

AGE, ORIGIN, AND EMPLACEMENT OF DIAMONDS:

Scientific Advances in the Last Decade

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Scientific advances in the past decade have completely altered our understanding of certain concepts relating to the age and origin of diamonds. As a generalization, most diamonds formed more than 990 million years ago, deep within the earth, from either of two rock types, peridotite and eclogite. They were stored below the base of cratons for varying periods of time, some as long as 3,200 million years, before being transported to the surface. Kimberlite and lamproite, the two rock types usually associated with diamonds, are only the mechanisms that brought diamonds to the surface and are in no way related to the formation of most diamonds. Other topics that are somewhat more speculative, for example, the source of carbon for the crystallization of diamonds and the mechanism of kimberlite and lamproite emplacement, are also discussed and the latest concepts presented.

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Acknowledgments: The authors sincerely thank Dr. A. J. A. Janse and Mr. P. J. Darragh, both of Perth, Australia, for their careful review of the manuscript.

Gems & Gemology, Vol. 27, No. 1, pp. 2-25
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The decade of the 1980s saw major advances in our understanding of the age, origin, and emplacement of diamonds. Much of the new data and their interpretations are found in highly technical scientific journals and conference proceedings that are rarely encountered by gemologists. Therefore, we have prepared this review article to update gemologists on some of the latest facts and concepts with respect to the above topics.

The information contained in this article is applicable to virtually all natural diamonds, both gem and industrial (figure 1), except possibly for certain rare types of diamonds, such as those referred to as "fibrous" or "coated," and microdiamonds, as well as for diamonds related to meteorite impacts. In addition to our own experiences, we have drawn from many volumes in the technical literature. For those interested in pursuing these topics further, we recommend the books by Ross (1989), Nixon (1987), Mitchell (1986), Glover and Harris (1984), Kornprobst (1984), and Dawson (1980), and the review articles by Gurney (1989) and Meyer (1985).

AGE OF DIAMONDS

Until recently, one of the major unresolved problems in diamond research revolved around the age of diamonds. Age dating of diamonds assists in understanding their origin, which is a significant factor in diamond exploration. For many minerals, age can be determined directly using a number of well-established geochronological techniques, such as the uranium-lead (U-Pb) method. However, because diamond is essentially pure carbon, it does not contain any of the radiogenic elements on which such methods depend. Even the well-known carbon-14 (^{14}C) method is useless for diamonds because it is restricted to organic carbon that has been involved in the earth's recent near-surface carbon cycle.

Although diamonds themselves cannot be dated, some of their minute inclusions, such as pyroxene and garnet,



Figure 1. Today, diamonds are the most popular gemstone and a valuable industrial material. As a consequence, there has been considerable research into the geologic origins of diamonds to aid in exploration and mining. The last decade, in particular, has produced some important advances in our understanding of the complex processes required for the formation and deposition of diamonds. The ultimate result of such research is evident in these superb earrings and necklace. The three large diamonds in the necklace are (from the left) 9.81, 16.18, and 12.73 ct; they are surrounded by 254 diamonds with a total weight of 67 ct; the earrings contain 84 diamonds with a total weight of 11 ct. Jewelry by Van Cleef and Arpels; photo courtesy of Sotheby's, New York.

can, because these minerals contain measurable quantities of the elements involved in radioactive decay systems. Some inclusions (e.g., garnet) were formed at the same time, and in the same place, as their mineral host (e.g., diamond), so that the age of the inclusion is also the age of the host. Detailed studies of olivine, garnet, pyroxene, chromite, and other minerals in diamond have shown that these minerals were growing adjacent to the diamond, which then grew around and enclosed them (figure 2). This physical relationship between diamond and its cogenetic inclusions is sometimes reflected by the crystal form of the silicate inclusions, which take on the morphology (called cubo-

octahedron) of the diamond rather than that of their species (figure 3).

Several attempts were made prior to 1981 to date inclusions in diamonds; the study by Kramers (1979) is the most significant. Using lead (Pb) isotopic compositions of sulphide inclusions in diamonds, he determined ages on the order of 2,000 million years (My) for inclusions in diamonds from the Finsch and Kimberley pipes in South Africa; those from the Premier mine appeared to be about 1,200 My in age. However, Richardson et al. (1984) were the first to date successfully a significant number of inclusions in diamonds, specifically inclusions of garnet in Finsch and Kimberley

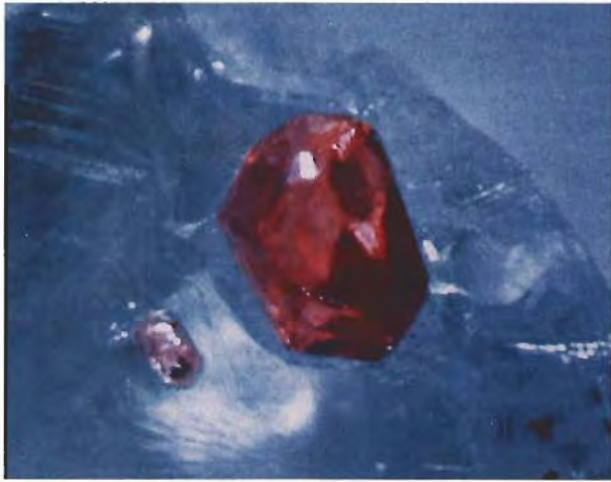


Figure 2. This garnet inclusion in a diamond (1 mm across) from the Finsch mine, South Africa, was dated by geochronological methods to be about 3,300 million years old. Because such inclusions undoubtedly formed at the same time as their hosts, they are the best means of age dating diamonds, which cannot be tested directly by standard dating methods. Photo courtesy of Dr. S. H. Richardson.

diamonds, by means of the relatively new samarium-neodymium (Sm-Nd) geochronological method combined with the rubidium-strontium (Rb-Sr) technique. Table 1 summarizes these results along with more recent data (Richardson, 1986; Richardson et al., 1990) on diamonds from several other pipes in southern Africa and Australia. (For a discussion of some earlier studies that have a bearing on the dating of inclusions in diamonds, see Meyer, 1985, and Gurney, 1989.)

The results presented in table 1 may well be the most striking information about diamonds to emerge in the past decade, not only because they put accurate ages on diamonds in millions of years (My) but also because of other implications, as discussed below:

1. Diamonds are old and may have been forming continually, certainly intermittently, throughout most of earth's history. The 2,300 My period between ~3,300 and 990 My represents about half of the earth's 4,500 My existence, and inclusions in diamond may yet be found that extend this range.
2. Diamonds are usually very much older than the kimberlite that brought them to the surface. For example, diamonds from the Kim-



Figure 3. Trigons, which are typical of a diamond octahedron, can be seen on the face of this flattened inclusion of pyrope garnet, with a colorless enstatite (orthopyroxene) or olivine crystal at the end. These features are taken as evidence that the diamond has forced its crystal habit on the guest mineral during the simultaneous crystallization of inclusion and host. Photomicrograph by Eduard J. Gübelin; transmitted illumination, magnified 50 \times . From Gübelin and Koivula (1986, p. 95).

berley pipe are as much as 3,200 My older than the age of kimberlite emplacement (i.e., when the pipe reached the surface, about 100 My ago). This example implies that: (a) diamonds can be stored deep within the earth for an extended period of time before being carried to the surface by the kimberlite; and (b) kimberlite is merely the transporting medium for bringing diamonds (as well as other materials) to the surface. This process has been picturesquely described by the analogy of an elevator or a bus (the kimberlite) picking up passengers (diamonds) in the earth's mantle along its route of ascent toward the surface. Note, though, that there is no resolvable age difference between the diamonds and kimberlite emplacement at the Premier mine. This suggests that, in this example, they may be contemporaneous. Whether the Premier mine is unusual awaits the determination of diamond ages from additional localities.

3. In samples from the Finsch mine, two ages—~3,300 and 1,580 My—have been obtained, the former for peridotitic, and the latter for eclogitic, inclusions. These two main types of inclusions in diamond are discussed in greater detail below. The presence of diamonds of different ages within one pipe can, for the present, most easily be explained by the fact

that kimberlites may obtain their diamonds from more than one geologic environment (mantle source) during their rise toward the surface.

- The data reported in table 1 have settled a long-standing debate in which scientists advocated one of two hypotheses with respect to the origin of diamonds. The "phenocryst school" maintained that diamonds originally formed at depth from the crystallization of a kimberlite magma (molten mass) and, hence, are genetically related to the magma and are *phenocrysts* (def: a relatively large crystal set in a fine-grained groundmass to which it is genetically related [Gk. *pheno*: to show + *cryst*{al}]). The "xenocryst school," on the other hand, believed that diamonds were formed prior to the intrusion of kimberlite, are not genetically related to it, and are merely accidental inclusions known as *xenocrysts* (def: a crystal or a fragment of a crystal included in a magma and not formed by the magma itself, i.e., foreign to it [Gk. *xeno*: strange, foreign + *cryst*{al}]). In view of the newly confirmed fact that diamonds are, in general, much older than their kimberlite (or lamproïte) host rocks, the xenocryst theory is now known to be correct. The data from the Premier mine (diamond and kimberlite are the same age) could be the result of an extremely short interval between the formation of dia-

mond at an extraneous source and its capture by the Premier kimberlite.

Although the concept that diamonds are xenocrysts in kimberlite was proposed as early as 1905, it was not until the Third International Kimberlite Conference, held in France in 1981, that "there was a realization that diamonds are xenocrysts in kimberlites" (Mitchell, 1986, p. 8). The proof, however, has come only since 1984, with the work of Richardson and his associates on the age of diamonds and their host rocks (table 1).

In summary, recent geochronological studies clearly show that most diamonds: (a) are much older than the volcanic rocks (kimberlite and lamproïte) that carried them to the surface; (b) are not genetically related to these volcanic rocks; and (c) have crystallized, possibly episodically, during a large part of earth's history. Further, it must be emphasized that it is the ability to date mineral inclusions separated from diamonds, which has only existed during the last decade, that has made age dating of diamonds possible. This is further evidence that mineral inclusions have great scientific value in addition to their gemological importance.

ORIGIN OF DIAMONDS

The study of the origin (genesis) of diamond ideally involves the collection, assimilation, and interpretation of a vast amount of data from many

TABLE 1. Ages of diamonds and emplacement of associated kimberlite^a pipes in My (millions of years), and type of inclusions.

Location (mine)	Age of diamonds (My)	Age of emplacement of kimberlite ^a pipe (My)	Type of inclusions in diamonds	Reference
Kimberley, South Africa	~3,300	~100	Peridotitic	Richardson et al. (1984)
Finsch, South Africa	~3,300	~100	Peridotitic	Richardson et al. (1984)
Finsch, South Africa	1,580	~100	Eclogitic	Richardson et al. (1990)
Premier, South Africa	1,150	1,100–1,200	Eclogitic	Richardson (1986)
Argyle, Australia ^a	1,580	1,100–1,200	Eclogitic	Richardson (1986)
Orapa, Botswana	990	~100	Eclogitic	Richardson et al. (1990)

^aIn the case of the Argyle sample, the pipe is a lamproïte.



Figure 4. Boulder-size xenoliths of eclogite, which frequently contain diamonds, are seen here at the Roberts Victor mine, near Kimberley, South Africa. Study of xenoliths such as these, which were brought up from the earth's mantle (depth at least 150 km) by kimberlite, enable scientists to determine pressure-temperature (P-T) conditions within the mantle and, by analogy, P-T conditions for the formation of diamonds.

disciplines related to the physical, chemical, and mineralogic properties of diamonds, the rocks in which they crystallize, as well as the rocks that brought them to the surface and in which they now are found as primary deposits. Clearly, such a broad survey is beyond the scope of this article. Therefore, we will focus on those aspects of diamond genesis that are of the greatest interest to gemologists, particularly those in which major advances have been made in the past decade. Such topics include: (1) the types and properties of rocks in which diamonds form; (2) the pressure-temperature conditions under which diamonds crystallize within the earth; and (3) the source of the carbon of which diamond is composed.

