

DIAMONDS, KIMBERLITES, AND LAMPROITES

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Summary

Diamond, the high-pressure form of carbon, is one of the most sought-after industrial minerals and most appreciated gems. Principal sources of diamonds are kimberlitic and lamproitic pipes, and alluvial or marine sediments partly derived from their erosion. Kimberlitic and lamproitic magmas are produced at great depth in Earth's mantle and may sample portions of diamondiferous lithosphere during their ascent to surface. The presence of diamond in the lithosphere requires particularly cold thermal regimes, which are typically achieved under ancient, stable geological provinces dated to over 1.6—usually more than 2.5—billion years. Because of the extreme worth of diamond, very low grades of even less than one carat per ton are often sufficient to warrant economically viable exploitation.

The origin of diamond is still far from thoroughly understood. A broadly accepted view involves precipitation of most diamonds from fluids or melts enriched in primordial mantle or recycled crustal carbon. Diamonds can be several hundred million to more than two billion years older than their host rocks, although apparently young stones are also found locally. Diamond exploration is carried out using various mineralogical and geophysical prospecting methods aimed at defining the composition, thickness, thermal regime, and redox conditions of the lithospheric mantle, and to detect the presence of mineralogical and lithological anomalies related to the presence of kimberlitic or lamproitic pipes. Diamond exploration takes place on every continent. Many high-potential target areas are located in as-yet poorly explored regions of the world, and therefore several new findings of economic deposits can be expected in the near future. Disordered social conditions, particularly in some African countries, are still a serious obstacle to development of modern exploration and mining strategies. Technological progress may lead to escalating exploitation of the enormous offshore resources of

Namibia and South Africa.

1. Introduction

Among naturally occurring materials, diamond is characterized by extraordinary physicochemical properties. From a crystal chemical point of view, diamond is the high-pressure, cubic form of carbon (space group $Fd\bar{3}m$, class $m\bar{3}m$), which is stable in the Earth at depths greater than ca. 120 km at 800 °C, increasing to greater than ca. 170 km at 1400 °C. It usually crystallizes as colorless or pale yellow to orange, brown, gray, or black octahedra, cubes, dodecahedra, and combinations of these forms. Twinned crystals may exhibit a flat habit known as “macle” and partially etched grains may appear rounded. Rarer colors are pink, red, green, blue, and violet. Diamond is a superb heat conductor and an excellent electrical insulator, although the gray-to-blue variety known as type IIb behaves as a semiconductor. Its extreme hardness (10 Mohs scale; 56–115 GPa Knoop Hardness Number), elevated melting point (3550 °C), very low reactivity to chemicals, and high refractive index (2.417), which confers it a prominent, adamantine luster, intense light dispersive properties, and great durability, make it one of the most sought-after industrial minerals and most appreciated gems.



Figure 1. Raw diamonds, South Africa (photo by C. Brogiato)

Since diamond is a very rare mineral, even in Earth’s deep interior, finding diamonds in accessible portions of Earth mainly relies on geological processes capable of conveying huge amounts of carbon-bearing material from depth to the surface. Principal primary sources of diamonds are kimberlites (named after the famous mining district of

Kimberley, RSA) and, to a lesser extent, lamproites. These are rocks derived from particular types of potassium-rich, magnesium-rich magmas generated at great depth by partial melting of Earth's mantle. Because of its elevated hardness, specific gravity (3.52 g cm^{-3} when pure), and resistance to alteration, diamond can be concentrated by sedimentary processes to form secondary alluvial and marine deposits (placers), partly derived from transport and accumulation of materials released by weathering and erosion of former diamond-bearing kimberlites and lamproites. Minor primary diamond occurrences are found in metamorphic terrains in orogenic collision zones, where diamond can form in response to high-pressure metamorphism of carbon-bearing rocks, in rocks affected by shock metamorphism related to meteoritic impact, and even in some meteorites. Ultrahigh-pressure metamorphic terrains in the Kokchetav massif (Northern Kazakhstan) contain exceptionally abundant microdiamonds (average size = 15–20 μm) with proven resources of ca. 3 billion carats. Diamonds have also occasionally been found in non-kimberlitic/lamproitic magmatic rocks of high-pressure origin. Because of their low grades or the small size of the diamonds, these minor settings have never emerged as an economically exploitable resource, while kimberlites, lamproites, and placers include the entire known world resource of commercial diamonds.

