with a transparent green surface that is formed by numerous faint green surface spots (0.76 ct).



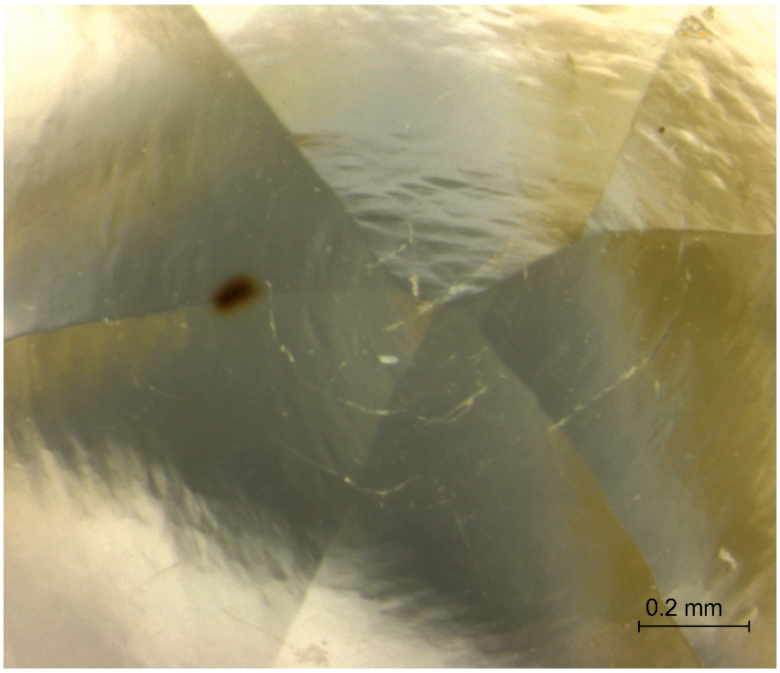
3-32: Cathodoluminescence (CL) image of the surface of an octahedral diamond with green surface spots. The green spots appear as dark spots or clusters on the CL image. Individual spots are surrounded by a dark ring. These dark rings are probably produced by alpha-rays with a slightly higher energy and deeper penetration depth compared to the alpha-rays that produced the central spots. Such higher-energy alpha-rays are produced in the decay-chain of naturally occurring radioisotopes.

Kimberlites are generally poor in radioactive elements, which is the reason why relatively few diamonds in kimberlites exhibit green surface skins or spots. Crustal rocks, such as granites, generally have much higher concentrations of radioactive elements. These elements are primarily contained in accessory minerals, such as zircon. In some cases, the occurrence of green surface skins and spots on diamonds from kimberlites can be linked to the presence of crustal xenoliths that are entrained in the kimberlite. Kimberlites from the Guaniamo area in Venezuela, for example, contain an exceptionally high percentage of diamonds (>50%) with green surface spots.[146] In this case, the kimberlites also contain an unusually high abundance of crustal xenoliths. Radioactive element-rich minerals from these xenoliths are the likely sources of the radiation that caused the widespread green spots on the diamonds in this deposit.

Groundwater is another potential source of radiation because radioactive elements can leach out of crustal rocks and dissolve in the groundwater. Once dissolved, the radioactive elements can percolate through the diamond host rock. If diamonds are in contact with this radioactive element-enriched groundwater, they can receive irradiation damage. Groundwater can evenly cover the surface of a diamond to cause a homogeneous irradiation effect. This type of irradiation is the most likely cause of homogeneous green surface skins. Diamonds with green surface skins are more abundant in the upper parts of some kimberlites where they are more likely to be exposed to groundwater. This has been observed, for example, at the Finsch mine in South Africa.[109]

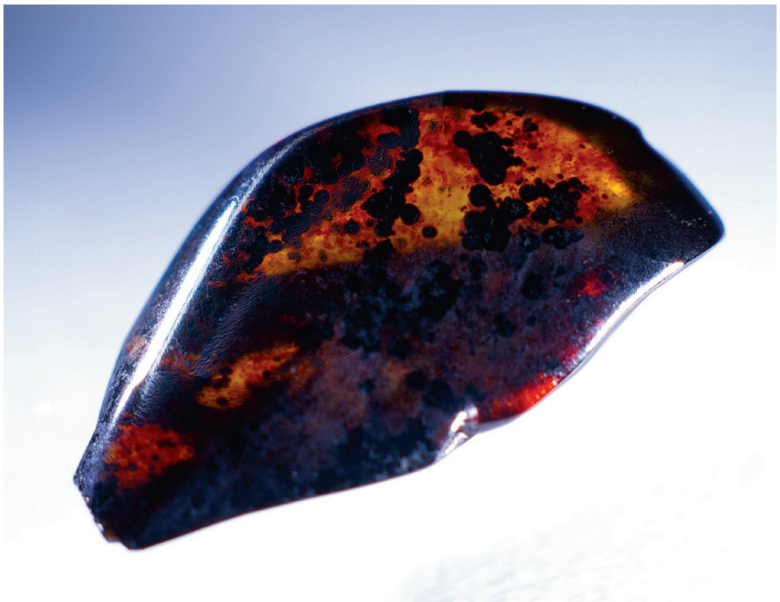
Green surface skins and spots are much more common on diamonds from placer deposits than they are on diamonds from kimberlites. Placer deposits generally contain abundant radioactive element-rich minerals. Some of these minerals have a high specific gravity and are concentrated in placer deposits along with diamonds. The exposure of the diamonds to these radioactive minerals causes the green skins and surface spots that are so abundant on diamonds from placer deposits.

The intensity of the green color depends on the intensity of the radiation and the length of time that the diamond was exposed to the radiation. Radioactive minerals generally emit radiation at very low intensities. As a result, it may require millions of years to produce visible radiation damage. It is, therefore, more common to find irradiated diamonds in older kimberlites and placer deposits. Some diamonds recovered from the ancient Witwatersrand conglomerate were all found to have green surface spots.[229] This conglomerate, which is more than 2.5 billion years old, is one of the world's oldest known diamond placer deposits. Other placer deposits containing diamonds with green skins and spots are widespread, but they are particularly common in South America and western Africa.[148, 149, 289, 304]



3-33: A single brown spot on the surface of a placer diamond from Echunga, South Australia.

3-34: Dark brown surface spots on an alluvial diamond from Arenapolis, Mato Grosso, Brazil (0.28 ct). The surface also exhibits multiple crescent-shaped percussion marks.

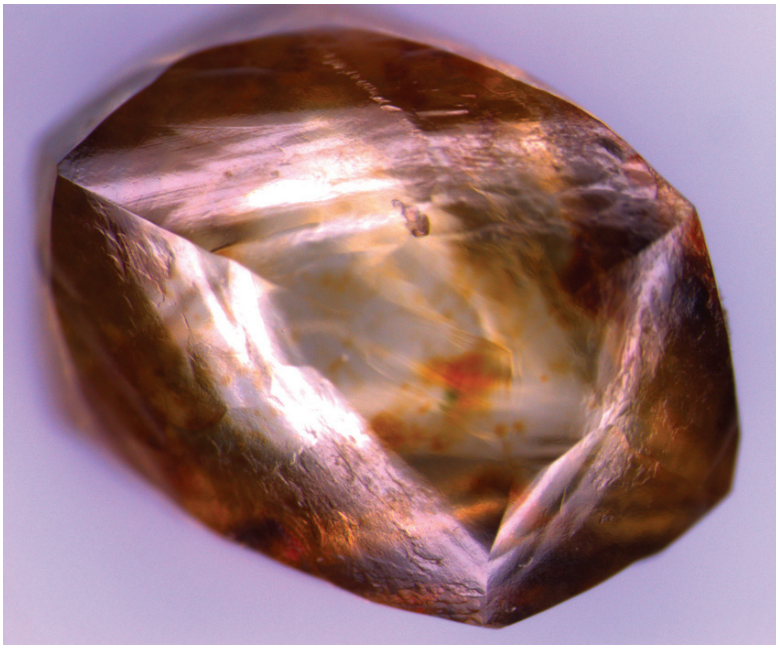


3-35: An unusual looking rounded dodecahedral diamond fragment with brown surface spots and clusters of black surface spots (0.55 ct). The physical characteristics of this diamond provide evidence for a complex post-formational history that includes fragmentation, resorption, irradiation, and thermal metamorphism.

Brown spots

A small number of diamonds exhibit brown surface spots (Fig. 3-33, Fig. 3-34, Fig. 3-35). Experiments have shown that green surface spots turn brown by annealing at temperatures above ~600°C.[304] Brown surface spots, therefore, are believed to form in nature during the heating of diamonds with pre-existing green spots. The heating events that caused the transformation from green to brown spots may have occurred on a small scale, for example, during localized volcanism, or they may have occurred on a large scale, such as during regional metamorphism.

3-36: Dodecahedral macle from Brazil with numerous green surface spots and a few brown surface spots (Ø: ~6 mm).



3-37: Placer diamond with numerous brown and a few green surface spots (0.07 ct). Springfield Basin, South Australia.

3-38: Distorted dodecahedral diamond with a homogeneous green surface skin and additional green and brown surface spots (1.62 ct). Bow River, Western Australia.

Most diamonds with brown spots are found in placer deposits, but brown spotted diamonds have also been discovered in some kimberlites.[304] This indicates that the kimberlites themselves experienced a thermal overprint.

In some cases, green and brown spots occur on the same diamond (Fig. 3-36, Fig. 3-37, Fig. 3-38), which indicates that the diamond received an additional dose of irradiation after experiencing earlier irradiation damage and a heating event. If green and brown spots are present on different parts of the diamond surface, it is evident that the diamond was shifted or transported between the irradiation events. Even though it may not be possible to unravel the exact details about the irradiation and thermal events, the mere presence of green and brown surface spots is a sign that a diamond has had a long history on the Earth's surface.

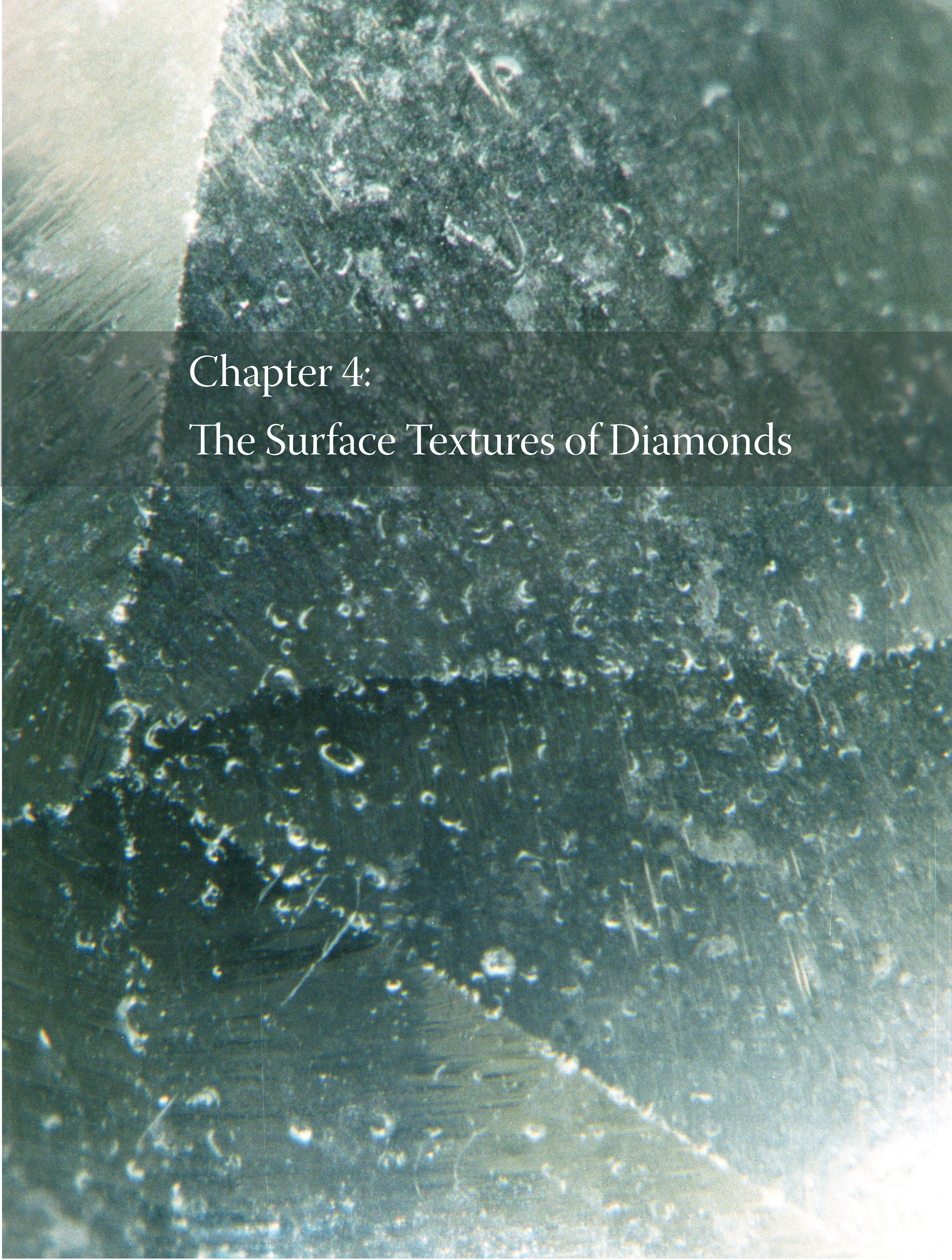
3-39: Grey fibrous diamond coat around a colorless monocrystalline diamond with octahedral habit (1.32 ct). The coated diamond is fragmented, which exposes its monocrystalline core.

Colors caused by inclusions

The presence of inclusions can have an influence on the color and transparency of a diamond. Small particles of graphite or other minerals can produce a grey appearance. This non-transparent grey, however, is quite distinct from the transparent grey body color that is caused by atomic impurities. A high abundance of minute inclusions can produce an opaque black color. Inclusion minerals that have been identified as the source of such black diamond colors include graphite, sulfides, magnetite, and hematite.[214, 297] Clouds of minute transparent inclusions can also cause the white color of some non-transparent monocrystalline diamonds.

Small inclusions of fluids and minerals are the main source of color in fibrous diamonds and fibrous coats (Fig. 3-39). In these cases, the color is usually accompanied by a cloudy, non-transparent appearance. If a true body color is present, it can influence the overall color of a fibrous diamond or a fibrous coat. The colors of fibrous diamonds are quite variable, and they can be found having green, yellow, brown, grey and black colors.

Chapter 4:
The Surface Textures of Diamonds



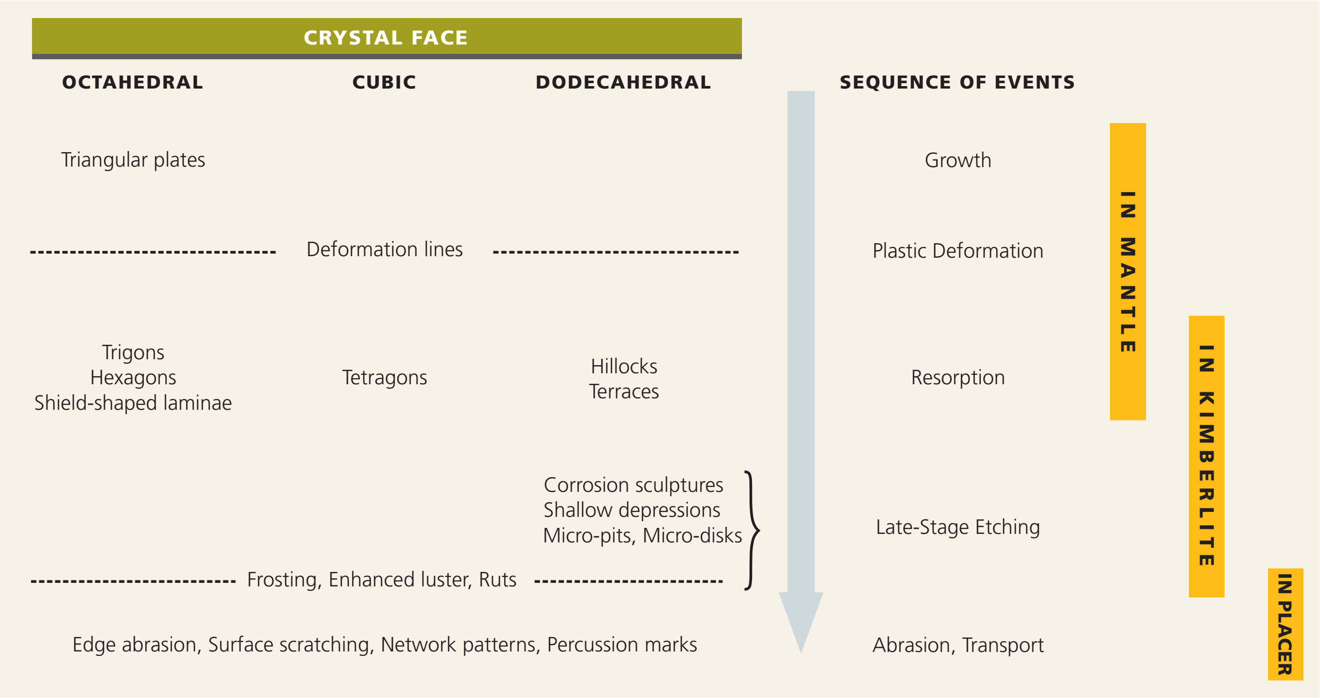
Previous page –
Percussion marks
on the surface of a
dodecahedral diamond.

Chapter 4:

The Surface Textures of Diamonds

Diamonds exhibit a wide range of surface textures that developed at different stages in the diamond's history. Some of the surface textures developed early and are linked to growth and resorption processes that occurred when the diamonds were residing in the Earth's mantle. Others formed during exposure to the kimberlitic magma, and others formed on the Earth's surface. Individual diamonds can exhibit many different types of surface textures, and the relationship between these textures can be used to reconstruct the sequence of events that have affected the diamonds since their formation.[241]

Most of the textures are restricted to particular crystal faces. This means that they occur either on octahedral, cubic, or dodecahedral crystal faces (Fig. 4-01). Some textures, however, can occur anywhere on a diamond.



4-01: Common surface textures of diamonds and their sequence of formation.

CRYSTAL FACE			
OCTAHEDRAL	CUBIC	DODECAHEDRAL	SEQUENCE OF EVENTS
Triangular plates			Growth
Deformation lines	Deformation lines	Deformation lines	Plastic Deformation
Trigons Hexagons Shield-shaped laminae	Tetragons	Hillocks Terraces	Resorption
		Corrosion sculptures Shallow depressions Micro-pits, Micro-disks	Late-Stage Etching
Frosting, Enhanced luster, Ruts	Frosting, Enhanced luster, Ruts	Frosting, Enhanced luster, Ruts	Late-Stage Etching
Edge abrasion, Surface scratching, Network patterns, Percussion marks	Edge abrasion, Surface scratching, Network patterns, Percussion marks	Edge abrasion, Surface scratching, Network patterns, Percussion marks	Abrasion, Transport

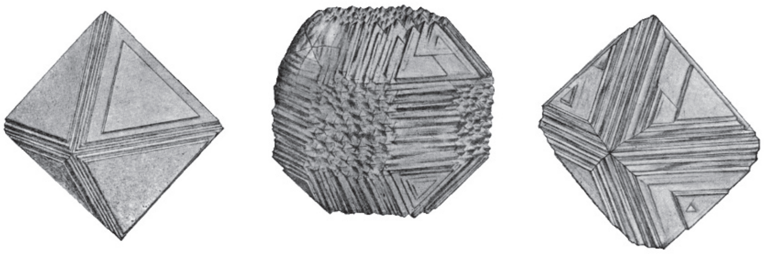
R. Tappert and M.C. Tappert, *Diamonds in Nature: A Guide to Rough Diamonds*,
DOI 10.1007/978-3-642-12572-0_4, © Springer-Verlag Berlin Heidelberg 2011

Textures on octahedral crystal faces

Triangular plates

Triangular plates are growth layers of variable thickness that develop on octahedral crystal faces (Fig. 4-02).[315] They can occur as single plates, or they can form multiple imbricated plates. The latter causes the diamonds to develop a stepped appearance (Fig. 4-03). Triangular plates have an octahedral form, but their original sharp edges can be rounded if the diamonds were affected by resorption (Fig. 4-04).

4-02: Octahedral diamond with multiple triangular growth plates of variable thickness (0.92 ct). The growth plates cause the stepped appearance of this diamond.

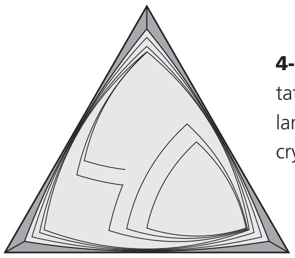


4-03: Octahedral diamonds with triangular growth plates in different configurations. Drawings from Fersmann and Goldschmidt (1911).

4-04: Slightly resorbed, rounded triangular growth plates on a stepped octahedral diamond (1.06 ct).

Shield-shaped laminae

Octahedral crystal faces can have superimposed laminae that are smaller than the underlying octahedral crystal face. The laminae have curved edges, which results in a shield-like outline (Fig. 4-05).[91] Compared to triangular growth plates, shield-shaped laminae are generally much thinner and have curved edges. Similar to triangular growth plates, multiple imbricated shield-shaped laminae can cause a stepped appearance (Fig. 4-06, Fig. 4-07). Shield-shaped laminae are the result of the resorption of individual growth layers.[214]



4-05: Idealized representation of shield-shaped laminae on an octahedral crystal face.

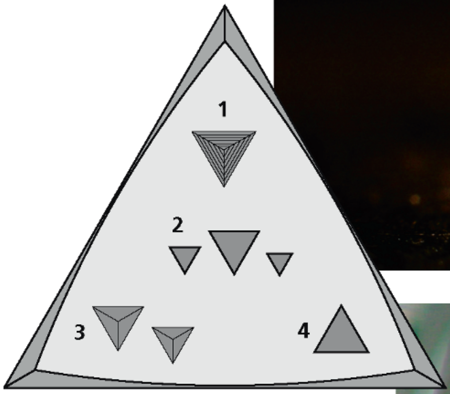
4-06: Rounded triangular growth plates and shield-shaped laminae on an octahedral diamond (1.01 ct).

4-07: Light brown diamond with multiple imbricated shield-shaped laminae (1.11 ct).

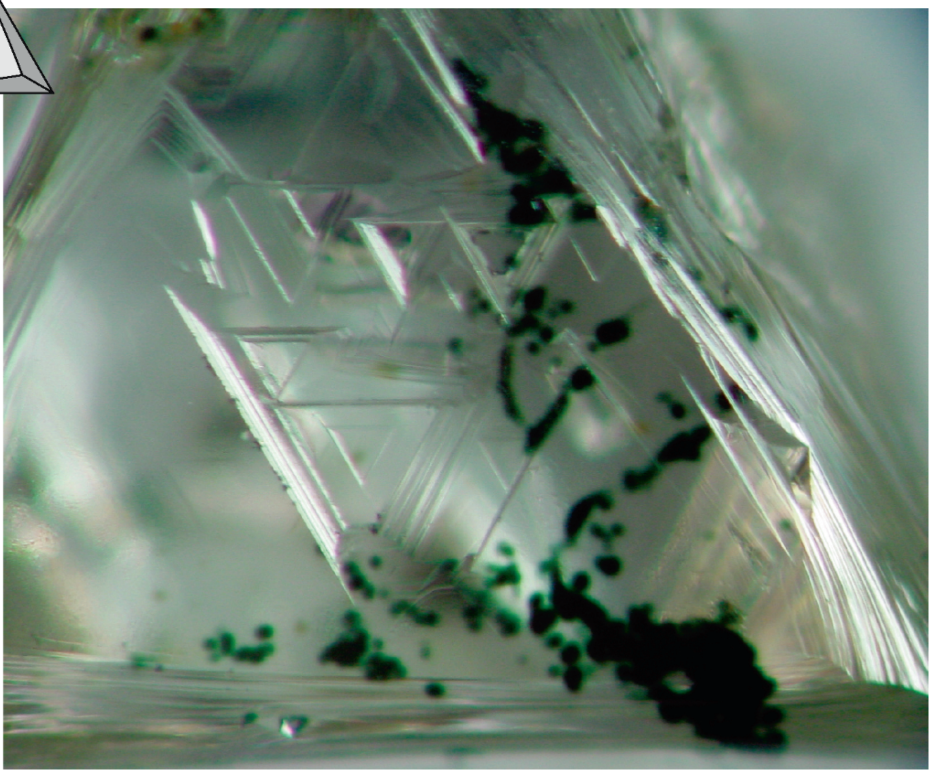
Triangular pits (trigons)

Triangular pits, which are generally referred to as trigons, are a very common and distinctive feature on octahedral crystal faces.[298] Trigons can be variable in size, and it is not uncommon to find trigons with a wide range of sizes on a single diamond (Fig. 4-08). Even octahedral crystals faces that visually appear pristine and smooth often contain microscopic trigons. Trigons with flat bottoms can be distinguished from other varieties that

4-08: Large terraced trigons on the surface of a slightly resorbed, octahedral diamond (1.03 ct). The negative trigons are oriented in the direction opposite to the underlying octahedral crystal face.



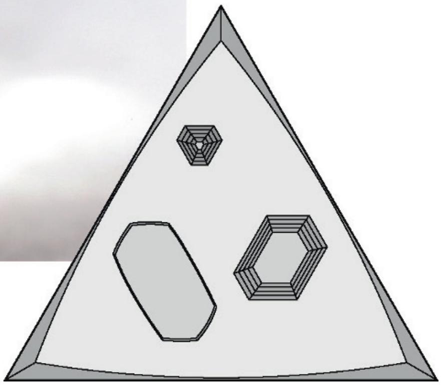
4-09: Different types of trigons: (1) terraced trigon, (2) flat-bottomed trigons, (3) pyramidal trigons, and (4) positively oriented trigon.



4-10: Multiple flat-bottomed trigons on the octahedral crystal face of an alluvial diamond from Boa Vista, Roraima, Brazil. The diamond exhibits green surface spots that cover some of the trigons, indicating that the surface spotting postdates the trigon formation. The field of view is ~2 mm.

have pyramidal or terraced bottoms (Fig. 4-09, Fig. 4-10). Trigons on natural diamonds are usually oriented in the direction opposite to the underlying crystal face, which is the reason why these trigons are referred to as negative trigons.[81] Negative trigons are considered to form when original growth surfaces are etched by fluids at high temperatures (~1000°C).[67, 213] Compared to negative trigons, trigons with positive orientations are extremely rare on natural diamonds.

4-11: Hexagonal pits (hexagons) on the surface of an octahedral diamond from Argyle, Western Australia (1.78 ct). Most of the hexagons are slightly rounded.



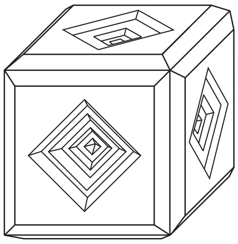
4-12: Idealized representation of hexagons on an octahedral diamond surface.

4-13: Hexagons on the surface of an octahedral diamond from Argyle, Western Australia (1.80 ct). Negative trigons are present on the bottom of the hexagons.

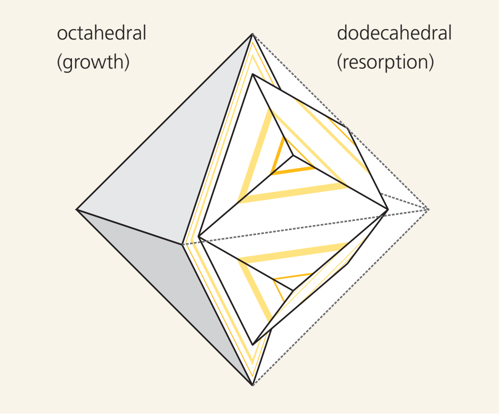
Six-sided pits (hexagons)

Some octahedral diamonds exhibit six-sided pits, which are referred to as hexagons. Hexagons can be quite large in their areal extent, and they can also be quite deep. Hexagons are usually flat bottomed, but their bottoms can be rugged (Fig. 4-11, Fig. 4-12). Compared to trigons, which have sharp edges, hexagons often have a rounded outline and smooth edges. Hexagons develop as original crystal faces are etched by fluids at high temperatures.[67] In some cases, negative trigons are present on the bottoms of hexagons, which indicates that the etching event that produced the trigons postdates the formation of the hexagons (Fig. 4-13). Hexagons are generally less common than trigons, but they are a frequent and typical surface feature on diamonds from the Argyle mine in Western Australia.

4-14: Deep tetragonal etch pits (tetragons) on the surface of a diamond with a cubic habit. The field of view is ~2 mm.



4-15: Simplified representation of tetragons on the surface of a diamond cube.



4-16: Illustration of the relationship between growth zoning in octahedral diamonds and terraces in resorbed dodecahedral diamonds.

Textures on cubic crystal faces

Tetragonal pits (tetragons)

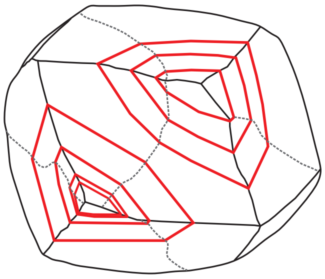
Diamond cubes exhibit very few characteristic surface textures. The only easily recognizable surface features of diamond cubes are tetragonal pits, which are referred to as tetragons (Fig. 4-14). The square outline of tetragons reflects the four-fold symmetry of the cubic crystal faces. The corners of tetragons usually point towards the edges of the underlying crystal face (negative orientation) (Fig. 4-15). Tetragons are often terraced, and they probably develop in a similar manner as trigons and hexagons—from the etching of the crystal faces by fluids at high temperatures.[219]

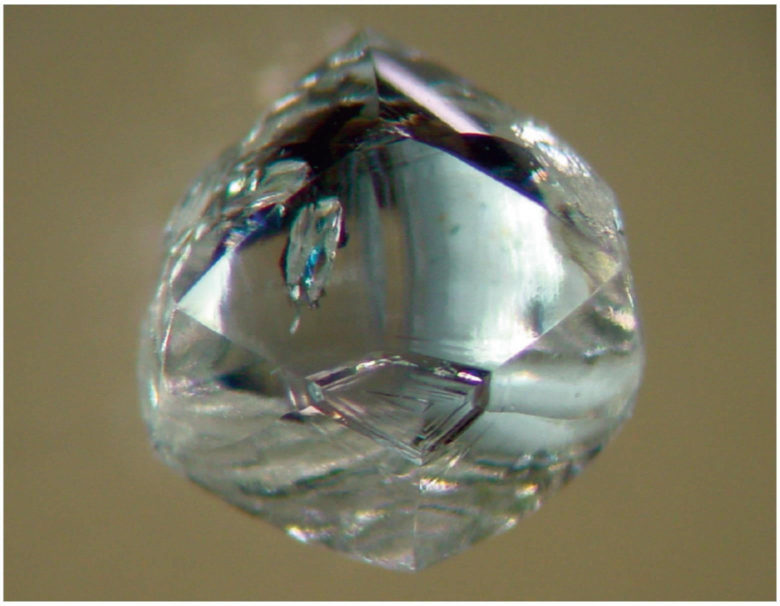
Textures on rounded dodecahedral crystal faces

Terraces

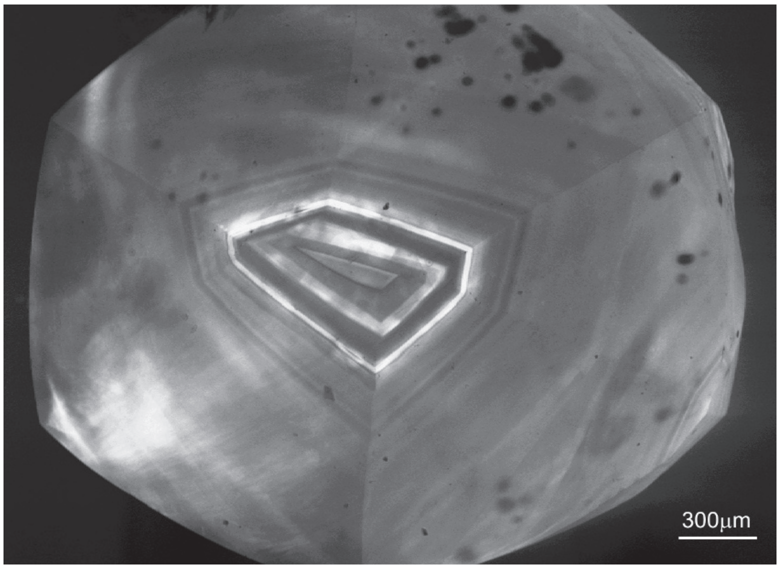
Terraces are concentric ridges or bands with a three- or six-sided outline that are developed around the three-fold axes of dodecahedral crystal faces (Fig. 4-16, Fig. 4-17). If relictic octahedral crystal faces are present, terraces usually follow their margins (Fig. 2-20). Terraces form when octahedral diamonds with strong growth zoning are resorbed and transformed into rounded dodecahedral diamonds.[202] The octahedral growth zones usually consist of layers with different concentrations of nitrogen. Depending on their nitrogen concentration, individual layers can be more resistant to resorption than others. As a result, some layers develop into terraces during the resorption process and are raised compared to the remaining crystal face (Fig. 4-18). The prominence of the terraces is influenced by the extent of the compositional differences between the layers and by the degree of resorption that the diamond has experienced.