Rocks in Which Diamonds Form. Now that it has been established that kimberlite and lamproite are only the transporting mechanisms for bringing diamonds to the surface, and are not genetically related to diamond, the question that must be answered is: From what type of magma or pre-existing material do diamonds actually crystallize? The two most rewarding areas of investigation in which answers to this question have been found are: (1) the study of diamond-bearing xenoliths, and (2) the study of mineral inclusions within diamonds.

Diamond-bearing Xenoliths. A *xenolith* can be defined as a rock fragment that is foreign to the igneous mass in which it occurs [Gk. *xeno*:

strange, foreign + *lith*: stone, rock]. Xenoliths are not formed from the magma itself; rather, they become included in the magma as it rises. Xenoliths may be as small as a single crystal, boulder size (figure 4), and even much larger (figure 5).

Xenoliths in kimberlites and lamproites represent fragments of wall rock adjacent to an intrusion that have broken off and been incorporated into the magma as it works its way along fractures or cracks to the surface. Thus, xenoliths may represent blocks of buried crustal formations brought closer to the surface, such as metamorphic rocks derived from deep-seated terrains within the earth's lower crust, or sedimentary rocks in the upper crust and, perhaps most importantly, rocks believed to be derived from the earth's upper mantle. Kimberlites and lamproites are the only means of obtaining samples of such deep rock types.

Xenoliths are usually rounded, especially if they originate at great depths, probably because of chemical dissolution at the margins of the fragments (e.g., figure 4), but they are likely to be angular if they originate from shallow wall rocks. Xenoliths that contain diamonds are extremely important because they permit us to determine the characteristics of the rock types from which diamonds crystallize. Such characteristics include chemical composition, pressure-temperature reg-

Figure 5. This rounded xenolith of sandstone, about 2 m in its longest dimension, is an example of rock broken off from the walls of the conduit along which the kimberlite magma ascended to the surface. As sandstone is characteristic of the upper part of the earth's crust (generally found within 10 km of the surface), this xenolith will not contain diamonds. Exact location unknown (probably South Africa).





Figure 6. Altered olivine and other magnesium-rich minerals (a "kelyphite" rim) surround this 8-cm-long xenocryst of garnet. The alteration resulted from reaction with kimberlite fluids. Chemical reactions, along with fragmentation by physical forces, tend to break up xenoliths, especially those of the peridotite type, releasing xenocrysts of diamond. From the Monastery mine, South Africa.

ime, the nature of any volatiles (e.g., CO_2 , H_2O) present, and other parameters pertinent to deciphering the genesis of diamonds. Eclogites and peridotites are the predominant xenoliths found to contain diamonds (see box A for details of the mineralogy, chemistry, and classification of these two rock types).

During transportation of both peridotitic and eclogitic xenoliths within kimberlite or lamproite, fragmentation of the xenoliths may take place, adding smaller xenoliths or even xenocrysts to the transporting magma; this is probably the best way to explain the occurrence of diamond xenocrysts, as well as single crystals of other minerals (e.g., garnet, chromite), in kimberlite and lamproite rocks. It is also important to recognize that xenoliths in kimberlite and lamproite do not always represent with fidelity the mineralogy and pressure-temperature conditions of the mantle in which they are supposed to have formed, because extensive modification may take place as they react chemically with the fluids in the transporting magmas (figure 6). Inclusions, however, are shielded from extraneous influences by the surrounding diamond, so the conditions of formation they indicate are considered better representations of the actual mantle conditions in which diamonds formed. By comparing inclusion and xenolith compositions, scientists are confident that they can recognize altered vs. unaltered compositions in their study of eclogites and peridotites.

Eclogite is a coarse-grained ultramafic rock consisting essentially of a granular aggregate of red

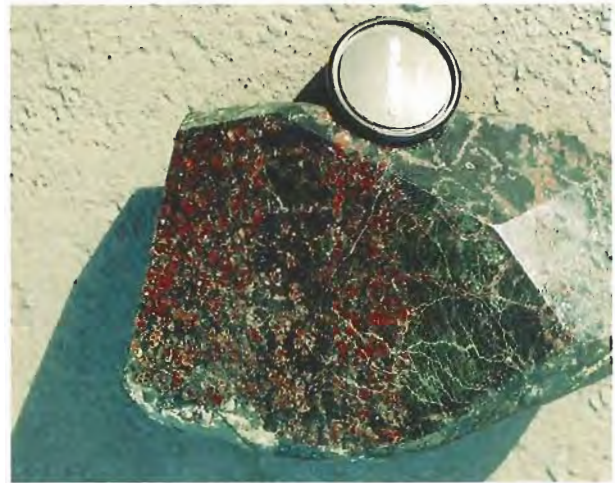
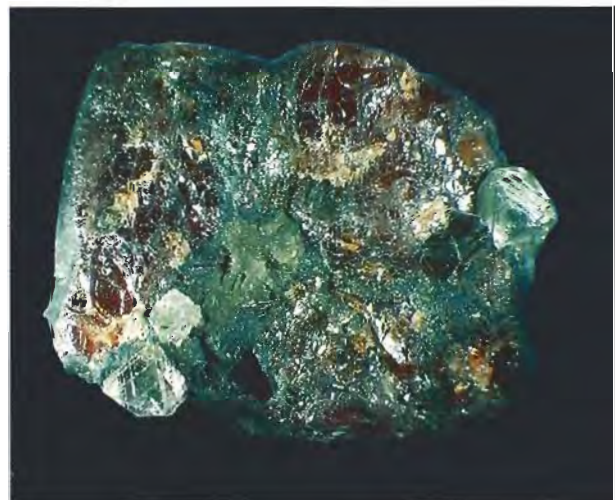


Figure 7. The polished surface of this eclogite xenolith specimen displays the pyrope-almandine garnet (red mineral) and clinopyroxene (green) that are its chief components. From the Roberts Victor mine, near Kimberley, South Africa.

garnet (almandine-pyrope) and green pyroxene (technically jadeitic clinopyroxene or a solid solution between jadeite and diopside), with minor amounts of rutile, kyanite, corundum, and coesite (figure 7). Eclogite is indicative of a high pressure-high temperature (with emphasis on the former) environment, consistent with that in which dia-

Figure 8. Diamonds protrude from the surface of this broken eclogite xenolith obtained from the Ardo-Excelsior mine, South Africa. Such samples, corroborated by experimental studies in which the pressure-temperature conditions required for the formation of garnet and clinopyroxene are taken into account, are considered evidence that diamond may crystallize as a primary constituent of an eclogite.



BOX A: CLASSIFICATION AND NOMENCLATURE OF IGNEOUS ROCKS

The subdivisions of igneous rocks named in figure A-1 are those used by most geologists. Of special significance in this review article are the terms *mafic* and *ultramafic*, because kimberlite, peridotite, and eclogite are ultramafic rocks. The term *mafic* (from *magnesium* and *ferric* [iron]) is used to describe a rock composed chiefly of one or more iron-magnesium (ferro-magnesium) dark-colored minerals such as py-

roxene, amphibole, and olivine. Typically a rock of this type will have 42–52 wt.% SiO₂ and 16–26 wt.% combined FeO and MgO. Basalt (extrusive or volcanic) and gabbro (intrusive or plutonic) are the most common mafic rocks. The term *ultramafic* is applied to a rock with even lower SiO₂ than a mafic rock (we use the division at 42 wt.%) and, by analogy, even higher FeO and MgO. These rocks are composed of

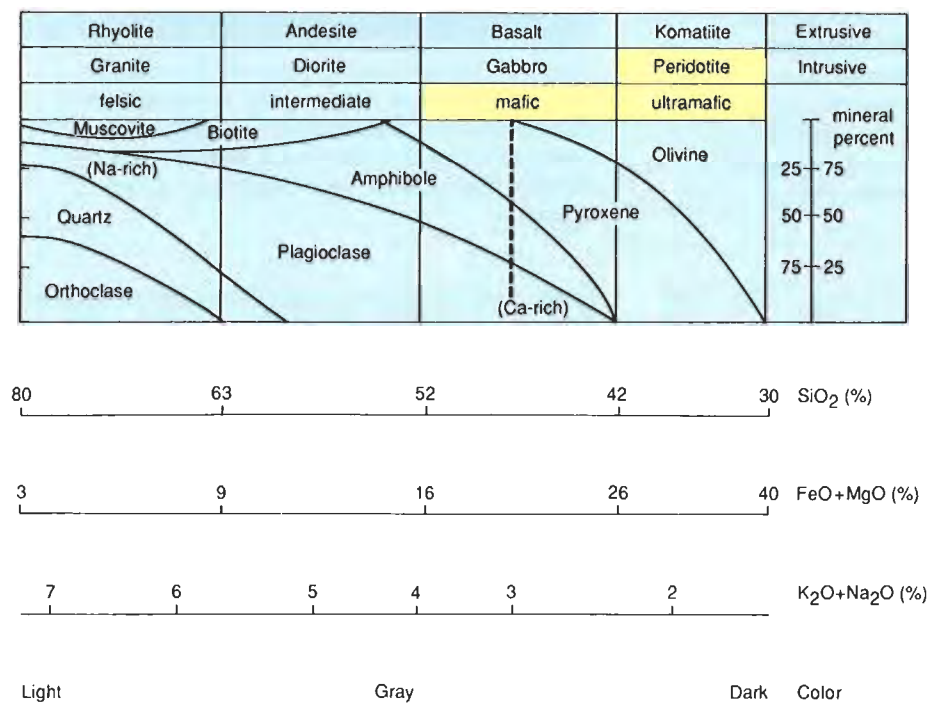


Figure A-1. This illustration shows the mineralogic compositions, selected chemical changes, and changes in color associated with the common extrusive and intrusive igneous rocks. The center of each vertical column represents the average mineralogic and chemical compositions of each rock. For example, the average basalt (see vertical broken line) would have about 48 vol.% pyroxene, 28 vol.% amphibole, 24 vol.% calcium-rich plagioclase, and a trace of olivine. A chemical analysis would yield about 47 wt.% SiO₂ and 20 wt.% FeO + MgO.

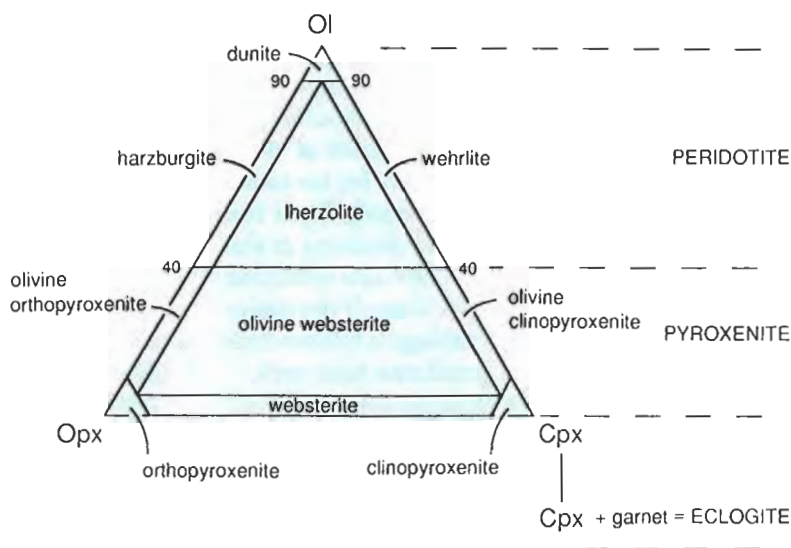
monds form (figure 8). Typically, eclogite occurs in deep crustal metamorphic regions below continents; it became eclogite by means of solid-state (metamorphic) transformation of previously existing rock, probably basalt. Eclogite found in the mantle probably forms in the same way, through subduction of crustal rocks (discussed below). As an aside, in its own right unaltered eclogite could well be considered a gem material because of the combination of two very attractive gem minerals (again, see figure 7).