Notably, only a small percentage of known kimberlites and lamproites are diamondiferous; even when so, their grade is always very low, never exceeding ~5 parts per million. The percentage of economically exploitable kimberlites and lamproites is even lower. Overall, of the ca. 8000 kimberlite/lamproite pipes known in the world just about a thousand contain diamond, and in only about a hundred is diamond present in economically interesting quantities. The economic cut-off grade is heavily dependent on the quality and, in part, the size of the stones. The presence of precious gem-quality diamonds, characterized by absence of visible defects, high transparency, and pleasing coloring, can significantly lower the cut-off grade. For gem diamonds, intensity of color is inversely proportional to value, although pure and highly saturated colors (“fancy diamonds”) may be extremely valuable. In any case, because of the particularly high economic value of diamond, very low grades can often be sufficient to justify exploitation. As an example, the famous Kimberley Mine, RSA, has supplied diamonds for only 0.625 metric carats per ton, corresponding to a total production of 3 t diamonds for 24 Mt of raw material, and the kimberlitic breccia of the Koffiefontein Mine, RSA, has been exploited at tenors of 0.1 metric carats per ton, 35% of which in the form of gem-quality diamonds. The proportion of gem-quality stones may vary significantly between different pipes (for example, ca. 40–55% for South African kimberlites, but only 5% for the MIBA mine in Zaire and the Argyle mine in Western Australia). Compared to bedrock deposits, diamond placers usually yield a much higher proportion of large and high-quality stones, as small and flawed crystals are more easily destroyed during transport by streams and rivers. In marine deposits such as those of the southern African West Coast, the proportion of gem-quality diamonds may exceed 98%.

2. Kimberlites and Lamproites

Kimberlites and lamproites are highly magnesian ($\text{MgO} > 25\%$ weight) magmatic rocks which are enriched in volatiles (water, carbon dioxide, and fluorine) and carry anomalously high contents of elements such as K, Na, Ba, Sr, rare earth elements, Ti,

Zr, Nb, and P.

Kimberlites are mostly hybrid rocks, and often escape rigid definition. They were originally regarded as a member of lamprophyric rock clan, but have recently been reclassified and formally subdivided into two groups.

- *Group 1* includes the most classical kimberlites, originally termed “basaltic” kimberlites: that is, ultrabasic ($\text{SiO}_2 < 45 \text{ wt}\%$), potassic (K/Na atomic ratio > 1), volatile-rich (dominantly CO_2) rocks, characterized by the presence of macro- (0.5–10 mm) and megacrysts (1–20 cm) of magnesium-rich minerals such as olivine, ilmenite, pyropic garnet, variably chromium-rich diopsidic pyroxene, phlogopite, enstatite, and Ti-poor chromite, set in a fine matrix of olivine, serpentine, carbonate, and other accessory Mg- and/or Ca-rich minerals. Both the macro- and the megacrysts are at least in part xenocrysts, or accidental crystalline components derived from disruption of country-rocks (essentially deep-seated mantle peridotites and eclogites) cross-cut by the rising kimberlite magma.
- *Group 2* kimberlites (syn. orangeites), originally termed “micaceous” or “lamprophyric” kimberlites, are ultrapotassic ($\text{K/Na} > 3$), peralkaline ($(\text{K} + \text{Na})/\text{Al} > 1$), volatile-rich (dominantly H_2O) rocks, characterized by the presence of phlogopite and olivine as macrocrysts, in a groundmass made of phlogopite, olivine, and diopside, commonly zoned to titanian aegirine, spinel ranging in composition from Mg-bearing chromite to Ti-bearing magnetite, perovskite, and other minerals. They have greater mineralogical affinity with lamproites (see below) than with Group 1 kimberlites.

Lamproites are defined as ultrapotassic, peralkaline, Mg- and Ti-rich rocks, characterized by extremely variable contents (5–90% volume) of any of the following minerals: Ti-phlogopite, Ti-K-richterite, Mg-olivine, Al- and Na-poor diopside, Fe-bearing leucite, and Fe-bearing sanidine. In addition, they are by definition devoid of plagioclase, Na-feldspar, melilite, monticellite, Ti-garnet, and feldspatoid minerals other than leucite.