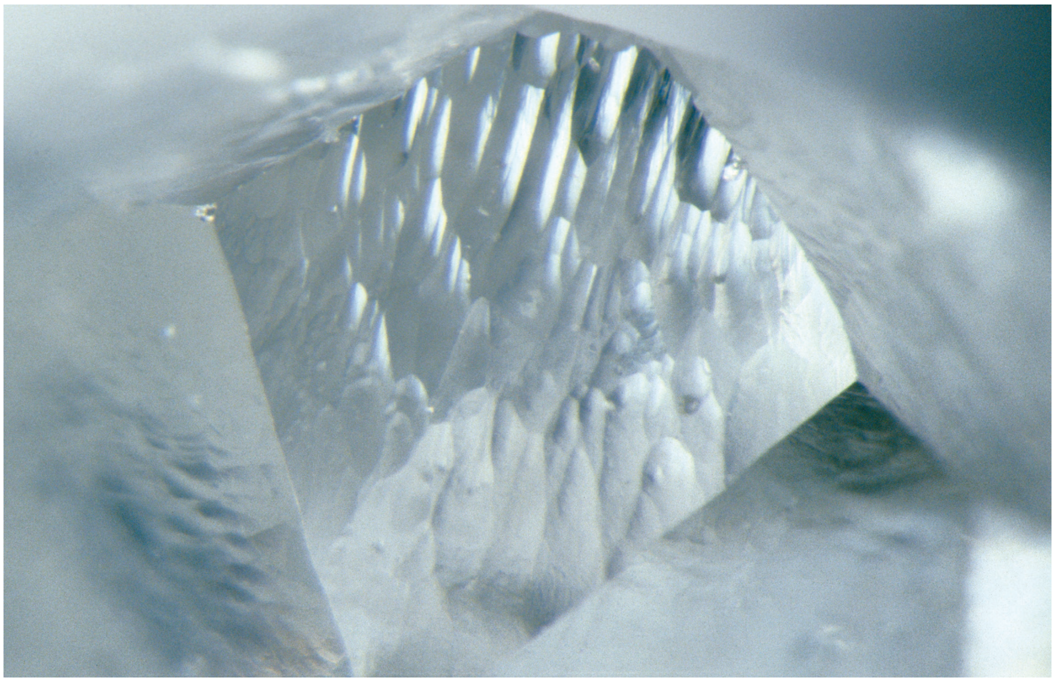
4-17: *Left,* Concentric terraces on the surface of a rounded dodecahedral diamond (1.00 ct). *Below,* Simplified representation of the main crystal faces with the terraces outlined in red.





4-18: *Left,* Rounded dodecahedral diamond (0.16 ct) with prominent terraces from Boa Vista, Roraima, Brazil. The diamond also contains a colorless olivine inclusion. *Below left,* Cathodoluminescence (CL) image showing the octahedral growth zones. The terraces coincide with the brightest areas in the CL image. These zones have the highest nitrogen contents.

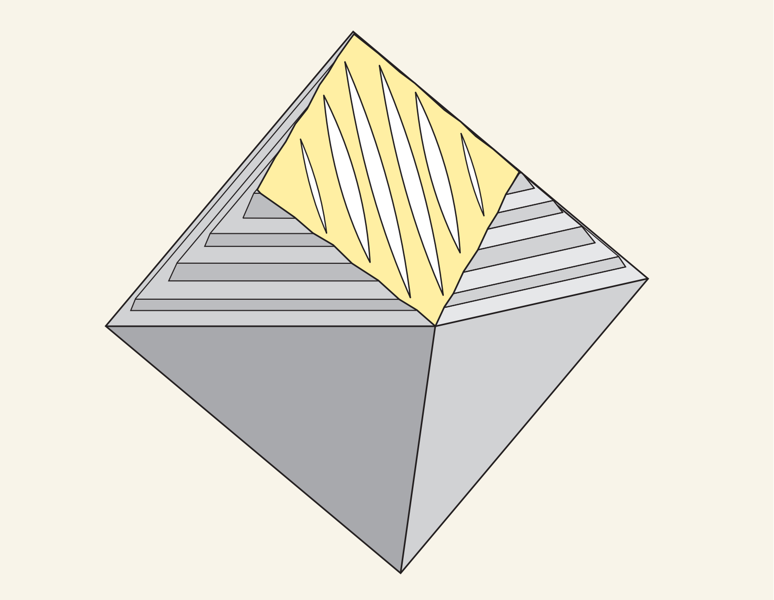




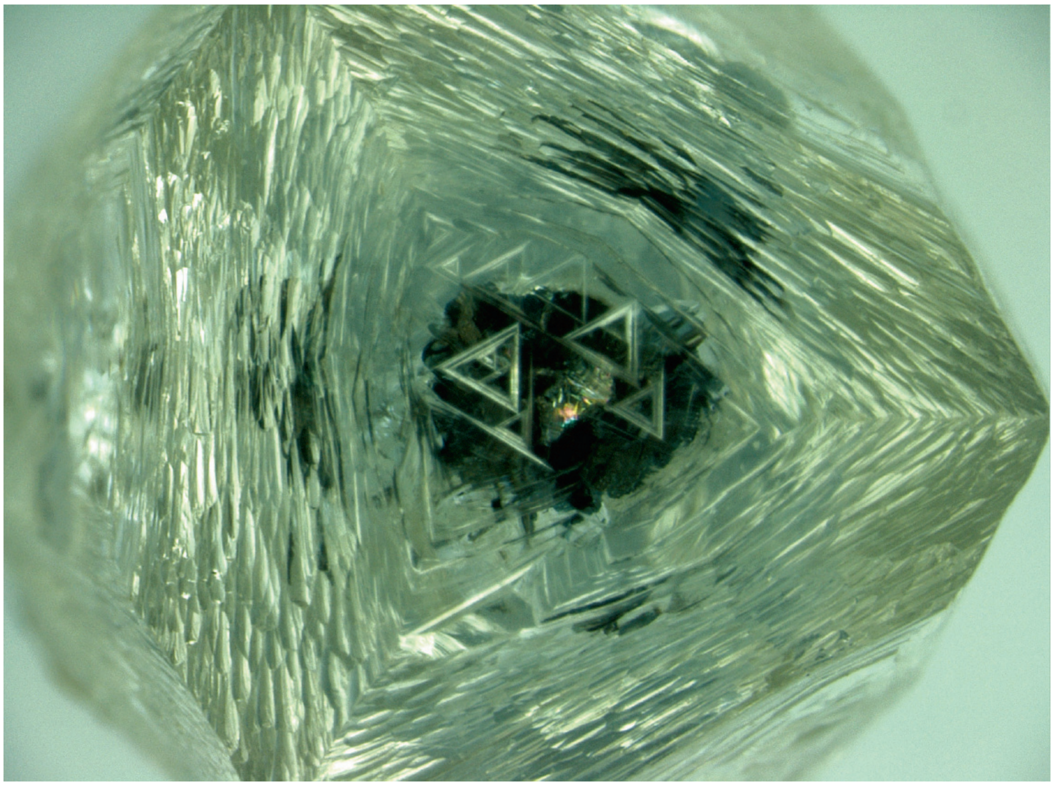
4-19: Drop-shaped hillocks on the dodecahedral crystal face of a diamond from the Jagersfontein mine, South Africa. The field of view is ~2 mm.

Hillocks

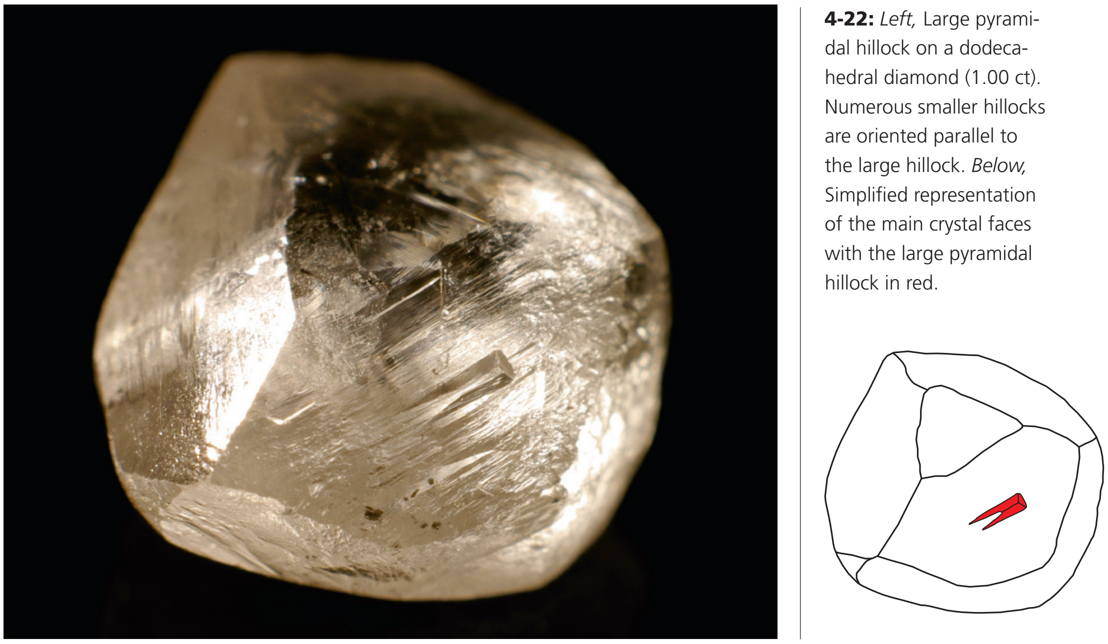
Hillocks are a common feature on dodecahedral crystal faces.[214] They can occur as isolated features, or they can occur in groups (Fig. 4-19). Similar to terraces, hillocks are usually aligned concentrically around the three-fold axes of dodecahedral crystal faces (Fig. 4-20). Hillocks are also oriented parallel to the margins of relictic octahedral crystal faces, if these are preserved (Fig. 4-21). Hillocks can have pyramidal or rounded, drop-like shapes, and they are often elongated. Pyramidal hillocks are generally restricted to diamonds that are only moderately resorbed (Fig. 4-22). More severe resorption causes the hillocks to become increasingly rounded (Fig. 4-23). The presence and shape of a hillock is strongly influenced by the original growth habit of the diamond and the degree of resorption. Stepped diamonds, for example, are more likely to develop hillocks during resorption than diamonds with smooth crystal faces.



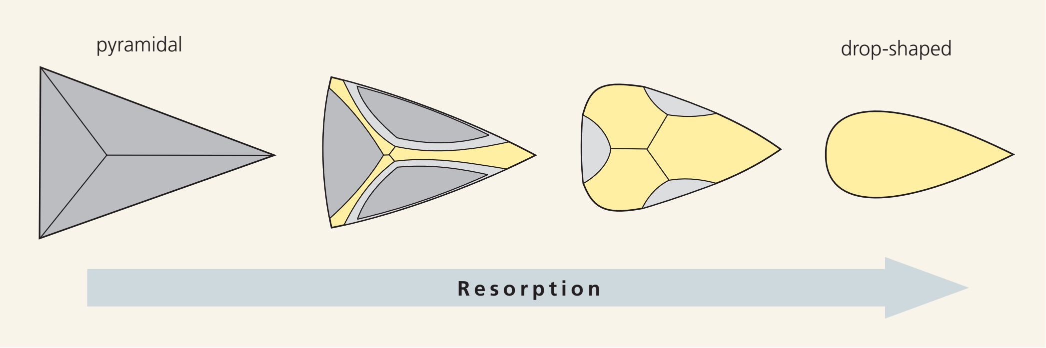
4-20: Orientation of hillocks (white) with respect to octahedral (grey) and dodecahedral (yellow) crystal faces. Modified from Orlov (1977).



4-21: Elongated, drop-shaped hillocks on dodecahedral crystal faces of a diamond from South Africa. The remnants of an octahedral crystal face are marked by the presence of trigons and shield-shaped laminae. The drop-shaped hillocks are oriented parallel to the edges of the relictic octahedral crystal face. A sulfide inclusion within the diamond is visible through the octahedral crystal face. A characteristic rosette of opaque fractures surrounds the sulfide. The field of view is ~6 mm.

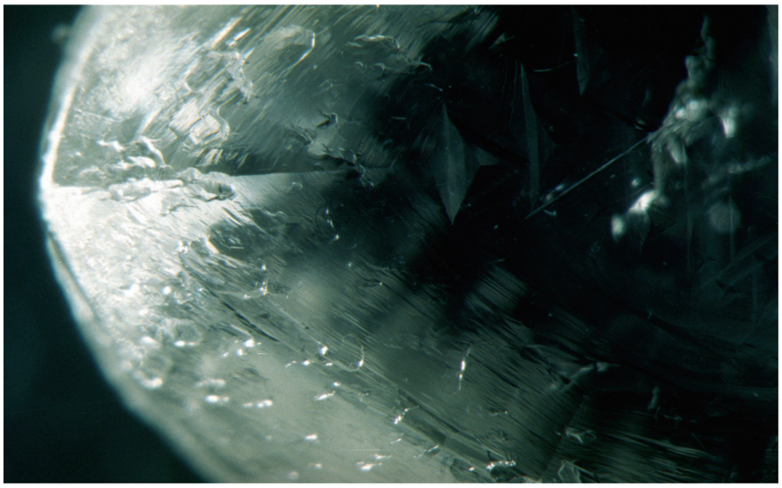


4-22: *Left,* Large pyramidal hillock on a dodecahedral diamond (1.00 ct). Numerous smaller hillocks are oriented parallel to the large hillock. *Below,* Simplified representation of the main crystal faces with the large pyramidal hillock in red.



4-23: The transition from a pyramidal hillock to a drop-shaped hillock.

4-24: Corrosion sculptures on the surface of a rounded macle. The field of view is ~3 mm.



4-25: *Right,* Pale yellow, dodecahedral diamond with corrosion sculptures and terraces (0.94 ct). *Below,* Close-up of the corrosion sculptures. The field of view is ~2 mm.

Corrosion sculptures and shallow depressions

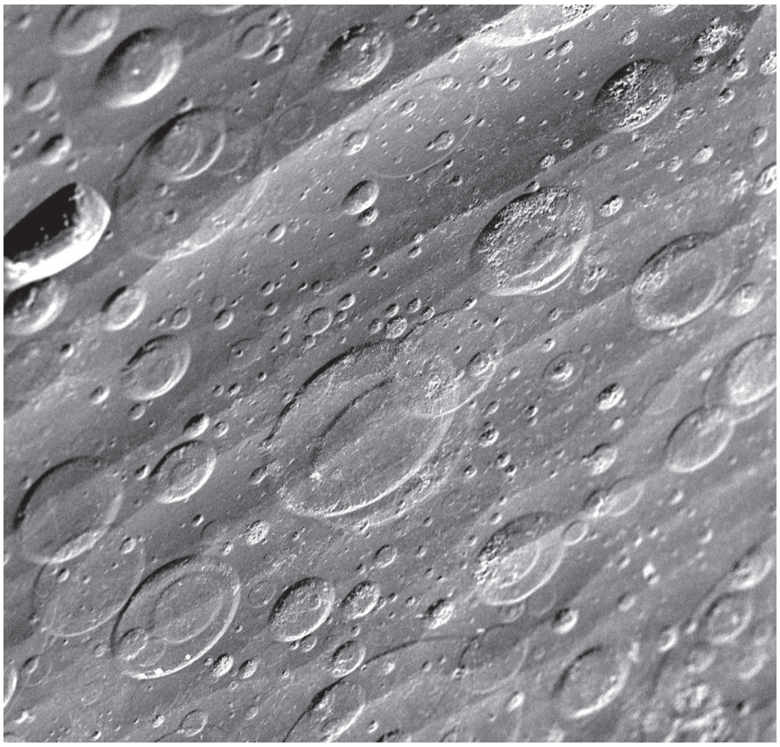
Dodecahedral crystal faces occasionally exhibit pits with elliptical or irregularly curved outlines.[214, 307, 315] Some pits are deep and have distinctly striated bottoms (Fig. 4-24). These are generally referred to as corrosion sculptures. In other cases, the pits are shallow and have smooth bottoms. These types of pits are classified as shallow depressions.[240] Shallow depressions can coalesce and cover large parts of the diamond surface (Fig. 4-25). Corrosion sculptures and shallow depressions can occur together on the same diamond.

The development of corrosion sculptures and shallow depressions is caused by late-stage etching that postdates the formation of terraces and hillocks. Diamonds with corrosion sculptures were found to be more abundant in the higher levels of some kimberlites,[307] which indicates that the etching that produced the corrosion sculptures occurred close to the Earth's surface within the cooling kimberlitic magma.

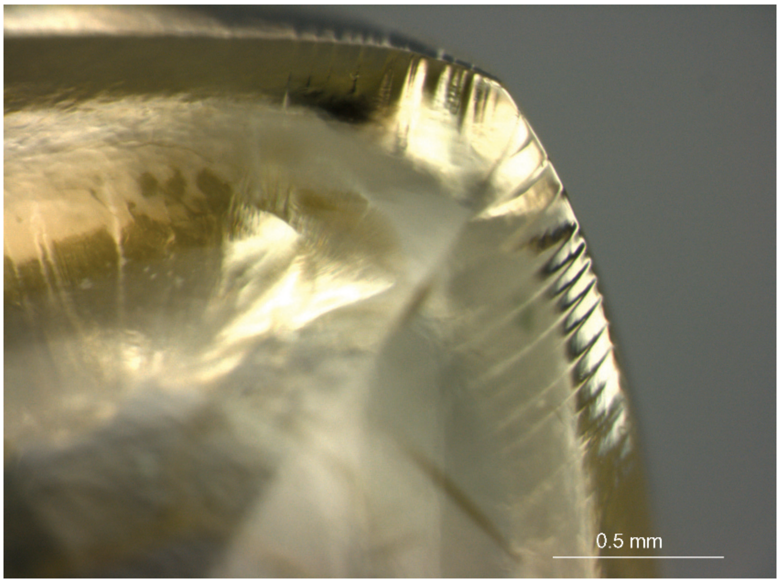
Micro-disks and micro-pits

Some dodecahedral crystal faces exhibit distinctly circular features, which occur either as slightly raised disks or as circular pits (Fig. 4-26). The diameters of the individual disks or pits can be quite variable, but they are mostly of microscopic size. The formation of micro-disks and micro-pits also postdates the formation of terraces and hillocks, and they are, therefore, linked to late-stage etching. Micro-disks and micro-pits can occur in association with corrosion sculptures and shallow depressions.

It has been suggested that the presence of small bubbles on the diamond surface during late-stage etching is responsible for the development of micro-disks. The bubbles, in this case, protected the surface of the diamond from the etching, leaving raised disks.[218]



4-26: Circular micro-pits on a dodecahedral crystal face of a placer diamond from the Springfield Basin, South Australia. The original dodecahedral crystal face exhibits elongated hillocks. Since the micro-pits formed on the top of the hillocks, they must be late-stage etch features. The field of view is 90 micrometers.

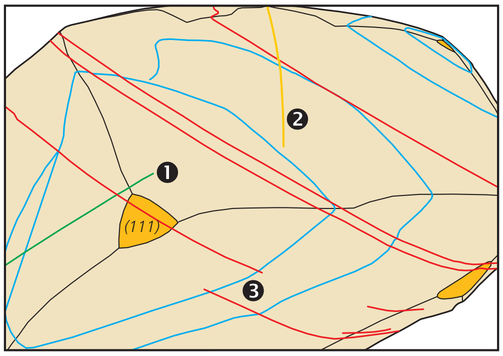


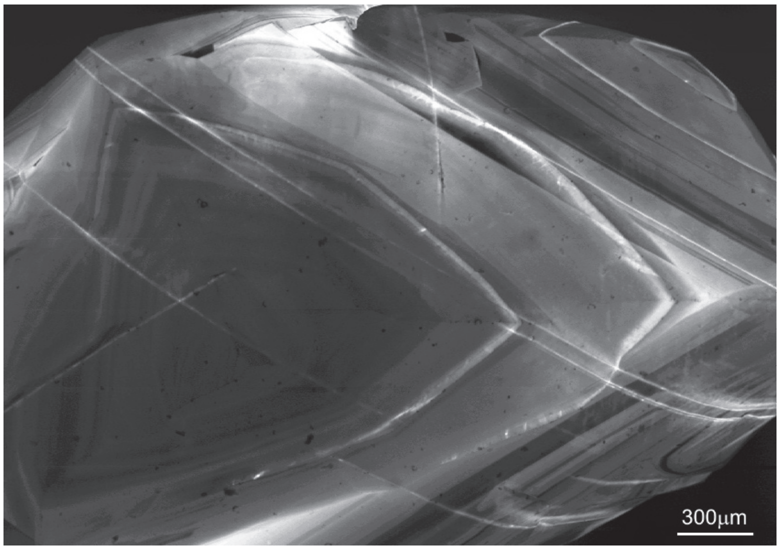
4-27: Deformation lines on a dodecahedral placer diamond from Echunga, South Australia. The deformation lines are accentuated by resorption.

Textures not restricted to specific crystal faces

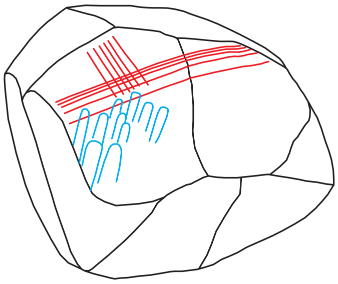
Deformation lines

Dodecahedral crystal faces commonly exhibit sets of closely spaced lineations that formed in response to plastic deformation (Fig. 4-27). These lineations, which are referred to as deformation lines, can extend across adjacent crystal faces. Up to four sets of deformation lines with different orientations can be present on a single diamond (Fig. 4-28, Fig. 4-29, Fig. 4-30, Fig. 4-31).[315] Deformation lines are caused by the displacement and shifting of carbon atoms along octahedral planes (glide-planes). The four sets of deformation lines, therefore, coincide with the four possible orientations of the octahedral planes. At the intersection of the glide-planes with the diamond surface, the diamond is more resistant to resorption. These intersections, therefore, become enhanced during resorption.



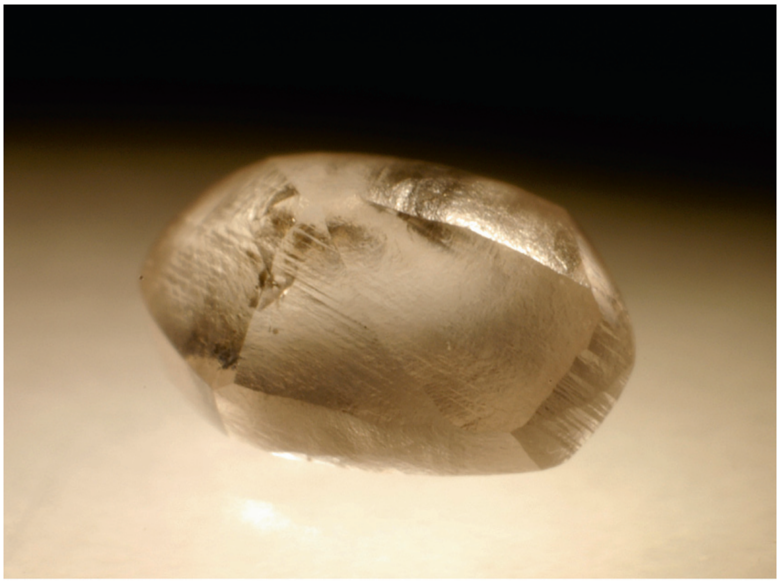


4-28: *Right,* Cathodoluminescence image of a dodecahedral diamond from Canastra, Minas Gerais, Brazil. The diamond exhibits deformation lines that appear as straight bright lines that cut across some of the original octahedral growth zones. Three distinct sets of deformation lines can be distinguished. These are oriented parallel to octahedral planes within the diamond. *Above,* Illustration of the main crystal faces and the location of the deformation lines (set 1–3). Growth zoning is marked in blue.

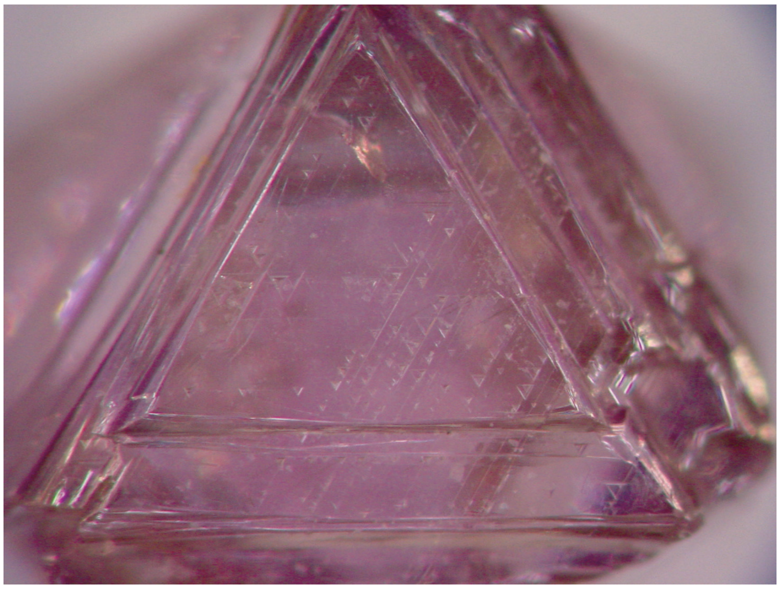


4-29: *Left,* Brown dodecahedral diamond with two sets of deformation lines oriented in different directions (1.13 ct). The diamond also exhibits elongated hillocks that follow a third direction. *Above,* Simplified representation of the main crystal faces and the location of the deformation lines (red) and the hillocks (blue).

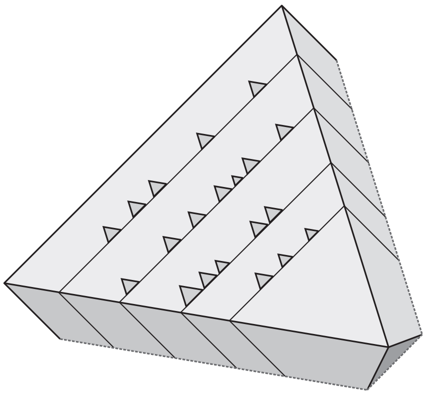
4-30: Colorless dodecahedral diamond with two distinct sets of deformation lines (1.00 ct).



4-31: Colorless dodecahedral diamond from Guinea, with deformation lines (0.22 ct).



4-32: Deformation lines on an octahedral crystal face of a pink diamond from the Mir mine, Russia. Parallel rows of flat-bottomed trigons follow the trend of the deformation lines. The field of view is ~2 mm.



4-33: Orientation of deformation lines and trigons on an octahedral crystal face.

Deformation lines are less obvious on un-resorbed octahedral crystal faces. In some cases, however, they can be marked by rows of trigons that are aligned along the deformation lines (Fig. 4-32, Fig. 4-33). Multiple parallel rows of trigons can occur on the same octahedral crystal face. Although deformation lines can occur on diamonds of any color, they are particularly common on brown and pink diamonds. Plastic deformation occurs at high temperatures and high pressures,[58] most likely within the Earth's mantle.

Surface frosting

Some diamonds exhibit surface frosting that covers parts of the diamond or the entire diamond surface. The frosting can have a fine or a relatively coarse texture that usually causes the diamond to appear dull (Fig. 4-34, Fig. 4-35). Surface frosting is caused by numerous microscopically small etch pits, which probably formed during rapid late-stage etching within the cooling kimberlite.[240]

4-34: Fine frosting on the surface of a dodecahedral diamond with a green surface color (0.26 ct).

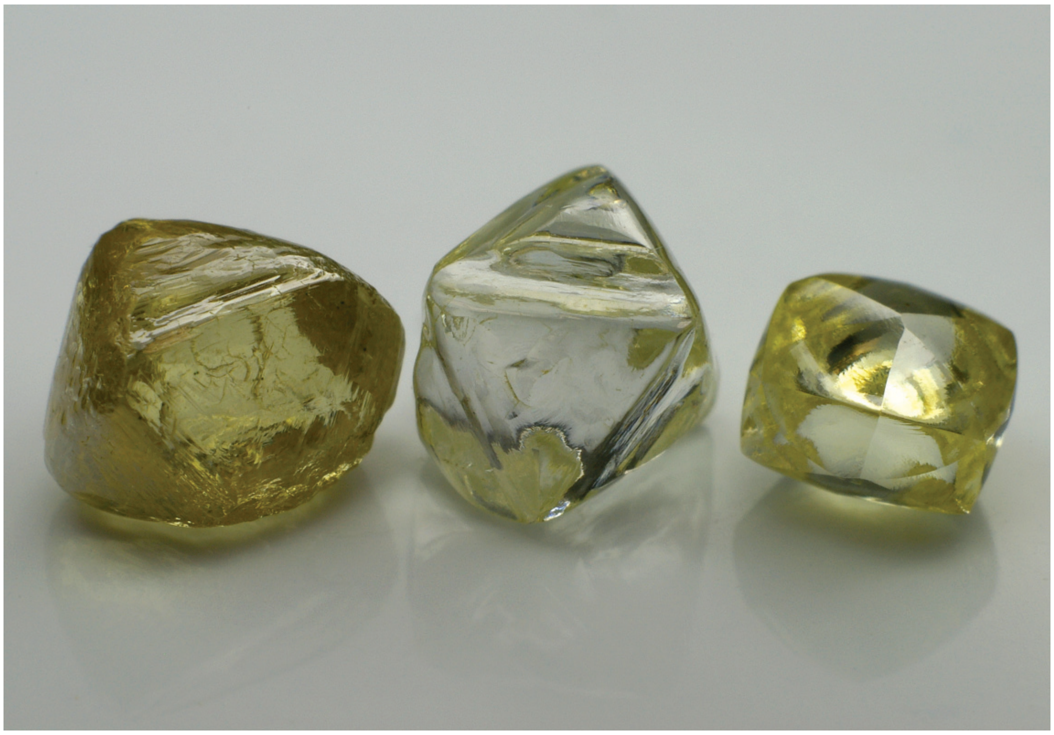
4-35: Coarse frosting on the surface of a rounded dodecahedral diamond with a green surface color (0.32 ct).

Enhanced luster

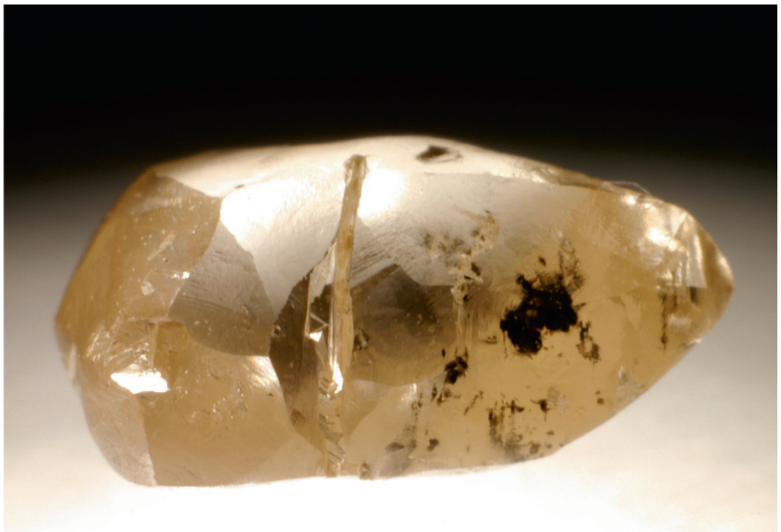
Some diamonds are characterized by conspicuously lustrous surfaces that lack fine surface textures. Such enhanced luster is particularly common on dodecahedral diamonds, but it can also occur on rounded octahedral diamonds (Fig. 4-36). The enhanced luster is possibly the result of late-stage, high-temperature (~1000°C) etching.[224]

Ruts

Ruts are deep etch-channels in diamond surfaces that do not follow specific crystallographic directions (Fig. 4-37, Fig. 4-38). They are most likely related to the presence of preexisting planes of weakness within the diamond, such as those caused by fractures that have been widened by etching or resorption.[214]



4-36: Placer diamonds from Echunga, South Australia (l – r: 0.84 ct, 1.0 ct, and 0.46 ct). The dodecahedral and rounded octahedral diamonds exhibit glossy surfaces with enhanced luster.



4-37: A large rut on a light brown, dodecahedral diamond from Guinea (0.77 ct).

4-38: A rut intersecting a parallel intergrowth of two octahedral diamonds with a fibrous coat (1.09 ct).

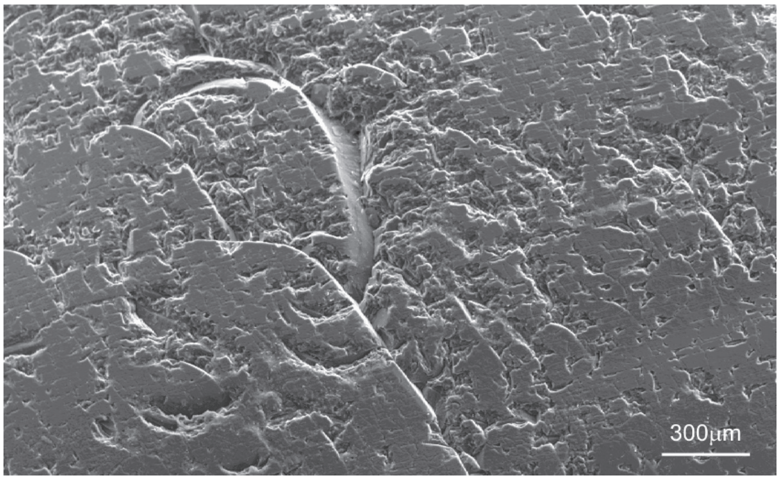
4-39: Pale yellow, dodecahedral diamond (1.11 ct) with large crescent-shaped percussion marks that formed as a result of particle impact during transport.