Peridotite is a general term for a coarse-grained ultramafic rock consisting chiefly of olivine with or without other mafic (high in Fe and Mg) minerals, such as pyroxenes (again, see box A). Garnet and spinel frequently occur in small

amounts. Peridotite is believed to be the most common and abundant rock type in the earth's mantle. Most peridotitic diamonds are formed in garnet-bearing harzburgite, with minor amounts formed in lherzolite (Gurney, 1989).

Following our practice of illustrating important concepts and features, such as eclogite xenoliths (figures 4, 7, 8), we would like to show a photograph of a diamondiferous peridotite xenolith, but such xenoliths are extremely rare and are typically extensively altered. Whereas over 100 diamond-bearing eclogites have been described in detail in the literature, there are probably fewer than 20 comparable descriptions for diamondiferous peridotite xenoliths. This is most remarkable, since harzburgite is probably the source of

Figure A-2. This classification scheme for ultramafic (intrusive) rocks, recommended by a Committee of the IUGS (International Union of Geological Sciences), is based on the proportions of olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx). The apexes of the triangle represent 100% each of the above-mentioned minerals. Most diamonds found in rocks broadly called peridotite are actually from rocks more accurately classified as harzburgite (see text for details). Eclogite is actually a specific case of clinopyroxene plus garnet, as is shown at the lower right corner of the diagram.



olivine and pyroxene, usually together as in peridotite, but each may constitute a rock on its own: dunite and pyroxenite, respectively.

The ultramafic rock peridotite is particularly important in gemology both because it is one of the two rocks from which diamonds crystallize (eclogite is the other) and because it is the rock from which melts of kimberlite and lamproite (the two rock types that transport diamonds to the surface) originate.

From figure A-2, however, we see that there are two broad categories of ultramafic rocks, peridotites and pyroxenites. The classification of a rock as peridotite or pyroxenite depends on the volume percentages of the mafic minerals olivine and pyrox-

ene. That is, peridotite must contain more than 40 vol.% olivine (Ol), with the remainder orthopyroxene (Opx) and/or clinopyroxene (Cpx). Peridotite, in fact, is actually a general name that includes the more specific rock types dunite, harzburgite, lherzolite, and wehrlite, the distinction between them being the relative proportions of Ol, Opx, and Cpx. For example, dunite must contain at least 90 vol.% olivine, with Opx and Cpx combined providing the remaining volume percentage. Harzburgite, the variety of peridotite from which many diamonds crystallize, contains 40–90 vol.% olivine, 5–60 vol.% orthopyroxene, and not more than 5 vol.% clinopyroxene. As the diagram indicates, eclogite is actually clinopyroxene plus garnet.

most of the diamonds in kimberlite (discussed in detail in the next section). Clearly, diamond-containing peridotite xenoliths must have been disaggregated by some incredibly efficient process. Several mechanisms have been proposed to explain this phenomenon, based mainly on laboratory experiments involving the gases CO₂ and H₂O, which are likely to be found in the mantle. It has been suggested that these gases are released following certain mineral reactions (e.g., the breakdown of dolomite, for CO₂) within the peridotite area of stability in the mantle, resulting in the self-destruction of diamondiferous peridotite xenoliths [Gurney, 1989, p. 957].

Mineral Inclusions in Diamond. The study of

mineral inclusions in diamonds has been greatly aided by the advent of new analytical techniques, which have resulted in major discoveries during the past decade. As every gemologist knows, even those "large inclusions" that can be seen with the naked eye in diamonds classified as I₂ or I₃ are very small indeed. Yet, such instruments as the electron microprobe and the even more recent ion microprobe now make it possible to analyze chemically minerals and rock fragments as small as one micrometer (μm, one millionth of a meter). Other analytical techniques, such as Raman spectroscopy and X-ray diffraction, permit the identification of minerals while they are still within the diamond but cannot provide chemical data.

The subject and importance of mineral inclu-

sions in diamonds have been reviewed comprehensively by Meyer (1987) and by Gurney (1989). As was explained above in connection with the dating of diamonds, the assumption is made that in order for most minerals (e.g., garnet) or aggregates of minerals (e.g., eclogite or peridotite) to be included within another mineral (e.g., diamond), both the inclusion and host must have been forming at the same time and place. Therefore, we can conclude that both have a common origin. Thus, if the inclusions are of the peridotitic assemblage it follows that the diamond formed within peridotite host rock.

Most of the mineral inclusions in diamond are very small ($\sim 100 \mu\text{m}$) and usually are composed of just one mineral (monomineralic); however, bi-mineralic and polymineralic inclusions do occur. The multiphase mineral inclusions are particularly important not only in determining peridotitic or eclogitic origin, but also because analyses of the chemical and physical properties of two or more coexisting minerals enable us to estimate the pressure and temperature environments in which they and, by analogy, the host diamond formed.

In total, 22 contemporaneously formed (syngenetic) minerals have been found as inclusions in diamond, including diamond itself (Gurney, 1989). Six of these occur in both the peridotitic and eclogitic assemblages: olivine, orthopyroxene, clinopyroxene, garnet, chromite, and sulphides (e.g., pyrrhotite). Four other minerals – rutile, ky-

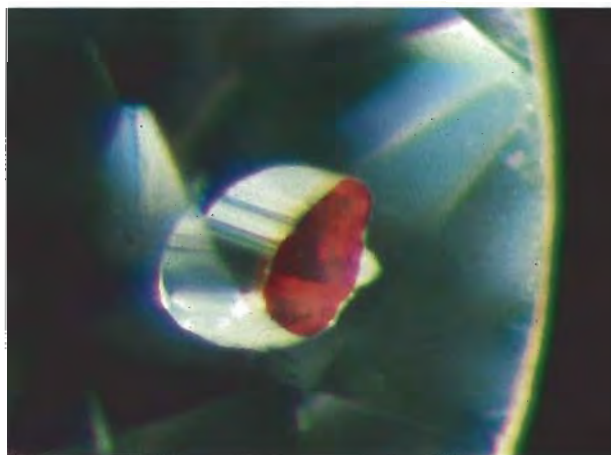
anite, corundum, and coesite – are minor constituents characteristic only of the eclogitic assemblage (figure 9). The remaining 11 minerals are so rare that they need not be considered here. Unfortunately, inclusions in diamonds cannot be used to determine geographic origin, as is frequently possible with colored stones (Gübelin and Koivula, 1986, p. 88).

Detailed chemical studies of the most important minerals listed above have made it possible to characterize with confidence 98% of all included diamonds as peridotitic (mainly harzburgite) or eclogitic (sometimes referred to, respectively, as "P-type" and "E-type" diamonds). The minerals in one type of mineral assemblage chemically will not be the same as those in the other type; that is, they are mutually exclusive. The only exception would be the very rare case in which the diamond began to grow in one environment (e.g., eclogitic) and then was moved and later continued to crystallize in a different environment (e.g., peridotitic). However, both P- and E- type diamonds may be found within the same kimberlite pipe, indicating that the pipe sampled at least two different "diamond source areas" en route to the surface.

A logical question could be raised concerning the categorization of a diamond as P- or E-type if the inclusion consisted of a single mineral, say, garnet, that is common to both types of occurrences. This matter may be resolved by determining the chemical composition of that inclusion (see figure 10). For example, the ideal formula for a pyrope-almandite garnet would be a mixture of both garnet types; that is, both Mg and Fe can substitute in the silicate structure so that the formula for any specific garnet in this series could be written as $(\text{Mg, Fe})_3\text{Al}_2\text{Si}_3\text{O}_{12}$. However, from figure 10 it can be seen that the relative proportions of Fe and Mg and minor Ca in garnet differ, characteristically, for both the P- and E-types of diamond associations; specifically, P-type garnets have higher Mg and lower Fe than do E-type garnets. Other inclusions in diamond (e.g., olivine, orthopyroxene) can be classified by similar analytical methods. Returning briefly again to garnet, experienced individuals can accurately distinguish between the two types on the basis of color. The pyrope type is typically purple-red whereas almandine is usually orange-red.

As discussed earlier, diamondiferous xenoliths of the E-type are relatively abundant, whereas diamondiferous P-types are very rare. Yet P-type

Figure 9. This ruby is the first definitely identified as an inclusion in diamond. It proves that the diamond is of eclogitic origin. Photomicrograph by Eduard J. Gübelin; darkfield illumination, magnified 100 \times . From Gübelin and Koivula (1986, p. 97).



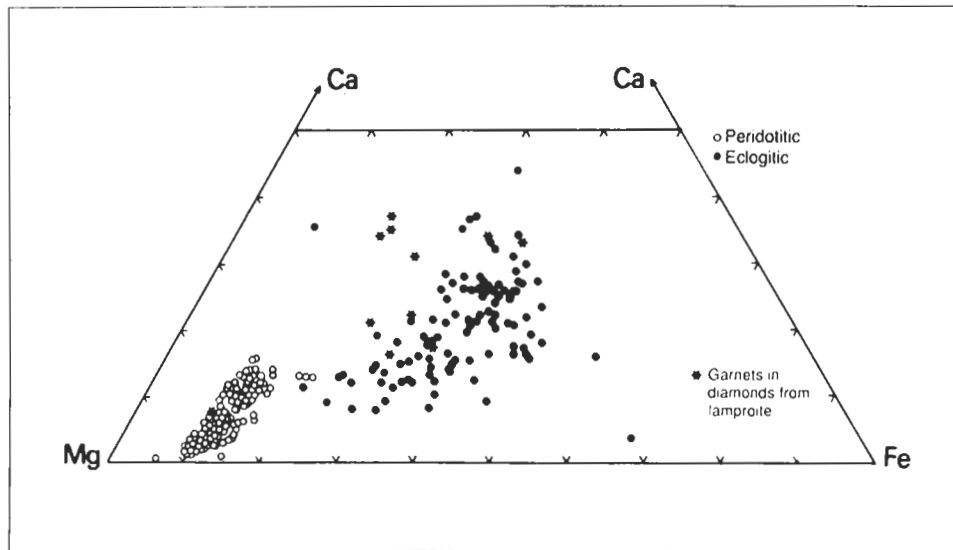


Figure 10. This plot shows the relative abundances of calcium (Ca), magnesium (Mg), and iron (Fe) in garnet inclusions from diamonds worldwide. Peridotitic garnets are much higher in Mg, and lower in both Fe and Ca, than garnets from eclogites. Although not shown, peridotitic garnets are higher in chromium than eclogitic garnets; the latter also have minor, but characteristic, sodium, that is, >0.09% Na₂O. (Adapted from Meyer, 1987.)

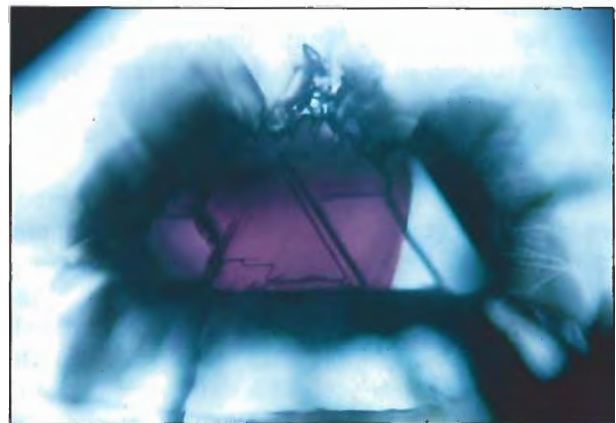
inclusions are much more common than the E-type. It is clear that once mineral inclusions are encapsulated within diamond, they are protected from reactions with the surrounding magma, or from disaggregation, as occurs with the diamondiferous peridotite xenoliths. Therefore, it seems logical to accept the relative abundances of P-type and E-type assemblages that occur as inclusions in diamonds as most representative of their relative proportions and, by analogy, the relative importance of each rock type as the source material from which diamonds originate. Although various scientists will propose different proportions, we believe that peridotite-type inclusions outnumber the eclogite type by a ratio of 3:1. P-type diamonds are particularly more abundant in smaller sizes.