The origin of both kimberlites and lamproites is by small degrees of partial melting at high-pressure of variably metasomatized, potassium-enriched mantle sources, such as phlogopite \pm magnesite-bearing garnet harzburgites. Their most likely sources are in mantle plumes that rise from as deep as the lower mantle into the upper mantle. Age determinations indicate distinct intrusion episodes, which appear to have been synchronous on a global scale approximately 1000, 450–500, 400, 200, 100, and 50 Ma. Kimberlites and lamproites commonly constitute the filling of volcanic pipes and explosive diatremes, often of limited area ($< 1 \text{ km}^2$) but of considerable vertical extent (up to 2 km for some kimberlites) and frequently forming clusters. The pipes represent the exits to Earth’s surface used by magmas during the last stages of their ascent from the mantle. Feeder sills and dykes, often connecting different pipes, may occur at deeper structural levels. Both pipes and dykes can be diamondiferous. A typical kimberlitic pipe (Figure 2) has a carrot-like shape and comprises:

- a lower *root zone* constituted by true magmatic material (*hypabyssal kimberlite*),

called *blue ground* by miners as opposed to the intensely weathered *yellow ground* of higher-level zones;

- an intermediate *diatreme zone* made up of an easily weathered agglomerate of lapillis, disrupted crustal and mantle-derived xenoliths, kimberlitic clasts, and isolated kimberlitic minerals, set in a fine-grained matrix (*tuffisitic kimberlite*); and
- an upper *crater zone* made of well-bedded and poorly consolidated pyroclastic, maar (in other words, lacustrine) and partially reworked deposits (*volcaniclastic kimberlite*).

In general, the presence of these lithological facies depends on the character of the eruption as well as on the level of erosion. Multistage intrusions are common. Lamproite pipes tend to have a slightly different, funnel-like shape, with relatively shallow craters, usually less than 300 m in depth. In many lamproite pipes, the volcaniclastic facies is intruded by a later magmatic phase that gave rise to lava lakes or domes. Differences in diamond grade may exist between different structural portions of a single kimberlite/lamproite pipe, especially in the case of multistage intrusions. The superficial, reworked, crater-zone sediments may be of higher grade, due to residual concentration and natural winnowing of fines.

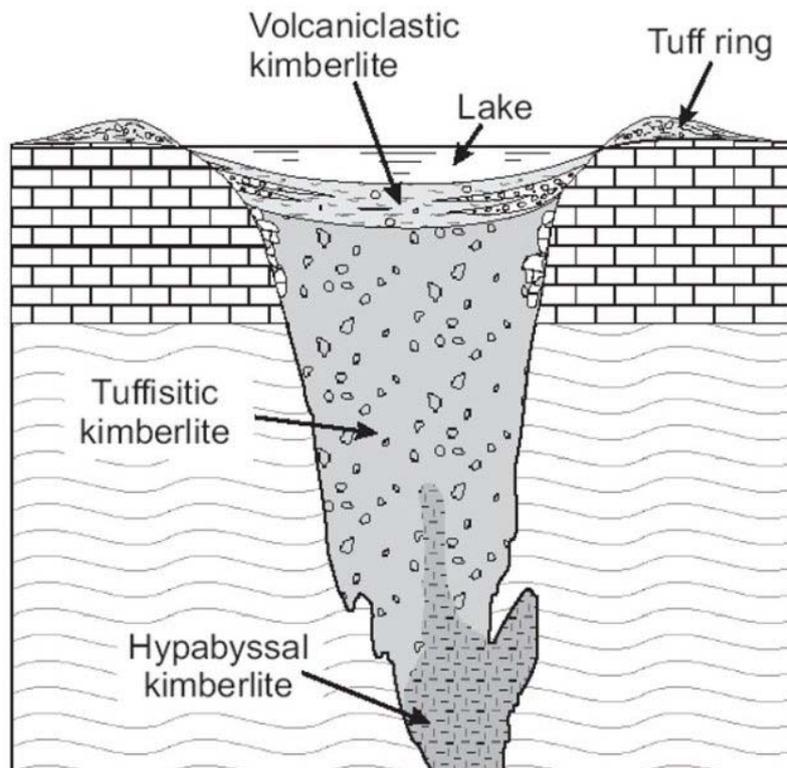


Figure 2. Schematic section of a kimberlite pipe

It is believed that kimberlitic and lamproitic magmas, rich in volatile components (mainly CO₂ and H₂O), ascend rapidly (several tens of kilometers per hour on average, but perhaps several hundred kilometers per hour for the last few kilometers) through the lithosphere, facilitated also by the presence of lithospheric faults. During the rise,