Surface textures on placer diamonds

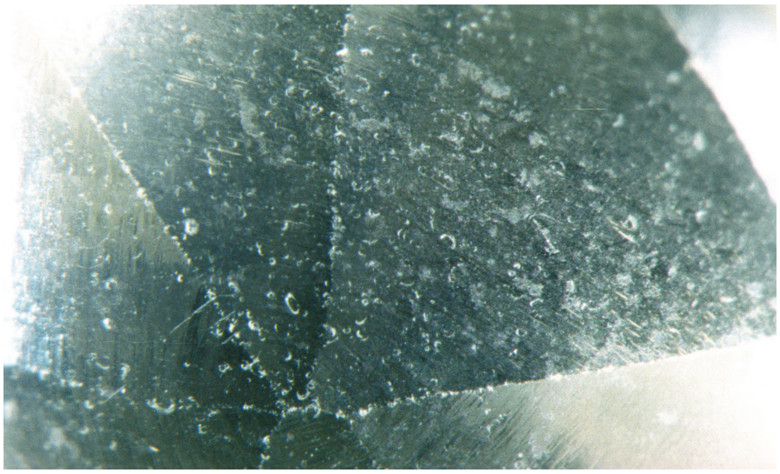
Diamonds from placer deposits exhibit a range of distinctive surface textures that are either absent or rare on diamonds recovered directly from kimberlites. These textures are generally the result of abrasion during transport on the Earth's surface.

Percussion marks

Diamonds from placer deposits occasionally exhibit fractures and spall scars that have crescent-shaped, rounded, or hexagonal outlines (Fig. 4-39). These fractures can be the result of particle impacts on the diamond surface. In this case, the size of the fracture, or percussion mark, is largely related to the size of the impacting particle and its energy. The fractures can extend deep into the interior of the diamond following the directions of the octahedral planes (Fig. 4-40).[123, 124] Percussion marks on placer diamonds likely form in high energy environments, like fast flowing rivers or beach settings. In these environments, particles such as pebbles or boulders can saltate and collide with the diamond causing surface damage or even completely breaking the diamond. Percussion marks may also form by the collision of diamonds with hard rock surfaces. Very small percussion marks may be the result of windblown sand grains hitting the diamond surface (Fig. 4-41).[240] Percussion marks can also be present on diamonds from kimberlitic deposits. In these cases, they may have formed during kimberlite emplacement or during the processing of the kimberlite ore (e.g. crushing and transport).



4-40: Scanning electron microscope (SEM) image of crescent-shaped percussion marks and network patterns on the surface of an alluvial diamond from Arenapolis, Mato Grosso, Brazil. The network patterns consist of two sets of fine, parallel grooves.

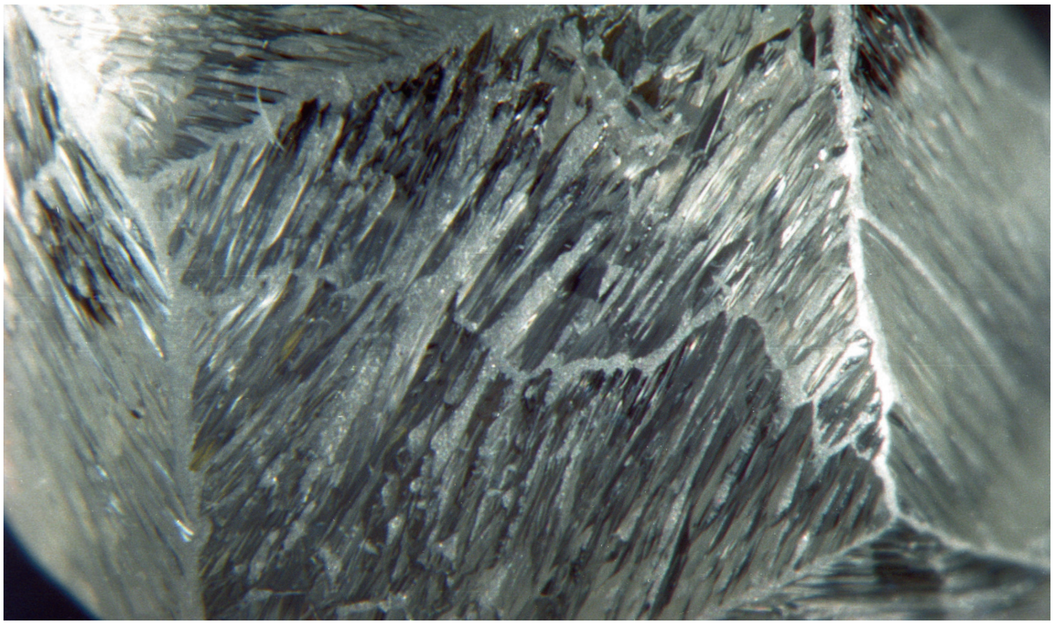


4-41: Surface of a rounded dodecahedral diamond with numerous small percussion marks. The small size of the percussion marks suggests they may have been caused by the impact of windblown sand grains. The field of view is ~3 mm.

Edge abrasion, surface abrasion, and scratch marks

Placer diamonds can be subjected to varying degrees of abrasion that produce a rough surface.[240] Abrasion primarily affects the most protruding features, such as the sharp crystal edges. Small degrees of edge abrasion are characterized by the appearance of a few small fractures on the sharpest edges (Fig. 4-42). With increasing degrees of abrasion, less pronounced edges and crystal faces are affected. For example, flat crystal faces may show scratch marks (Fig. 4-43), and sharper crystal edges may be rounded and have a dull appearance. In extreme cases, the abrasion can result in a distinctively rounded diamond with few clear surface areas (Fig. 4-44), or completely dull surfaces (Fig. 4-45). Abrasion textures, like percussion marks, are mainly related to the processes that occur in high-energy environments, such as the transport of diamonds over exposed bedrock on the bottom of a riverbed. Rivers also contain potholes where diamonds can be trapped, and the contact of the diamonds with the walls of the potholes can cause the abrasion of placer diamonds.[240]

4-42: *Right,* Dodecahedral diamond (1.04 ct) with abraded hillocks and crystal edges. *Below,* Close-up of the abraded hillocks and crystal edges.



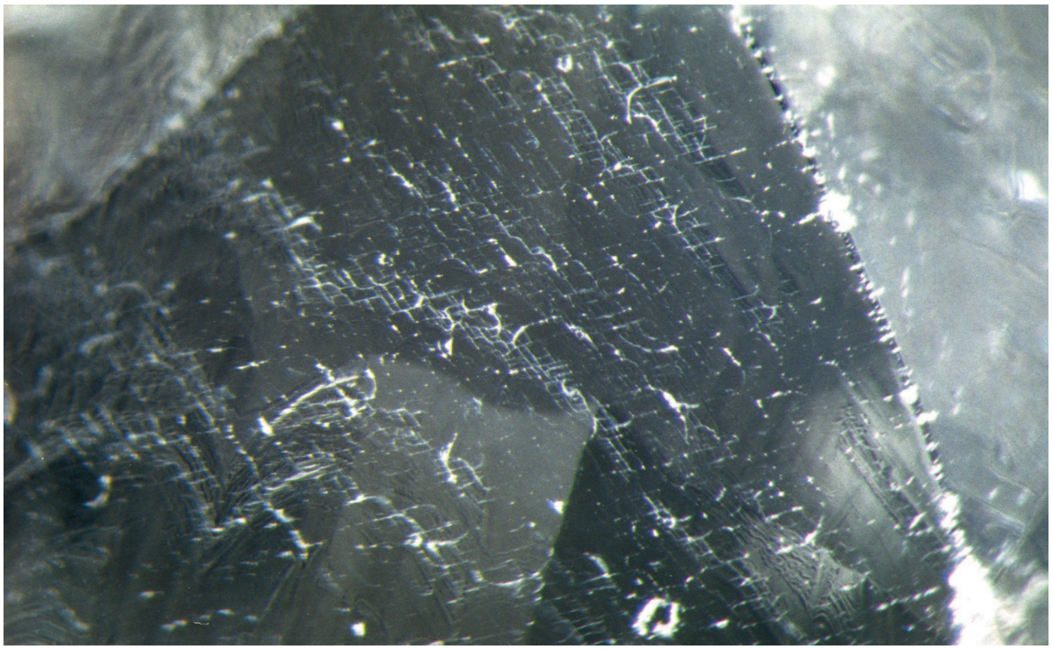
4-43: Dodecahedral diamond (1.13 ct) with abraded edges and scratched crystal faces. Inclusions inside the diamond cause the orange color.

4-44: Abraded dodecahedral diamond (1.10 ct). The deepest parts of the surfaces are not abraded indicating that the diamond was scratched on a hard surface, such as the sidewalls of a pothole within a riverbed.

4-45: Dodecahedral diamond with a strongly abraded surface (0.95 ct).

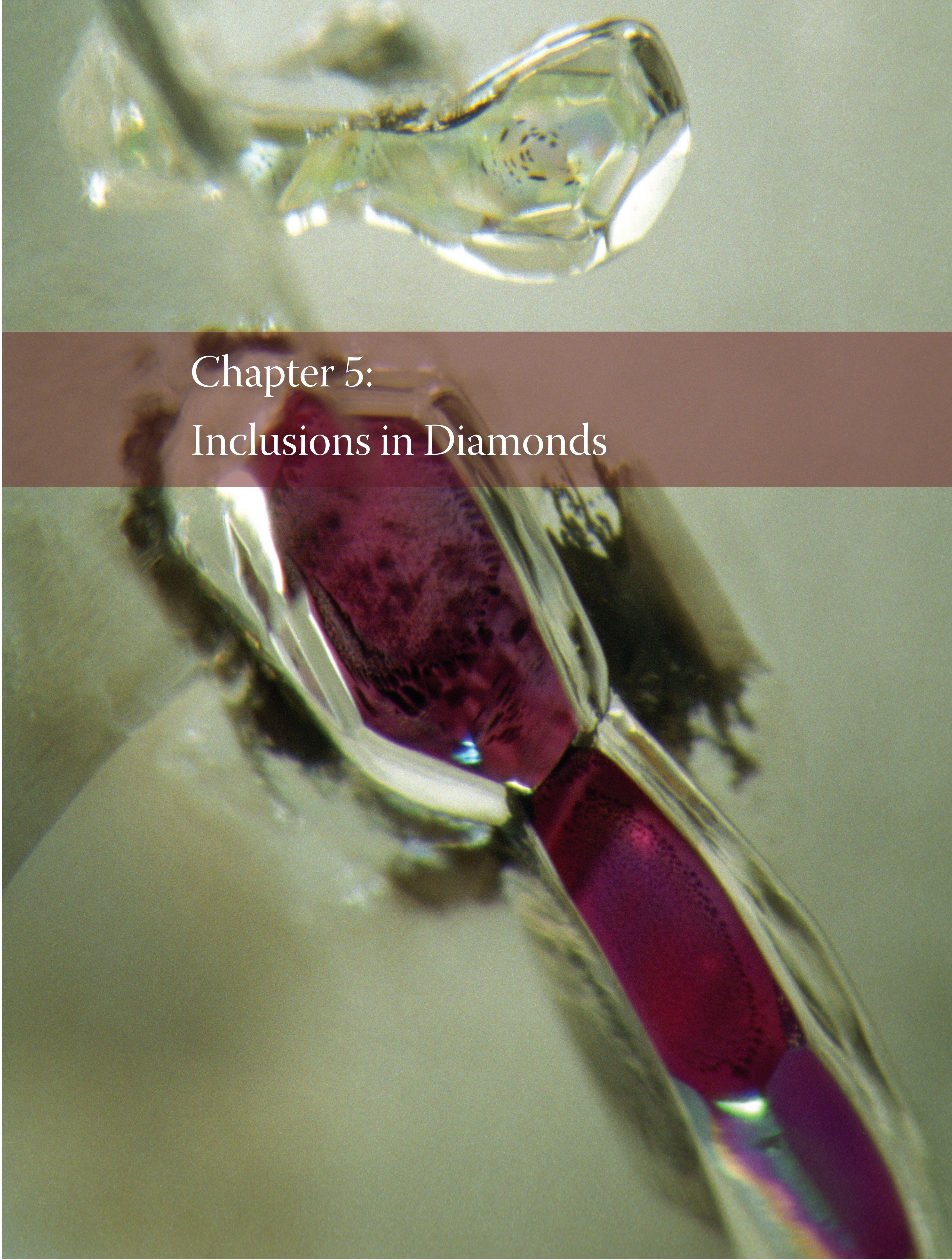
Network patterns

Network patterns on the surface of placer diamonds consist of parallel, tightly-spaced grooves (Fig. 4-46).[66, 240] The grooves generally occur where octahedral planes intersect the diamond surface. The space between the grooves can vary from a few micrometers to tens of micrometers. On dodecahedral crystal faces, the intersection of two sets of grooves produces a distinctive rhombic pattern. On octahedral crystal faces, network patterns are generally less regular. The presence of network patterns is linked to a minor dislocation of carbon atoms along octahedral planes, similar to deformation lines. During residence in a placer environment, these dislocations are enhanced by etching.[66] Network patterns are often associated with edge abrasion.



4-46: *Right,* Faint network patterns on the surface of a dodecahedral diamond (1.19 ct). *Below,* Close-up of the network patterns.

Chapter 5:
Inclusions in Diamonds



Previous page –
Mineral inclusions
in a diamond from
Damtshaa, Botswana.

Chapter 5:
Inclusions in Diamonds

Diamonds frequently contain inclusions. These inclusions can alter the appearance and transparency of a diamond and are often undesired constituents in gemstone diamonds. On the other hand, inclusions can provide insights into the origin of diamonds. Although inclusions can be found in all morphological types of diamonds (i.e. monocrystalline, fibrous, and polycrystalline diamonds) the characteristics of the inclusions can be quite different for each diamond type. Monocrystalline and polycrystalline diamonds, for example, typically contain inclusions of other minerals, whereas fibrous diamonds usually contain inclusions of fluids.[189, 208, 275]

Inclusions in monocrystalline diamonds

Most of the inclusions in monocrystalline diamonds are rather nondescript. They commonly occur as dark flakes, spots, clouds, or as coatings on internal fractures. In many cases, these inclusions consist merely of graphite, the low-pressure polymorph of diamond.[107] Aside from these nondescript inclusions, monocrystalline diamonds occasionally contain inclusions of other minerals, including various silicates, oxides, and sulfides, which were part of the growth environment of the diamond.[193] Once enclosed by the host diamond, these mineral inclusions were protected from alteration.

The mineral inclusions in monocrystalline diamonds have received considerable scientific attention because they are pristine samples from parts of the Earth's mantle that are otherwise inaccessible. Therefore, they contain valuable information about the composition and geological history of the Earth's interior. This information is also of importance to the diamond mining and exploration industry (e.g. locating new diamond deposits) and in the gem trade (e.g. tracing and evaluating diamonds).

Inclusion characteristics

Mineral inclusions in monocrystalline diamonds can range in size from the sub-microscopic to the millimeter scale. Larger diamonds are statistically more likely to contain more inclusions, and these inclusions are more likely to be larger. The abundance of diamonds containing visually recognizable mineral inclusions other than graphite is generally quite small, but the abundance varies between deposits. At some southern African

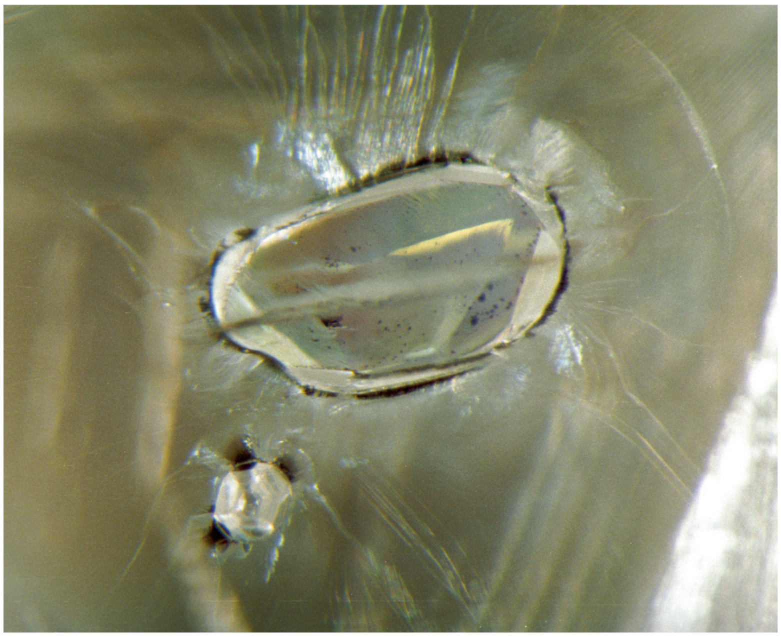
R. Tappert and M.C. Tappert, *Diamonds in Nature: A Guide to Rough Diamonds*,
DOI 10.1007/978-3-642-12572-0_5, © Springer-Verlag Berlin Heidelberg 2011

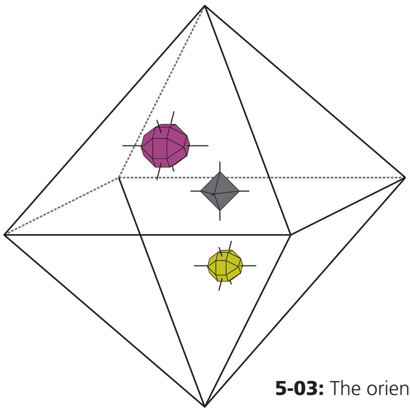
5-01: *Right,* Strongly elongated peridotitic garnet inclusion (~1 mm in length). The crystal faces of the garnet are oriented parallel to the octahedral growth directions of the diamond, which are marked by terraces. This indicates that the inclusion and diamond crystallized, or re-crystallized, at the same time. One of the dodecahedral crystal faces of the diamond has been polished for better visibility. *Below right,* Close-up of the peridotitic garnet inclusion. The garnet has crystal faces that resemble a strongly distorted cubo-octahedron.

diamond mines, an average of only one percent of the diamonds in the ~2 mm size fraction contained visually recognizable mineral inclusions.[275]

Many mineral inclusions in monocrystalline diamonds exhibit well-developed crystal faces and distinctive shapes.[315] The shapes are typically octahedral or cubo-octahedral, and they are often distorted to some degree (Fig. 5-01). These regular shapes are even developed by minerals like olivine or pyroxene that do not have cubic crystal structures and under normal growth conditions would not develop an octahedral or cubo-octahedral shape. This means that the diamond imposes its shape onto the enclosed mineral.[105]

5-02: *Left,* Colorless inclusions (large inclusion is ~1 mm) of an unknown mineral in a flattened dodecahedral diamond from the Venetia mine, South Africa. The main crystal face of the large inclusion is oriented parallel to a relictic octahedral crystal face of the diamond. The diamond has been polished for better visibility. *Below left,* Close-up of the inclusions. It is notable that the crystal faces of the smaller inclusion are oriented in the same direction as those of the larger inclusion.

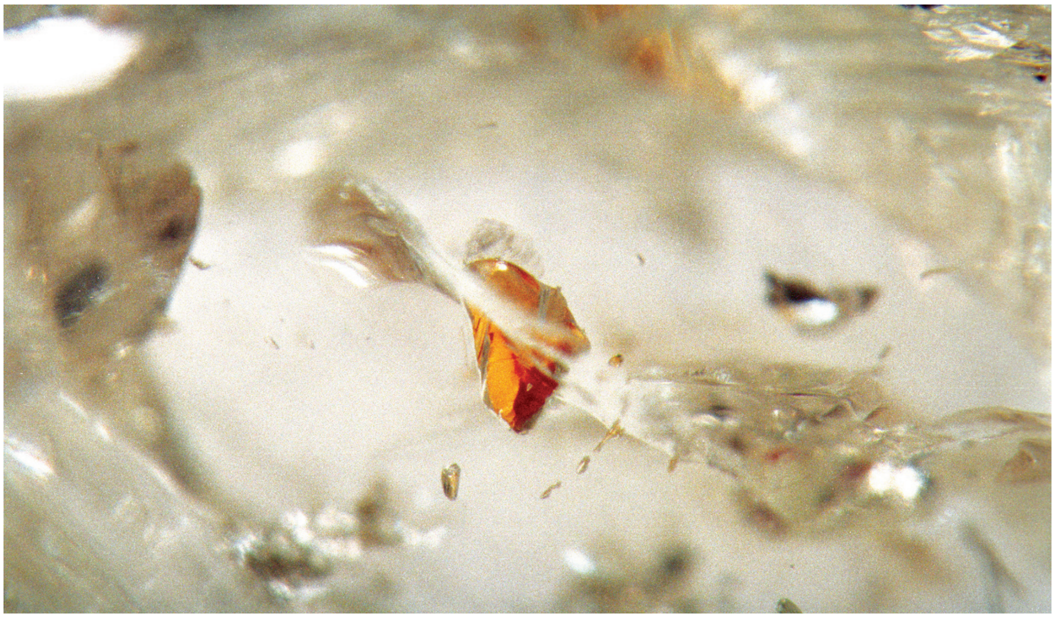




5-03: The orientations of inclusion minerals with cubo-octahedral and octahedral crystal shapes shown in relation to an octahedral host diamond.

The crystal faces of mineral inclusions are also often aligned parallel to the octahedral crystal faces of the host diamond, which indicates that the inclusions are not randomly oriented within the diamond (Fig. 5-02).[196] Furthermore, x-ray analyses have shown that the crystal faces and the crystal axes of the inclusions can be aligned with those of the host diamond. This means that the inclusions and the host diamond form an epitaxial intergrowth (Fig. 5-03).[104]

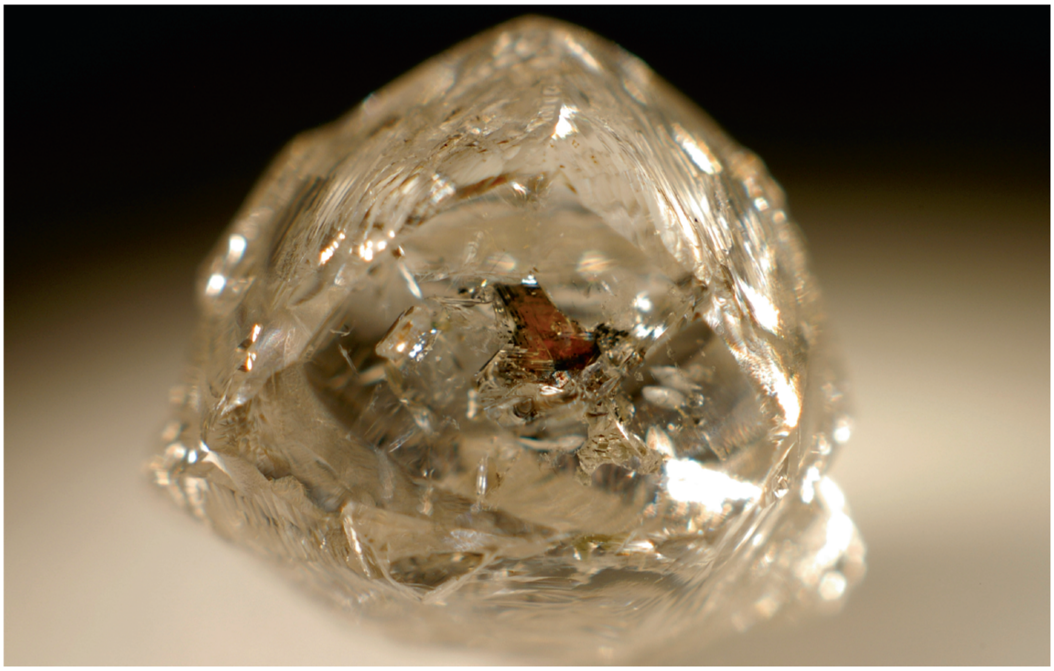
The close crystallographic relationship between the inclusion and the diamond provides evidence that both crystallized at the same time. These mineral inclusions, therefore, are often interpreted as being syngenetic



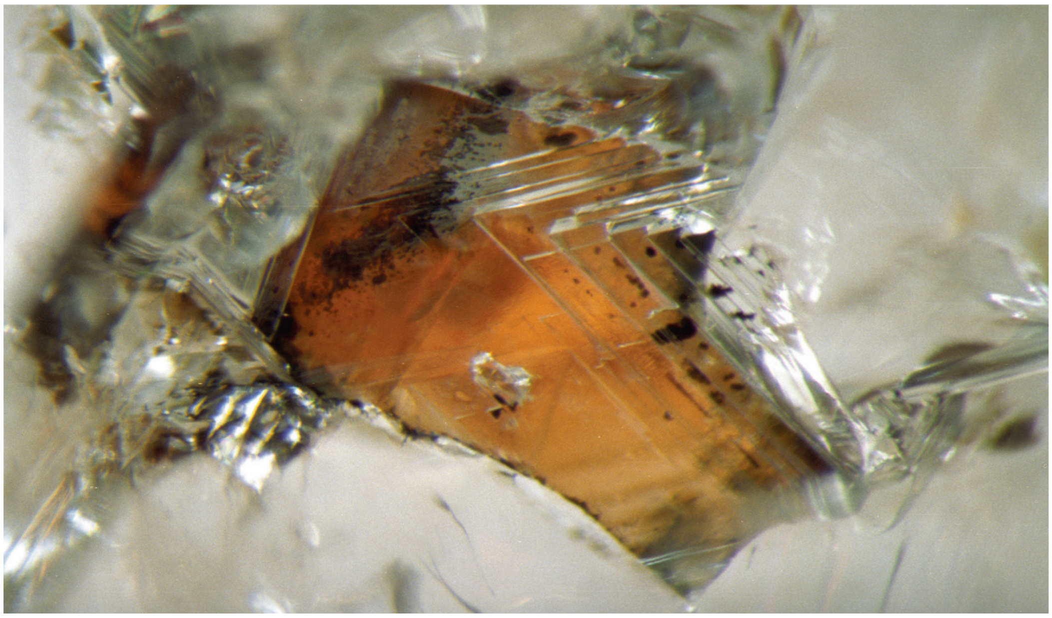
5-04: *Right,* Eclogitic garnet inclusion with its characteristic orange color in a strongly resorbed and slightly distorted diamond (Ø: ~6 mm). The diamond surface is polished for better visibility. *Below right,* Close-up of the eclogitic garnet inclusion. The lack of a distinctive crystal shape indicates that the garnet may be protogenetic.

with the host diamond.[105] The observation that the mineral inclusions and their host diamonds crystallized at the same time seems to contradict the premise that diamonds grow from fluids or melts that percolate through an already existing lithospheric mantle. The most likely solution for this apparent contradiction is that the (pre-existing) minerals that were incorporated in the diamond re-crystallized at the same time as the diamond was growing. The re-crystallization of the host rocks would also create the spaces necessary for diamonds to develop their typical growth habits.

Some mineral inclusions do not exhibit well-developed crystal faces or crystal shapes, nor do they have a close crystallographic relationship with the host diamond (Fig. 5-04). These inclusions possibly crystallized before the diamond and consequently could be classified as protogenetic inclusions.[105, 193]

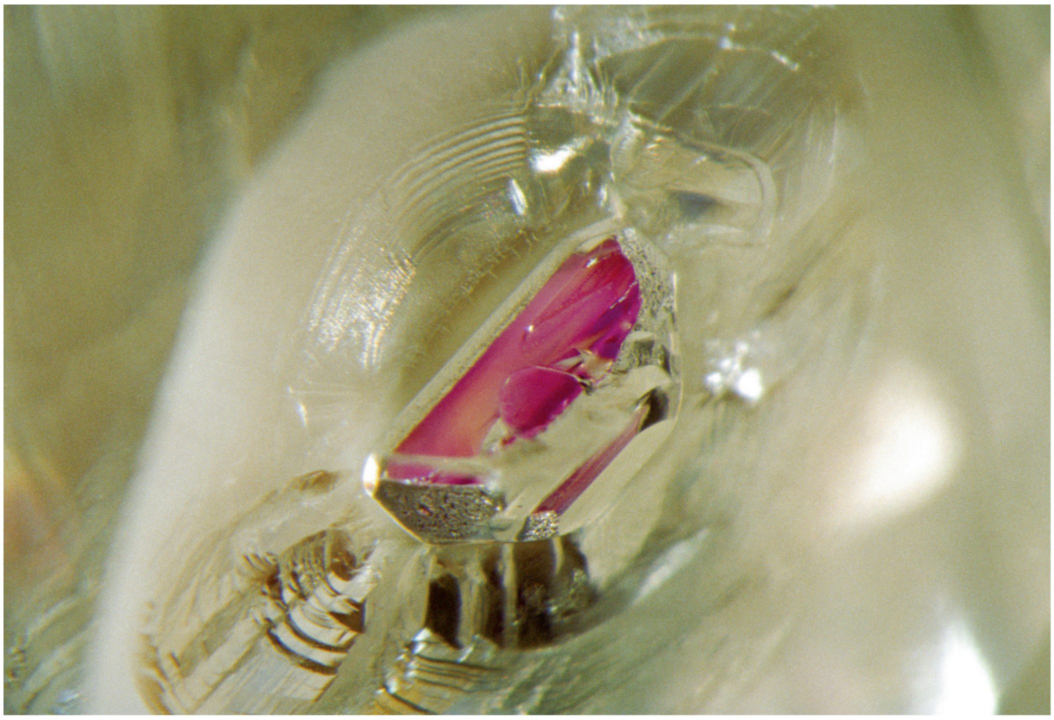


5-05: *Left,* Rounded dodecahedral diamond containing an altered (epigenetic) mineral inclusion (Ø: ~7 mm). The diamond surface is polished for better visibility. *Below left,* Close-up of the inclusion, which contains dark cloudy patches that are characteristic for altered inclusions.



Unlike syngenetic and protogenetic mineral inclusions, epigenetic minerals formed after the growth of the host diamonds.[106] The formation of epigenetic minerals is generally linked to processes that occurred to the diamond during transport in a kimberlitic magma or during residence on the Earth's surface. Epigenetic minerals often have little or no genetic relationship with the host diamond, which is the reason why relatively little scientific attention is paid to them. However, a wide range of minerals have been identified as epigenetic.[41, 106, 193] A common epigenetic mineral in diamond is graphite, which can form as a late-stage product on internal fractures. Epigenetic minerals also include secondary minerals that formed on the surface of the diamond, commonly in deep etch pits, ruts, or fractures. In addition, epigenetic minerals comprise syngenetic or protogenetic inclusions that were altered while residing within the diamond.[106] In this case, alteration can occur through fractures that connect the inclusion

5-06: *Right,* Purplish-red peridotitic garnet inclusion in a rounded dodecahedral diamond (Ø: ~8 mm). The inclusion is surrounded by fractures. A dodecahedral crystal face is polished for better visibility. *Below right,* Close-up of the peridotitic garnet inclusion, which exhibits well-defined crystal faces.



mineral to the diamond surface. Fluids permeating through the fractures can alter or dissolve the original inclusions. Even very small fractures can act as conduits for fluids that destroy inclusions and precipitate secondary alteration minerals.

It is not always possible to determine if an inclusion mineral has been affected by alteration or if it is a secondary precipitate. Therefore, it can be difficult to distinguish between epigenetic minerals and true inclusions. Minerals located close to visible fractures or to the surface of a diamond are particularly prone to alteration and must be examined closely. Epigenetic minerals or altered inclusions can sometimes be recognized by a cloudy appearance (Fig. 5-05).

Identification of inclusions

A large number of minerals have been identified as inclusions in diamonds (Table 5-01). Most of these minerals are rare, and some of them have only been found once. Only around a dozen minerals occur frequently, and it is possible to identify some of these based on their visual appearance. The visual identification of mineral inclusions is easiest for those minerals that have distinctive colors or other unique features. Inclusions of peridotitic garnets, for example, can often be identified by their distinctive purplish-red color (Fig. 5-06). However, the visual identification of a mineral inclusion based solely on its color can be challenging. The intensity of a color can vary depending on the chemical composition of the mineral and its size. Smaller inclusions tend to have a less intense color compared to larger inclusions. Inclusions that lack distinguishing features can be even more difficult or impossible to visually identify. Several minerals, for example, are colorless, and their identification requires more advanced analytical techniques (Fig. 5-07).