Pressure-Temperature Conditions in Which Diamonds Form. A knowledge of the pressure and temperature (P-T) regime in which diamonds crystallize is essential for determining the geologic origin of diamonds. *Geobarometry* is the discipline in geology that employs methods, such as the analysis of pressure-indicative minerals, to determine the pressure under which a mineral or rock formed. For example, the presence of coesite, known to be a high pressure form of SiO₂ (quartz, at low pressure), yields important information regarding pressure conditions. *Geothermometry* is the discipline concerned with the temperature of formation of similar materials.

Both of these disciplines depend heavily on experimental laboratory procedures, such as the synthesis of specific minerals under carefully controlled pressure-temperature conditions, to simulate natural situations. Again, the inclusions

in diamonds are valuable in this research. In some cases, the analysis of a single inclusion for just one chemical element is sufficient. In other cases, particularly in geothermometry, several co-existing and touching mineral phases ideally should be present in the diamond (figure 11). For a variety of reasons, assumptions usually are made and the results sometimes lack the desired precision. (Technically, the temperatures and pressures determined are those that existed when the mineral systems were last in equilibrium, which may not

Figure 11. A purple chrome pyrope garnet and a colorless pyroxene have united to form a trapeze in the host diamond. This bimineralic inclusion lies parallel to an octahedron face. Co-existing and touching mineral phases such as these are ideal for geothermometry studies. Photomicrograph by Henry O. A. Meyer; bright-field illumination, magnified 40×. From Gübelin and Koivula (1986, p. 95).



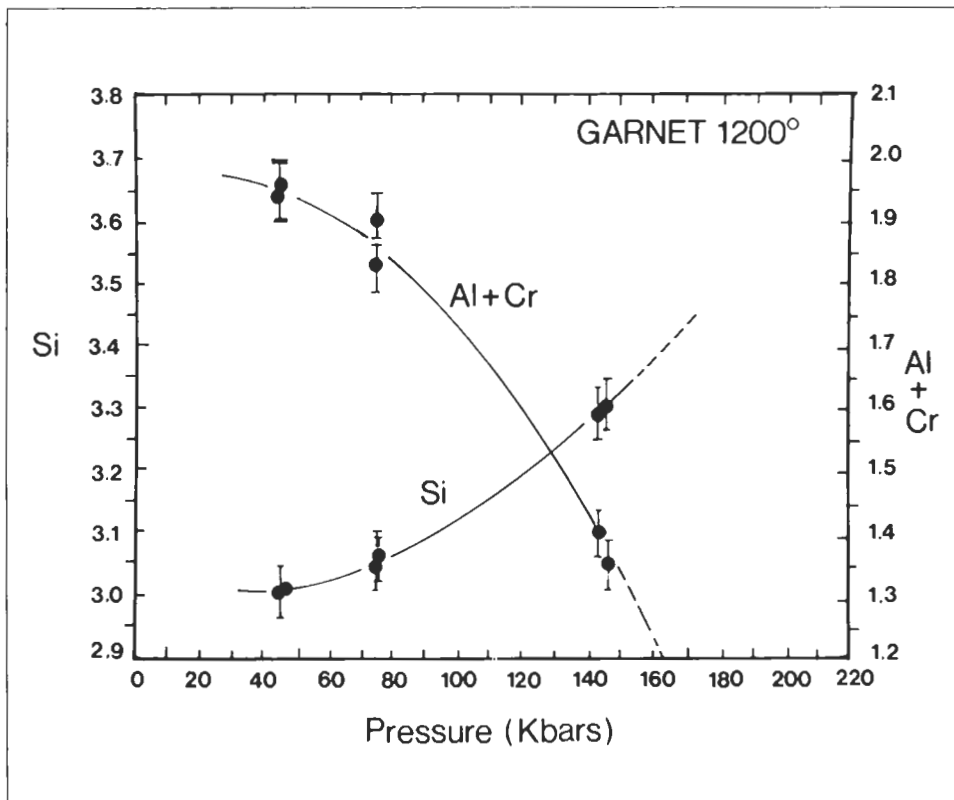


Figure 12. This diagram shows how increasing silicon (Si) and decreasing aluminum (Al) + chromium (Cr) are accommodated in the structure of garnet (which crystallizes at 1200°C) with increasing pressure (kbars). (Units are in atoms per unit cell.) Studies such as this enable the determination of pressure-temperature conditions for inclusions in diamonds at the time of formation. For example, if a garnet contains 3.0 atoms per unit cell of Si, and 1.95 atoms per unit cell of Al + Cr, it crystallized at a pressure of about 45 kbars. Data are from eclogitic garnet inclusions in diamonds from the Monastery mine, South Africa (Moore and Gurney, 1985).

agree precisely with the temperature and pressure of diamond formation.)

Examples of the types of minerals used, and elements determined, for geobarometry include: (a) aluminum substitution in orthopyroxene (enstatite) co-existing with garnet, (b) potassium substitution in clinopyroxene, and (c) sodium substitution in garnet. In all of these cases, elevated amounts of Al, K, and Na are indicative of high pressures. Examples of geothermometry include methods based on: (a) the partitioning (relative proportions) of the Ca and Mg contents of co-existing orthopyroxene (enstatite) and clinopyroxene (diopside), (b) the relative abundances of Fe and Mg in these same pyroxenes, and (c) the relationship between Fe and Mg in coexisting garnet and orthopyroxene. In figure 12, we illustrate how the pressure at the time of formation of an eclogitic garnet inclusion within a diamond can be determined.

There have been many determinations made in the past decade of the pressures and temperatures at which mineral inclusions in diamond crystallized (see, e.g., Ross, 1989). Meyer (1985) has evaluated these and concluded that in the peridotitic type of inclusions the temperature of crystallization ranged from 900° to 1300°C and pressure from 45 to 60 kbar. At 30, 50, and 60 kbar the

approximate depths within the earth are 100, 150, and 200 km, respectively. Eclogitic-type inclusions fell within the same temperature range, but it was not possible to estimate their pressure of formation. Considering the rate at which temperatures increase with depth (geothermal gradient) under continental areas, as well as the corresponding increase in pressure, the estimated depth of formation of P-type diamonds is in the range 150–200 km, which is within the upper mantle. E-type diamonds appear to have higher temperatures of crystallization and to form at greater depths than do P-types. In fact, based on geobarometry, Moore and Gurney (1985) have shown that E-type diamonds in at least one South African mine (Monastery) have origins that may be deeper than 300 km, but still within the upper mantle. It must not be assumed, however, that all E-type diamonds originate from such depths.

Sources of Carbon in Diamond. The source of the carbon from which diamonds form has been a subject of interest and controversy for over a hundred years; suggestions have ranged from coal in the 1800s to carbon dioxide and methane today (see Janse, 1984, and Meyer, 1985, for the historic aspects). It is now generally agreed that there are two sources of carbon, as determined by stable

carbon isotope studies, specifically the ratio of carbon-13 to carbon-12. For the sake of convenience, these ratios are reported as "delta values" and specifically, in the case of the carbon isotopes, as $\delta^{13}\text{C}$. (Technically, a delta value is the difference between the isotope ratio in a sample and that in a standard, divided by the ratio in the standard, and expressed in parts per thousand.)

A plot of the $\delta^{13}\text{C}$ of several hundred diamonds, from many geographic locations as well as from both eclogitic and peridotitic origins, is presented in figure 13. Inspection of this figure will show a shaded area in the narrow range of -2 to -9 $\delta^{13}\text{C}$, with a peak between -5 and -6 $\delta^{13}\text{C}$. This is the area in which almost all peridotitic diamonds will plot. Although the $\delta^{13}\text{C}$ of many eclogitic diamonds will also plot in this narrow range, others will plot elsewhere on the diagram; they are not confined to the narrow range. These important data in figure 13 have been interpreted to imply that there are at least two carbon sources for diamonds: The peridotitic source, with few exceptions, is characterized by the narrow $\delta^{13}\text{C}$ range of -2 to -9 , whereas the eclogitic source may have any $\delta^{13}\text{C}$ value between $+3$ and -34 . In addition, detailed studies of the distributions of the populations have shown that there frequently are specific associations at specific localities. For example, at the Roberts Victor mine in South Africa, the eclogitic diamonds have two different $\delta^{13}\text{C}$ values of about -16 and about -5 , which suggests two different eclogitic source areas for the carbon in these diamonds. The question arises, then: What are the major sources of carbon, that is, for the peridotitic and eclogitic diamonds?

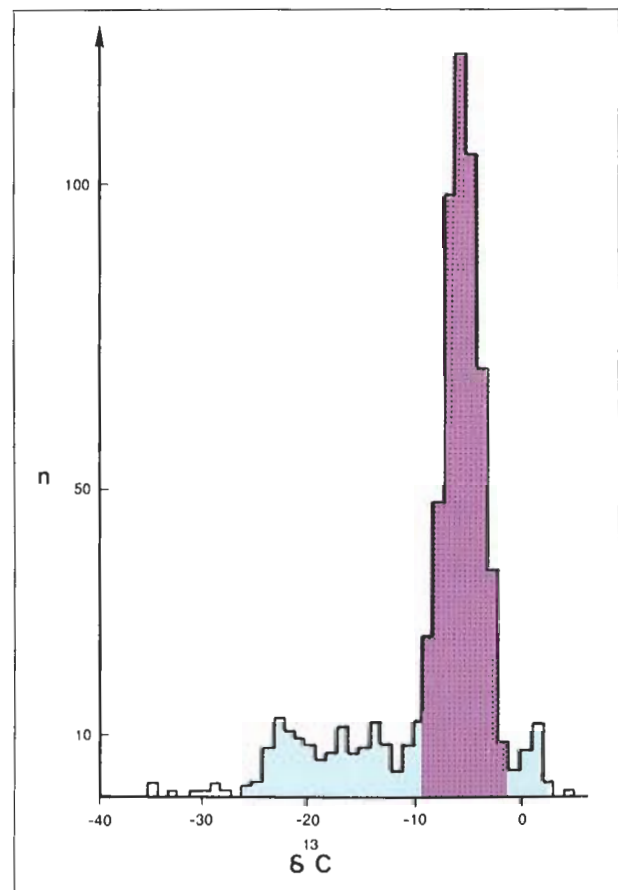
Peridotitic diamonds are believed to have a carbon source that is derived from a homogeneous (because of the narrow range of $\delta^{13}\text{C}$ values) con-
 ducting zone within the upper mantle. This carbon may have been one of the original components of primitive earth that accumulated in the mantle perhaps 4,500 My ago, became well mixed through convection, and then remained in place until it crystallized into diamond within peridotite.

Eclogitic diamonds are a different story because of the broad range of $\delta^{13}\text{C}$ values. The $\delta^{13}\text{C}$ values for the carbon in carbonate minerals (e.g., calcite) and hydrocarbons span the range of $+3$ to -34 . These values are identical to those found in eclogitic diamonds and are the basis for the theory that the carbon in such diamonds originates in material brought from the earth's near-surface

environment by subduction to the depths (>150 km) necessary for the formation of diamonds.