portions of peridotites and eclogites—the main constituents of the stiff lithospheric mantle—are sampled by the magma and transported to the surface as xenoliths. A few kilometers from the surface the magma charged with gases, in part derived from interaction with groundwaters, erupts explosively, forming diatremes filled with fluidized fragments of magma, xenoliths (and xenocrysts derived from their disruption), and country-rock fragments. Diamond itself—for the most part originally contained in mantle eclogites and peridotites formed under suitable pressure, temperature, and redox conditions and appropriate C, O, and H contents—is sampled from its original sites and entrained in the uprising magma as xenocrysts, or as an accessory mineral included in the xenoliths. As for lamproites, only the olivine lamproites are found to be potentially diamondiferous since other varieties, such as leucite lamproites, presumably originate at too shallow depth.

3. Distribution of Diamond Deposits and World Production

Virtually all primary diamondiferous provinces are confined within ancient *cratons*, or regions that have remained stable and have not been involved in rifting or orogenic processes for a long geological period. The age of the continental crust in these areas is thus generally Archaean: in other words, older than ca. 2.5 Ga (Figure 3). This paradigm has long been known as “Clifford’s rule.” The only significant exception to Clifford’s rule is the extremely high-grade Argyle lamproite in Western Australia, which is located in an off-craton setting within a Proterozoic mobile belt. A few other economic or possibly economic lamproites (for example at Bobi, Côte d’Ivoire; Prairie Creek, Arkansas, USA) are located on Proterozoic terranes. No primary diamond deposit is known in crustal terranes younger than 1.6 Ga. This peculiar association suggests a link between the presence of diamonds and the age of the subcontinental lithosphere, and Clifford’s rule has long been considered as a valuable selection criterion in diamond exploration programs. It is worth noting here that diamondiferous kimberlites and lamproites are usually fairly young compared to the age of the lithosphere in which they have intruded. Many (including most South African examples) are Cretaceous, many others are Palaeozoic (as in the Sakha Republic, Siberia), but the whole array extends from the Proterozoic (for example Premier Pipe, RSA; Argyle, Western Australia) to the Neogene (such as some 22 Ma examples in Western Australia), with significant clustering of ages on a global scale. Most primary deposits are associated with secondary deposits, which may locally constitute the major resource. Only the most important are shown in Figure 3. Some geologically ancient secondary deposits, such as those of Myanmar, Thailand, and Indonesia, do not seem to be spatially related to any primary deposits, but may well have been so at the time of their formation, when continental plates had a different distribution on Earth’s surface. In some cases, the apparent lack of parent primary deposits may indicate simply that they have not yet been discovered, as is probably the case for alluvial diamonds in Côte d’Ivoire, Ghana, and other localities.

The size of diamond stones range from that of the very small microdiamonds (under 0.5 mm in diameter) to that of the famous Cullinan Diamond, recovered in South Africa in 1905, which reached 3106 carats. In primary deposits, diamond frequency decreases exponentially with increasing size. This systematic trend is a useful guide in preliminary evaluations of diamond productivity, in which the abundance of microdiamonds is used

to predict the overall grade. The total estimated quantity of diamond mined in the world up to the year 2000 is ca. 3.2 billion carats (645 t), and over 100 million carats (~22 t) are produced every year.