Table 5-01: Mineral inclusions in monocrystalline diamonds (other than graphite and diamond)

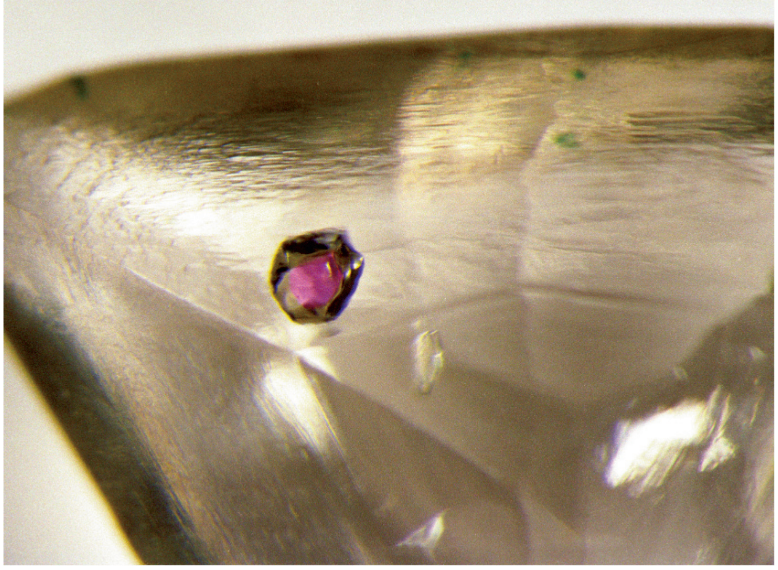
Lithospheric Inclusions				**Sublithospheric Inclusions**	
PERIDOTITIC SUITE		**ECLOGITIC SUITE**		**ASTHENOSPHERE/TRANSITION ZONE**	
Olivine	$Mg_2[SiO_4]$	(including [1]calc-silicate and [2]websteritic inclusions)		Majoritic Garnet	$(Mg,Fe)_3(Al,Si)_2[SiO_4]_3$
Pyrope Garnet	$Mg_3(Al,Cr)_2[SiO_4]_3$	Pyrope-Almandine Garnet	$(Mg,Fe)_3Al_2[SiO_4]_3$	**LOWER MANTLE**	
Orthopyroxene	$Mg_2[Si_2O_6]$	Clinopyroxene	$(Ca,Na)(Mg,Al)[Si_2O_6]$	Ferropericlase	$(Mg,Fe)O$
Clinopyroxene	$(Ca,Cr)Mg[Si_2O_6]$	Sulfides	various, usually Ni-poor	Mg-Si-Perovskite*	$MgSiO_3$
Chromite	$(Mg,Fe)Cr_2O_4$	Kyanite	$Al_2O[SiO_4]$	Ca-Si-Perovskite*	$CaSiO_3$
Sulfides	various, usually Ni-rich	Sanidine[1]	$K[AlSi_3O_8]$	TAPP	$(Mg,Fe)_3(Al,Cr)_2Si_3O_{12}$
		Coesite[1]	SiO_2	Stishovite*	SiO_2
		Rutile	TiO_2	Corundum	Al_2O_3
		Corundum	Al_2O_3	Type-III Pyroxene/Garnet*	$(Na,Mg)(Al,Mg)[Si_2O_6]$
		Orthopyroxene[2]	$Mg_2[Si_2O_6]$	*crystal structure inferred	

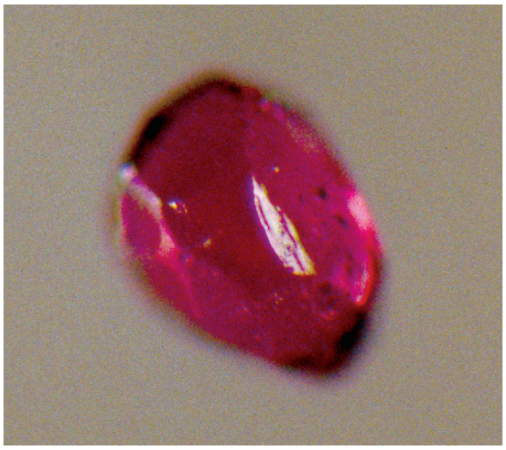
Uncertain and/or Rare Mineral Inclusions in Diamonds (with selected references)

Native Iron[263]	Fe	Eskolaite[174]	Cr_2O_3	Titanite[49]	$CaTiO[SiO_4]$
Native Chromium[90]	Cr	Perovskite[165, 192]	$CaTiO_3$	Zircon[190]	$Zr[SiO_4]$
Nickel-Chromium alloy[90]	$NiCr$	Ilmenite[190]	$(Mg,Fe,Mn)TiO_3$	Staurolite[46]	$(Fe,Mg)_2Al_9O_6[(Si,Al)O_4]_4(O,OH)_2$
Moissanite[140, 204]	SiC	Loparite-(K,Cr)[165]	$(K,Ca,Sr,REE,Th)(Cr,Ti,Fe,Nb)O_3$	Chevkinite-(Cr)[165]	$(REE,Sr,Th)_4(Mg,Fe,Ca)Cr_2(Ti,Al,Nb)_2O_8[Si_2O_7]_2$
Cohenite[252]	FeC	Lindsleyite[170, 266]	$(Ba,Sr)(Ti,Zr,Fe,Cr)_{21}O_{38}$	Melilite[49]	$(Ca,Na)_2(Al,Mg,Fe)[(Al,Si)SiO_7]$
Molybdenite[49]	MoS_2	Yimengite[18]	$K(Cr,Ti,Mg,Fe,Al)_{12}O_{19}$	Amphibole[110, 192]	$NaCa_2(Mg,Fe)_4Al[(Al_2Si_6)O_{22}](OH)_2$
Fluorite[30]	CaF_2	Magnesite[170, 309]	$Mg[CO_3]$	Phlogopite[170, 228, 266]	$KMg_3[AlSi_3O_{10}](OH,F)_2$
Wüstite[270]	FeO	Calcite[184]	$Ca[CO_3]$	Plagioclase[306]	$Na[AlSi_3O_8]$-$Ca[Al_2Si_2O_8]$
Magnetite[105]	Fe_3O_4	Apatite[90]	$Ca[PO_4]_3(OH)$		

5-07: A colorless mineral inclusion in an octahedral diamond (0.04 ct) from the Jagersfontein mine, South Africa. After it was released from the host diamond, the inclusion was identified as an eclogitic clinopyroxene.

5-08: *Right,* Peridotitic garnet inclusion in a macle from Boa Vista, Roraima, Brazil. The inclusion is slightly masked by the rough surface texture of the diamond. The field of view is ~3 mm. *Below,* The peridotitic garnet inclusion after it was released from the host diamond. The crystal faces are now visible.

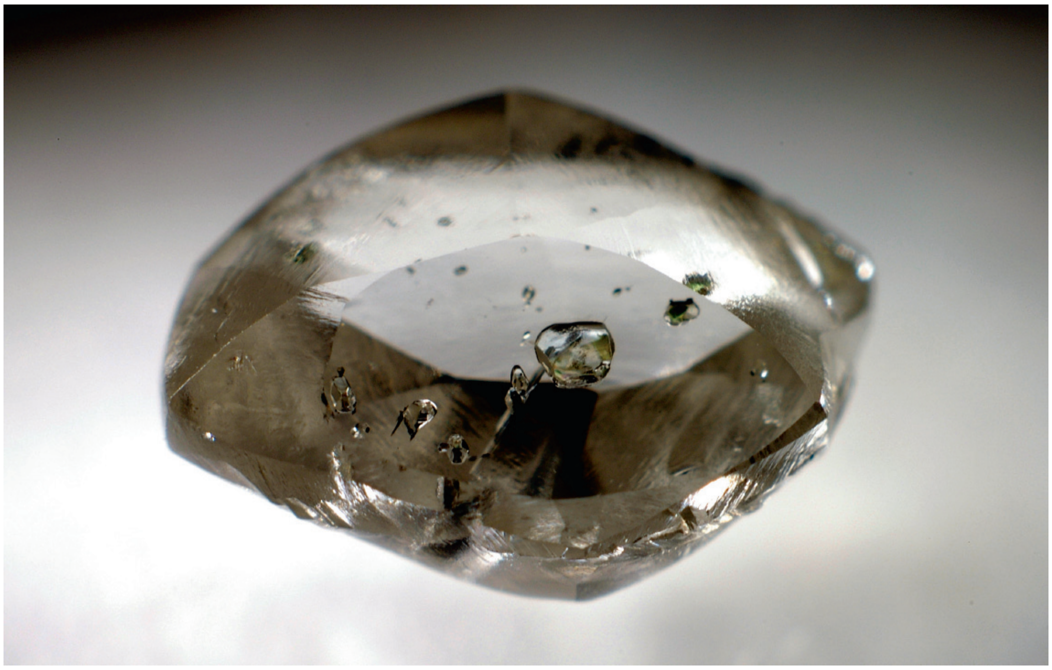


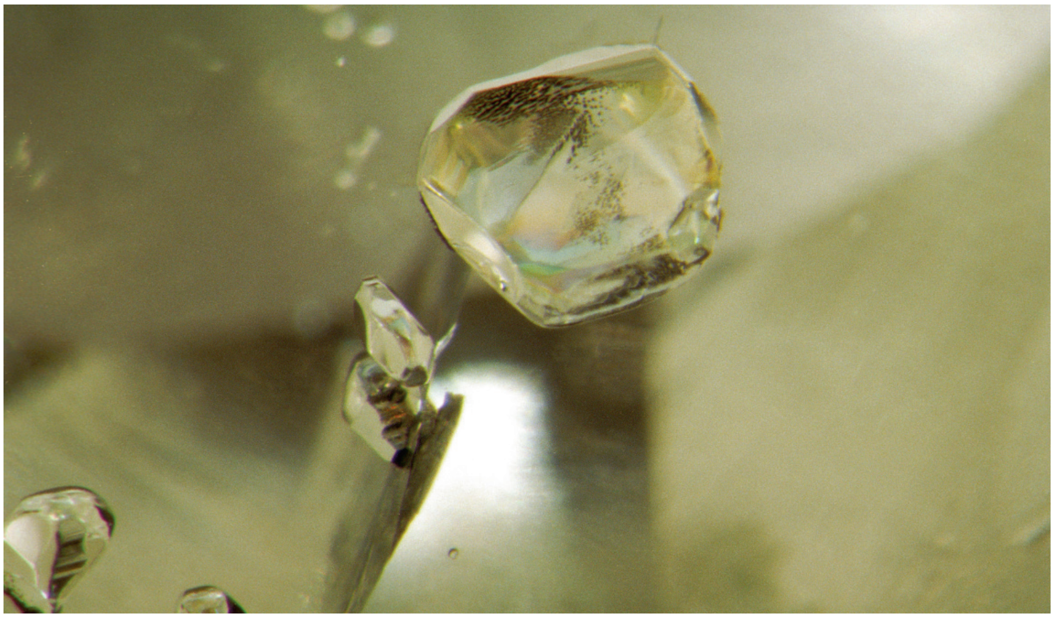


Fractures within diamonds can also complicate mineral identification, especially if they occur around inclusions. The fractures around inclusions are often caused by differences in the expansion properties of the enclosed mineral and the host diamond. During transport to the Earth's surface, changes in pressure and temperature can cause the enclosed minerals to fracture the host diamond. Certain minerals are more prone to fracturing their hosts than others. Inclusions of sulfide minerals, for example, are very often surrounded by extensive fracture systems (see Fig. 5-16). In addition, large inclusions are also more likely to fracture their host diamond than smaller inclusions.

Problems with the visual identification of mineral inclusions can also be caused by the surface of the diamond. Surface frosting and other surface textures can obscure the interior of the diamond (Fig. 5-08). The interface between some mineral inclusions and their host diamond are very reflective, a phenomenon caused by the difference in the refractive index between inclusion and diamond. These reflections can mask the color, particularly of weakly colored inclusions (Fig. 5-09).

Although the visual examination of mineral inclusions can provide some information about their identity, it is often necessary to use other analytical techniques to determine their precise composition. Some analytical techniques can be applied to an inclusion still enclosed in a diamond (in-situ); others require the inclusion to be liberated. In-situ techniques, including Raman-spectroscopy[87, 130] and x-ray diffractometry,[105, 214] are capable of identifying minerals, but they provide limited information about their exact chemical composition. To determine the chemical composition of a mineral inclusion with accuracy, it is usually necessary remove the inclusion from the diamond. This can be done by crushing or by polishing the diamond until the inclusion is exposed.[16, 248] Alternatively, the diamond can be burned in air at temperatures above 700ºC.[310] Most inclusion minerals are not affected by these temperatures, and they will remain in the residue after the diamond has been burned. Once released from the diamond, a wide range of analytical techniques, including electron microprobe analysis or mass spectrometry, can be used to accurately determine the chemical and isotopic composition of the mineral inclusion.





5-09: *Left,* Inclusions of unidentified minerals in a rounded dodecahedral diamond (Ø: ~7 mm) from the Koffiefontein mine, South Africa. The interface between the inclusions and the diamond is so reflective that it prevents the identification of the inclusions' true colors. *Below left,* A close-up of the inclusions. The dark material is graphite that formed from internal graphitization.

Classification of inclusions

Based on their composition, the majority of mineral inclusions in diamonds worldwide can be subdivided into two distinct suites: peridotitic and eclogitic.[193, 262] Diamonds containing these mineral inclusions can be classified as either peridotitic or eclogitic diamonds. The two suites relate to the two main types of mantle rocks, peridotites and eclogites. The presence of these two inclusion suites is reflected in the frequent occurrence of peridotites and eclogites as xenoliths in kimberlites. Even though a single diamond can contain more than one mineral, it is extremely rare to find a mix of peridotitic and eclogitic minerals in a single diamond.

In addition to these frequently occurring inclusion suites, less common and compositionally distinct suites, such as websteritic and calc-silicate suites, have been identified in diamonds from some deposits.[4, 95, 194, 264]

The presence of inclusions belonging to these less common suites indicates that the host diamonds formed in unconventional mantle rocks, which may only be present on a regional scale. Some rare minerals found as inclusions cannot be linked to an inclusion suite because their compositions are not diagnostic for a particular type of mantle rock. In contrast, graphite and diamond inclusions in diamonds are very common and can occur in any type of diamond.

Studies on mineral inclusions indicate that the vast majority of diamonds (~99%) formed within the lithospheric mantle at depths between 140-250 kilometers.[97, 275] Over the last twenty-five years, a small number of diamonds have been found to contain mineral inclusions that originated from much greater depths beneath the base of the lithosphere. These sublithospheric diamonds formed below the continental keels in the asthenosphere (250-410 km), the transition zone (410-670 km), and even in the lower mantle (>670 km).[116] Less than 1% of the global diamond production is believed to come from the sublithospheric mantle.[272]

Inclusions of graphite and diamond

Graphite is the most common mineral inclusion in diamonds. Within diamonds, graphite usually occurs as fine black flakes. A large number of dispersed graphite inclusions can change the color of a diamond to grey or black. The presence of abundant graphite flakes indicates that the diamonds crystallized in unfavorable conditions. In these cases, the diamonds may have formed only marginally within the diamond stability field (Fig. 1-03).[86]

Graphite can also be present as coatings on fractures within diamonds. In these cases, graphite formed as an epigenetic mineral in response to internal stress.[107] The fractures around mineral inclusions and the interfaces between the inclusions and the host diamond are also often coated with epigenetic graphite (Fig. 5-10).[108]

Inclusions of well-developed graphite crystals are far less common than graphite flakes and coatings. Some graphite inclusions have hexagonal crystal morphologies—which relate to the hexagonal crystal structure of graphite—and they can also be crystallographically aligned with the host diamond.[88] In these cases, the graphite inclusions are likely to be protogenetic and pre-date the host diamond.

Inclusions of diamonds within diamonds are not uncommon, but they are often difficult to recognize. The enclosed diamond may only be visible if there is an apparent interface between it and the host diamond, or if the enclosed diamond is distinct from the host diamond (e.g. a different color). Inclusions of diamond in diamonds usually have octahedral morphologies and may be recognized by having a slightly different orientation compared to the host diamond.[315]

Diamonds from the lithospheric mantle

Peridotitic mineral inclusions

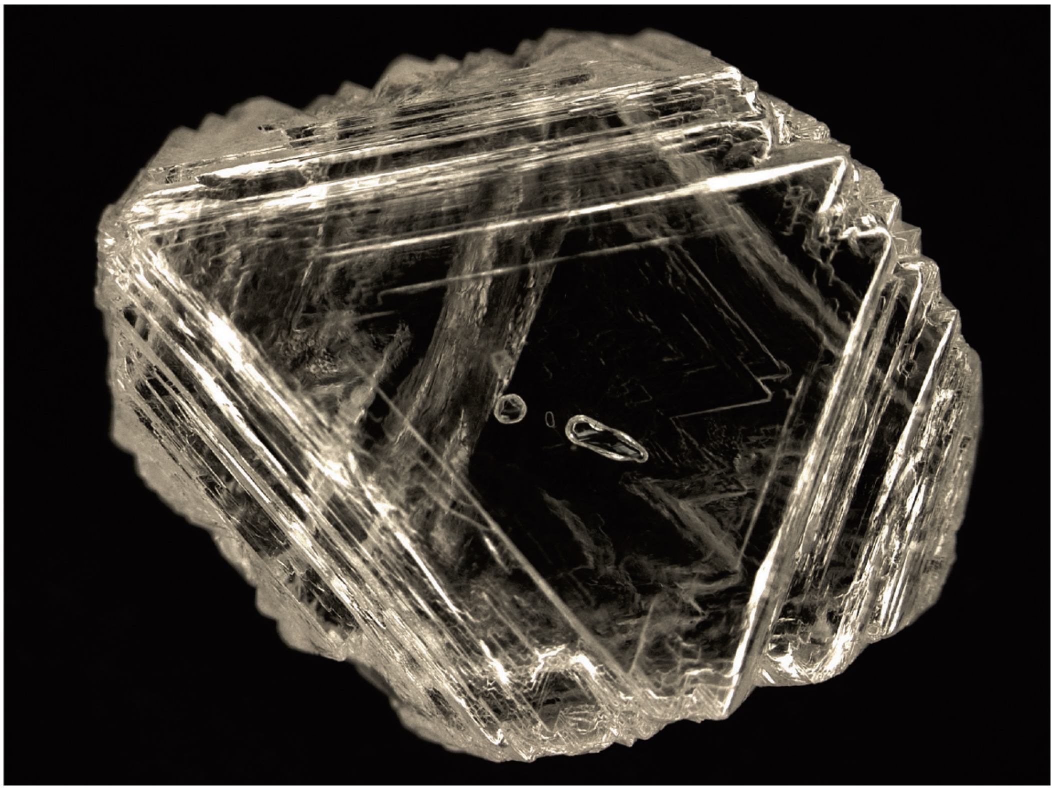
Diamonds containing inclusions of peridotitic minerals are estimated to be 2–3 times more common on a worldwide scale than diamonds with eclogitic minerals.[275] Between deposits, however, the proportion of peridotitic and eclogitic diamonds can vary considerably. Even within a deposit, different size fractions of diamonds may have different proportions of peridotitic and eclogitic diamonds. The predominance of peridotitic

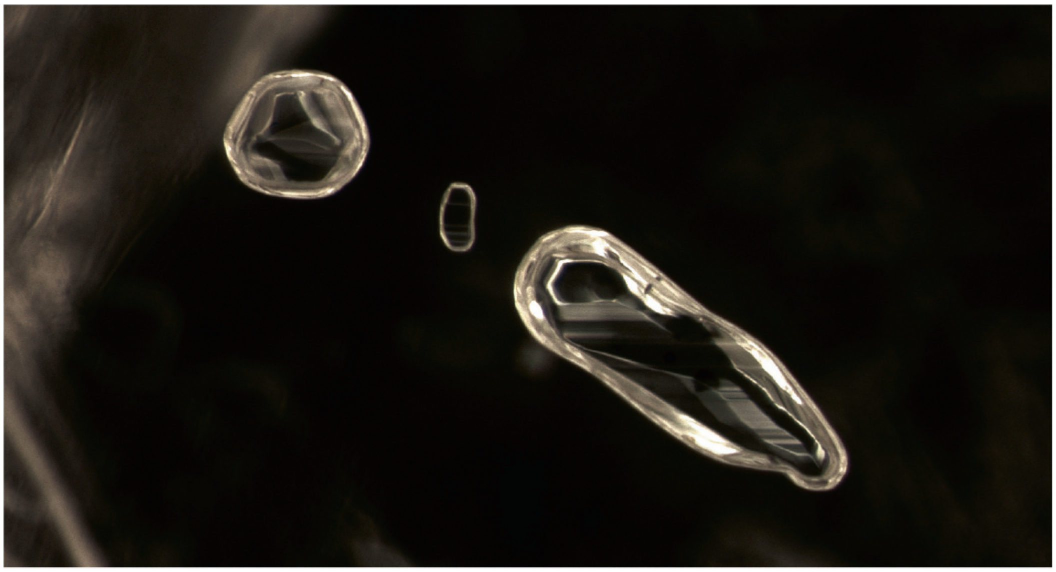
5-10: *Left,* A peridotitic garnet inclusion with multiple faint yellow (olivine?) inclusions in a diamond from Damtshaa, Botswana, which represent a typical peridotitic inclusion suite. The diamond is polished parallel to octahedral planes for better visibility, and the main crystal faces of the inclusion are oriented parallel to this plane. *Below left,* A close-up of the peridotitic garnet inclusion. The interface between the inclusion and diamond, and the fractures surrounding the inclusion, are covered with graphite. The field of view is ~1 mm.

diamonds worldwide is not surprising, since peridotitic rocks are believed to comprise the bulk of the lithospheric mantle.[236]

Peridotitic mineral inclusion assemblages can be used to constrain the pressure and temperature conditions that prevailed during the formation of the host diamond. Research on peridotitic inclusions indicates that the diamonds in the lithospheric mantle generally formed at temperatures between ~900-1300°C and pressures between ~40-80 kilobars, which is equivalent to mantle depths between ~140-250 kilometers (Fig. 1-02).[9, 193, 275] However, regional variations in the composition of peridotitic inclusion minerals exist, and these variations contain important information about the geological history and the diamond formation conditions within a particular region.

One of the most common and characteristic minerals that occurs as an inclusion in peridotitic diamonds is *olivine*. Olivine inclusions in



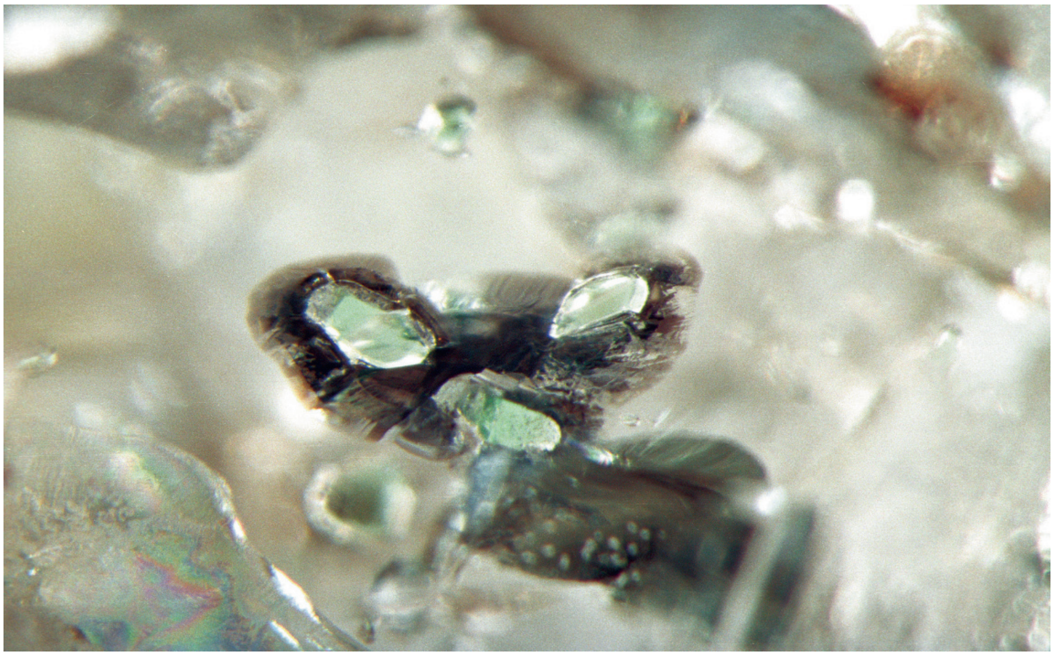


5-11: *Right,* Colorless orthopyroxene inclusions in a diamond (Ø: ~3 mm) from the Jagersfontein mine, South Africa. It is notable that the inclusions are aligned perpendicular to the right crystal edge of the diamond. *Below right,* A close-up of the orthopyroxene inclusions.

diamonds are usually magnesium rich, which means that they contain a high forsterite component.[193] Olivine inclusions are colorless, or they have a slightly yellowish or greenish hue (Fig. 5-10).[105] Visually they are often indistinguishable from other colorless or weakly-colored inclusions. Olivine is the most abundant mineral in peridotitic rocks; therefore, its frequent occurrence as an inclusion in peridotitic diamonds is to be expected.

Garnet is a common and distinctive inclusion mineral. Peridotitic garnet inclusions usually have a high pyrope component and can contain substantial amounts of chromium.[188] They are characterized by their intense red and purplish-red colors (Fig. 5-01, Fig. 5-10). Due to their intense color, peridotitic garnet inclusions are usually easy to recognize.

Inclusions of *orthopyroxene* are not uncommon, but they are usually

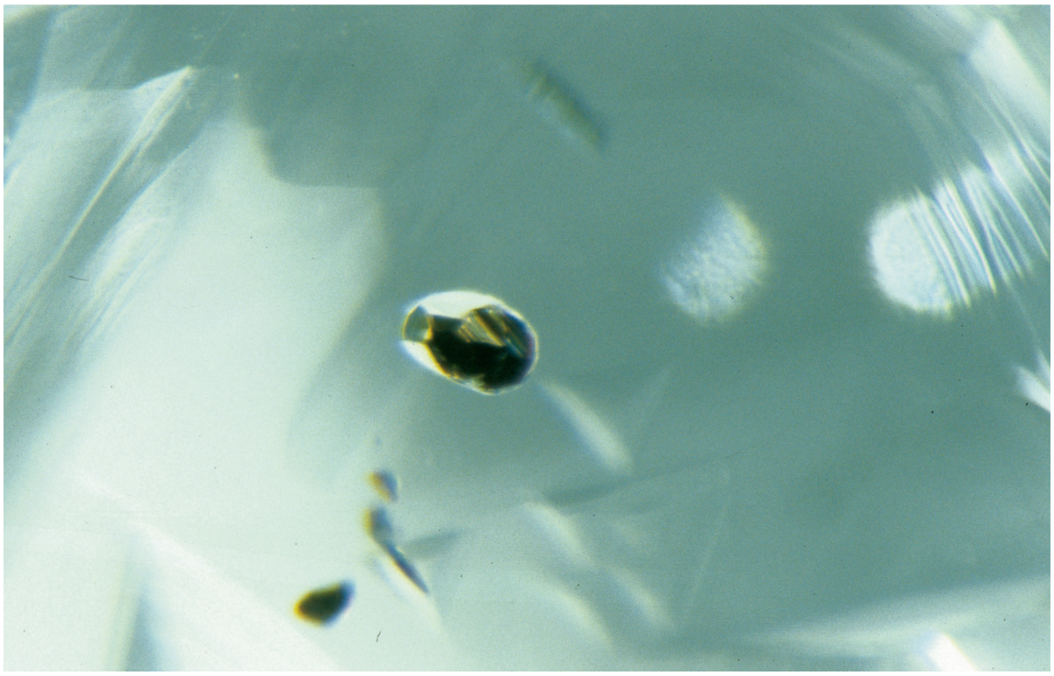


5-12: *Left,* Multiple inclusions of peridotitic clinopyroxene with their characteristic green color in an irregular diamond (Ø: ~7 mm). Some of the inclusions are surrounded by graphite-coated fractures. *Below left,* A close-up of the peridotitic clinopyroxene inclusions.

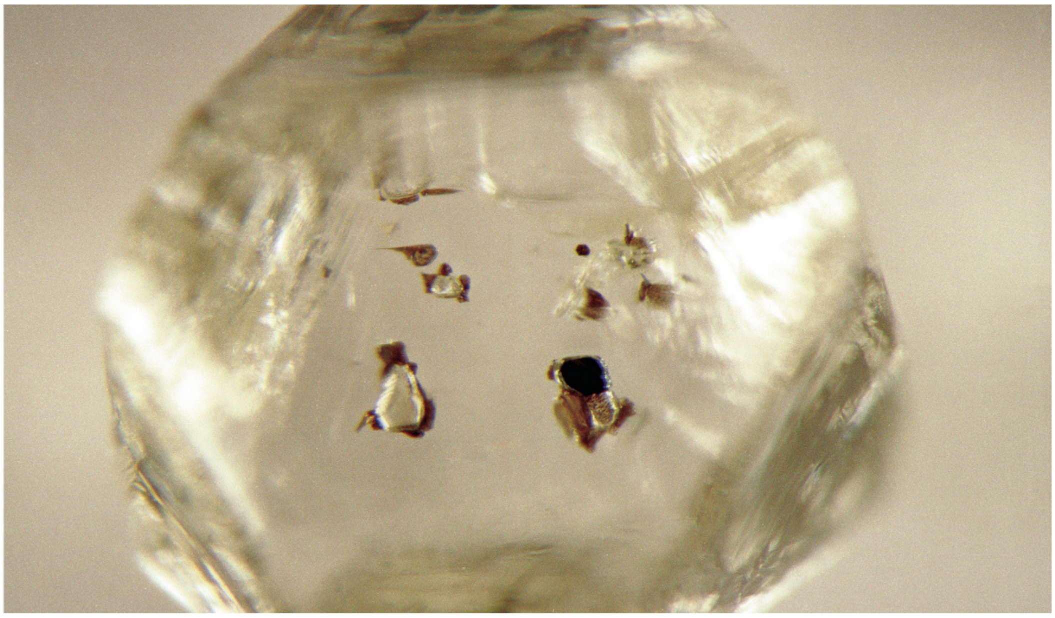
colorless or have a faint yellowish hue (Fig. 5-11). Therefore, they cannot be visually distinguished from other colorless mineral inclusions—especially from the more common olivine.[105] Like olivine, orthopyroxene inclusions are generally rich in magnesium, which means they have a high enstatite component.

Clinopyroxenes are also not uncommon in peridotitic diamonds, and they often have a distinctive emerald-green color, but they can also be pale-green (Fig. 5-12). They have a high diopside component and contain variable amounts of chromium. The intensity of the green color generally increases with the chromium content.

Chromite is a spinel-group mineral that frequently occurs as inclusion in peridotitic diamonds. Chromite inclusions are usually black and



5-13: Chromite inclusion in a diamond from the Jagersfontein mine, South Africa. The field of view is ~1 mm.

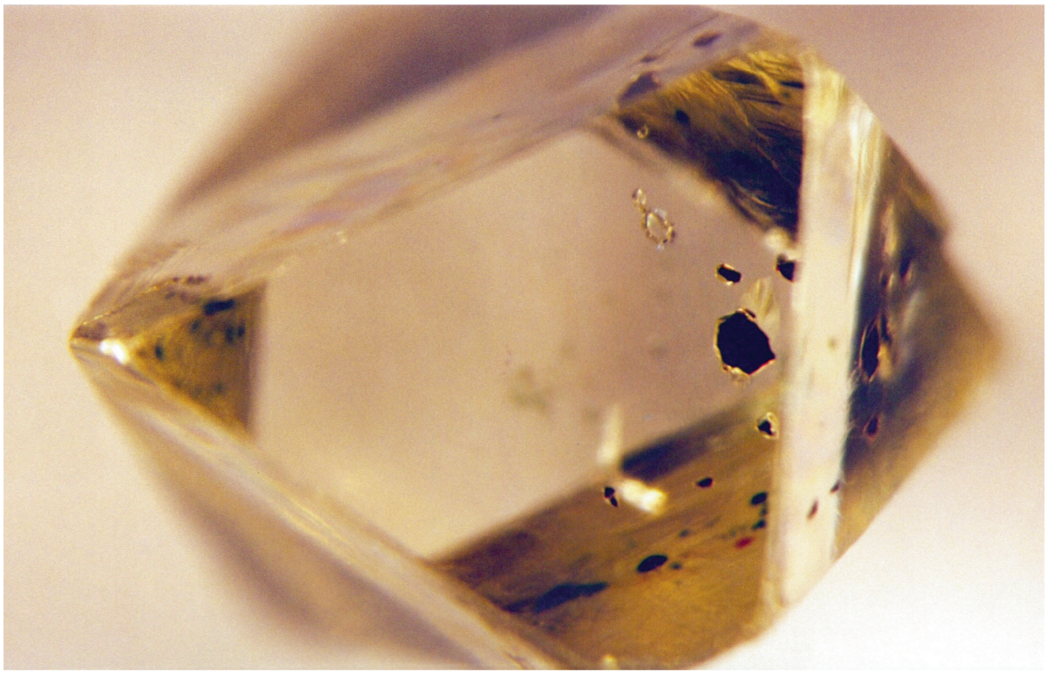


5-14: A typical peridotitic inclusion suite: a black chromite inclusion with colorless olivine inclusions in a diamond (Ø: ~2 mm) from Boa Vista, Roraima, Brazil. The olivine inclusions are surrounded by graphite-coated fractures. The chromite is in direct contact with an olivine.

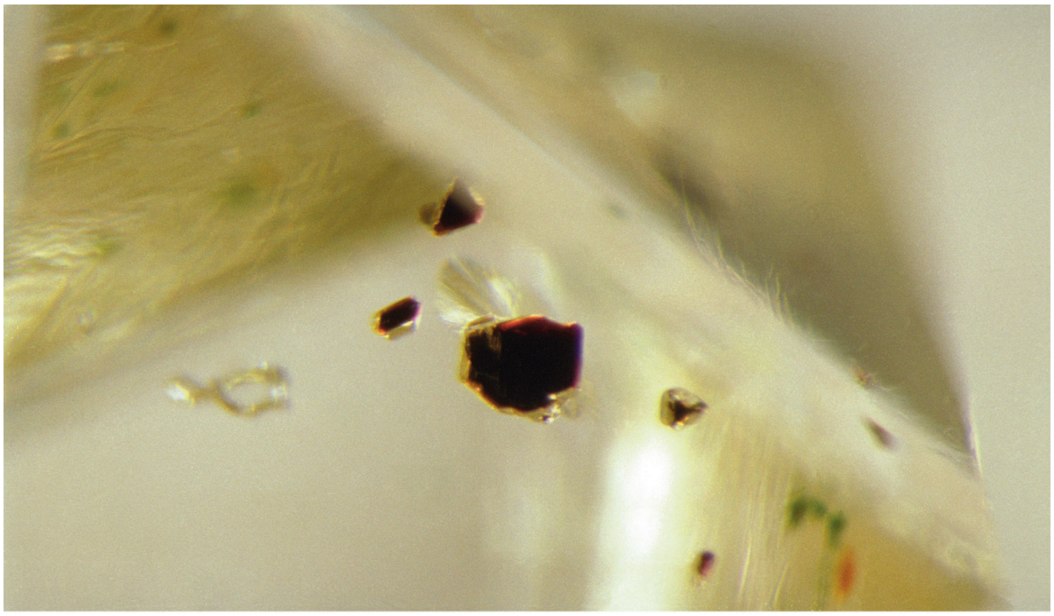
opaque, and they may resemble graphite (Fig. 5-13, Fig. 5-14). They can often be visually distinguished from graphite because thin chromite crystals and the edges of larger chromite crystals are slightly translucent and exhibit a distinctive reddish-brown color (Fig. 5-15).[105] Similar to other peridotitic minerals, chromite inclusions are usually magnesium rich, which means they contain a high magnesiochromite component.