Eclogites have a bulk chemical composition that is virtually identical to that of basalt, but the minerals comprising basalts (primarily the clinopyroxene augite and Ca-rich plagioclase feldspars; see box A) are different from those of eclogites (that is, garnet and the clinopyroxene omphacite) because of the different pressure and temperature environment in which the latter crystallize. Eclogites are formed at higher pressures

Figure 13. The distribution of carbon isotope ratios, $\delta^{13}\text{C}$, in diamonds from many geographic locations and from both eclogitic and peridotitic rock origins is illustrated here. The shaded region, with $\delta^{13}\text{C}$ values of -2 to -9 , is the range for diamonds from peridotitic assemblages; eclogitic values may range anywhere from $+3$ to -34 (including the peridotitic range). The letter n indicates the number of samples. See text for further details. From Gurney (1989).



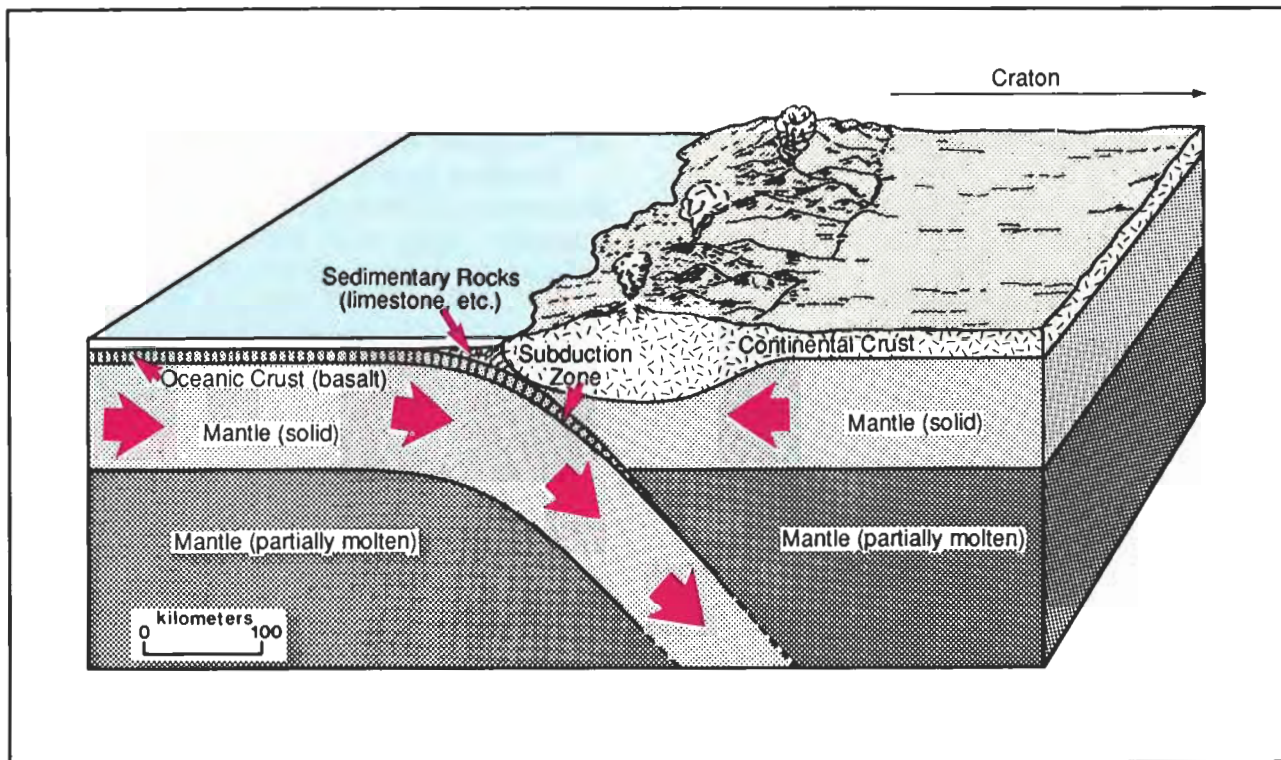


Figure 14. The theory of plate tectonics explains how the earth's solid outer portion (the lithosphere) is divided into a number of rigid thin segments (plates) which move in various ways including downward at certain boundaries, particularly where continents collide. This figure illustrates an oceanic basaltic plate being moved downward (subduction) into a region of higher pressures and temperatures below a craton (a part of the earth that has been stable for a long time; includes continental shields and platforms). Carbon present within the plate in the form of limestone (calcite) or other carbonate-bearing rocks, or as hydrocarbons (including organic remains), could be the source of this element (carbon) for diamonds formed in eclogite. (Vertical scale is exaggerated.)

relative to basalt during and following certain earth movements and mountain building (tectonic) events; basalts caught up in such tectonic processes may recrystallize into high-pressure eclogite. But, could eclogite within the earth's mantle, at depths of 150 km and greater, also represent basalt that has been converted to eclogite?

When continents collide, basalt, which is the main rock type in the oceanic basins, is pushed down beneath the continents by a process called subduction, into regions of higher pressures and temperatures (figure 14), where it eventually can be converted to eclogite. Carbon, in the form of limestone (calcite) or other carbonate rocks, or in the form of hydrocarbons (e.g., organic matter such as bacteria, algae), may have been included in the subducted slab and thus could be the source material for eventual conversion to diamond.

EMPLACEMENT OF DIAMONDS

To understand the emplacement of diamonds near the surface of the earth, we need to consider the following topics:

- ◆ What rocks did the emplacement
- ◆ Where emplacement occurred
- ◆ When emplacement occurred
- ◆ How emplacement occurred

What Rocks Did the Emplacement. We have referred repeatedly to the fact that diamonds were carried to the surface (i.e., emplaced) by kimberlite and lamproite. To understand this emplacement mechanism, it is important to understand the similarities, differences, and relationships between kimberlite and lamproite.

The most accurate definition available of the rock called kimberlite is presented in box B. For the

BOX B: WHAT IS KIMBERLITE?

One would think that the meaning of the term *kimberlite* would be well understood and that it would have a universally accepted definition. However, although *kimberlite* was first introduced over a hundred years ago, based on descriptions of the diamond-bearing pipes of Kimberley, South Africa, there is still no unanimity on its definition (see, e.g., Glover and Harris, 1984; Clement et al., 1984; and Mitchell, 1989).

The problem stems, in part, from the fact that a satisfactory definition of *kimberlite* must take into account mineralogic composition, chemical composition, texture, and origin. This is a difficult task, indeed.

Most kimberlite professionals now accept the definition of Clement et al. (1984, pp. 223–224), but it is very complex. For a gemological audience, the definition of Dawson (1984, pp. 104–105) is instructive and, in its imaginative presentation, illustrates the complexity of defining kimberlite satisfactorily:

"In short, KIMBERLITE IS A HYBRID ROCK, comprising:

FRAGMENTS OF HIGH-T [temperature]
PERIDOTITE AND ECLOGITE

plus
MEGACRYSTS

which have reacted with
RELATIVELY LOW-T, VOLATILE-RICH MATRIX
and, during and after intrusion, with
HIGH-LEVEL GROUNDWATER
and in many diatreme-facies kimberlites

there is variable input of
WALL ROCK MATERIAL [e.g. basalt, gneiss, shale]"

[The following terms mentioned above and not previously explained are briefly defined. *Megacryst*: coarse single crystal; nongeneric term for a phenocryst or xenocryst. *Matrix*: groundmass, finer grained than megacrysts. *Diatreme*: a general term for a volcanic pipe that is emplaced in rocks by a gaseous explosion and is filled with angular broken fragments called breccia.]

Dawson uses the term *hybrid* in this explanation because kimberlite contains a mixture of (foreign) xenoliths (peridotite, eclogite, and other rock types) and xenocrysts (diamonds and others) in addition to the normal crystallization products from the kimberlite magma.

We offer the following simpler, though less precise, definition which augments that of Dawson (1984):

Kimberlite is a hybrid, volatile-rich, potassic, ultra-

mafic igneous rock derived from deep in the earth (>150 km below the surface) which occurs near the surface as small volcanic pipes, dikes, and sills. It is composed principally of olivine (both as phenocrysts and in groundmass), with lesser amounts of phlogopite, diopside, serpentine, calcite, garnet, ilmenite, spinel, and/or other minerals; diamond is only a rare constituent.

Use of the adjectives "volatile-rich, potassic, ultramafic" to describe kimberlite indicates that there is an important and characteristic chemical signature for this rock. *Volatile-rich* (readily vaporizable, gaseous) refers to the high contents of CO₂ (8.6% average, mostly in calcite) and H₂O (7.2% average, in serpentine and phlogopite), in kimberlites. The average potassium content (K₂O = 0.6%–2.0%) is high for an ultramafic rock, whereas the average SiO₂ content (25%–35%) is extremely low for an igneous rock. In the case of kimberlite, Fe₂O₃ averages 12.7% and MgO, 23.8%. (All of the preceding values are from Mitchell, 1989, p. 35 and analysis 10, table I, p. 36.) Although not mentioned, or even implied, in this definition, there are also unusually high concentrations, for ultramafic rocks, of certain nonessential elements found in small quantities (i.e., "trace elements"). Examples are niobium (Nb), zirconium (Zr), strontium (Sr), barium (Ba), rubidium (Rb), and cerium (Ce). These all occur in amounts significantly less than 0.1%; nevertheless, they are geochemically significant and are also important indicators of the presence of kimberlite for exploration purposes.

Exactly how kimberlites form is a subject of intense study. Although several hypotheses have been presented in the past, Eggler (1989, p. 496) reports that "partial melting of carbonated peridotite is preferred." That is, when a peridotite containing a small amount of a carbonate mineral such as dolomite (source of CO₂) as well as phlogopite (source of potassium) becomes hotter, a small portion (less than 10%) of the rock will melt initially. The fluid (magma) resulting from this partial melting will have the chemical characteristics of kimberlite mentioned above (volatile-rich, potassic, ultramafic). This process probably takes place at pressures of 50–65 kbar and temperatures of about 1200°–1500°C. Thus, kimberlite magmas, like diamonds, originate from peridotite in the upper mantle at depths of perhaps 150–200 km. It is important to remember, however, that the consensus is that diamonds will only crystallize from peridotite (in addition to eclogite) and not from kimberlite (except possibly in special cases) for reasons that are not known, and that diamonds will occur in kimberlite only as xenocrysts.

purposes of this discussion, we need only consider the highlights presented in box B and recognize the following characteristics of kimberlite.

- Kimberlite is a dark-colored (referred to as "blue ground" when fresh) hybrid rock; that is, it is a mixture of the crystallization products of the kimberlite magma itself (e.g., olivine, phlogopite) plus xenocrysts and xenoliths of peridotite and eclogite derived from the upper mantle.
- Chemically, kimberlite is an ultramafic, potassic, volatile-rich (CO₂, H₂O) rock that formed deep within the earth (at least at the depth of diamond formation) at high pressures and temperatures.
- Kimberlite is intruded from the mantle into the earth's crust; near the surface, it takes the form of a cone-shaped pipe characterized by a volcanic explosion and the formation of breccia (angular broken fragments) within the pipe (see below).

Lamproite was a relatively obscure rock type until 1979, when it was found to host primary deposits of diamonds in Australia. To date, it is only the second rock type to have gained this distinction. Although it has been the subject of many studies over the last decade, like kimberlite it is not easily defined. Currently, *lamproite* refers to a group of rocks closely related in chemical composition (a clan) rather than to a specific rock variety. Nevertheless, certain chemical, textural, and mineralogic characteristics are recognized:

- Lamproite has a characteristic gray to greenish gray mottled appearance and, like kimberlite, is a hybrid rock. The primary magmatic crystallization products, most notably olivine, occur both as phenocrysts and as groundmass constituents. Upper-mantle xenoliths and xenocrysts are the same as those found in kimberlites.
- Chemically, lamproite is an ultrapotassic (potassium values are typically 6%–8% K₂O, compared to 0.6%–2.0% K₂O for kimberlites), magnesium-rich (mafic) igneous rock. Significant trace elements include zirconium (Zr), niobium (Nb), strontium (Sr), barium (Ba), and rubidium (Rb); these same elements also are enriched in kimberlites (see box B). On the other hand, CO₂, which is enriched in kimberlite (average 8.6%), generally is low (<1%) in lamproite, but another volatile element, fluorine (F), is enriched in the latter. Lamproites are also lower in

magnesium (Mg), iron (Fe), and calcium (Ca), but higher in silicon (Si) and aluminum (Al), than kimberlites.