Except for graphite, *sulfides* are the most common group of minerals found as inclusions in diamonds.[15, 94, 96, 252] The high abundance of sulfide inclusions is in contrast to their relative scarcity in xenoliths. This indicates that the presence of sulfides in the Earth's mantle provides a favorable environment for diamond crystallization.

Sulfide inclusions are opaque and generally have a metallic luster. They are often surrounded by disc-shaped fractures that can take the form of rosettes (Fig. 5-16). These fractures are commonly coated with smeared-



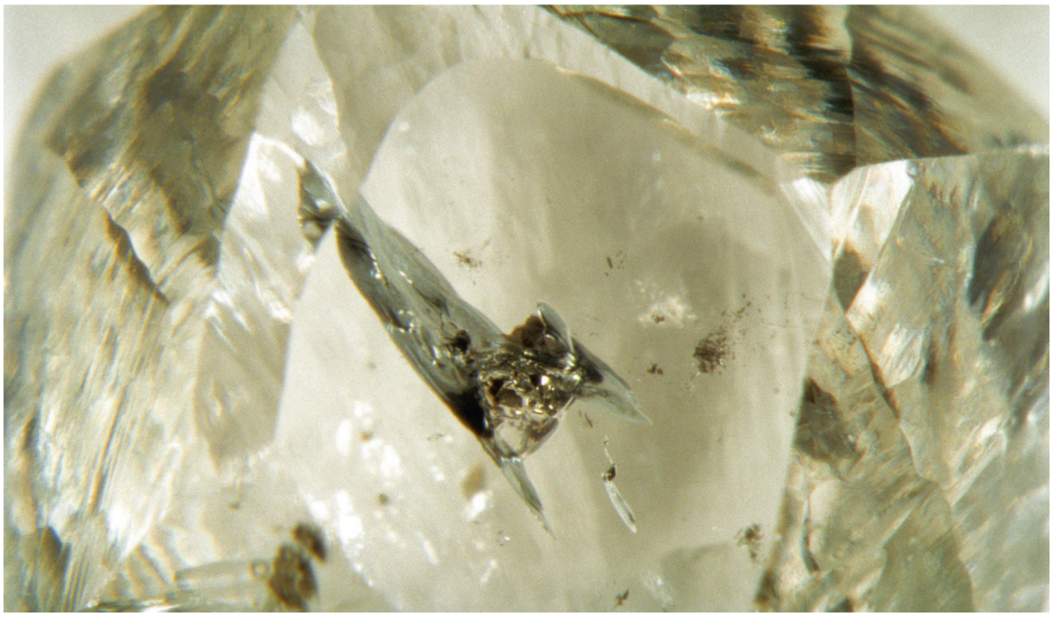
5-15: *Left,* Multiple chromite inclusions and small colorless olivine inclusions in an octahedral diamond (Ø: ~3 mm) from Boa Vista, Roraima, Brazil. The host diamond exhibits green and brown surface spots. *Below left,* A close-up of the chromite inclusions shows that the edges of the chromites are slightly translucent and have a characteristic reddish-brown color.



out sulfides or graphite, which causes the fractures to exhibit a metallic luster (Fig. 5-17).[106] The fracture systems commonly mask the actual sulfide inclusion. Smaller sulfide inclusions may be completely dispersed along the fractures (Fig. 5-18).

Sulfides were usually incorporated into the diamond during growth as homogeneous mixtures of iron-, nickel-, and copper-bearing sulfides with variable compositions. In some cases, these homogeneous mixtures are preserved in their original compositions. In other cases, different sulfide minerals precipitated from the original mono-sulfide solid-solution during cooling. Pyrrhotite ($Fe_{1-X}S$) and pentlandite ($(Fe,Ni)_9S_8$) are most common, but pyrite (FeS_2), chalcopyrite ($CuFeS_2$), cubanite ($CuFe_2S_3$), and heazelwoodite (Ni_3S_2) have also been found.[17, 55] Peridotitic sulfide inclusions are usually more nickel-rich (>12 wt% Ni) compared to eclogitic sulfides (<12 wt% Ni), but the distinction is not always clear-cut.[17, 97]

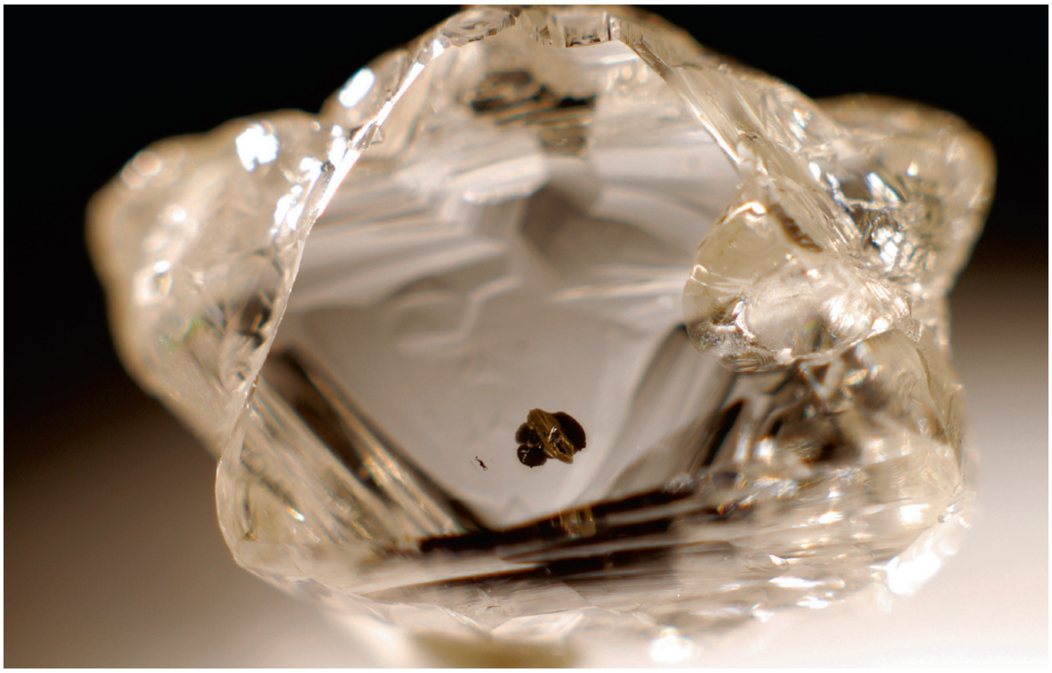
5-16: *Right,* Sulfide inclusion in a rounded dodecahedral diamond (Ø: ~7 mm). A dodecahedral crystal face is polished for better visibility. *Below right,* A close-up of the inclusion. The silvery-grey inclusion is surrounded by disc-shaped fractures that are filled with sulfide material, which gives it a distinctive metallic luster.

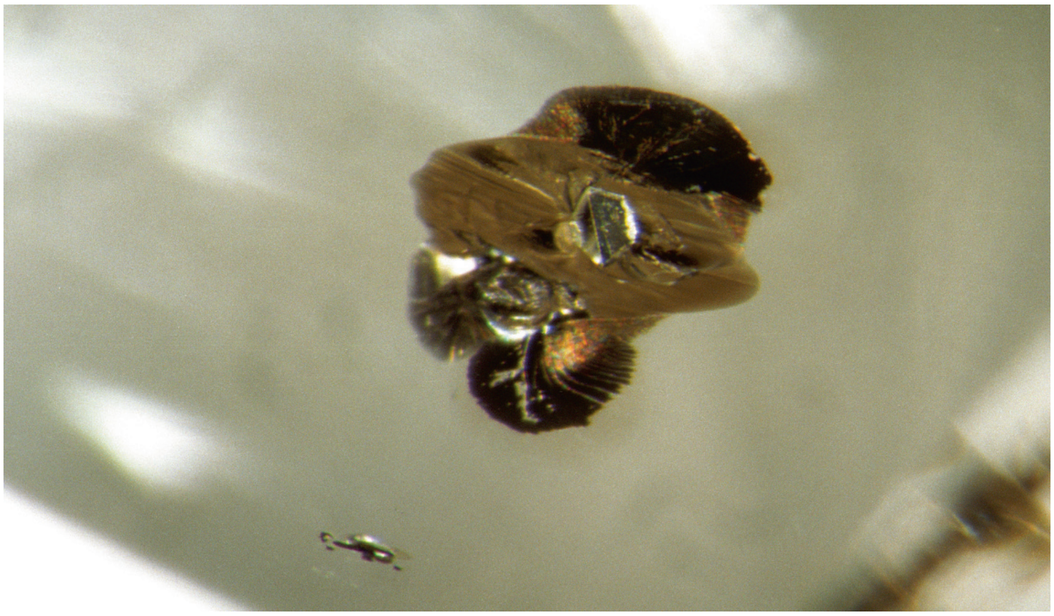


Eclogitic mineral inclusions

Despite the observation that peridotitic diamonds are more common than eclogitic diamonds on a worldwide scale, a number of deposits, including some major diamond mines, are dominated by eclogitic diamonds. The Orapa and Jwaneng mines in Botswana,[22, 56, 95] the Jagersfontein and Monastery mines in South Africa,[53, 205, 302] and the Argyle mine in Australia[140] are a few examples. The relatively high proportion of eclogitic diamonds worldwide is remarkable because eclogites are considered to be a minor constituent (≤ 5%) of the lithospheric mantle.[246] This indicates that eclogites in the Earth's mantle contain, on average, more diamonds than typical peridotites.

Geochemically, eclogites are similar to mafic crustal rocks, such as basalts and gabbros. In fact, eclogites can be viewed as their high-pressure equivalents. The origin of eclogites in the lithospheric mantle is





5-17: *Left,* Sulfide inclusion in a star-shaped diamond twin (Ø: ~8 mm). The sulfides are surrounded by disc-shaped fractures that are brassy and black. The octahedral crystal face of the diamond has been polished for better visibility. *Below left,* A close-up of the sulfide inclusion showing the brassy color of the smeared-out sulfide material in the fracture system around the inclusion. The actual inclusion, which has a distinctive octahedral shape, is visible in the center of the fracture rosette.

controversial. Eclogites have been interpreted to represent cumulates of mafic magmas that crystallized deep within the lithospheric mantle.[119, 212] Other evidence suggests that most of the eclogites in the lithospheric mantle formed from shallow crustal rocks that were transferred to the mantle by plate tectonics.[134] In this scenario, oceanic crust, which consists primarily of basalts and gabbros, was forced into the Earth's mantle at subduction zones (Fig. 1-02). During the subduction, the basalts and gabbros converted into eclogites. Some of these eclogites were then incorporated into the lithospheric mantle roots where they became the host rocks for the eclogitic diamonds.

Garnets, along with clinopyroxenes, are the most common inclusion minerals found in eclogitic diamonds. Eclogitic garnet inclusions have a distinctive orange color (Fig. 5-04, Fig. 5-19, Fig. 5-20). They consist mainly of almandine and pyrope components, but they can also contain

5-18: Smeared-out sulfide material on fractures in a diamond (Ø: ~3 mm) from the Jagersfontein mine, South Africa.

significant amounts of the calcium-endmember grossular. Very calcium-rich varieties have been recovered from diamond deposits in eastern Australia and southern Africa.[49, 185, 264] These calcium-rich garnets, which are generally found in association with calcium-rich clinopyroxenes, are the main constituents of the calc-silicate suite.

Clinopyroxene inclusions in eclogitic diamonds are generally pale-green, but bluish hues are also possible (Fig. 5-20, Fig. 5-21).[228] Eclogitic clinopyroxenes are difficult to distinguish visually from pale-green peridotitic clinopyroxenes, but compared to their peridotitic counterparts, eclogitic clinopyroxenes generally have higher sodium contents. In this case, they are classified as omphacites, which are mixtures of diopside and jadeite endmembers.

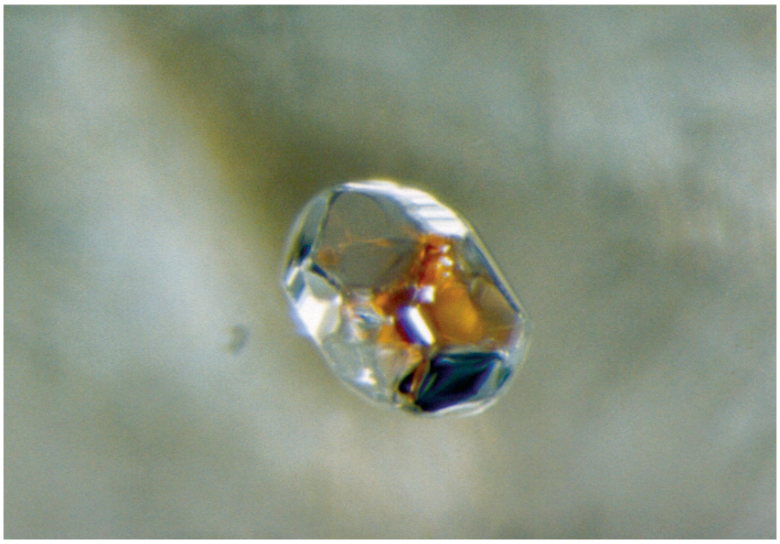
As previously mentioned, *sulfide* inclusions are very common in diamonds. Sulfides in eclogitic diamonds usually have lower nickel contents (<12 wt% Ni) compared to peridotitic sulfides (>12 wt% Ni).[17] As a result, nickel-bearing sulfide minerals are rare in eclogitic diamonds, and pyrrhotite ($Fe_{1-X}S$) is the dominant sulfide mineral.

A number of minerals occur less frequently as inclusions in eclogitic diamonds, but they are important members of the eclogitic suite and are useful in identifying eclogitic diamonds.

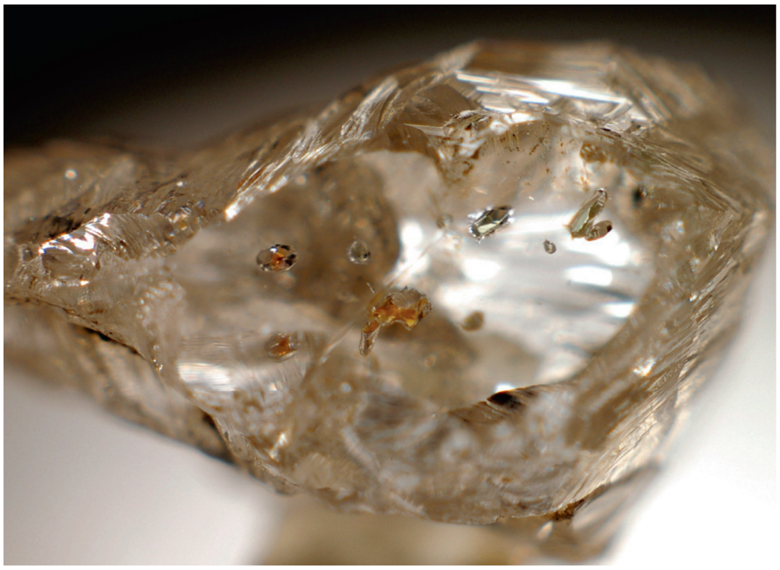
Inclusions of pale blue *kyanite* occur occasionally as inclusions.[94, 228] Visually, kyanite inclusions may be mistaken for bluish clinopyroxenes or moissanite inclusions. Kyanite is also a component of some eclogitic xenoliths.

Corundum inclusions have been identified in eclogitic diamonds from several deposits worldwide.[185, 205, 216, 287] Corundum usually occurs as a colorless inclusion mineral (Fig. 5-22), but is has also been found in its red-colored variety ruby,[191, 311] and in its blue-colored variety sapphire.[127] The red color of the ruby variety is caused by the presence of minor amounts of chromium, which is unusual because eclogitic minerals are usually poor in chromium.

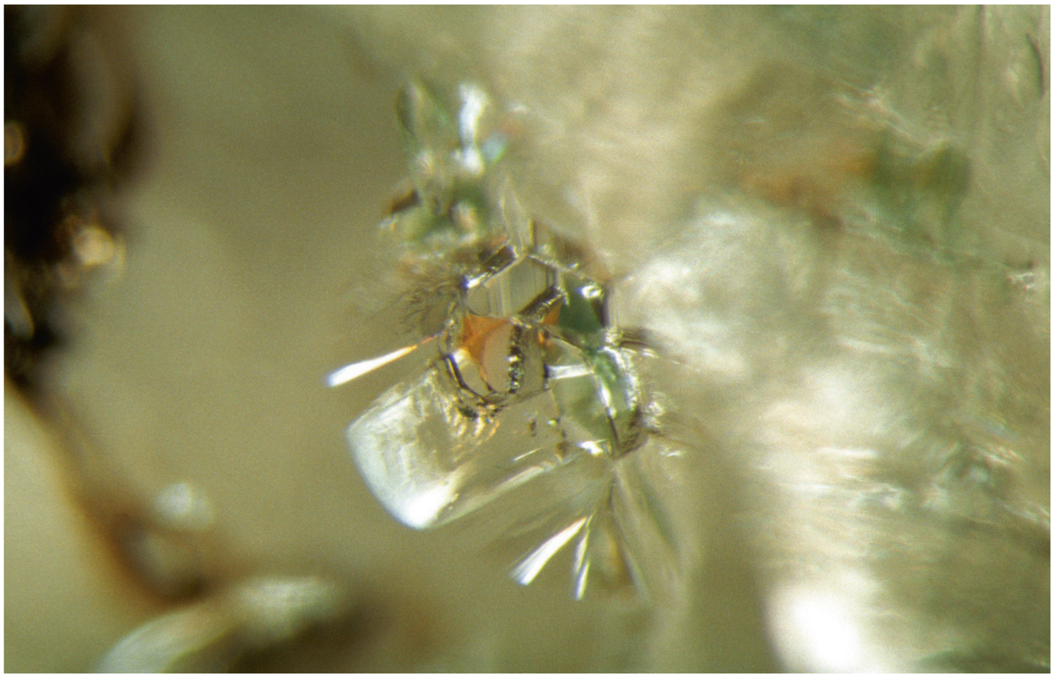
Rutile is another infrequently occurring constituent of the eclogitic suite.[50, 207, 226, 268] Inclusions of rutile are usually moderately transparent or



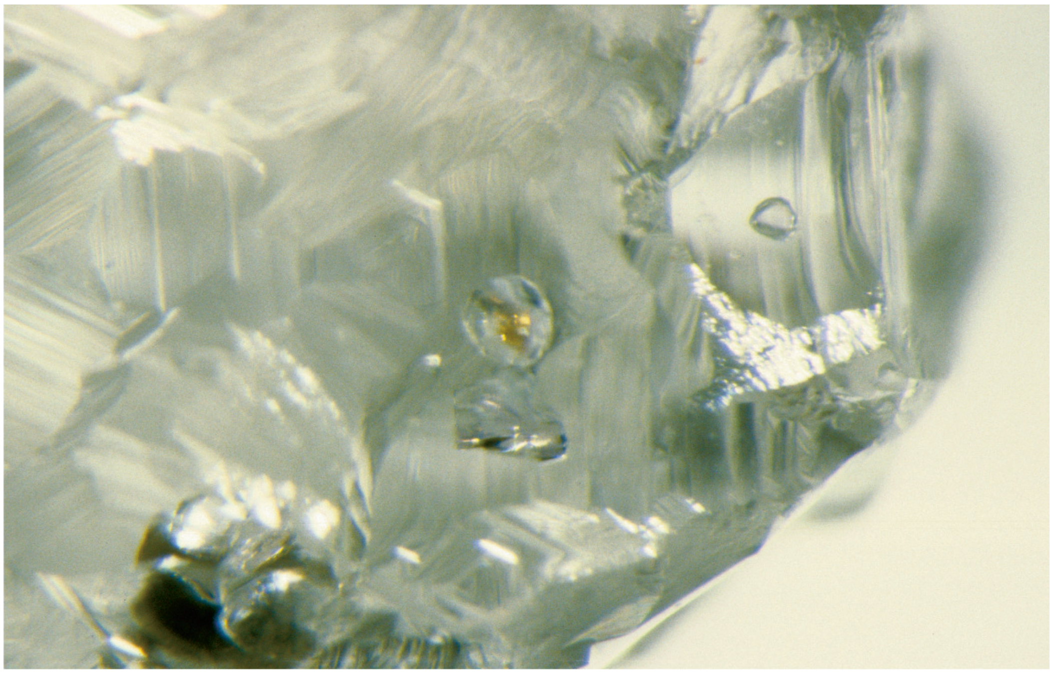
5-19: Eclogitic garnet inclusion (Ø: ~150µm) with characteristic orange color and distinctive crystal faces. Some of the inclusion color is masked by reflections on the inclusion-diamond interface.



5-20: Typical eclogitic inclusion suite: multiple orange garnets and pale green clinopyroxene inclusions. The field of view is ~7 mm.



5-21: Inclusions of orange eclogitic garnet and touching pale green clinopyroxene. The field of view is ~1 mm.



5-22: Inclusions of colorless corundum and orange eclogitic garnet in a diamond from the Jagersfontein mine, South Africa. The field of view is ~2 mm.

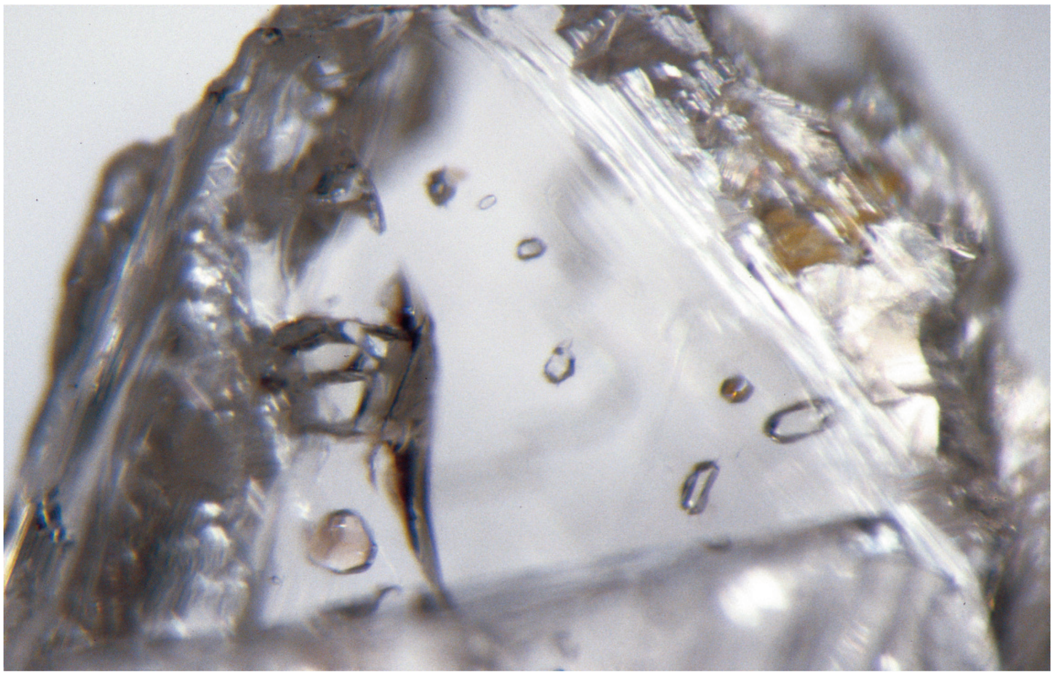
opaque and have a dark-red or brownish color.[120, 105] Like kyanite and corundum, rutile is also a typical mineral component of eclogite xenoliths.[93]

The alkali-feldspar *sanidine* is another colorless mineral that has been identified as rare inclusions in diamonds of eclogitic affinity.[192, 228] Although sanidine is by far more common in crustal rocks, it occasionally occurs as a constituent of eclogite and grospydite (calc-silicate) xenoliths in kimberlites.[260]

Coesite occasionally occurs as colorless inclusions in eclogitic diamonds.[95, 146, 205, 216, 261] Although coesite is chemically identical to quartz, it is characterized by a different crystal structure. The conclusive identification of coesite, therefore, requires a crystallographic analysis.[195] Coesite, which is a high pressure polymorph of quartz, is the stable form of SiO_2 at the pressure conditions within the lithospheric mantle. After being enclosed in the diamond, coesite inclusions can retain their crystal structure because they are shielded by the surrounding diamond, which prevents their conversion to quartz at low pressures.

Coesite inclusions have been found in association with inclusions of the calc-silicate group, which include garnet and clinopyroxene inclusions that are more calcium-rich than their typical eclogitic counterparts.[49, 264] Based on the distinctive oxygen isotope composition of coesite inclusions in diamonds from Guaniamo, Venezuela, it was suggested that these diamonds formed in rocks that were originally part of a subducted ocean floor.[247]

Although *orthopyroxene* is common as a mineral inclusion in peridotitic diamonds, it can also occur with garnets of eclogitic affinity (Fig. 5-23). Diamonds containing orthopyroxene with eclogitic garnet (i.e. almandine-rich garnet) are sometimes placed into the websteritic inclusion suite.[54] The websteritic inclusion suite can be viewed as a transition between the peridotitic and eclogitic suite.[4] Even though diamonds with websteritic inclusions do not occur at every diamond deposit, they can comprise a considerable fraction of the diamond population at some deposits.[275]



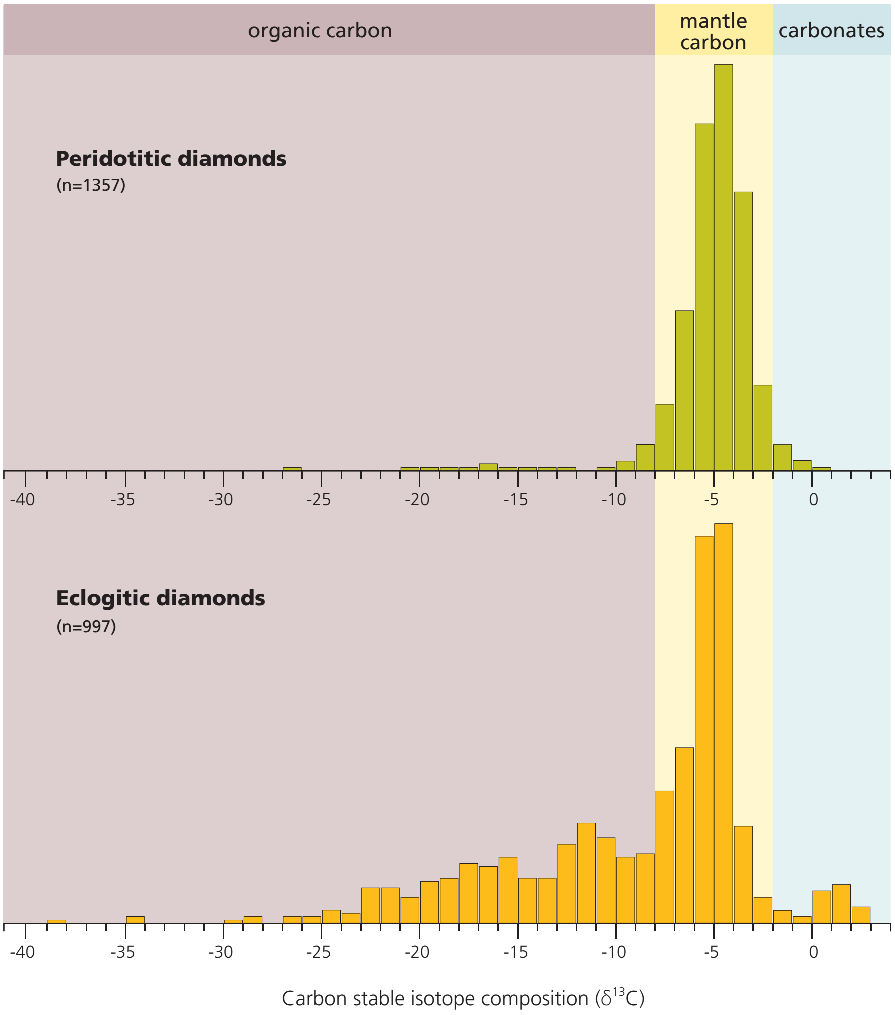
5-23: Inclusions of colorless orthopyroxene and orange eclogitic garnet in a diamond from the Jagersfontein mine, South Africa. The inclusions belong to the websteritic suite.

Carbon isotopes and the sources of diamond carbon

Additional information about the origin of diamonds can be obtained from their carbon stable isotope compositions. The relative abundance of the stable carbon isotopes ^{13}C and ^{12}C can identify the source of the carbon from which the diamonds grew. Carbon isotopic compositions are conventionally quoted as $\delta^{13}C$, which denotes the difference in the ratio of ^{13}C and ^{12}C between a sample and a standard (given in permil). The more negative the $\delta^{13}C$ value, the more depleted the sample is in ^{13}C.

Peridotitic diamonds have a narrow range of $\delta^{13}C$ values, and most peridotitic diamonds fall between -2 and -8‰ (Fig. 5-24).[23] These carbon isotope values are considered to be typical for primordial mantle carbon and suggest that peridotitic diamonds formed mainly from carbon that was directly sourced from the Earth's mantle.[141] Eclogitic diamonds, in contrast, have a much wider range of carbon isotope values ($\delta^{13}C$: +4 to -40‰), and a considerable proportion of eclogitic diamonds have very negative $\delta^{13}C$ values (-10 to -40‰) (Fig. 5-24).[52, 158] These very negative carbon isotope values overlap with the values of typical organic matter, such as that derived from plants or animals.[245] On the other hand, some eclogitic diamonds are isotopically heavy and have positive $\delta^{13}C$ values (0 to +4‰). These heavy isotope values, which are similar to the $\delta^{13}C$ values of marine carbonates, are particularly prominent among diamonds that contain inclusions of the calc-silicate suite.[264]

The wide range of isotopic compositions of eclogitic diamonds is a sign that the diamonds grew from carbon that was derived from mixed sources. The very light and the very heavy isotope values are consistent with at least part of the eclogitic diamond population in the lithospheric mantle growing from surface-derived carbon sources, such as subducted organic carbon and carbonates.

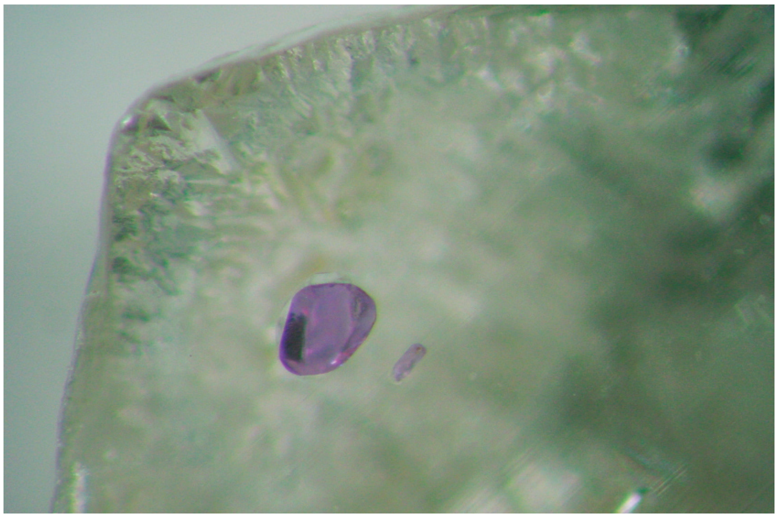


5-24: Histogram showing the carbon stable isotope compositions ($\delta^{13}C$) of peridotitic and eclogitic diamonds from deposits worldwide in relationship to typical $\delta^{13}C$ values for organic carbon, mantle carbon, and marine carbonates. Diamond data from Cartigny (2005).

The ages of diamonds

Major efforts have been made to determine the crystallization ages of diamonds as these ages may provide insights into the causes and timing of diamond formation events in Earth's history. Determining the ages of diamonds, however, is not straightforward because diamonds do not contain radioisotopes that can be used to obtain radiometric ages. Different approaches have been taken to circumvent this problem.

Crystallization ages of diamonds can be estimated by using the aggregation states of nitrogen impurities. As mentioned earlier, nitrogen impurities migrate through the crystal lattice during the diamond's residence in the Earth's mantle, and over time, the nitrogen impurities form complex aggregates. The relative proportion of the different types of nitrogen aggregates, mainly A- and B-centers, can be used to estimate the mantle residence time and, therefore, the crystallization age of individual diamonds.[72, 293] One of the main problems with this approach is that the ambient mantle temperatures strongly influence the aggregation of nitrogen. Temperature differences of only a few tens of degrees can dramatically change the aggregation rate. In order to determine the crystallization ages accurately, it is necessary to have tight constraints on the temperature conditions during the residence time of the diamond in the mantle. Such constraints, however, rarely exist, and as a result, the nitrogen aggregation ages often have a high degree of uncertainty.