- Lamproites, like kimberlites, occur as pipes, dikes, and sills, but lamproite pipes resemble champagne glasses, rather than cones, in shape.

A comparison of the minerals present in the two rock types is particularly informative (table 2). The fact that several major, as well as some minor, minerals are common to both rock types suggests that their respective magmas have similar chemical characteristics. Further, the xenocrystic minerals are identical, which suggests that kimberlites and lamproites were, at some time in their histories, in the same high pressure-high temperature environments characterized by eclogite and peridotite (in the Argyle olivine lamproite of Australia, there are far more eclogitic than peridotitic xenocrysts in diamonds). From table 2 we see that lamproite has a number of additional minerals that distinguish it from kimberlite (although not all are present in all lamproites). These

TABLE 2. Minerals found in kimberlite and lamproite.

Minerals	Kimberlite	Lamproite
Minerals that crystallize directly from kimberlite and lamproite magmas		
Major		
Olivine	✓	✓
Diopside	✓	✓
Phlogopite	✓	✓
Calcite	✓	
Serpentine	✓	
Monticellite	✓	
Leucite		✓
Amphibole		✓
Enstatite		✓
Sanidine		✓
Minor		
Apatite	✓	✓
Perovskite	✓	✓
Ilmenite	✓	✓
Spinel	✓	✓
Priderite		✓
Nepheline		✓
Wadeite		✓
Xenocryst minerals derived from the upper mantle		
Olivine	✓	✓
Garnet	✓	✓
Clinopyroxene	✓	✓
Orthopyroxene	✓	✓
Chromite	✓	✓

include, for example, the minerals leucite (KAlSi_2O_6), sanidine (KAlSi_3O_8), wadeite ($\text{K}_2\text{ZrSi}_3\text{O}_9$) and priderite $[(\text{K},\text{Ba})(\text{Ti},\text{Fe})_8\text{O}_{16}]$, from which the potassium- and zirconium-enriched character of lamproites is derived.

In summary, based on their chemical, textural, mineralogic (including those of the xenoliths and xenocrysts), and emplacement (e.g., as pipes) characteristics, kimberlites and lamproites have much in common. Certainly, the similarities are greater than the differences. Both rock types probably formed by partial melting (see box B) of similar, yet distinctive, peridotitic material at greater depths than any other known volcanic rocks. Pressures of origin can be related to the upper mantle at depths of at least 150 km, and temperatures probably were in the range of 1100°–1500°C; kimberlites appear to have crystallized at the middle to upper part of the temperature range and lamproites at the lower end. Both rock types have transported mantle xenoliths and xenocrysts, including diamonds, to the surface, although not all kimberlites and lamproites contain diamonds. Finally, it should be noted that only recently has lamproite been recognized as a host for diamond deposits and that there is no known fundamental reason why other mantle-derived rocks with sufficiently deep origins could not also transport diamonds from the same peridotitic and eclogitic sources.

Where Emplacement Occurred. There are two aspects to the topic of where emplacement of kimberlite and lamproite occurred: geographic and geologic. Both of these topics were reviewed thoroughly by Clifford (1970), Janse (1984), and Dawson (1989). Most emphasis will be placed on kimberlites because there is far more information available on these rocks than on lamproites.

Kimberlites are widespread around the earth, and over 3,000 are known in southern Africa alone. This figure includes both dikes and pipes (sills are rare), of which the former are more abundant. There are about 100 kimberlites in North America, with perhaps 60 located in what is called the Colorado-Wyoming State Line District. Of the total number of kimberlites worldwide, fewer than 1,000 contain any diamonds, only 50–60 have ever been economic, and only about 12 major pipes are being mined today. Most of the well-known diamond-producing pipes have a surface area of between 5 and 30 hectares (about 12–75 acres); in South Africa, they typically contain about one carat of rough diamond per five tons of kimberlite ore.

Kimberlites tend to occur in clusters, with 6 to 40 (excluding dikes) in any one. Certain areas, such as South Africa, Siberia, and northwestern Tanzania, contain many clusters. The five main pipes at Kimberley, South Africa, cover a circular area with a diameter of 10 km, but the entire cluster, including dikes, occupies an area with a diameter of 40 km. Janse (1984) suggests that the distance between several major clusters in both South Africa and Siberia is generally about 400 km, although the use of such estimates has been questioned by Gurney (1989). The ratio of economic to noneconomic pipes in clusters varies considerably: Janse (1984) gives figures ranging from 5 out of 15 at Kimberley and 3 out of 29 at Orapa (Botswana), to 1 out of 30 at Alakit (Siberia); some clusters, of course, have no economic value.

Unfortunately, there are no similar statistics for lamproites. Not only is the discovery of the Argyle deposit in Western Australia relatively recent, but many of the rocks previously called lamproites, as well as related types, are presently being reevaluated and reclassified. Such studies, for example, have resulted in the reclassification of the diamond-bearing Prairie Creek (Murfreestboro), Arkansas, pipe from a kimberlite to an olivine lamproite.

However, studies of kimberlites, and to a lesser extent lamproites, have provided valuable information about the geologic distribution of the diamond-bearing rocks in the earth's crust. Figure 15 shows that the geographic distribution of primary diamond deposits, predominantly kimberlites, is not random but is confined to regions of the continental crust that are old cratons (defined below). This is an observed fact that was well formalized by Clifford in several publications, culminating in Clifford (1970). It illustrates, too, the fact that kimberlites are never found in oceanic environments or young mountain belts. A *craton* (again, see figure 14) is part of the earth's crust that has attained stability and has been little deformed for a very prolonged period of time (generally more than 1,500 My). Effectively, the term applies to extensive, stable continental areas and consists of two parts: (a) a *shield* (the exposed core of a craton, e.g., the Canadian Shield), and (b) a *platform* (the part of the craton, covered by generally flat-lying sediments and sometimes associated volcanics, e.g., basalts, that is adjacent to, and an extension of, the shield). Cratons are the nuclei of all continents, and all present-day continents, except Europe, have more than one craton (again, see figure 15),



Figure 15. This world map of primary diamond deposits (i.e., those in pipes) shows cratonic areas (dashed lines) with major economic diamond deposits (large solid diamonds), minor economic deposits (small solid diamonds), and subeconomic deposits (small open diamonds). The economic deposits are in kimberlites except for the Australian deposit(s), which are in lamproite. Note that several cratons have no known diamond deposits. From Gurney (1989) and based on data in Janse (1984).

which are usually of different ages. This suggests that the continents of today may be composites of the remnants of ancient continents, each of which had its own craton. Kimberlites have been found within most cratons on all continents. Some cratons have far more diamond production and potential than others. For example, the Kaapvaal (Kalahari) craton of southern Africa has seven of the world's 11 established diamond-producing clusters.

Studies of the locations of kimberlites within cratons (this detail is not shown in figure 15) reveal that the occurrence of kimberlite pipes is most common within the younger, generally flat-lying sedimentary platform rocks that rest on the Archean (>2,500 My old) part of a craton. Very few important kimberlite pipes are known in the exposed cores (shield areas) of cratons, the principal examples being the West African and Tanzanian cratons, probably because they have been extensively eroded. This has resulted in the generalization among kimberlite specialists that the most favorable location for diamond-containing

kimberlites is "on-craton" as opposed to "off-craton," that is, "on" the Archean part of the craton (including the sedimentary platform rocks above) as opposed to "off" it. The latter location includes any younger part of the craton and adjoining *mobile belts* (i.e., linear regions adjacent to cratons that were subjected to folding due to cratonic collisions and later became mountain belts, such as the present Alps). Mobile belts may eventually become "fused" to cratons. However, generalizations such as this can be dangerous. For example, the Argyle lamproite, the largest producer of diamonds in the world today, is in a mobile belt that became part of a craton 1,800 My ago. The significance of cratons from the point of view of the "storage" of diamonds between the time of their formation and their being brought to the surface will be discussed later.

When Emplacement Occurred. Diamond-bearing kimberlites and probably lamproites have intruded into the earth's crust for a very long period, as evidenced by the occurrence of diamonds in the

2,600-My-old Witwatersrand conglomerate in South Africa. The presence of diamonds in this paleoplacer (alluvial) deposit requires that a still older kimberlite (or lamproite) existed.

The oldest known kimberlites still preserved are the 1,600-My-old intrusions near Kuruman, northern Cape Province, South Africa, which are situated on the Kaapvaal Craton but contain no diamonds. Subsequently, there was a period of extensive kimberlite emplacement about 1,200 My ago, again in South Africa (e.g., Premier mine; see table 1) but also in India and Mali. Other important episodes of kimberlite intrusion are presented in table 3.

Although information on lamproites is less readily available, they are known to cover a range from the Argyle pipe, which was intruded ~1,200 My ago, to the Ellendale lamproites (about 50 bodies are known and several are potentially economic), approximately 400 km from the Argyle deposit, which were intruded in early Miocene time (~20 My ago) into platform sediments of Devonian and Permian age (~400–250 My). Some lamproites in Wyoming, Antarctica, and a few other localities may have been emplaced within the last one million years.

We may deduce from the large number of new age dates obtained in the past decade that: (a) kimberlite and/or lamproite intrusions can occur at several different times in the same vicinity; and

(b) most kimberlites and lamproites were emplaced in the last 200 My, although there were major intrusions at least as early as 1,600 My ago and possibly prior to 2,600 My ago.

How Emplacement Occurred. It is generally accepted that kimberlite and lamproite magmas result from the partial melting of similar, yet distinctive, peridotitic material 150–350 km below the earth's surface, that they intruded into cratons, and that the process of emplacement has been operative, during some periods more than others, at least since 2,600 My ago. Beyond this point matters become more speculative, particularly on the details of how emplacement occurred. Topics that must be considered are: (1) the rate of ascent of diamond-bearing kimberlites and lamproites; and (2) the configuration and formation of diatremes. Again, most emphasis will be placed on kimberlite.

Rate of Ascent. The rate of ascent of kimberlites is most frequently determined on the basis of the following observations: (a) diamonds are preserved during their ascent to the surface rather than reverting to graphite, being converted to carbon dioxide (CO₂), or dissolving in the kimberlite magma (figures 16 and 17); and (b) the diamond-bearing kimberlites also transport large xenoliths from as deep as 200 km below the surface (again, see figure 4). Both of these observations require that the ascent to the surface be reasonably rapid. During slow ascent, or ascent with many intermediate stops, diamond would likely revert to graphite (which in the pressure-temperature conditions in the earth's crust is thermodynamically more stable than diamond) and the heavy xenoliths would tend to settle back through the magma. At Beni Bouchera, Morocco, for example, we know that diamonds were transformed to graphite because they were not transported rapidly to the surface by kimberlite or lamproite (Slodkevich, 1983). The fall in temperature and pressure was sufficiently slow to permit the conversion; only with a rapid decrease in temperature and pressure will the carbon atoms "freeze" in the metastable diamond structure (figure 18).

Although we know that the ascent is rapid, estimates of the exact velocity depend on various assumptions. For our purposes, the ascent rates proposed by Egger (1989) of 10–30 km per hour are realistic. In other words, diamonds are brought to

TABLE 3. Times of intrusion of selected kimberlite provinces (modified from Dawson, 1989).