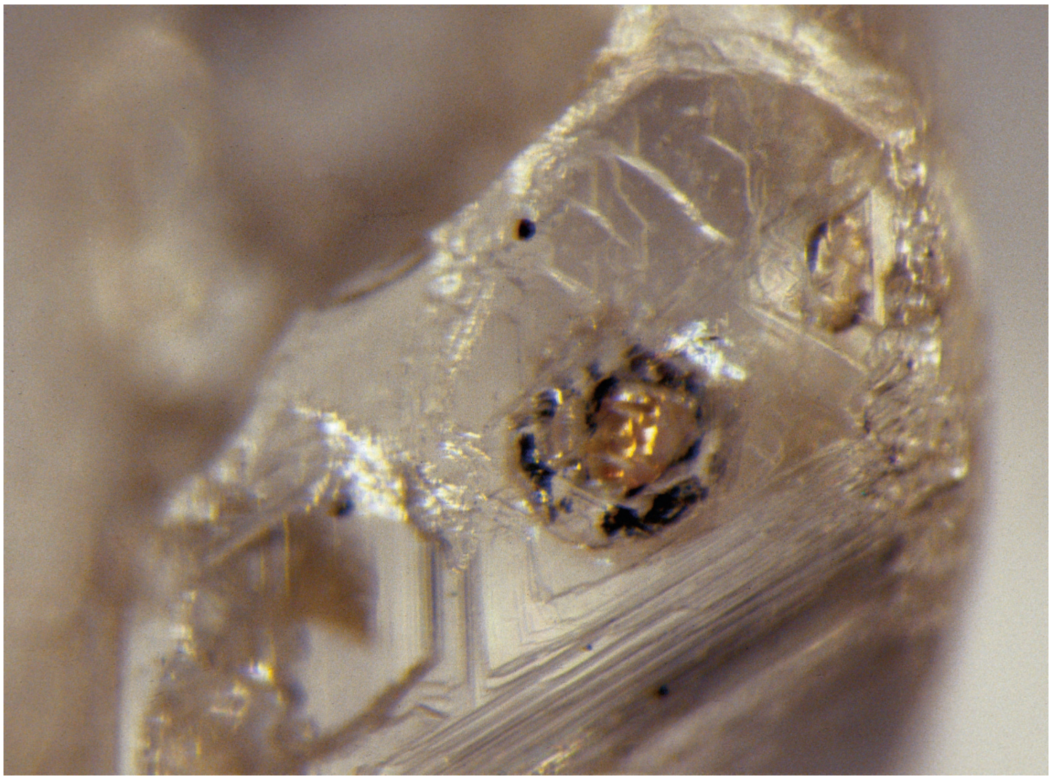


5-25: Peridotitic garnet inclusions on the polished surface of a diamond. Similar garnet inclusions have been used to determine radiometric ages. The field of view is ~4 mm.

An alternative dating approach uses the ages of mineral inclusions. Unlike the diamonds themselves, some of the mineral inclusions contain radioisotopes that can be used to determine radiometric ages (Fig. 5-25). A range of isotope systems have been applied to different types of inclusion minerals, including the samarium-neodymium (Sm-Nd) and the argon-argon (Ar-Ar) systems for clinopyroxenes and garnets,[19, 225, 232, 233, 234] the uranium-lead (U-Pb) system for sulfides and zircons,[157, 166] and the rhenium-osmium (Re-Os) system for sulfides.[5, 220] The Re-Os isotope system in particular is widely used because of the high abundance of sulfide inclusions in diamonds. The radiometric ages obtained for the inclusions are extremely variable and range from Archean ages (3.8-2.5 billion years) to the kimberlite eruption ages. Despite the large range, the oldest inclusion ages (>3 billion years) tend to be restricted to peridotitic minerals. Eclogitic mineral inclusions tend to be younger and are mainly Paleo- to Mesoproterozoic (1.5-2.5 billion years) in age.[221, 275]

The radiometric ages of inclusion minerals are often interpreted to be identical to the crystallization ages of the host diamonds.[221] Archean ages of inclusion minerals, in this case, would suggest that these diamonds formed early in Earth's history. After their formation, they would have resided in the mantle for hundreds of millions or billions of years before being transported to the Earth's surface by a kimberlitic magma.[234] This interpretation, however, has been challenged, and it has been suggested that the inclusions may preserve ages that predate the diamond formation event.[269, 292] This idea is fueled by apparent discrepancies between the ages of the inclusions and the observed nitrogen aggregation states of the host diamonds. Diamonds from the Ekati and Diavik mines in Canada, for example, generally have low nitrogen aggregation states (<20% B-centers),[63, 288] which indicate that they are relatively young (or they were stored for a long time at abnormally low temperatures). Yet many of the sulfide inclusions in these diamonds produced Archean to Paleoproterozoic ages.[6, 27, 313]

Despite the lack of indisputable evidence that the age of the inclusion mineral represents the age of the host diamond, the inclusion ages provide valuable information about the history of the diamond source rocks and the evolution of the Earth's mantle. The Archean ages of some peridotitic inclusions indicate that the peridotitic source rocks in the lithospheric mantle formed early in Earth's history. On the other hand, the apparent



5-26: Minerals from the asthenosphere/transition zone: a majoritic garnet inclusion in a diamond from the Jagersfontein mine, South Africa. The garnet inclusion has the typical orange color of eclogitic garnets. The inclusion is surrounded by graphite-coated fractures. The field of view is ~2 mm.

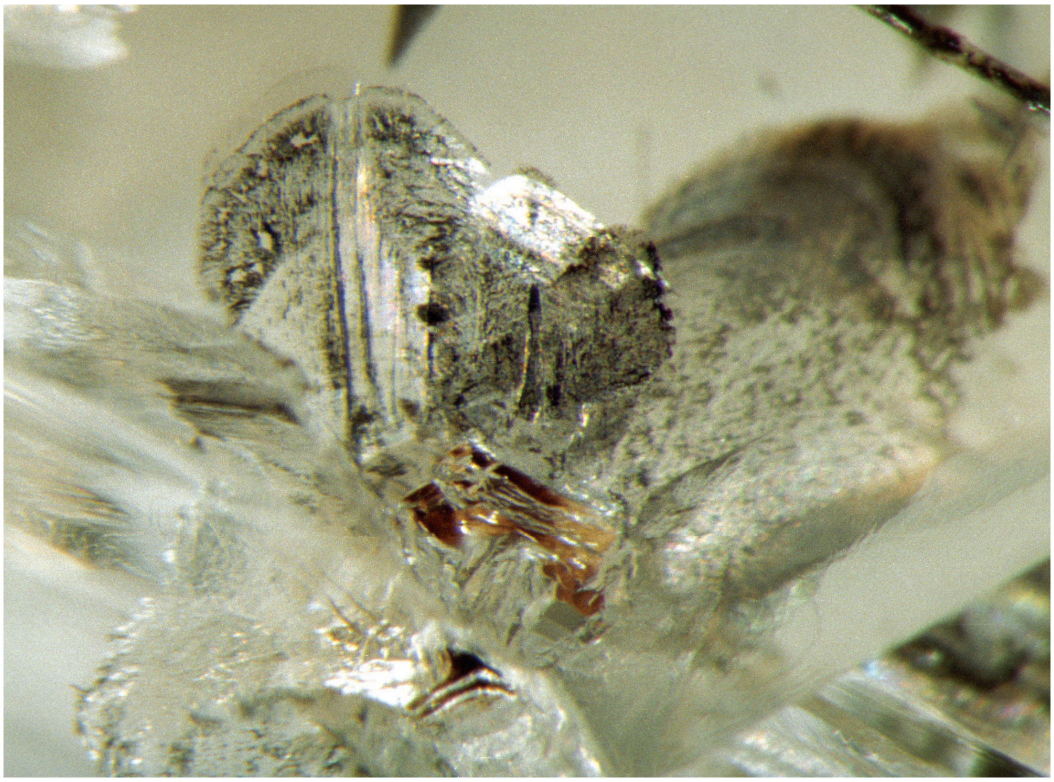
younger ages of eclogitic inclusions suggest that the eclogitic rocks were later additions to the lithospheric mantle. These younger ages also support the notion that the sources of the eclogitic diamonds formed through subduction.

Independent age constraints show that some diamonds are certainly very old. Diamonds occur in volcanic rocks of Late-Archean age (~2.7 Ga) at Wawa, Canada.[57, 169, 274] They are also present in the Late-Archean (>2.5 Ga) Witwatersrand conglomerate in South Africa.[229] On the other hand, some diamonds must be geologically much younger because they contain poorly aggregated nitrogen (e.g. Type Ib diamonds, see chapter 3). These diamonds must have formed just prior to the kimberlite emplacement. In other cases, diamonds can be considered young because they contain mineral inclusions with radiometrically young ages. Based on these observations, it is certain that diamonds formed throughout most of Earth's history, and claims about the general antiquity of lithospheric diamonds[101] should be considered with caution.

Diamonds from the sublithospheric mantle

Inclusions in asthenosphere and transition zone diamonds (250-670 km)

Diamonds from the asthenosphere and the transition zone (Fig. 1-02) are characterized by the presence of *majoritic garnets*. Majoritic garnets form as a result of the dissolution of pyroxene into the crystal structure of garnet, which occurs at pressures of more than ~80 kilobars. Such high pressures exist in the Earth's mantle only at depths of more than 250 kilometers. Compositionally, majoritic garnets are characterized by higher silicon contents compared to garnet inclusions from the shallower lithosphere.[128] Visually, however, majoritic garnets are not distinguishable from their non-majoritic counterparts. Most majoritic garnet inclusions are of eclogitic composition. They exhibit the distinctive orange color of



5-27: Minerals from the lower mantle: a brown ferropericlase inclusion in a diamond. The inclusion, which is partially masked by reflections on the inclusion-diamond interface, is surrounded by an extensive fracture system. Many of the fractures are covered by graphite. The field of view is ~2 mm.

eclogitic garnet inclusions from lithospheric diamonds (Fig. 5-26). Only a few diamonds contain majoritic garnets of peridotitic and websteritic composition.[272]

The existence of majoritic garnets in the Earth's mantle was predicted based on high-pressure experiments,[235] but it was not until the mid-1980s that majoritic garnets were first identified as inclusions in diamonds from the Monastery mine in South Africa.[203] Diamonds with majoritic garnet inclusions were subsequently discovered in other deposits worldwide, but the number of diamonds with majoritic garnet inclusions in a deposit is usually very small. Only three diamond sources are known to produce a higher abundance of majoritic garnet-bearing diamonds: the Jagersfontein mine in South Africa,[53] the Kankan district in Guinea,[273] and the São Luiz-Juina area in western Brazil.[125]

Majoritic garnet-bearing diamonds have never been found within xenoliths, nor do majoritic garnets exist as discrete mineral components in xenoliths. At low pressures, majoritic garnets are not stable, and they break down into their garnet and pyroxene components. Some xenoliths, however, have been identified that appear to contain the break-down products of former majoritic garnets.[102, 244]

Despite the fact that the typical asthenosphere and transition zone is believed to consist of peridotitic rocks, most of the majoritic garnet inclusions in diamonds are eclogitic. This indicates that diamonds containing these majoritic garnets formed in unusual mantle environments. It has been proposed that these diamonds formed in oceanic crust that was subducted to asthenosphere and transition zone depths[286] (Fig. 1-02). The carbon that formed the diamonds was probably derived from the subducting oceanic crust and may have originated from organic matter and carbonates that were originally deposited on the ocean floor.

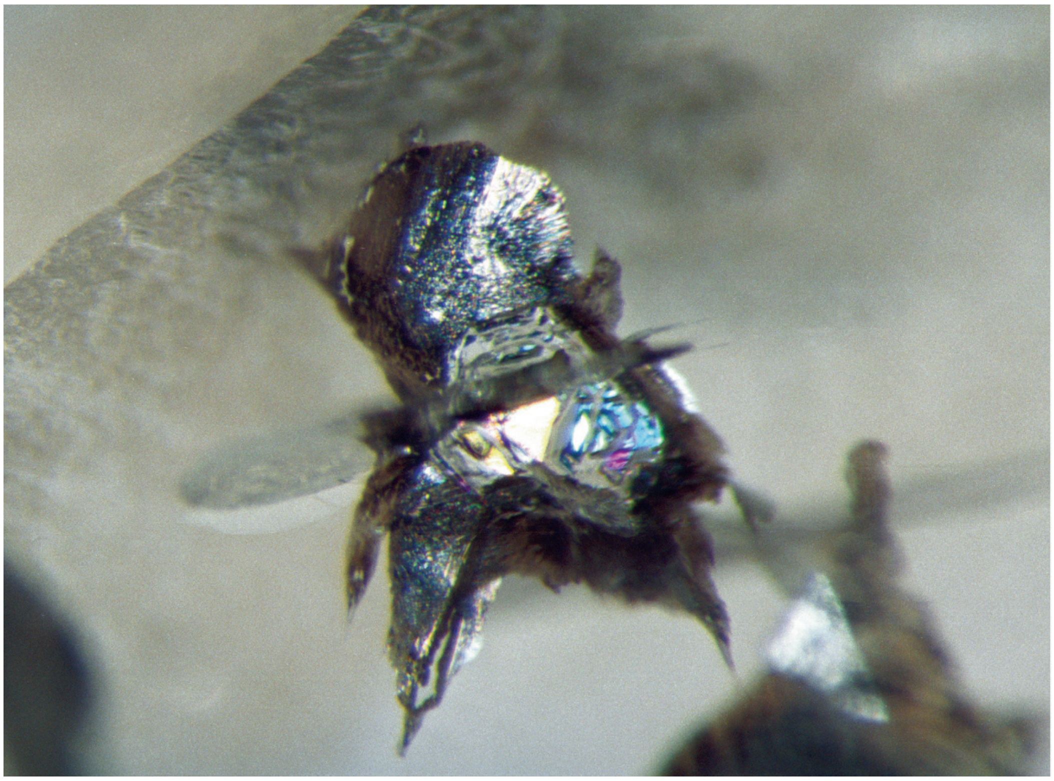
5-28: Small ferropericlase inclusions in a diamond from Kankan, Guinea (Ø: ~6 mm). The ferropericlase inclusions are surrounded by graphite-coated fractures. The brown color and the lack of well-defined crystal faces are characteristic features of Type II diamonds, which are prevalent among lower mantle diamonds.

Inclusions in lower mantle diamonds (>670 km)

The boundary between the transition zone and the lower mantle is located at a depth of ~670 kilometers (Fig. 1-02). This boundary is a major geophysical feature, and it is caused by a change in the mineralogical composition of the mantle. At this boundary, the dominant mineral phases of the upper mantle convert to denser high-pressure minerals. These include iron-bearing periclase, which is also referred to as ferropericlase ((Mg,Fe)O), and a magnesium-silicon oxide ($MgSiO_3$) (Fig. 5-27).[75, 284] The latter mineral has a chemical composition similar to orthopyroxene (=enstatite), but it has the crystallographic structure of perovskite. Therefore, it is referred to as Mg-Si-perovskite. The existence of ferropericlase and Mg-Si-perovskite in the lower mantle was predicted from high-pressure experiments, and they are considered to be the main mineral constituents of the lower mantle.[237]

Mineral inclusions of possible lower mantle origin were first noted in diamonds from the Eurelia/Orroroo area in South Australia, and the Koffiefontein mine in South Africa.[249] These diamonds contained inclusions of ferropericlase and orthopyroxene ($MgSiO_3$). The orthopyroxene was considered to have formed in the lower mantle as Mg-Si-perovskite and converted to orthopyroxene at lower pressures. Since then, additional diamonds containing lower mantle inclusions were discovered at several other deposits worldwide. The number of lower mantle diamonds recovered is very small, and only a few deposits have produced more than one or two lower mantle diamonds. Among these, only the Juina/São Luiz area in Brazil and the Kankan district in Guinea have produced both types of sublithospheric diamonds, lower mantle and asthenosphere/transition zone diamonds, with some frequency.[116, 147, 271]

Lower mantle diamonds are generally Type II diamonds, which means that they contain little or no nitrogen. Like other Type II diamonds, they



5-29: Inclusion of ferropericlase in a diamond. A fine graphite film on the inclusion-diamond interface probably causes the iridescence. The inclusion is surrounded by graphite coated fractures. The field of view is ~1 mm.

tend to lack well-developed crystal morphologies, and they often have brownish colors.[147] Commonly they exhibit signs of plastic deformation, such as deformation lines (Fig. 5-28). The inclusions in lower mantle diamonds generally have fractures around them that are caused by the expansion of the mineral inclusion as it is transported to the Earth's surface (Fig. 5-29).

The most common mineral inclusion in lower mantle diamonds is *ferropericlase*. Ferropericlase can generally be distinguished from other mineral inclusion by its brown color, which is caused by the presence of iron (Fig. 5-27). The interface between the diamond and the ferropericlase inclusion is often distinctly iridescent, which is probably caused by a thin layer of graphite (Fig. 5-28, Fig. 5-29).

Most of the ferropericlase inclusions in diamonds are magnesium-rich, but iron-rich varieties also exist. Because of their high iron content, the latter are also classified as wüstites or magnesiowüstites. They are particularly common among diamonds from the São Luiz/Juina area in Brazil.[117] Although ferropericlase inclusions are generally considered to be lower mantle minerals, especially if they occur with Mg-Si-perovskite, it has been pointed out that diamonds containing only ferropericlase inclusions could have also formed outside the lower mantle in compositionally unusal source rocks.[13, 173]

Compared to ferropericlase, the identification of *Mg-Si-perovskite* is not trivial because Mg-Si-perovskite inevitably converts to its low-pressure polymorph orthopyroxene outside the lower mantle. Only the presence of ferropericlase with orthopyroxene in the same diamond provides indirect evidence that the orthopyroxene inclusion was originally incorporated as Mg-Si-perovskite in the lower mantle. At upper mantle pressures, ferropericlase and orthopyroxene are not stable together, and they react to form an olivine polymorph.[172] Former Mg-Si-perovskites may also be identified by their nickel contents, which are expected to be considerably lower (<0.02 wt% Ni) than true lithospheric orthopyroxene inclusions (0.1-0.2 wt% Ni).[154]

A rare mineral phase that has also been identified as a lower mantle mineral is calcium-silicon oxide ($CaSiO_3$). It is also believed to have crystallized with a perovskite structure and is, therefore, referred to as *Ca-Si-perovskite*.[117] At lower pressures, Ca-Si-perovskite is not stable and converts to wollastonite. Since wollastonite is not a typical lithospheric mineral, its presence indicates a lower mantle origin for the diamond.

Another mineral found as an inclusion in lower mantle diamonds has a garnet-like composition but is characterized by a tetragonal crystal structure. Accordingly, this mineral has been named tetragonal-almandine-pyrope-phase or *TAPP*.[114, 126] Inclusions of TAPP, which are generally rare, have a distinctive apple-green color.[114]

A polymorph of silica has also been found in lower mantle diamonds. At the high pressures in the lower mantle, the silica phase is likely to have existed as the high-pressure polymorph *stishovite*.[117]

Lower mantle diamonds also contain rare inclusions of sodium and aluminum-rich pyroxenes (*type-III pyroxenes*).[126] These pyroxenes may have crystallized in the lower mantle with a garnet structure.[85] Like other inclusion minerals from the lower mantle, they probably converted into lower pressure minerals during their ascent to the Earth's surface.

Several other minerals, including various micro- and nano-inclusions, are associated with lower mantle diamonds.[316, 317] Their authenticity as genuine lower mantle minerals is often not well established. Some of these minerals may be the break-down products of undetermined lower mantle minerals, or they may be epigenetic phases.

The lower mantle diamonds and their mineral inclusions are the only fragments of mantle material from depths beneath the 670 kilometer boundary. Neither xenoliths nor xenocrysts of lower mantle origin are known. As a result, the lower mantle diamonds and their mineral inclusions can provide unique insights into the mineralogical composition, the diamond formation processes, and the dynamics of the lower mantle.

Most of the mineral inclusions in lower mantle diamonds have compositional affinities to peridotites. However, because of the many phase-transformations at high pressures, the mineral associations that define peridotites and eclogites no longer exist in the lower mantle.

Many aspects about the nature of the lower mantle diamonds still remain uncertain. It is not clear if a link between lower mantle diamonds and diamonds from the asthenosphere and transition zone exists. Both types of diamonds occur together at some diamond deposits, suggesting that their formation may be linked to a common but unusual mantle environment.[118] Although it is not possible, at this point, to determine the exact depths at which lower mantle diamonds formed, there is some evidence that suggests their formation is restricted to the top of the lower mantle, close to the 670 kilometer boundary.[183] In this case, it might be the presence of subducted oceanic slabs accumulating at the 670 kilometer boundary that has instigated the formation of the lower mantle diamonds.[129, 290]

Inclusions of uncertain origin

A range of minerals have been found as inclusions in diamonds that cannot be linked to the typical lithospheric or sublithospheric inclusion suites. These minerals usually occur as isolated inclusions and many of them have only been found once.

Some of these inclusions indicate that the source rocks for the diamonds were compositionally distinct from the conventional peridotitic or eclogitic rocks. The presence of websteritic and calc-silicate minerals as inclusions in diamonds and in xenoliths proves that such unconventional source rocks exist. A different type of unconventional source rock may be reflected in the phlogopite-, carbonate-, and titanate-bearing mineral inclusion assemblages, such as those found in some diamonds from the Namibian coast.[170] In this case, the diamonds probably formed in an atypical, possibly metasomatized part of the mantle. Although it is likely that more of these unconventional diamond source rocks exist within the mantle, it is unlikely that they are volumetrically significant.

Inclusions in fibrous diamonds

Inclusions in fibrous diamonds and fibrous coats are distinct from those found in typical monocrystalline diamonds. Fibrous diamonds and fibrous coats can contain millions of inclusions of submicrometer size. These inclusions cause the cloudy appearance of these diamonds. They generally consist of fluids, which can be isolated or found in combination with various minerals.[31, 208] Even though the compositions of the fluid inclusions within a single fibrous diamond or fibrous coat are generally quite uniform, different diamonds and diamonds from different deposits can have a range of fluid compositions. Inclusions containing saline solutions (e.g. brines), silicic solutions, and solutions rich in carbonates have been identified.[131, 162] Most of the minerals associated with the fluid inclusions are distinct from the typical inclusions found in monocrystalline diamonds. They include carbonates, halides, apatite, and micas.[161] However, inclusions of peridotitic and eclogitic minerals have also been identified.[132] Typical monocrystalline diamonds generally do not contain fluid inclusions, but some of them have cloudy cores. These cores contain inclusions that are very similar to the fluid inclusions of fibrous diamonds and fibrous coats.[323]

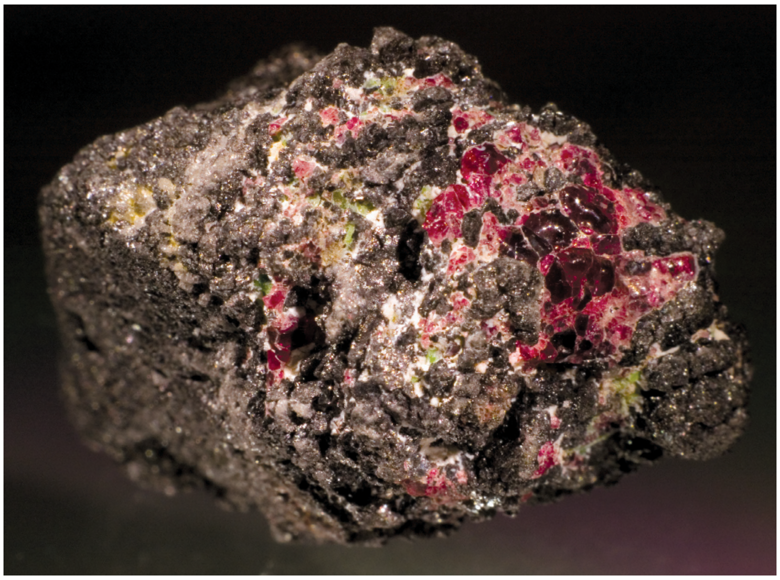


Fig. 5-30: Polycrystalline diamond aggregate with intergrowths of peridotitic garnet (red) and clinopyroxene (green) from the Diavik mine, Northwest Territories, Canada (54 ct.).

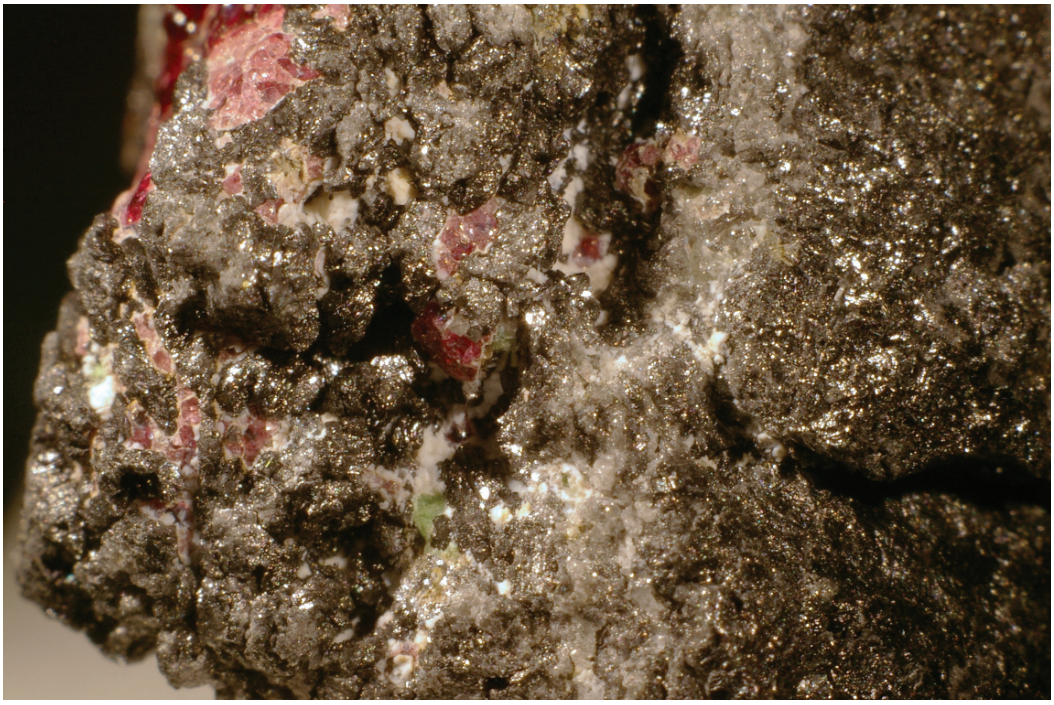


Fig.5-31: Close-up of the polycrystalline diamond aggregate (previous figure).

Inclusions in polycrystalline diamonds

Polycrystalline diamonds do not typically contain inclusions, but they can contain other minerals as interstitial phases. For example, framesites often contain mantle-derived minerals that prove their mantle origin (Fig. 2-55). The interstitial minerals in framesites generally have typical eclogitic or peridotitic compositions (Fig. 5-30, Fig. 5-31).[133, 135, 167] Carbonados, on the other hand, do not contain mantle-derived minerals. Instead, they contain exotic minerals, such as florencite, that coat the pore spaces.

Unlike mineral inclusions in monocrystalline diamonds, the interstitial minerals that occur in polycrystalline diamonds may have not been fully protected from alteration. Therefore, it is often not possible to exclude that the minerals in polycrystalline diamonds have been modified or that they formed as epigenetic phases long after the formation of the diamonds.

References

A

1 Abduriyim, A. and Kitamura, M. (2002) Growth morphology and change in growth conditions of a spinel-twinned natural diamond. *Journal of Crystal Growth*, 237-239: 1286-1290.

2 Anders, A. and Zinner, E. (1993) Interstellar grains in primitive meteorites: Diamond, silicon carbide, and graphite. *Meteoritics*, 28: 490-514.

3 Applin, K.E.S. (1972) Sampling of alluvial diamond deposits in West Africa. *Transactions of the Institution of Mining and Metallurgy, Section A (Mining Industry)*, 81: 62-77.

4 Aulbach, S., Stachel, T., Viljoen, K.S., Brey, G.P. and Harris, J.W. (2002) Eclogitic and websteritic diamond sources beneath the Limpopo Belt–Is slab-melting the link? *Contributions to Mineralogy and Petrology*, 143: 56-70.

5 Aulbach, S., Shirey, S.B., Stachel, T., Creighton, S., Muehlenbachs, K., and Harris, J.W. (2009) Diamond formation episodes at the southern margin of the Kaapvaal Craton: Re-Os systematics of sulfide inclusions from the Jagersfontein Mine. *Contributions to Mineralogy and Petrology*, 157: 525-540.

6 Aulbach, S., Stachel, T., Creaser, R.A., Heaman, L.M., Shirey, S.B., Muehlenbachs, K., Eichenberg, D. and Harris, J.W. (2009) Sulphide survival and diamond genesis during formation and evolution of Archaean subcontinental lithosphere: A comparison between the Slave and Kaapvaal cratons. *Lithos*, 112, Supplement 2: 747-757.

B

7 Bogert, C.H.v.d., Smith, C.P., Hainschwang, T. and McClure, S.F. (2009) Gray-to-blue-to-violet hydrogen-rich diamonds from the Argyle mine, Australia. *Gems and Gemology*, 45: 20-37.

8 Bowen, D.C., Ferraris, R.D., Palmer, C.E. and Ward, J.D. (2009) On the unusual characteristics of the diamonds from Letseng-la-Terae kimberlites, Lesotho. *Lithos*, 112, Supplement 2: 767-774.

9 Boyd, F.R., Gurney, J.J. and Richardson, S.H. (1985) Evidence for a 150-200 km thick Archean lithosphere from diamond inclusion thermobarometry. *Nature*, 315: 387-389.

10 Boyd, F.R. and Gurney, J.J. (1986) Diamonds and the African lithosphere. *Science*, 232: 472-477.

11 Boyd, S.R., Mattey, D.P., Pillinger, C.T., Milledge, H.J., Mendelssohn, M.J. and Seal, M. (1987) Multiple growth events during diamond genesis: An integrated study of carbon and nitrogen isotopes and nitrogen aggregation state in coated stones. *Earth and Planetary Science Letters*, 86: 341-353.

12 Breeding, C.M. and Shigley, J.E. (2009) The "type" classification system of diamonds and its importance in gemology. *Gems and Gemology*, 45: 96-111.

13 Brey, G.P., Bulatov, V., Girnis, A., Harris, J.W. and Stachel, T. (2004) Ferropericlase–A lower mantle phase in the upper mantle. *Lithos*, 77: 655-663.

14 Bruton, E. (1978) Diamonds. Chilton Book Company, Radnor, Pennsylvania, 532 pp.

15 Bulanova, G.P., Spetsius, Z.V. and Leskova, N.V. (1990) Sulfides in diamonds and mantle xenoliths from kimberlite pipes of Yakutia. Nauka, Novosibirsk, 117 pp.

16 Bulanova, G.P. (1995) The formation of diamond. *Journal of Geochemical Exploration*, 53: 1-23.

17 Bulanova, G.P., Griffin, W.L., Ryan, C.G., Shestakova, O.Y. and Barnes, S.J. (1996) Trace elements in sulfide inclusions from Yakutian diamonds. *Contributions to Mineralogy and Petrology*, 124: 111-125.

18 Bulanova, G.P., Muchemwa, E., Pearson, D.G., Griffin, B.J., Kelley, S.P., Klemme, S. and Smith, C.B. (2004) Syngenetic inclusions of yimengite in diamond from Sese kimberlite (Zimbabwe)–Evidence for metasomatic conditions of growth. *Lithos*, 77: 181-192.

19 Burgess, R., Turner, G., Laurenzi, M. and Harris, J.W. (1989) ^{40}Ar/^{39}Ar laser probe dating of individual clinopyroxene inclusions in Premier eclogitic diamonds. *Earth and Planetary Science Letters*, 94: 22-28.

20 Bursill, L.A. and Glaisher, R.W. (1985) Aggregation and dissolution of small and extended defect structures in Type Ia diamond. *American Mineralogist*, 70: 608-613.

C

21 Capdevila, R., Arndt, N., Letendre, J. and Sauvage, J.F. (1999) Diamonds in volcaniclastic komatiite from French Guiana. *Nature*, 399: 456-458.

22 Cartigny, P., Harris, J.W. and Javoy, M. (1998) Eclogitic diamond formation at Jwaneng: No room for a recycled component. *Science*, 280: 1421-1424.

R. Tappert and M.C. Tappert, *Diamonds in Nature: A Guide to Rough Diamonds*,
DOI 10.1007/978-3-642-12572-0, © Springer-Verlag Berlin Heidelberg 2011

23 Cartigny, P., Harris, J.W., Phillips, D., Girard, M. and Javoy, M. (1998) Subduction-related diamonds? –The evidence for a mantle-derived origin from coupled ^{13}C-^{15}N determinations. *Chemical Geology*, 147: 147-159.

24 Cartigny, P., Harris, J.W. and Javoy, M. (2001) Diamond genesis, mantle fractionations and mantle nitrogen content: A study of δ^{13}C-N concentrations in diamonds. *Earth and Planetary Science Letters*, 185: 85-98.

25 Cartigny, P., Chinn, I., Viljoen, K.S. and Robinson, D. (2004) Early Proterozoic ultrahigh pressure metamorphism: Evidence from microdiamonds. *Science*, 304: 853-855.

26 Cartigny, P. (2005) Stable isotopes and the origin of diamonds. *Elements*, 1: 79-84.

27 Cartigny, P., Farquhar, J., Thomassot, E., Harris, J.W., Wing, B., Masterson, A., McKeegan, K. and Stachel, T. (2009) A mantle origin for Paleoarchean peridotitic diamonds from the Panda kimberlite, Slave Craton: Evidence from ^{13}C-, ^{15}N- and ^{33,34}S-stable isotope systematics. *Lithos*, 112, Supplement 2: 852-864.

28 Cartigny, P. (2010) Mantle-related carbonados? Geochemical insights from diamonds from the Dachine komatiite (French Guiana). *Earth and Planetary Science Letters*, 296: 329-339.

29 Casanova, R. (1972) A repeated twin in natural diamond from Tortiya, Ivory Coast. *American Mineralogist*, 57: 1871-1873.

30 Chan, C.L. (1991) Diamonds and their mineral inclusions from the Prairie Creek intrusives, Arkansas. *In*: R. Messier, J.T. Glass, J.E. Butler, and R. Roy (editors) New diamond science and technology. Proceedings of the 2nd International Conference, Washington, DC. Materials Research Society, Pittsburgh, pp.193-194.

31 Chrenko, R.M., McDonald, R.S. and Darrow, K.A. (1967) Infra-red spectra of diamond coat. *Nature*, 213: 474-476.

32 Chrenko, R.M. (1973) Boron, the dominant acceptor in semiconducting diamond. *Physical Review B*, 7: 4560-4567.

33 Chrenko, R.M., Tuft, R.E. and Strong, H.M. (1977) Transformation of the state of nitrogen in diamond. *Nature*, 270: 141-144.

34 Clark, C.D., Ditchburn, R.W. and Dyer, H.B. (1956) The absorption spectra of natural and irradiated diamonds. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 234: 363-381.

35 Clarke, R.S.J., Appleman, D.E. and Ross, D.R. (1981) An Antarctic iron meteorite contains preterrestrial impact-produced diamond and lonsdaleite. *Nature*, 291: 396-398.

36 Clement, C.R. and Skinner, E.M.W. (1985) A textural-genetic classification of kimberlites. *South African Journal of Geology*, 88: 403-409.

37 Clifford, T.N. (1966) Tectono-metallogenic units and metallogenic provinces of Africa. *Earth and Planetary Science Letters*, 1: 421-434.

38 Collins, A.T. (1982) Colour centres in diamond. *Journal of Gemmology*, 18: 37-75.

39 Collins, A.T. (1999) Things we still don't know about optical centres in diamond. *Diamond and Related Materials*, 8: 1455-1462.

40 Collinson, D.W. (1998) Magnetic properties of polycrystalline diamonds. *Earth and Planetary Science Letters*, 161: 179-188.

41 Correns, C.W. (1931) Über Diamanten mit Quarzeinlagerungen. *Zeitschrift für Kristallographie*, 80: 37-44.

42 Cotty, W.F. and Wilks, E.M. (1971) Differences between diamonds from different sources. *Diamond Research*, 1971: 8-11.

43 Creighton, S., Stachel, T., McLean, H., Muehlenbachs, K., Simonetti, A., Eichenberg, D. and Luth, R. (2008) Diamondiferous peridotitic microxenoliths from the Diavik diamond mine, NT. *Contributions to Mineralogy and Petrology*, 155: 541-554.

44 Custers, J.F.H. (1955) Large Type II diamonds. *Nature*, 174: 901.

45 Custers, J.F.H. (1955) Semiconductivity of a Type IIb diamond. *Nature*, 176: 173-174.

D

46 Daniels, L.R.M., Gurney, J.J. and Harte, B. (1996) A crustal mineral in a mantle diamond. *Nature*, 379: 153-156.

47 Davies, G. (1976) The A nitrogen aggregate in diamond-its symmetry and possible structure. *Journal of Physics C: Solid State Physics*, 9: 537-542.

48 Davies, R.M., O'Reilly, S.Y. and Griffin, W.L. (2002) Multiple origins of alluvial diamonds from New South Wales, Australia. *Economic Geology*, 97: 109-123.

49 Davies, R.M., Griffin, W.L., O'Reilly, S.Y. and Andrew, A.S. (2003) Unusual mineral inclusions and carbon isotopes of alluvial diamonds from Bingara, eastern Australia. *Lithos*, 69: 51- 66.

50 Davies, R.M., Griffin, W.L., O'Reilly, S.Y. and Doyle, B.J. (2004) Mineral inclusions and geochemical characteristics of microdiamonds from the DO27, A154, A21, A418, DO18, DD17 and Ranch Lake kimberlites at Lac de Gras, Slave Craton, Canada. *Lithos*, 77: 39-55.

51 De, S., Heaney, P.J., Hargraves, R.B., Vicenzi, E.P. and Taylor, P.T. (1998) Microstructural observations of polycrystalline diamond: a contribution to the carbonado conundrum. *Earth and Planetary Science Letters*, 164: 421-433.

52 Deines, P., Harris, J.W. and Gurney, J.J. (1987) Carbon isotopic composition, nitrogen content, and inclusion composition of diamonds from the Roberts Victor kimberlite, South Africa: Evidence for ^{13}C depletion in the mantle. *Geochimica et Cosmochimica Acta*, 51: 1227-1243.

53 Deines, P., Harris, J.W. and Gurney, J.J. (1991) The carbon isotopic composition and nitrogen content of lithospheric and asthenospheric diamonds from the Jagersfontein and Koffiefontein kimberlite, South Africa. *Geochimica et Cosmochimica Acta*, 55: 2615-2625.

54 Deines, P., Harris, J.W. and Gurney, J.J. (1993) Depth-related carbon-isotope and nitrogen concentration variability in the mantle below the Orapa kimberlite, Botswana, Africa. *Geochimica et Cosmochimica Acta*, 57: 2781-2796.

55 Deines, P. and Harris, J.W. (1995) Sulfide inclusion chemistry and carbon isotopes of African diamonds. *Geochimica et Cosmochimica Acta*, 59: 3173-3188.

56 Deines, P., Harris, J.W. and Gurney, J.J. (1997) Carbon isotope ratios, nitrogen content and aggregation state, and inclusion chemistry of diamonds from Jwaneng, Botswana. *Geochimica et Cosmochimica Acta*, 61: 3993-4005.

57 De Stefano, A., Lefebvre, N. and Kopylova, M. (2006) Enigmatic diamonds in Archean calc-alkaline lamprophyres of Wawa, southern Ontario, Canada. *Contributions to Mineralogy and Petrology*, 151: 158-173.

58 De Vries, R.C. (1975) Plastic deformation and "work-hardening" of diamond. *Materials Research Bulletin*, 10: 1193-1199.

59 De Vries, R.C. and Robertson, C. (1985) The microstructure of ballas (polycrystalline diamond) by electrostatic charging in the SEM. *Journal of Materials Science Letters*, 4: 805-807.

60 De Weerdt, F. and Van Royen, J. (2001) Defects in coloured natural diamonds. *Diamond and Related Materials*, 10: 474-479.

61 De Wit, M.C.J. (1999) Post-Gondwana drainage and the development of diamond placers in western South Africa. *Economic Geology*, 94: 721-740.

62 Dobrzhinetskaya, L.F., Eide, E.A., Larsen, R.B., Sturt, B.A., Trønnes, R.G., Smith, D.C., Taylor, W.R. and Posukhova, T.V. (1995) Microdiamond in high-grade metamorphic rocks of the Western Gneiss Region, Norway. *Geology*, 23: 597-600.

63 Donnelly, C.L., Stachel, T., Creighton, S., Muehlenbachs, K. and Whiteford, S. (2007) Diamonds and their mineral inclusions from the A154 South pipe, Diavik diamond mine, Northwest Territories, Canada. *Lithos*, 98: 160-176.

64 Downes, P.J. and Bevan, A.W.R. (2007) Diamonds in Western Australia. *Rocks and Minerals*, 82: 66-73.

E

65 El Goresy, A., Gillet, P., Chen, M., Künstler, F., Graup, G. and Stähle, V. (2001) In situ discovery of shock-induced graphite-diamond phase transition in gneisses from the Ries Crater, Germany. *American Mineralogist*, 86: 611-621.

66 Emara, S.H. and Tolansky, S. (1957) The microstructure of dodecahedral faces of diamond. *Proceedings of the Royal Society London A*, 239: 289-295.

67 Evans, T. and Sauter, D.H. (1961) Etching of diamond surfaces with gases. *Philosophical Magazine*, 6: 429-440.

68 Evans, T. and Phaal, C. (1962) Imperfections in Type I and Type II diamonds *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 270: 538-552.

69 Evans, T. (1976) Diamonds. *Contemporary Physics*, 17: 45-70.

70 Evans, T., Qi, Z. and Maguire, J. (1981) The stages of nitrogen aggregation in diamond. *Journal of Physics C: Solid State Physics*, 14: 379-384.

71 Evans, T. and Qi, Z. (1982) The kinetics of the aggregation of nitrogen atoms in diamond. *Proceedings of the Royal Society A*, 381: 169-178.

72 Evans, T. and Harris, J.W. (1989) Nitrogen aggregation, inclusion equilibration temperatures and the age of diamonds. *In*: J. Ross et al. (editors) Kimberlites and related rocks, Volume 2. Their mantle/crust setting, diamonds and diamond exploration. Proceedings of the 4th International Kimberlite Conference. Geological Society of Australia, Special Publication No.14. Blackwell, Carlton, pp. 1001-1006.

73 Evans, T. (1992) Aggregation of nitrogen in diamonds. *In*: J.E. Field (editor) The properties of natural and synthetic diamond. Academic Press, pp. 259-290.

F

74 Fazakerley, V. (1990) Bow river alluvial diamond deposit. *In*: F.E. Hughes (editor) Geology of the Mineral Deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 1659-1664.

75 Fei, Y. and Bertka, C.M. (1999) Phase transitions in the Earth's mantle and mantle mineralogy. *In*: Y. Fei, C.M. Bertka and B.O. Mysen (editors) Mantle petrology: Field observations and high-pressure experimentation. A tribute to Francis R. (Joe) Boyd. Special Publication No.6. The Geochemical Society, Houston, pp. 189-207.

76 Fersmann, A.v. and Goldschmidt, V.M. (1911) Der Diamant. Carl Winther, Heidelberg, 274 pp.

77 Field, J.E. (1992) The properties of natural and synthetic diamond. Academic Press, 710 pp.

78 Field, M. and Scott Smith, B.H. (1999) Contrasting geology and near-surface emplacement of kimberlite pipes in southern Africa and Canada. *In*: J.J. Gurney, J.L. Gurney, M.D. Pascoe and S.H. Richardson (editors) Proceedings of the 7th International Kimberlite Conference, Volume 1. Red Roof Design, Cape Town, pp. 214-237.

79 Fipke, C.W., Gurney, J.J. and Moore, R.O. (1995) Diamond exploration techniques emphasising indicator mineral geochemistry and Canadian

examples. *Bulletin of the Geological Survey of Canada*, 423: 1-86.

80 Fisher, D., Sibley, S.J. and Kelly, C.J. (2009) Brown colour in natural diamond and interaction between the brown related and other colour-inducing defects. *Journal of Physics: Condensed Matter*, 21: 364213 (10pp.).

81 Frank, F.C., Puttick, K.E. and Wilks, E.M. (1958) Etch pits and trigons on diamond. *Philosophical Magazine*, 3: 1262-1279.

82 Fritsch, E. and Scarratt, K. (1992) Natural-color nonconductive gray-to-blue diamonds. *Gems and Gemology*, 28: 35-42.

83 Fritsch, E. (1998) The nature of color in diamonds. *In*: G.E. Harlow (editor) The nature of diamonds. Cambridge University Press, Cambridge, pp. 23-47.

G

84 Garai, J., Haggerty, S.E., Rekhi, S. and Chance, M. (2006) Infrared absorption investigations confirm the extraterrestrial origin of carbonado diamonds. *Astrophysical Journal Letters*, 653: 153-156.

85 Gasparik, T. and Hutchison, M.T. (2000) Experimental evidence for the origin of two kinds of inclusions in diamonds from the deep mantle. *Earth and Planetary Science Letters*, 181: 103-114.

86 Giardini, A.A. and Tydings, J.E. (1962) Diamond synthesis: Observations on the mechanism of formation. *American Mineralogist*, 47: 1393-1421.

87 Gillet, P., Sautter, V., Harris, J., Reynard, B., Harte, B. and Kunz, M. (2002) Raman spectroscopic study of garnet inclusions in diamonds from the mantle transition zone. *American Mineralogist*, 87: 312-317.

88 Glinnemann, J., Kusaka, K. and Harris, J.W. (2003) Oriented graphite single-crystal inclusions in diamond. *Zeitschrift für Kristallographie*, 218: 733-739.

89 Gordon, W.T. (1945) A note on some large diamonds recently recovered from the gravels of the Woyie River, Sierra Leone. *Bulletin of the Imperial Institute*, 43: 111-120.

90 Gorshkov, A.I., Titkov, S.V., Bao, Y.N., Ryabchikov, I.D. and Magazina, L.O. (2006) Microinclusions in diamonds of octahedral habit from kimberlites of Shandong Province, eastern China. *Geology of Ore Deposits*, 48: 326-334.

91 Grantham, D.R. and Allen, J.B. (1960) Kimberlite in Sierra Leone. *Overseas Geology and Mineral Resources*, 8: 5-25.

92 Griffin, W.L., Win, T.T., Davies, R., Wathanakul, P., Andrew, A., Metcalfe, I. and Cartigny, P. (2001) Diamonds from Myanmar and Thailand: Characteristics and possible origins. *Economic Geology*, 96: 159-170.

93 Gurney, J.J., Siebert, J.C. and Whitfield, G.G. (1969) A diamondiferous eclogite from the Roberts Victor mine. Geological Society of South Africa. Special Publication No.2, pp. 351-357.

94 Gurney, J.J., Harris, J.W. and Rickard, R.S. (1979) Silicate and oxide inclusions in diamonds from the Finsch kimberlite pipe. *In*: H.O.A. Meyer and F.R. Boyd (editors) Kimberlites, diatremes, and diamonds: Their geology, petrology, and geochemistry. Proceedings of the 2nd International Kimberlite Conference, Volume 1, American Geophysical Union, Washington, DC, pp. 1-15.

95 Gurney, J.J., Harris, J.W. and Rickard, R.S. (1984) Silicate and oxide inclusions in diamonds from the Orapa Mine, Botswana. *In*: J. Kornprobst (editor) Kimberlites II: The mantle and crust-mantle relationships. Proceedings of the 3rd International Kimberlite Conference. Elsevier, Amsterdam, pp. 3-9.

96 Gurney, J.J., Harris, J.W., Rickard, R.S. and Moore, R.O. (1985) Premier mine diamond inclusions. *Transactions of the Geological Society of South Africa*, 88: 301-310.

97 Gurney, J.J. (1989) Diamonds. *In*: J. Ross et al. (editors) Kimberlites and related rocks, Volume 2. Their mantle/crust setting, diamonds and diamond exploration. Proceedings of the 4th International Kimberlite Conference. Geological Society of Australia, Special Publication No.14. Blackwell, Carlton, pp. 935-965.

98 Gurney, J.J. (1990) The diamondiferous roots of our wandering continent. *South African Journal of Geology*, 93: 424-437.

99 Gurney, J.J., Levinson, A.A. and Smith, H.S. (1991) Marine mining of diamonds off the west coast of southern Africa. *Gems and Gemology*, 27: 206-219.

100 Gurney, J.J., Hildebrand, P.R., Carlson, J.A., Fedortchouk, Y. and Dyck, D.R. (2004) The morphological characteristics of diamonds from the Ekati property, Northwest Territories, Canada. *Lithos*, 77: 21-38.

101 Gurney, J.J., Helmstaedt, H.H., Richardson, S.H. and Shirey, S.B. (2010) Diamonds through time. *Economic Geology*, 105: 689-712.

H

102 Haggerty, S.E. and Sautter, V. (1990) Ultradeep (greater than 300 kilometers), ultramafic upper mantle xenoliths. *Science*, 248: 993-996.

103 Haggerty, S.E. (1999) A diamond trilogy: superplumes, supercontinents, and supernovae. *Science*, 285: 851-860.

104 Harris, J.W. (1968) The relative orientation of solid mineral inclusions in diamond. *In*: Papers and Proceedings of the 5th General Meeting (International Mineralogical Association), Cambridge 1966. Mineralogical Society, London, pp. 163-168.

105 Harris, J.W. (1968) The recognition of diamond inclusions. Part 1: Syngenetic mineral inclusions. *Industrial Diamond Review*, 28: 402-410.

106 Harris, J.W. (1968) The recognition of diamond inclusions. Part 2: Epigenetic mineral inclusions. *Industrial Diamond Review*, 28: 458-461.

107 Harris, J.W. (1972) Black material on mineral inclusions and in internal fracture planes in diamond. *Contributions to Mineralogy and Petrology*, 35: 22-33.

108 Harris, J.W. and Vance, E.R. (1972) Induced graphitisation around crystalline inclusions in diamond. *Contributions to Mineralogy and Petrology*, 35: 227-234.

109 Harris, J.W., Hawthorne, J.B., Oosterveld, M.M. and Wehmeyer, E. (1975) A classification scheme for diamond and a comparative study of South African diamond characteristics. *In*: L.H. Ahrens, J.B. Dawson, A.R. Duncan and A.J. Erlank (editors) *Physics and Chemistry of the Earth*, 9: 765-783.

110 Harris, J.W. and Gurney, J.J. (1979) Inclusions in diamond. *In*: J.E. Field (editor) Properties of diamond. Academic Press, New York, pp. 555-594.

111 Harris, J.W., Hawthorne, J.B. and Oosterveld, M.M. (1979) Regional and local variations in the characteristics of diamonds from some southern African kimberlites. *In*: H.O.A. Meyer and F.R. Boyd (editors) Kimberlites, diatremes and diamonds: Their geology, petrology and geochemistry. Proceedings of the 2nd International Kimberlite Conference, Volume 1. American Geophysical Union, Washington, DC, pp. 27-41.

112 Harris, J.W., Hawthorne, J.B. and Oosterveld, M.M. (1986) A comparison of characteristics of diamonds from the Orapa and Jwaneng kimberlite pipes in Botswana. *In*: 4th International Kimberlite Conference, Extended Abstracts. Geological Society of Australia, Abstract Volume 16, pp. 395-397.

113 Harris, J.W., Duncan, D.J., Zhang, F., Mia, Q. and Zhu, Y. (1994) The physical characteristics and syngenetic inclusion geochemistry of diamonds from pipe 50, Liaoning Province, People's Republic of China. *In*: H.O.A. Meyer and O.H. Leonardos (editors) Diamonds: Characterization, genesis and exploration. Proceedings of the 5th International Kimberlite Conference, Volume 2. Companhia de Recursos Minerais – CPRM, Special Publication 1/B Jan/94, Brasília, pp. 106-115.

114 Harris, J., Hutchison, M.T., Hursthouse, M., Light, M. and Harte, B. (1997) A new tetragonal silicate mineral occurring as inclusions in lower mantle diamonds. *Nature*, 387: 486-488.

115 Harrison, E.R. and Tolansky, S. (1964) Growth history of a natural octahedral diamond. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 279: 490-496.

116 Harte, B. and Harris, J.W. (1994) Lower mantle associations preserved in diamonds. *Mineralogial Magazine*, 58A: 384-385.

117 Harte, B., Harris, J.W., Hutchison, M.T., Watt, G.R. and Wilding, M.C. (1999) Lower mantle mineral associations in diamonds from São Luiz, Brazil. *In*: Y. Fei, C.M. Bertka and B.O. Mysen (editors) Mantle petrology: Field observations and high-pressure experimentation. A tribute to Francis R. (Joe) Boyd. Special Publication No.6., The Geochemical Society, Houston, pp. 125-153.

118 Harte, B. (2010) Diamond formation in the deep mantle: The record of mineral inclusions and their distribution in relation to mantle dehydration zones. *Mineralogical Magazine*, 74: 189-215.

119 Hatton, C.J. and Gurney, J.J. (1987) Roberts Victor eclogites and their relation to the mantle. *In*: P.H. Nixon (editor) Mantle Xenoliths. John Wiley & Sons, Chichester, pp. 453-463.

120 Hawthorne, J.B. (1975) Model of a kimberlite pipe. *In*: L.H. Ahrens, J.B. Dawson, A.R. Duncan and A.J. Erlank (editors) *Physics and Chemistry of the Earth*, 9: 1-10.

121 Heaman, L.M., Kjarsgaard, B.A. and Creaser, R.A. (2003) The timing of kimberlite magmatism in North America: Implications for global kimberlite genesis and diamond exploration. *Lithos*, 71: 153-184.

122 Heaney, P.J., Vicenzi, E.P. and De, S. (2005) Strange diamonds: The mysterious origin of carbonado and framesite. *Elements*, 1: 85-89.

123 Howes, V.R. and Tolansky, S. (1955) Pressure crack-figures on diamond faces. I. The octahedral face. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 230: 287-293.

124 Howes, V.R. and Tolansky, S. (1955) Pressure crack-figures on diamond faces. II. The dodecahedral and cubic faces. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 230: 294-301.

125 Hutchison, M.T., Cartigny, P. and Harris, J.W. (1999) Carbon and nitrogen composition and physical characteristics of transition zone and lower mantle diamonds from São Luiz, Brazil. *In*: J.J. Gurney, J.L. Gurney, M.D. Pascoe and S.H. Richardson (editors) Proceedings of the 7th International Kimberlite Conference, Volume 1. Red Roof Design, Cape Town, pp. 372-382.

126 Hutchison, M.T., Hursthouse, M.B. and Light, M.E. (2001) Mineral inclusions in diamonds: Associations and chemical distinctions around the 670-km discontinuity. *Contributions to Mineralogy and Petrology*, 142: 119-126.

127 Hutchison, M.T., Nixon, P.H. and Harley, S.L. (2004) Corundum inclusions in diamonds– Discriminatory criteria and a corundum compositional dataset. *Lithos*, 77: 273– 286.

I

128 Irifune, T. (1987) An experimental investigation of the pyroxene-garnet transformation in a pyrolite composition and its bearing on the constitution of the mantle. *Physics of the Earth and Planetary Interiors*, 45: 324-336.

129 Irifune, T. and Ringwood, A.E. (1993) Phase transformations in subducted oceanic crust and buoyancy relationships at depths of 600-800 km in the mantle. *Earth and Planetary Science Letters*, 117: 101-110.

130 Izraeli, E.S., Harris, J.W. and Navon, O. (1999) Raman barometry of diamond formation. *Earth and Planetary Science Letters*, 173: 351-360.

131 Izraeli, E.S., Harris, J.W. and Navon, O. (2001) Brine inclusions in diamonds: A new upper mantle fluid. *Earth and Planetary Science Letters*, 187: 323-332.

132 Izraeli, E.S., Harris, J.W. and Navon, O. (2004) Fluid and mineral inclusions in cloudy diamonds from Koffiefontein, South Africa. *Geochimica et Cosmochimica* Acta, 68: 2561-2575.

J

133 Jacob, D.E., Viljoen, K.S., Grassineau, N. and Jagoutz, E. (2000) Remobilization in the cratonic lithosphere recorded in polycrystalline diamond. *Science*, 289: 1182-1185.

134 Jacob, D.E. (2004) Nature and origin of eclogite xenoliths from kimberlites. *Lithos*, 77: 295-316.

135 Jacob, D.E., Kronz, A. and Viljoen, K.S. (2004) Cohenite, native iron and troilite inclusions in garnets from polycrystalline diamond aggregates. *Contributions to Mineralogy and Petrology*, 146: 566-576.

136 Janse, A.J.A. (1994) Is Clifford's rule still valid? Affirmative examples from around the world. *In*: H.O.A. Meyer and O.H. Leonardos (editors) Diamonds: Characterization, genesis and exploration. Proceedings of the 5th International Kimberlite Conference, Volume 2. Companhia de Recursos Minerais – CPRM, Special Publication 1/B Jan/94, Brasília, pp. 215-235.

137 Janse, A.J.A. (2007) Global rough diamond production since 1870. *Gems and Gemology*, 43 98-112.

138 Jaques, A.L., Lewis, J.D., Smith, C.B., Gregory, G.P., Ferguson, J., Chappell, B.W. and McCulloch, M.T. (1984) The diamond-bearing ultrapotassic (lamproitic) rocks of the West Kimberley region, Western Australia. *In*: J. Kornprobst (editor) Kimberlites I: Kimberlites and related rocks. Proceedings of the 3rd International Kimberlite Conference. Elsevier, Amsterdam, pp. 225-254.

139 Jaques, A.L., Lewis, J.D. and Smith, C.B. (1986) The kimberlites and lamproites of Western Australia. Geological Survey of Western Australia Bulletin 132, 268 pp.

140 Jaques, A.L., Hall, A.E., Sheraton, J.W., Smith, C.B., Sun, S.S., Drew, R.M., Foudoulis, C. and Ellingsen, K. (1989) Composition of crystalline inclusions and C-isotopic composition of Argyle and Ellendale diamonds. *In*: J. Ross et al. (editors) Kimberlites and related rocks, Volume 2. Their mantle/crust setting, diamonds and diamond exploration. Proceedings of the 4th International Kimberlite Conference. Geological Society of Australia, Special Publication No.14. Blackwell, Carlton, pp. 966-989.

141 Javoy, M., Pineau, F. and Delorme, H. (1986) Carbon and nitrogen isotopes in the mantle. *Chemical Geology*, 57: 41-62.

142 Jeynes, C. (1978) Natural polycrystalline diamond. *Industrial Diamond Review*, 38: 14-23.

143 Jones, R. (2009) Dislocations, vacancies and the brown colour of CVD and natural diamond. *Diamond and Related Materials*, 18: 820-826.

K

144 Kagi, H., Takahashi, K., Hidaka, H. and Masuda, A. (1994) Chemical properties of Central African carbonado and its genetic implications. *Geochimica et Cosmochimica Acta*, 58: 2629-2638.

145 Kaminsky, F.V. (1991) Carbonado and yakutite: Properties and possible genesis. *In*: H.O.A. Meyer and O.H. Leonardos (editors) Diamonds: Characterization, genesis and exploration. Proceedings of the 5th International Kimberlite Conference, Volume 2. Companhia de Recursos Minerais – CPRM, Special Publication 1/B Jan/94, Brasília, pp. 136-143.

146 Kaminsky, F.V., Zakharchenko, O.D., Griffin, W.L., Channer, D.M.D. and Khachatryan-Blinova, G.K. (2000) Diamond from the Guaniamo area, Venezuela. *The Canadian Mineralogist*, 38: 1347-1370.

147 Kaminsky, F.V., Zakharchenko, O.D., Davies, R.M., Griffin, W.L., Khachatryan-Blinova, G.K. and Shiryaev, A.A. (2001) Superdeep diamonds from the Juina area, Mato Grosso State, Brazil. *Contributions to Mineralogy and Petrology*, 140: 734-753.

148 Kaminsky, F.V., Zakharchenko, O.D., Khachatryan, G.K. and Shiryaev, A.A. (2001) Diamonds from the Coromandel area, Minas Gerais, Brazil. *Revista Brasileira de Geociências*, 31: 583-596.

149 Kaminsky, F.V., Zakharchenko, O.D., Khachatryan, G.K., Griffin, W.L. and Channer, D.M.D. (2006) Diamond from the Los Coquitos area, Bolivar State, Venezuela. *The Canadian Mineralogist*, 44: 323-340.

150 Kamioka, H., Shibata, K., Kajizuka, I. and Ohta, T. (1996) Rare-earth element patterns and carbon isotopic composition of carbonados: implications for their crustal origin. *Geochemical Journal*, 30: 189-194.

151 Kanda, C.J. and Henderson, E.P. (1939) Identification of diamond in the Canyon Diablo iron. *American Mineralogist*, 24: 677-680.

152 Kane, R.E., McClure, S.F. and Menzhausen, J. (1990) The legendary Dresden Green diamond. *Gems and Gemology*, 26: 248-266.

153 Kennedy, C.S. and Kennedy, G.C. (1976) The equilibrium boundary between graphite and diamond. *Journal of Geophysical Research*, 81: 2467-2470.

154 Kesson, S.E. and Fitz Gerald, J.D. (1992) Partitioning of MgO, FeO, NiO, MnO and Cr_2O_3 between magnesian silicate perovskite and magnesiowüstite: Implications for the origin of inclusions in diamond and the composition of the lower mantle. *Earth and Planetary Science Letters*, 111: 229-240.

155 King, J.M., Moses, T.M., Shigley, J.E., Welbourn, C.M., Lawson, S.C. and Cooper, M. (1998) Characterizing natural-color Type IIb blue diamonds. *Gems and Gemology*, 34: 246-268.

156 King, J.M., Shigley, J.E., Guhin, S.S., Gelb, T.H. and Hall, M. (2002) Characterization and grading of natural-color pink diamonds. *Gems and Gemology*, 38: 128-147.

157 Kinny, P.D. and Meyer, H.O.A. (1994) Zircon from the mantle–A new way to date old diamonds. *Journal of Geology*, 102: 475-481.

158 Kirkley, M.B., Gurney, J.J., Otter, M.L., Hill, S.J. and Daniels, L.R. (1991) The application of C isotope measurements to the identification of the sources of C in diamonds–A review. *Applied Geochemistry*, 6: 477-494.

159 Kirkley, M.B., Gurney, J.J. and Rickard, R.S. (1994) Jwaneng framesites: Carbon isotopes and inclusion compositions. *In*: H.O.A. Meyer and O.H. Leonardos (editors) Diamonds: Characterization, genesis and exploration. Proceedings of the 5th International Kimberlite Conference, Volume 2. Companhia de Recursos Minerais – CPRM, Special Publication 1/B Jan/94, Brasília, pp. 127-135.

160 Kjarsgaard, B.A. and Levinson, A.A. (2002) Diamonds in Canada. *Gems and Gemology*, 28: 208-238.

161 Klein-BenDavid, O., Wirth, R. and Navon, O. (2006) TEM imaging and analysis of microinclusions in diamonds: A close look at diamond-growing fluids. *American Mineralogist*, 91: 353-365.

162 Klein-BenDavid, O., Izraeli, E.S., Hauri, E. and Navon, O. (2007) Fluid inclusions in diamonds from the Diavik mine, Canada and the evolution of diamond-forming fluids. *Geochimica et Cosmochimica Acta*, 71: 723-744.

163 Kletetschka, G., Taylor, P.T., Wasilewski, P.J. and Hill, H.G.M. (2000) Magnetic properties of aggregate polycrystalline diamond: implications for carbonado history. *Earth and Planetary Science Letters*, 181: 279-290.

164 Koeberl, C., Masaitis, V.L., Shafranovsky, G.I., Gilmour, I., Langenhorst, F. and Schrauder, M. (1997) Diamonds from the Popigai impact structure, Russia. *Geology*, 25: 967-970.

165 Kopylova, M.G. Rickard R.S., Kleyenstueber A., Taylor W.R., Gurney J.J. and Daniels L.R.M. (1997) First occurrence of strontian K-Cr loparite and Cr-chevkinite in diamonds. *In*: Proceedings of the 6th International Kimberlite Conference, Volume 2. Diamonds: characterization genesis and exploration. *Russian Geology and Geophysics*, 38: 405-420.

166 Kramers, J.D. (1979) Lead, uranium, strontium, potassium and rubidium in inclusion-bearing diamonds and mantle derived xenoliths from South Africa. *Earth and Planetary Science Letters*, 42: 58-70.

167 Kurat, G. and Dobosi, G. (2000) Garnet and diopside-bearing diamondites (framesites). *Mineralogy and Petrology*, 69: 143-159.

L

168 Lang, A.R. (1974) Glimpses into the growth history of natural diamonds. *Journal of Crystal Growth*, 24/25: 108-115.

169 Lefebvre, N., Kopylova, M. and Kivi, K. (2005) Archean calc-alkaline lamprophyres of Wawa, Ontario, Canada: Unconventional diamondiferous volcaniclastic rocks. *Precambrian Research*, 138: 57-87.

170 Leost, I., Stachel, T., Brey, G.P., Harris, J.W. and Ryabchikov, I.D. (2003) Diamond formation and source carbonation: Mineral associations in diamonds from Namibia. *Contributions to Mineralogy and Petrology*, 145: 15-24.

171 Lipschutz, M.E. (1964) Origin of diamonds in the ureilites. *Science*, 143: 1431-1434.

172 Liu, L.G. (1975) Post-oxide phases of forsterite and enstatite. *Geophysical Research Letters*, 2: 417-419.

173 Liu, L.G. (2002) An alternative interpretation of lower mantle mineral associations in diamonds. *Contributions to Mineralogy and Petrology*, 144: 16-21.

174 Logvinova, A.M., Wirth, R., Sobolev, N.V., Seryotkin, Y.V., Yefimova, E.S., Floss, C. and Taylor, L.A. (2008) Eskolaite associated with diamond from the Udachnaya kimberlite pipe, Yakutia, Russia. *American Mineralogist*, 93: 685-690.

175 Lux, B., Haubner, R., Holzer, H. and DeVries, R.C. (1997) Natural and synthetic polycrystalline diamond, with emphasis on ballas. *International Journal of Refractory Metals and Hard Materials*, 15: 263-288.

M

176 Machado, W.G., Moore, M. and Woods, G.S. (1985) On the dodecahedral growth of coated diamonds. *Journal of Crystal Growth*, 71: 718-727.

177 Machado, W.G., Moore, M. and Yacoot, A. (1998) Twinning in natural diamond. II. Interpenetrant cubes. *Journal of Applied Crystallography*, 31: 777-782.

178 Marshall, T.R. and Baxter-Brown, R. (1995) Basic principles of alluvial diamond exploration. *Journal of Geochemical Exploration*, 53: 277-292.

179 Masaitis, V.L., Shafranovsky, G.I., Grieve, R.A.F., Langenhorst, F., Peredery, W.V., Therriault, A.M., Balmasov, E.L. and Fedorova, I.G. (1999) Impact diamonds in the Suevitic Breccias of the Black Member of the Onaping Formation, Sudbury Structure, Ontario, Canada. *In*: B.O. Dressler and V.L. Sharpton (editors) Large meteorite impacts and planetary evolution II. The Geological Society of America, Special Paper 339, Boulder, pp. 317-321.

180 Massonne, H.J. (1999) A new occurrence of microdiamonds in quartzofeldspathic rocks of the Saxonian Erzgebirge, Germany, and their metamorphic evolution. *In*: J.J. Gurney, J.L. Gurney, M.D. Pascoe and S.H. Richardson (editors) Proceedings, 7th International Kimberlite Conference, Volume 2. Red Roof Design, Cape Town, pp. 533-539.

181 McCallum, M.E. and Eggler, D.H. (1976) Diamonds in an upper mantle peridotite nodule from kimberlite in southern Wyoming. *Science*, 192: 253-256.