Geologic age	Time (My ago)	Locality
Eocene	50–55	Namibia, Tanzania
Upper Cretaceous	65–80	Southern Cape (South Africa)
Middle Cretaceous	80–100	Kimberley (South Africa), Lesotho, Botswana, Brazil
Lower Cretaceous	115–135	Angola, West Africa, Siberia
Upper Jurassic	145–160	Eastern North America, Siberia
Devonian	340–360	Colorado-Wyoming, Siberia
Ordovician	440–450	Siberia
Upper Proterozoic	810	Northwest Australia
Middle Proterozoic	1,100–1,250	Premier (South Africa), India, Mali
Lower Proterozoic	1,600	Kuruman (South Africa)

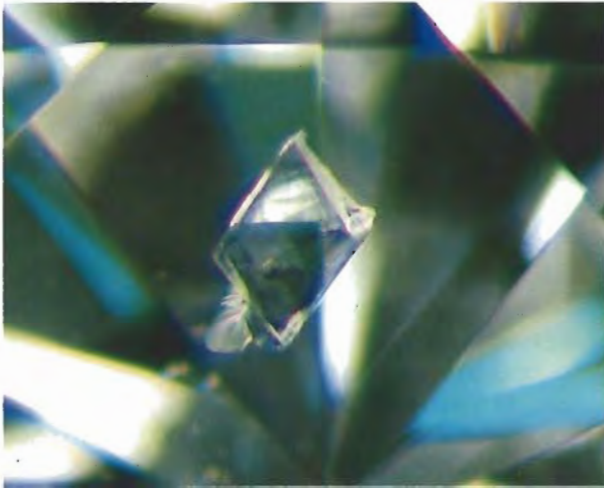


Figure 16. Extremely well-shaped diamonds with sharp octahedral edges, as seen just below the table facet of this host mineral, are unusual. Special conditions were required for their preservation; for example, they may have been protected within another mineral (diamond, in this case) or in an eclogite xenolith. Otherwise, it is likely that they would have been resorbed (dissolved) in a kimberlite or lamproite magma. Photomicrograph by Eduard J. Gübelin; dark-field illumination, magnified 20×. From Gübelin and Koivula (1986, p. 97).

the surface from their storage areas at depths of at least 110 km (at the base of cratons) in 4–15 hours! Further, as the surface is approached, within the last 2–3 km, the velocity increases dramatically to perhaps several hundred kilometers per hour, for reasons that are explained later.

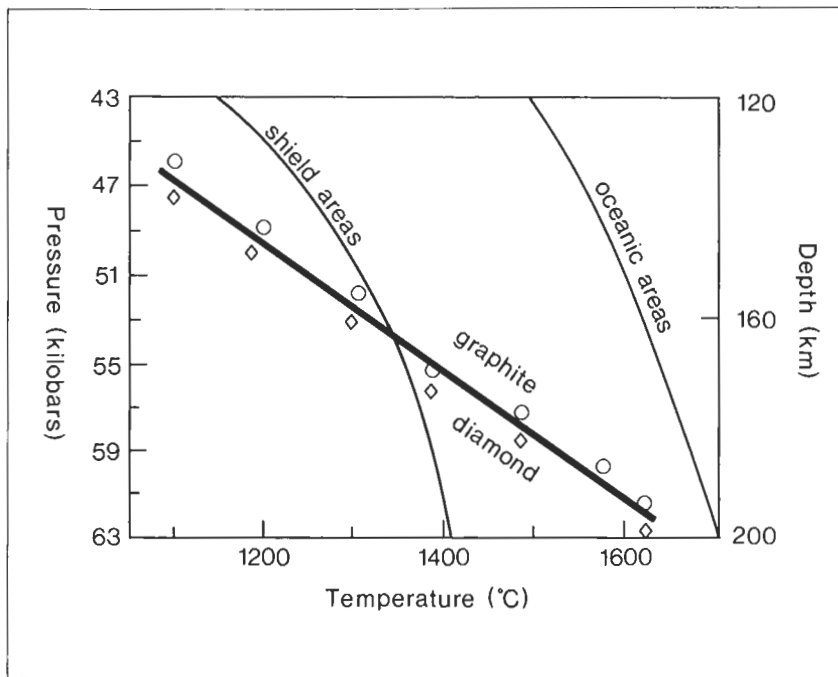
An obvious requirement for kimberlites to reach the surface is the availability of fractures that extend from below the base of the craton, through solid rock, for a distance in the vicinity of 150 km; these deep fractures are only possible in geologically stable areas. Exactly how these deep fractures are generated, and are even repeated from time to time in identical localities to account for kimberlite intrusions of widely different ages within the same pipe, is a matter that is not well understood. For our purposes it is only necessary to recognize the existence of a problem concerning the origin of the deep fractures and to observe that several hypotheses have been proposed, for example, crack propagation by magmatic fracturing (Eggler, 1989) and crustal thinning linked with major plate movements (Dawson, 1989). Mitchell (1986) has reviewed older theories.

Configuration and Formation of Diatremes. The term *diatreme* is synonymous in this article with the terms *breccia pipe* and simply *pipe*: It is a general term for a volcanic pipe that is emplaced in rocks by a gaseous explosion and is filled with angular broken fragments called breccia [Gk. *dia*: through + *trem(a)*: perforation = to pierce, drive through]. As a general term, *diatreme* can be used for pipes of many types in numerous geologic situations (e.g., diatremes of basalt erupting along fractures); however, the combination of features described below is possibly unique to kimberlite diatremes (and related rocks, e.g., lamproites) primarily because of the great depths from which they originate as well as the amounts and types of

Figure 17. The irregular rounded shapes frequently found on diamonds result when the transporting kimberlite (or lamproite) magmas react with, and dissolve, the diamond, starting with the octahedral edges. Isolation of diamonds from transporting magmas (see figure 16), or very rapid ascent to the surface, can minimize this effect. Photo © GIA and Tino Hammid.



Figure 18. The diamond-graphite equilibrium line is plotted here against the geothermal gradients for the continental shield (craton) and oceanic areas. (A geothermal gradient is the rate of increase of temperature with increasing depth in the earth and averages about 25°C per kilometer in the earth's crust.) Under the oceans, temperature rises much more rapidly with depth than it does under the shield areas. The geothermal gradient line for the shield areas intersects the diamond-graphite equilibrium line at 53 kbars (and about 1325°C), which corresponds to a depth of about 160 km. Under oceanic areas, it intersects at depths greater than 200 km, which is unsuitable for the production of diamonds. Modified from the GIA Diamonds course.



gases they contain. The characteristic features of kimberlite diatremes are: (a) their general shape, and (b) their three distinct depth zones (root, diatreme, crater) which, in combination, are the configuration of the pipe (figure 19).

The classic, early 20th-century studies of kimberlite pipes in the Kimberley area, South Africa, demonstrated that they occur as carrot-shaped, vertical intrusions that pinch out at depth. These observations have stood the test of time. With increasing depth of the mines over the years, new observations were made and older ones refined. These include: (a) the fragmental (brecciated) nature of kimberlite, particularly in the diatreme zone; (b) the fact that kimberlite is a "cold" rock, inasmuch as there are very few indications of thermal effects (e.g., contact metamorphism) on either the wall rocks or xenoliths of the diatreme zone as would be expected for a rising molten magma; and (c) the observation that the pipes become narrower with depth, eventually thinning into feeder dikes that are rarely thicker than one meter. In other parts of Africa, important surface features of kimberlite diatremes, e.g., maar and tuff rings (see below), were also recognized.

Hawthorne (1975) combined all the above features and facts relating to kimberlite pipes and developed an idealized model, which is illustrated in modified form in figure 19. This figure, which is a basis for modern concepts of emplacement,

shows the three different zones within an idealized kimberlite.

The *root zone* is the deepest part of the pipe. It is characterized by an irregular outline and by numerous distinct intrusive phases of kimberlite and igneous features, and it extends about 0.5 km vertically about 2–3 km below the surface. It is composed of crystallized kimberlite magma with the megascopic appearance of a typical intrusive igneous rock, along with xenoliths and xenocrysts and frequently with some small breccia fragments. With depth, the root zone grades into individual feeder dikes, also of kimberlite (but without certain characteristics such as breccia), which extend downward indefinitely, but probably not continuously, as the fractures along which the magmas moved probably opened and then closed after magma passed through. Root zones and feeder dikes may contain diamonds among the xenocrysts, but they have been mined only on a small scale because of their limited volume. Economic mining is generally limited by the width of the dikes, which are usually only about 60 cm wide (although they may, rarely, be 10 m wide, known as a "blow").

The *diatreme zone* (not to be confused with diatreme = pipe) is much greater in vertical extent than the root zone and is the most important source of diamonds because of its volume. It ranges from 1 to 2 km in height and extends to within 300

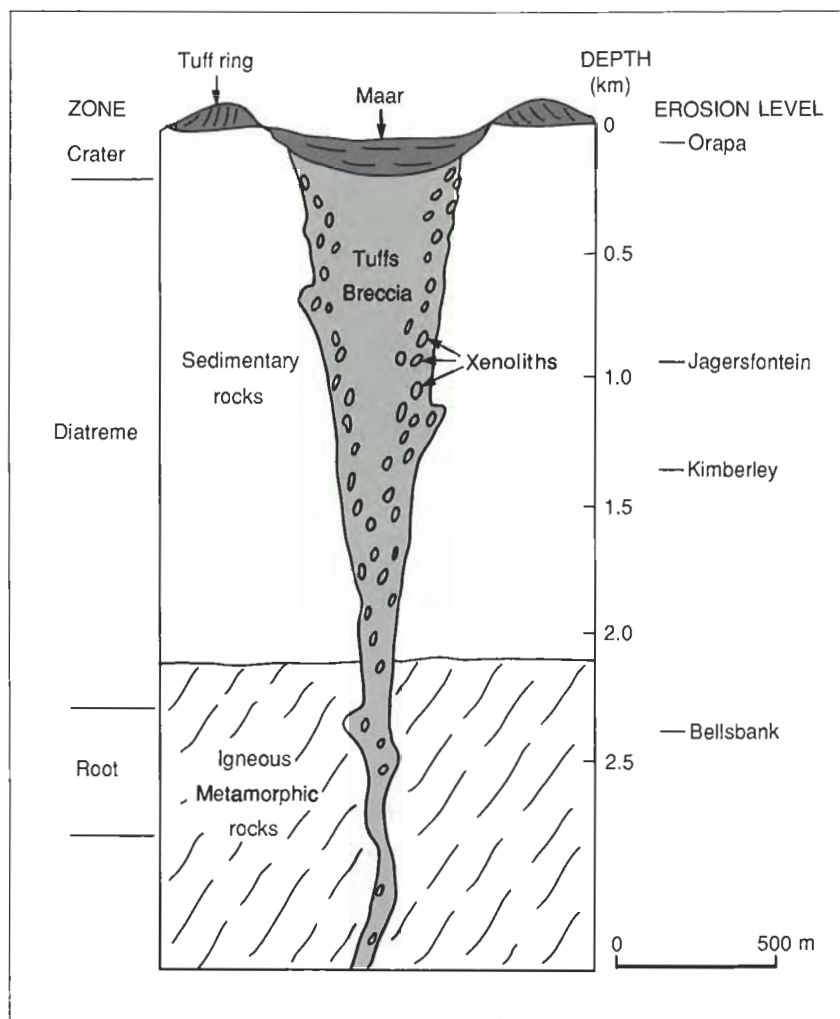


Figure 19. This idealized model of a kimberlite pipe includes the root, diatreme, and crater zones. Also shown are the present erosion levels at the Orapa pipe in Botswana and the Jagersfontein, Kimberley, and Bellsbank pipes in South Africa. Adapted from Hawthorne (1975).

m of the surface, in the idealized situation in which it has not been eroded (again, see figure 19). The diatreme zone contains xenoliths and xenocrysts from the mantle, as well as rock fragments derived from the crustal rocks through which the kimberlite passed, including wall rock (e.g., basalt, gneiss, shale) in the vicinity of the pipe. The main characteristics of this zone, however, are the kimberlite breccias and other fragmental rocks (e.g., tuffs) associated with explosive magmas.