182 McCallum, M.E., Huntley, P.M., Falk, R.W. and Otter, M.L. (1994) Morphological, resorption and etch feature trends of diamonds from kimberlite populations within the Colorado-Wyoming state line district. *In*: H.O.A. Meyer and O.H. Leonardos (editors) Diamonds: Characterization, genesis and exploration. Proceedings of the 5th International Kimberlite Conference, Volume 2. Companhia de Recursos Minerais – CPRM, Special Publication 1/B Jan/94, Brasília, pp. 32-50.

183 McCammon, C., Hutchison, M. and Harris, J. (1997) Ferric iron content of mineral inclusions in diamonds from Sao Luiz: A view into the lower mantle. *Science*, 278: 434-436.

184 McDade, P. and Harris, J.W. (1999) Syngenetic inclusion bearing diamonds from Letseng-la-Terai, Lesotho. *In*: J.J. Gurney, J.L. Gurney, M.D. Pascoe and S.H. Richardson (editors) Proceedings, 7th International Kimberlite Conference, Volume 2. Red Roof Design, Cape Town, pp. 557-565.

185 Mc Kenna, N., Gurney, J.J., Klump, J. and Davidson, J.M. (2004) Aspects of diamond mineralisation and distribution at the Helam Mine, South Africa. *Lithos*, 77: 193-208.

186 Menneken, M., Nemchin, A.A., Geisler, T., Pidgeon, R.T. and Wilde, S.A. (2007) Hadean diamonds in zircon from Jack Hills, Western Australia. *Nature*, 448: 917-920.

187 Meyer, H.O.A., Milledge, H.J. and Nave, E. (1965) Natural irradiation damage in Ivory Coast diamonds. *Nature*, 206: 392.

188 Meyer, H.O.A.(1968) Chrome pyrope: an inclusion in natural diamond. *Science*, 160: 1446-1447.

189 Meyer, H.O.A. and Boyd, F.R. (1972) Composition and origin of crystalline inclusions in natural diamonds. *Geochimica et Cosmochimica Acta*, 36: 1255-1273.

190 Meyer, H.O.A. and Svisero, D.P. (1975) Mineral inclusions in Brazilian diamonds. *In*: L.H. Ahrens, J.B. Dawson, A.R. Duncan and A.J. Erlank (editors) *Physics and Chemistry of the Earth*, 9: 785-795.

191 Meyer, H.O.A. and Gübelin, E. (1981) Ruby in diamond. *Gems and Gemology*, 17: 153-156.

192 Meyer, H.O.A. and McCallum, M.E. (1986) Mineral inclusions in diamonds from the Sloan kimberlites, Colorado. *Journal of Geology*, 94: 600-612.

193 Meyer, H.O.A. (1987) Inclusions in diamond. *In*: P.H. Nixon (editor) Mantle xenoliths. John Wiley & Sons, Chichester, pp. 501-522.

194 Meyer, H.O.A., Milledge, H.J., Sutherland, F.L. and Kennewell, P. (1997) Unusual diamonds and unique inclusions from New South Wales, Australia. *In*: Proceedings of the 6th International Kimberlite Conference, Volume 2. Diamonds: Characterization genesis and exploration. *Russian Geology and Geophysics*, 38: 305-331.

195 Milledge, H.J. (1961) Coesite as an inclusion in G.E.C. synthetic diamonds. *Nature*, 190: 1181.

196 Mitchell, R.S. and Giardini, A.A. (1953) Oriented olivine inclusions in diamond. *American Mineralogist*, 38: 136-138.

197 Moore, A. and Moore, J. (2006) A glacial ancestry for the Somabula diamond-bearing alluvial deposit, Central Zimbabwe. *South African Journal of Geology*, 109: 625-636.

198 Moore, A. (2009) Imaging diamond with x-rays. *Journal of Physics: Condensed Matter*, 21: 364217 (15pp.).

199 Moore, A.E. (2009) Type II diamonds: Flamboyant megacrysts? *South African Journal of Geology*, 112: 23-38.

200 Moore, J.M. and Moore, A.E. (2004) The roles of primary kimberlitic and secondary Dwyka glacial sources in the development of alluvial and marine diamond deposits in southern Africa. *Journal of African Earth Sciences*, 38: 115-134.

201 Moore, M. and Lang, A.R. (1974) On the internal structure of natural diamonds of cubic habit. *Philosophical Magazine*, 26: 1313-1325.

202 Moore, M. and Lang, A.R. (1974) On the origin of the rounded dodecahedral habit of natural diamond. *Journal of Crystal Growth*, 26: 133-139.

203 Moore, R.O. and Gurney, J.J. (1985) Pyroxene

solid solution in garnets included in diamonds. *Nature*, 318: 553-555.

204 Moore, R.O., Otter, M.L., Rickard, R.S., Harris, J.W. and Gurney, J.J. (1986) The occurrence of moissanite and ferro-periclase as inclusion in diamonds. *In*: 4th International Kimberlite Conference, Extended Abstracts. Geological Society of Australia, Abstract Volume 16, pp. 409-411.

205 Moore, R.O. and Gurney, J.J. (1989) Mineral inclusions in diamond from Monastery kimberlite, South Africa. *In*: J. Ross et al. (editors) Kimberlites and related rocks, Volume 2. Their mantle/crust setting, diamonds and diamond exploration. Proceedings of the 4th International Kimberlite Conference. Geological Society of Australia, Special Publication No.14. Blackwell, Carlton, pp. 1029-1041.

206 Moses, T.M., Reinitz, I.M., Johnson, M.L., King, J.M. and Shigley, J.E. (1997) A contribution to understanding the effect of blue fluorescence on the appearance of diamonds. *Gems and Gemology*, 33: 244-259.

207 Mvuemba Ntanda, F., Moreau, J. and Meyer, H.O.A. (1982) Particularités des inclusions cristallines primaires des diamants du Kasai, Zaïre. *Canadian Mineralogist*, 20: 217-230.

N

208 Navon, O., Hutcheon, I.D., Rossman, G.R. and Wasserburg, G.J. (1988) Mantle-derived fluids in diamond micro-inclusions. *Nature*, 335: 784-789.

209 Nemchin, A.A., Whitehouse, M.J., Menneken, M., Geisler, T., Pidgeon, R.T. and Wilde, S.A. (2008) A light carbon reservoir recorded in zircon-hosted diamond from Jack Hills. *Nature*, 454: 92-95.

210 Nixon, P.H. (1987) Mantle Xenoliths. John Wiley & Sons, Chichester, 844 pp.

211 Nixon, P.H. (1995) The morphology and nature of primary diamondiferous occurrences. *Journal of Geochemical Exploration*, 53: 41-71.

O

212 O'Hara, M.J., Saunders, M.J. and Mercy, E.L.P. (1975) Garnet-peridotite, primary ultrabasic magma and eclogite: interpretation of upper mantle processes in kimberlite. *In*: L.H. Ahrens, J.B. Dawson, A.R. Duncan and A.J. Erlank (editors) *Physics and Chemistry of the Earth*, 9: 571-604.

213 Omar, M., Pandya, N.S. and Tolansky, S. (1954) The etching of diamond. I. Octahedron faces *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 225: 33-40.

214 Orlov, Y.L. (1977) The Mineralogy of the Diamond. John Wiley & Sons, New York, 235 pp.

215 Orlov, Y.L. and Kaminsky, F.V. (1981) A new (XI) variety of polycrystalline diamond aggregates–"Carbonado with lonsdaleite". *Doklady Akademii Nauk SSSR*, 259: 459-461. (in Russian)

216 Otter, M.L. and Gurney, J.J. (1989) Mineral inclusions in diamond from the Sloan diatremes, Colorado-Wyoming state line kimberlite district, North America. *In*: J. Ross et al. (editors) Kimberlites and related rocks, Volume 2. Their mantle/crust setting, diamonds and diamond exploration. Proceedings of the 4th International Kimberlite Conference. Geological Society of Australia, Special Publication No.14. Blackwell, Carlton, pp. 1042-1053.

217 Ozima, M. and Tatsumoto, M. (1997) Radiation induced diamond crystallization: Origin of carbonados and its implications on meteorite nano-diamonds. *Geochimica et Cosmochimica Acta*, 61: 369-376.

P

218 Pandeya, D.C. and Tolansky, S. (1961) Microdisk patterns on diamond dodecahedra. *Proceedings of the Physical Society*, 78: 12-16.

219 Pandya, N.S. and Tolansky, S. (1954) The etching of diamond. II. Cleavage, dodecahedron and cube faces. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 225: 40-48.

220 Pearson, D.G., Shirey, S.B., Harris, J.W. and Carlson, R.W. (1998) Sulphide inclusions in diamonds from the Koffiefontein kimberlite, South Africa: Constraints on diamond ages and mantle Re-Os systematics. *Earth and Planetary Science Letters*, 160: 311-326.

221 Pearson, D.G. and Shirey, S.B. (1999) Isotopic dating of diamonds. *In*: D.D. Lambert and J. Ruiz (editors) Applications of radiogenic isotopes to ore deposit research. SEG Reviews Volume 12. Society of Economic Geologists, Littleton, pp. 143-171.

222 Pearson, D.G., Canil, D. and Shirey, S.B. (2003) Mantle samples included in volcanic rocks: Xenoliths and diamonds. *In*: R.W. Carlson (editor) Treatise on geochemistry. Elsevier, Amsterdam, pp. 171-275.

223 Peltonen, P., Kinnunen, K.A. and Huhma, H. (2002) Petrology of two diamondiferous eclogite xenoliths from the Lahtojoki kimberlite pipe, eastern Finland. *Lithos*, 63: 151- 164.

224 Phaal, C. (1965) Surface studies of diamond. *Industrial Diamond Review*, 25: 486-489 and 591-595.

225 Phillips, D., Onstott, T.C. and Harris, J.W. (1989) ^{40}Ar/^{39}Ar laser-probe dating of diamond inclusions from the Premier kimberlite. *Nature*, 340: 460-462.

226 Phillips, D., Harris, J.W. and Viljoen, K.S. (2004) Mineral chemistry and thermobarometry of inclusions from De Beers Pool diamonds, Kimberley, South Africa. *Lithos*, 77: 155-179.

227 Polinard, E. (1929) Les diamants translucides et opaques des gisements de la Bushimaie. *Annales de la Société Géologique de Belgique*, 52: 179-215.

228 Prinz, M., Manson, D.V., Hlava, P.F. and Keil, K. (1975) Inclusions in diamonds: Garnet lherzolite and eclogite assemblages. *In*: L.H. Ahrens, J.B. Dawson, A.R. Duncan and A.J. Erlank (editors) *Physics and Chemistry of the Earth*, 9: 797-815.

R

229 Raal, F.A. (1969) A study of some gold mine diamonds. *American Mineralogist*, 54: 292-296.

230 Read, G. and Janse, A.J.A. (2009) Diamonds: Exploration, mines and marketing. *Lithos*, 112, Supplement 1: 1-9.

231 Reutskii, V.N., Logvinova, A.M. and Sobolev, N.V. (1999) Carbon isotopic composition of polycrystalline diamond aggregates with chromite inclusions from the Mir kimberlite pipe, Yakutia. *Geochemistry International*, 37: 1073-1078.

232 Richardson, S.H., Gurney, J.J., Erlank, A.J. and Harris, J.W. (1984) Origin of diamonds from old continental mantle. *Nature*, 310: 198-202.

233 Richardson, S.H. (1986) Latter day origin of diamonds from eclogitic paragenesis. *Nature*, 322: 623-626.

234 Richardson, S.H. and Harris, J.W. (1997) Antiquity of peridotitic diamonds from the Siberian craton. *Earth and Planetary Science Letters*, 151: 271-277.

235 Ringwood, A.E. and Major, A. (1971) Synthesis of majorite and other high pressure garnets and perovskites. *Earth and Planetary Science Letters*, 12: 411-418.

236 Ringwood, A.E. (1975) Composition and petrology of the earth's upper mantle. McGraw-Hill, London, 618 pp.

237 Ringwood, A.E. (1991) Phase transformations and their bearing on the constitution and dynamics of the mantle. *Geochimica et Cosmochimica Acta*, 55: 2083-2110.

238 Robertson, R., Fox, J.J. and Martin, A.E. (1934) Two types of diamond. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, 232: 463-535.

239 Robinson, D.N. (1978) The characteristics of natural diamonds and their interpretation. *Minerals Science and Engineering*, 10: 55-72.

240 Robinson, D.N. (1979) Surface textures and other features of diamonds, University of Cape Town, unpublished Ph.D. thesis, Cape Town, 221 pp.

241 Robinson, D.N., Scott, J.A., Van Niekerk, A. and Anderson, V.G. (1989) The sequence of events reflected in the diamonds of some southern African kimberlites. *In*: J. Ross et al. (editors) Kimberlites and related rocks, Volume 2. Their mantle/crust setting, diamonds and diamond exploration. Proceedings of the 4th International Kimberlite Conference. Geological Society of Australia, Special Publication No.14. Blackwell, Carlton, pp. 990-1000.

242 Rudnick, R.L. and Nyblade, A.A. (1999) The thickness and heat production of Archean lithosphere: Constraints from xenolith thermobarometry and surface heat flow. *In*: Y. Fei, C.M. Bertka and B.O. Mysen (editors) Mantle petrology: Field observations and high-pressure experimentation. A tribute to Francis R. (Joe) Boyd. Special Publication No.6. The Geochemical Society, Houston, pp. 3-12.

S

243 Sano, Y., Yokochi, R., Terada, K., Chaves, M.L. and Ozima, M. (2002) Ion microprobe Pb-Pb dating of carbonado, polycrystalline diamond. *Precambrian Research*, 113: 155-168.

244 Sautter, V., Haggerty, S.E. and Field, S. (1991) Ultradeep (greater than 300 kilometers) ultramafic xenoliths–Petrological evidence from the transition zone. *Science*, 252: 827-830.

245 Schidlowski, J.M., Hayes, J.M. and Kaplan, I.R. (1983) Isotopic inferences of ancient biochemistries: carbon, sulfur, hydrogen, and nitrogen. *In*: J.W. Schopf (editor) Earth's earliest biosphere. Princeton University Press, Princeton, pp. 149-186.

246 Schulze, D.J. (1989) Constraints on the abundance of eclogite in the upper mantle. *Journal of Geophysical Research*, 94: 4205-4212.

247 Schulze, D.J., Harte, B., Valley, J.W., Brenan, J.M. and Channer, D.M.D. (2003) Extreme crustal oxygen isotope signatures preserved in coesite in diamond. *Nature*, 423: 68-70.

248 Schulze, D.J., Harte, B., Valley, J.W. and Channer, D.M.D. (2004) Evidence of subduction and crust-mantle mixing from a single diamond. *Lithos*, 77: 349- 358.

249 Scott Smith, B.H., Danchin, R.V., Harris, J.W. and Stracke, K.J. (1984) Kimberlites near Orroroo, South Australia. *In*: J. Kornprobst (editor) Kimberlites I: Kimberlites and related rocks. Proceedings of the 3rd International Kimberlite Conference. Elsevier, Amsterdam, pp. 121-142.

250 Scott Smith, B.H. and Skinner, E.M.W. (1984) Diamondiferous lamproites. *The Journal of Geology*, 92: 433-438.

251 Seal, M. (1965) Structure in diamonds as revealed by etching. *American Mineralogist*, 50: 105-123.

252 Sharp, W.E. (1966) Pyrrhotite: A common inclusion in South African diamonds. *Nature*, 211: 402-403.

253 Shatsky, V., Ragozin, A., Zedgenizov, D. and Mityukhin, S. (2008) Evidence for multistage evolution in a xenolith of diamond-bearing eclogite

from the Udachnaya kimberlite pipe. *Lithos*, 105: 289-300.

254 Shelkov, D.A., Verchovsky, A.B., Milledge, H.J., Kaminsky, F.V. and Pillinger, C.T. (1998) Carbon, nitrogen, argon and helium study of impact diamonds from Ebeliakh alluvial deposits and Popigai crater. *Meteoritics and Planetary Science*, 33: 985-992.

255 Skinner, E.M. (1989) Contrasting Group I and Group II kimberlite petrology: Towards a genetic model for kimberlites. *In*: J. Ross et al. (editors) Kimberlites and related rocks, Volume 1. Their composition, occurrence, origin and emplacement. Proceedings of the 4th International Kimberlite Conference. Geological Society of Australia, Special Publication No.14. Blackwell, Carlton, pp. 528-544.

256 Skinner, E.M.W. and Marsh, J.S. (2004) Distinct kimberlite pipe classes with contrasting eruption processes. *Lithos*, 76: 183-200.

257 Slawson, C.B. (1950) Twinning in the diamond. *American Mineralogist*, 35: 193-206.

258 Smith, C.B., Bulanova, G.P., Kohn, S.C., Milledge, H.J., Hall, A.E., Griffin, B.J. and Pearson, D.G. (2009) Nature and genesis of Kalimantan diamonds. *Lithos*, 112 Supplement 2: 822-832.

259 Smith, J.V. and Dawson, J.B. (1985) Carbonado: Diamond aggregates from early impacts of crustal rocks? *Geology*, 13: 342-343.

260 Smyth, J.R. and Hatton, C.J. (1977) A coesite-sanidine grospydite from the Roberts Victor kimberlite. *Earth and Planetary Science Letters*, 34: 284-290.

261 Sobolev, N.V., Yefimova, E.S., Koptil, V.I., Lavrentev, Y.G. and Sobolev, V.S. (1976) Coesite, garnet and omphacite inclusions in Yakut diamonds. First finding of coesite paragenesis. *Doklady Akademii Nauk SSSR*, 230: 1442-1444. (in Russian)

262 Sobolev, N.V. (1977) Deep-seated inclusions in kimberlites and the problem of the composition of the upper mantle. American Geophysical Union, Washington, DC, 279 pp.

263 Sobolev, N.V., Efimova, E.S. and Pospelova, L.N. (1981) Native iron in Yakutian diamonds and its paragenesis. *Geologiya i Geofizika*, 22: 25-29. (in Russian)

264 Sobolev, N.V. (1984) Crystalline inclusions in diamonds from New South Wales, Australia. *In*: J.E. Glover and P.G. Harris (editors) Kimberlite occurrence and origin: A basis for conceptual models in exploration. University of Western Australia, pp. 213-226.

265 Sobolev, N.V. and Shatsky, V.S. (1990) Diamond inclusions in garnets from metamorphic rocks–A new environment for diamond formation. *Nature*, 343: 742-746.

266 Sobolev, N.V., Kaminsky, F.V., Griffin, W.L., Yefimova, E.S., Win, T.T., Ryan, C.G., Botkunov, A.I. (1997) Mineral inclusions in diamonds from the Sputnik kimberlite pipe, Yakutia. *Lithos*, 39: 135-157.

267 Sobolev, N.V., Sobolev, V.N., Snyder, G.A., Yefimova, E.S. and Taylor, L.A. (1999) Significance of eclogitic and related parageneses of natural diamonds. *International Geology Review*, 41: 129-140.

268 Sobolev, N.V. and Yefimova, E.S. (2000) Composition and petrogenesis of Ti-oxides associated with diamonds. *International Geology Review*, 42: 758-767.

269 Spetsius, Z.V., Belousova, E.A., Griffin, W.L., O'Reilly, S.Y. and Pearson, N.J. (2002) Archean sulfide inclusions in Paleozoic zircon megacrysts from the Mir kimberlite, Yakutia: Implications for the dating of diamonds. *Earth and Planetary Science Letters*, 199: 111-126.

270 Stachel, T., Harris, J.W. and Brey, G.P. (1998) Rare and unusual mineral inclusions in diamonds from Mwadui, Tanzania. *Contributions to Mineralogy and Petrology*, 132: 34-47.

271 Stachel, T., Harris, J.W., Brey, G.P. and Joswig, W. (2000) Kankan diamonds (Guinea) II: Lower mantle inclusion parageneses. *Contributions to Mineralogy and Petrology*, 140: 16-27.

272 Stachel, T. (2001) Diamonds from the asthenosphere and the transition zone. *European Journal of Mineralogy*, 13: 883-892.

273 Stachel, T., Harris, J.W., Aulbach, S. and Deines, P. (2002) Kankan diamonds (Guinea) III: $\delta^{13}C$ and nitrogen characteristics of deep diamonds. *Contributions to Mineralogy and Petrology*, 142: 465-475.

274 Stachel, T., Banas, A., Muehlenbachs, K., Kurszlaukis, S. and Walker, E.C. (2006) Archean diamonds from Wawa (Canada): Samples from deep cratonic roots predating cratonization of the Superior Province. *Contributions to Mineralogy and Petrology*, 151: 737-750.

275 Stachel, T. and Harris, J.W. (2008) The origin of cratonic diamonds–Constraints from mineral inclusions. *Ore Geology Reviews*, 34: 5-32.

276 Stachel, T., Harris, J.W. and Muehlenbachs, K. (2009) Sources of carbon in inclusion bearing diamonds. *Lithos*, 112, Supplement 2: 625-637.

277 Sunagawa, I. (1984) Morphology of natural and synthetic diamond crystals. *In*: I. Sunagawa (editor) Materials science of the Earth's interior. Terra Scientific, Tokyo, pp. 303-330.

278 Sunagawa, I. (2005) Crystals-Growth, morphology and perfection. Cambridge University Press, Cambridge, 295 pp.

279 Sutherland, D.G. (1982) The transport and sorting of diamonds by fluvial and marine processes. *Economic Geology*, 77: 1613-1620.

280 Sutherland, G.B.B.M., Blackwell, D.E. and Simeral, W.G. (1954) The problem of two types of diamond. *Nature*, 174: 901-904.

281 Sutton, J.R. (1928) Diamond, a descriptive treatise. Thomas Murby, London,118 pp.

282 Suzuki, S. and Lang, A.R. (1976) Occurrences of facetted re-entrants on rounded growth surfaces of natural diamonds. *Journal of Crystal Growth*, 34: 29-37.

283 Svisero, D.P. (1995) Distribution and origin of diamonds in Brazil–An overview. *Journal of Geodynamics*, 20: 493-514.

T

284 Takahashi, E. and Ito, E. (1987) Mineralogy of mantle peridotite along a model geotherm up to 700 km depth. *In*: M.H. Manghnani and Y. Syono (editors) High-pressure research in mineral physics. Terra Scientific, Tokyo, pp. 427-437.

285 Tappe, S., Foley, S.F., Kjarsgaard, B.A., Romer, R.L., Heaman, L.M., Stracke, A. and Jenner, G.A. (2008) Between carbonatite and lamproite–Diamondiferous Torngat ultramafic lamprophyres formed by carbonate-fluxed melting of cratonic MARID-type metasomes. *Geochimica et Cosmochimica Acta*, 72: 3258-3286.

286 Tappert, R., Stachel, T., Harris, J.W., Muehlenbachs, K., Ludwig, T. and Brey, G.P. (2005) Subducting oceanic crust: The source of deep diamonds. *Geology*, 33: 565-568.

287 Tappert, R., Stachel, T., Harris, J.W., Muehlenbachs, K., Ludwig, T. and Brey, G.P. (2005) Diamonds from Jagersfontein (South Africa): Messengers from the sublithospheric mantle. *Contributions to Mineralogy and Petrology*, 150: 505-522.

288 Tappert, R., Stachel, T., Harris, J.W., Shimizu, N. and Brey, G.P. (2005) Mineral inclusions in diamonds from the Panda kimberlite, Slave Province, Canada. *European Journal of Mineralogy*, 17: 423-440.

289 Tappert, R., Stachel, T., Harris, J.W., Muehlenbachs, K. and Brey, G.F. (2006) Placer diamonds from Brazil: Indicators of the composition of the Earth's mantle and the distance to their kimberlitic sources. *Economic Geology*, 101: 453-470.

290 Tappert, R., Foden, J., Stachel, T., Muehlenbachs, K., Goryniuk, M.C. and Wills, K. (2009) Deep mantle diamonds from South Australia: A record of Pacific subduction at the Gondwanan margin. *Geology*, 37: 43-46.

291 Tappert, R., Foden, J., Stachel, T., Muehlenbachs, K., Tappert, M. and Wills, K. (2009) The diamonds of South Australia. *Lithos*, 112, Supplement 2: 806-821.

292 Taylor, L.A., Anand, M., Promprated, P., Floss, C. and Sobolev, N.V. (2003) The significance of mineral inclusions in large diamonds from Yakutia, Russia. *American Mineralogist*, 88: 912-920.

293 Taylor, W.R., Jaques, A.L. and Ridd, M. (1990) Nitrogen-defect aggregation characteristics of some Australasian diamonds–Time-temperature constraints on the source regions of pipe and alluvial diamonds. *American Mineralogist*, 75: 1290-1310.

294 Titkov, S.V., Gorshkov, A.I., Vinokurov, S.F., Bershov, L.V., Solodov, D.I. and Sivtsov, A.V. (2001) Geochemistry and genesis of carbonado for Yakutian diamond deposits. *Geochemistry International*, 39: 228-236.

295 Titkov, S.V., Gorshkov, A.I., Magazina, L.O., Sivtsov, A.V. and Zakharchenko, O.D. (2004) Shapeless dark diamonds (yakutites) from placers of the Siberian platform and criteria of their impact origin. *Geology of Ore Deposits*, 46: 191-201.

296 Titkov, S.V., Shigley, J.E., Breeding, C.M., Mineeva, R.M., Zudin, N.G., Sergeev, A.M. (2008) Natural-color purple diamonds from Siberia. *Gems and Gemology*, 44: 56-64.

297 Titkov, S.V., Zudin, N.C., Gorshkov, A.I., Sivtsov, A.V. and Magazina, L.O. (2009) An investigation into the cause of color in natural black diamonds from Siberia. *Gems and Gemology*, 39: 200-209.

298 Tolansky, S. (1955) The microstructure of diamond surfaces. N.A.G. Press, London, 67 pp.

299 Tompkins, L.A. and Gonzaga, G.M. (1989) Diamonds in Brazil and a proposed model for the origin and distribution of diamonds in the Coromandel region, Minas Gerais, Brazil. *Economic Geology*, 84: 591-602.

300 Trueb, L.F. and De Wys, E.C. (1969) Carbonado: Natural polycrystalline diamond. *Science*, 165: 799-802.

301 Trueb, L.F. and Barrett, C.S. (1972) Microstructural investigation of ballas diamond. *American Mineralogist*, 57: 1664-1680.

302 Tsai, H.M., Meyer, H.O.A., Moreau, J. and Milledge, H.J. (1979) Mineral inclusions in diamonds: Premier, Jagersfontein and Finsch kimberlites, South Africa, and Williamson mine, Tanzania. *In*: F.R. Boyd and H.O.A. Meyer (editors) Kimberlites, diatremes, and diamonds: Their geology, petrology, and geochemistry. Proceedings of the 2nd International Kimberlite Conference, Volume 1. American Geophysical Union, Washington, DC, pp. 16-26.

V

303 Vance, E.R. and Milledge, H.J. (1972) Natural and laboratory α-particle irradiation of diamond. *Mineralogical Magazine*, 38: 878-881.

304 Vance, E.R., Harris, J.W. and Milledge, H.J. (1973) Possible origins of α-damage in diamonds from kimberlite and alluvial sources. *Mineralogical Magazine*, 39: 349-360.

305 Viljoen, K.S., Robinson, D.N., Swash, P.M., Griffin, W.L., Otter, M.L., Ryan, C.G. and Win, T.T. (1994) Diamond- and graphite-bearing peridotite xenoliths from the Roberts Victor Kimberlite, South Africa. *In*: H.O.A. Meyer and O.H. Leonardos (editors) Kimberlites, related

rocks and mantle xenoliths. Proceedings of the 5th International Kimberlite Conference, Volume 1. Companhia de Recursos Minerais – CPRM, Special Publication 1/A Jan/94, Brasília, pp. 285-303.

306 Viljoen, K.S., Phillips, D., Harris, J.W. and Robinson, D.N. (1999) Mineral inclusions in diamonds from the Venetia kimberlites, Northern Province, South Africa. *In*: J.J. Gurney, J.L. Gurney, M.D. Pascoe and S.H. Richardson (editors) Proceedings of the 7th International Kimberlite Conference, Volume 2. Red Roof Design, Cape Town, pp. 88-895.

W

307 Wagner, P.A. (1914) The diamond fields of southern Africa. Transvaal Leader, Johannesburg, 347 pp.

308 Wagner, P.A. and Merensky, H. (1928) The diamond deposits on the coast of Little Namaqualand. *Transactions of the Geological Society of South Africa*, 31: 1-41.

309 Wang, A., Pasteris, J.D., Meyer, H.O.A. and Dele-Duboi, M.L. (1996) Magnesite-bearing inclusion assemblage in natural diamond. *Earth and Planetary Science Letters*, 141: 293-306.

310 Wang, W., Sueno, S., Takahashi, E., Yurimoto, H. and Gasparik, T. (2000) Enrichment processes at the base of the Archean lithospheric mantle: Observations from trace element characteristics of pyropic garnet inclusions in diamonds. *Contributions to Mineralogy and Petrology*, 139: 720-733.

311 Watt, G.R., Harris, J.W., Harte, B. and Boyd, S.R. (1994) A high-chromium corundum (ruby) inclusion in diamond from the Sao-Luiz alluvial mine, Brazil. *Mineralogical Magazine*, 58: 490-493.

312 Welbourn, C.M., Rooney, M.L.T. and Evans, D.J.F. (1989) A study of diamonds of cube and cube-related shape from the Jwaneng mine. *Journal of Crystal Growth*, 94: 229-252.

313 Westerlund, K.J., Shirey, S.B., Richardson, S.H., Carlson, R.W., Gurney, J.J. and Harris, J.W. (2006) A subduction wedge origin for Paleoarchean peridotitic diamonds and harzburgites from the Panda kimberlite, Slave craton: Evidence from Re–Os isotope systematics. *Contributions to Mineralogy and Petrology*, 152: 275-294.

314 Wilks, J. and Wilks, E. (1991) Properties and applications of diamond. Butterworth-Heinemann, Oxford, 525 pp.

315 Williams, A.F. (1932) The Genesis of Diamond, Volume 2. Ernest Benn, London, 632 pp.

316 Wirth, S., Vollmer, C., Brenker, F., Matsyuk, S. and Kaminsky, F. (2007) Inclusions of nanocrystalline hydrous aluminium silicate "phase egg" in superdeep diamonds from Juina (Mato Grosso State, Brazil). *Earth and Planetary Science Letters*, 259: 384-399.

317 Wirth, R., Kaminsky, F., Matsyuk, S. and Schreiber, A. (2009) Unusual micro- and nano-inclusions in diamonds from the Juina Area, Brazil. *Earth and Planetary Science Letters*, 286: 292-303.

318 Woods, G.S., Purser, G.C., Mtimkulu, A.S.S. and Collins, A.T. (1990) The nitrogen content of Type Ia natural diamonds. *Journal of Physics and Chemistry of Solids*, 51: 1191-1197.

X

319 Xu, S.T., Okay, A.I., Ji, S.Y., Sengor, A.M.C., Wen, S., Liu, Y.C. and Jiang, L.L. (1992) Diamond from the Dabie-Shan metamorphic rocks and its implication for tectonic setting. *Science*, 256: 80-82.

Y

320 Yacoot, A., Moore, M. and Machado, W.G. (1998) Twinning in natural diamond. I. Contact twins. *Journal of Applied Crystallography*, 31: 767-776.

321 Yamaoka, S., Komatsu, H., Kanada, H. and Setaka, N. (1977) Growth of diamond with rhombic dodecahedral faces. *Journal of Crystal Growth*, 37: 349-352.

Z

322 Zaitsev, A.M. (2001) Optical properties of diamond: A data handbook. Springer, 502 pp.

323 Zedgenizov, D.A., Kagi, H., Shatsky, V.S. and Sobolev, N.V. (2004) Carbonatitic melts in cuboid diamonds from Udachnaya kimberlite pipe (Yakutia): evidence from vibrational spectroscopy. *Mineralogical Magazine*, 68: 61-73.

324 Zinchuk, N.N. and Koptil, V.I. (2007) Mineralogy of diamonds from the Ozernaya pipe, Ottorzhenets body, Pervomaiskaya and Novogodnyaya veins, Yakutia. *Geology of Ore Deposits*, 49: 308-317.

325 Zintchouk, N.N. and Koptil', V.I. (2003) Typomorphism of the Siberian platform diamonds. Nedra, Moscow, 603 pp. (in Russian)

Collection Credits

Mineralogy and Petrology Museum,
Department of Earth and Atmospheric Sciences,
University of Alberta, Edmonton, Canada:
1-04, 1-05, 1-08,
2-03, 2-05, 2-06, 2-07, 2-08, 2-09,
2-10, 2-12, 2-14, 2-15, 2-16, 2-20,
2-26, 2-30, 2-32, 2-36, 2-37, 2-38,
2-39, 2-42, 2-43, 2-45, 2-46, 2-52,
2-53, 2-55,
3-01, 3-02, 3-10, 3-13, 3-17, 3-20,
3-24, 3-25, 3-26, 3-27, 3-28, 3-30,
3-31, 3-35, 3-39,
4-02, 4-04, 4-06, 4-07, 4-08, 4-11,
4-17, 4-22, 4-24, 4-25, 4-29, 4-30,
4-31, 4-34, 4-35, 4-37, 4-38, 4-39,
4-41, 4-42, 4-43, 4-44, 4-45, 4-46,
5-01, 5-02, 5-04, 5-05, 5-06, 5-09,
5-10, 5-12, 5-16, 5-17, 5-19, 5-20,
5-21, 5-27, 5-28, 5-29, 5-30

Mineral collection of the
South Australian Museum,
Adelaide, Australia:
2-19, 2-24, 2-35, 2-48, 2-54, 2-56,
3-03, 3-04, 3-05, 3-06, 3-07, 3-18,
3-21, 3-22, 3-23, 3-29, 3-33, 3-36,
3-38
4-13, 4-21, 4-27, 4-36

Index