These features develop because within the kimberlite magma there are large amounts of dissolved gases, specifically carbon dioxide and water (see box B), under great pressure. At about 2–3 km below the surface, explosions occur in the ascending kimberlite magma as the gases expand enormously at the lower near-surface pressures. Because of these explosions, the rate of ascent of the kimberlite accelerates rapidly, to perhaps several hundred kilometers per hour. As the kimberlite breaks through the overhead crustal rocks,

the pipe takes on its conical shape and becomes wider. At the same time, those areas of kimberlite that had already crystallized as rock undergo fragmentation (brecciation). Because of the expansion of the gases, the kimberlite magma cools down rapidly so that there are few thermal reactions with the wall rocks or crustal xenoliths. With the temperature sufficiently low in relation to the lower pressure, the diamonds resist conversion to graphite and survive intact (figure 18).

The *crater zone* occupies the upper 300 m or so of a typical kimberlite diatreme which, at its formative stage, is a volcano. Whereas most volcanoes erupt molten lava, as typified by Mauna Loa in Hawaii, such probably is not the case with a kimberlite volcano. This is because, by the time the kimberlite has passed through the diatreme zone, it is no longer molten and does not flow out. Rather, it erupts as broken solid fragments of rock called *pyroclastics* [Gk. *pyro*: fire + *clastos*: broken into pieces], *tuffs* (a general term for all

consolidated pyroclastic rocks), or *lapilli* (loose pyroclastic material in the size range of 2–64 mm), among other terms. Another factor to be considered is that the rising kimberlite magma and/or pyroclastic material, while not molten, is still hot and will eventually encounter cooler groundwater at depths that vary with locality. As the groundwater turns to steam, the eruption becomes even more volatile and, in some special situations, very violent explosions occur. Returning briefly to Dawson's (1984) explanation of the term *kimberlite* (box B), we can now understand the reason for his including the concept of "high-level groundwater."

Kimberlite volcanoes have never been observed to explode in historic times. In Tanzania, Mali, and Botswana, however, there are rare examples of the surface expression of this phenomenon that have not yet been eroded away. These include *maars* (low-relief volcanic craters formed by shallow explosive eruptions, which may be filled with water if they intersect the water table, and which are surrounded by crater rings) and *tuff rings* (wide, low-rimmed accumulations of pyroclastic debris of tuff or lapilli, slightly larger in size than an associated maar). It is likely that the explosion lifts debris no more than several hundred meters into the air and that the tuff ring is typically about 50 m high and is quickly eroded.

Inspection of depths below the surface in figure 19 will show that the typical distance from the top of the crater zone to the base of the diatreme zone is about 2,300 m. Depending on the geomorphologic, topographic, and other characteristics of the emplacement site, and assuming an erosion rate of 1 m every 30,000 years (which is the average for the earth), it could be predicted that the vast majority (except the root zone) of a typical kimberlite diatreme would be completely eroded away in 69 My. During this period, it would be continually releasing diamonds into secondary deposits, such as alluvials or beach sands. In figure 19, we see that four southern African mines—Orapa, Jagersfontein, Kimberley, and Bellsbank—all of Cretaceous age (~100 My; see table 1), are eroded to distinctly different levels. From this it follows that the Bellsbank mine has limited remaining economic potential because the entire diamond-containing diatreme and crater zones have been eroded away, whereas the Orapa mine can look forward to potential economic production to a depth of about 2,000 m which, at the present rate of production, will take several hundred years.

It is premature to make more than passing comments on the emplacement aspects of diamondiferous lamproites, because only the Argyle mine is in production and only since late 1985. There are several scientific reports describing this mine, as well as the Ellendale lamproite pipes about 400 km distant, in the volumes edited by Ross (1989). Suffice it to say that there are many similarities between these pipes and those of kimberlite. As mentioned earlier, one interesting difference is in shape. Unlike kimberlites, which are carrot-like, the root and lower diatreme zones of lamproites are thin and stem-like, but toward the top the pipes flare out in a curved manner that gives a "champagne glass" shape in cross-section.

Diamond Sampling in the Mantle. Discussion of the sampling of diamonds in the mantle and their transportation to the surface requires the integration of many of the topics considered earlier. This is accomplished by reference to figure 20, a simplified version of a diagram first published by Haggerty (1986). This figure is based on an idealized cross-section of the earth through a craton and its subcontinental regions (the lithosphere), which are characterized by very long-term tectonic stability, such as no mountain building or plate movements. (Kimberlite magmas, which originate at depths below the base of cratons, do penetrate the cratons through narrow fractures, but this minor volcanic activity does not negate the concept of a tectonically stable craton.) In all such areas, because of the tectonic stability, there are low geothermal gradients (rates of increase in temperature with depth) by comparison with the oceanic parts of the world.

Figure 20 also reflects, as noted earlier, the fact that eclogitic diamonds appear to form at greater depths than do peridotitic diamonds. As indicated by arrows, the eclogites formed from oceanic basalts that traveled down from the ocean basins by means of plate tectonic movements. The diagram also shows the relative position of the mobile belts on either side of the craton.

Of great significance is the shaded zone at depths of 110–150 km and temperatures of 900°–1200°C. This zone, like the rest of the craton and its subcontinent, has not been actively involved in plate movements or other major tectonic activities for at least 1,500 My. Of possibly even greater significance, however, is the fact that diamonds are stable within this area. Thus, diamonds that formed in the deeper parts of this keel-

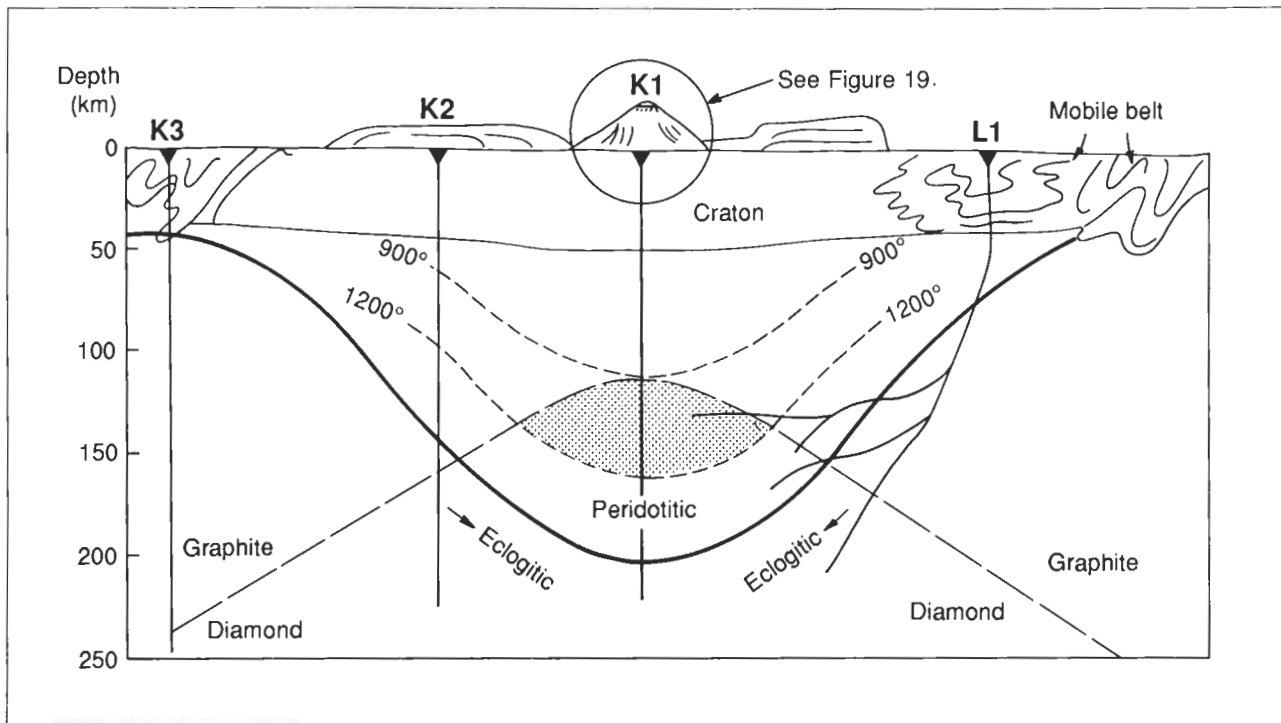


Figure 20. This model for the genesis of diamond is simplified from Haggerty (1986). The stable craton and subcratonic areas today are as much as 200 km thick (heavy solid line) and are bounded by mobile belts. The isotherms (lines connecting points of equal temperature) in the craton are concave downwards. The diamond stability field (area in which diamond is stable) is convex upward. The K1 kimberlite pipe is likely to have P-type diamonds because it sampled diamonds in the diamond "storage area" (shaded zone) at the keel of the craton, where this type of diamond is presumed to be present. Pipe K2 may have E-type diamonds. Kimberlite pipe K3 will be barren of diamonds. L1 is the possible location for Argyle-type lamproite pipes. See text for additional details.

shaped area, as well as those that formed elsewhere and somehow were moved into the same area, have been preserved and stored for as long as 3,200 My (see table 1 and accompanying discussion). One reason for the suggestion that diamonds in the storage zone may be of multiple origins is that in diamondiferous kimberlites (and lamproites) both P-type and E-type diamonds, in any proportions, may be found.

A kimberlite pipe such as K1 (figure 20), ideally situated over the keel of the craton, would be likely to contain diamonds, primarily of the P-type, provided other factors, such as a rapid ascent rate, are favorable. Pipe K2 would likely sample an eclogitic enclave hosting E-type diamonds, whereas kimberlite diatreme K3, which is "off craton," would probably be barren. The lamproite diatreme L1, as exemplified by the Argyle and Ellendale pipes in Australia, is also "off craton" in that it is intruded into the mobile belt; yet it is diamondiferous with both P-type and

E-type diamonds. To account for this, Haggerty (1986) suggests a "complex plumbing system" (a system of interconnecting fractures) that is able to sample appropriate preservation and storage areas.

CONCLUSIONS

Age-dating techniques applied to the mineral inclusions (e.g., garnet) within diamond show that the inclusions are very old, ranging from 990 to 3,300 My, but this range may be extended as more age determinations are made. Inasmuch as the inclusions formed at the same time as their diamond hosts, it follows that diamonds are equally as old. On the other hand, kimberlites and lamproites, the two rock types in which primary diamonds are found, are generally much younger (the most important diamond pipes range in age from about 100 to 1,200 My) and are not the rocks in which diamonds crystallize. Hence, kimberlite

and lamproite are merely the transporting media that bring diamonds to the surface by mechanisms that are not completely understood. Diamonds are formed at depths of 150–200 km below the surface; in the interval between their formation and their transport to the surface, they are stored under cratons at least 110 km below the surface, where the high pressure and relatively cool temperatures preserved them.

Study of both diamond-bearing xenoliths and mineral inclusions within diamonds shows that diamonds form within two different rock types, peridotite and eclogite. Carbon isotope studies on diamonds show that the carbon from which peridotitic diamonds crystallize originates from a

homogeneous source within the earth's mantle, whereas the carbon for eclogitic diamonds probably originates from sources on the earth's crust that have been subducted below cratons by plate movements.

Knowledge of the age, origin, and emplacement of diamonds is extremely valuable in the search for primary deposits. For example, exploration geologists now know that those areas with the greatest potential are ancient cratons that contain ultramafic rocks that originated at great depths. For the gemologist, such knowledge results in a better appreciation of the complex geologic processes that are required to bring the world's most important gem to the surface.

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