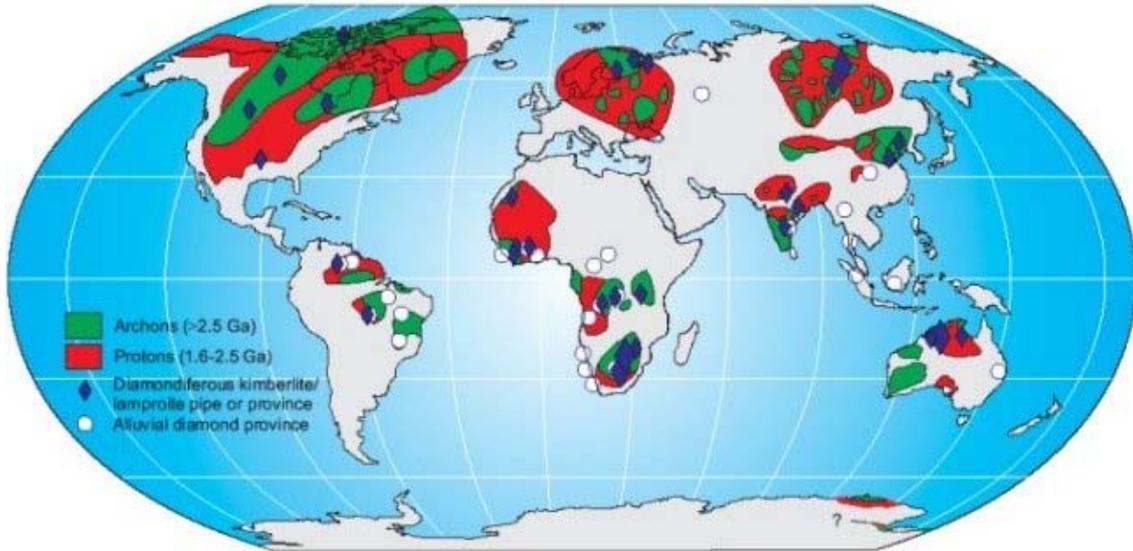


Figure 3. World distribution of main diamond deposits (adapted and modified from Janse and Sheahan, 1995)

<i>Country</i>	<i>Diamonds</i>		<i>Value</i>
	(1 000 carats)	\$/carat	(US\$,000)
Botswana	21 348	76	1 612 550
Russia	16 200	94	1 523 000
South Africa	9 733	101	984 601
Zaire	22 000	33	725 000
Angola	3 625	150	543 960
Australia	29 784	15	436 752
Canada	2 510	168	421 680
Namibia	1 611	257	413 529
Sierra Leone	600	230	138 000
Guinea	550	218	119 900
Central African Republic	450	205	92 250
Venezuela	450	130	58 500
Brazil	900	45	40 500
Tanzania	232	160	37 120
Liberia	200	160	32 000
Côte d'Ivoire	165	145	23 925
Ghana	500	38	19 000
China	146	103	15,104
Lesotho	43	345	14,714
Guyana	11	85	935

Total	111 058	65	7,253,020
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Source: *Mining Journal*, June 16, 2000, p. 466.

Table 1. World diamond production (1999)

The first findings of diamond were in alluvial deposits in India and Borneo. Brazil was the world's leading producer during the eighteenth and nineteenth centuries. It was only in 1870 that the first primary deposits were discovered in South Africa, following a fortuitous finding of an alluvial diamond in 1866. South Africa soon became a major producer, contributing more than 97% of the total world's diamond production at the beginning of the twentieth century. The closure of the Kimberley Mine in 1914 and important discoveries in other African countries (Namibia, Zaire, Angola, Ghana, Tanzania, Sierra Leone) between 1908 and 1932 drastically reduced South Africa's impact on the diamond market. Further major discoveries from 1954 to 1970 in Guinea, Côte d'Ivoire, Liberia, Russia, and Botswana, as well as new findings in South Africa, significantly enlarged the panorama of world diamond production. The opening of the exceptionally high-grade Argyle Mine in 1983 at once made Australia the world's leading diamond producer by volume, supplying over 35 million low-quality carats per year (decreasing to slightly below 30 million carats in 2000), but accounting for only 6% of world production by value. In terms of value, the main present-day producers are Botswana (including among others the Jwaneng Mine, the world's second producer by volume with 11.4 million carats per year and the first by value at \$1.14 billion per year), Russia (including among others the Udachnaya Mine, the world's second producer by value at \$930 million), and South Africa, followed by Zaire, Angola, Australia, Canada, and Namibia. Namibia's entire production is from secondary deposits and over half is from its enormous offshore resources, estimated at over 1.5 billion carats. Small operations are pursued in Lesotho, China, Brazil, Venezuela, Guyana, and India. Western and southern Africa, Finland, Russia, and especially Canada (its first mine in the Lac de Gras area, NWT, opened in October 1998) are currently the regions with the best potential for future diamond mining. Disordered social conditions, particularly in some African countries (Angola, Zaire, Sierra Leone), are still a serious obstacle to development of modern exploration and exploitation strategies. Because of the extremely large reserves in marine placers (possibly up to 3 billion carats along the western coast of Namibia and South Africa), considerable effort is currently being expended on exploitation of offshore deposits, particularly in view of the progressive exhaustion of many onshore mining sites. Large reserves are believed to exist off the north-western coast of Australia, in the Arctic Ocean off the coasts of Canada and Russia, and off the west coast of Africa. Antarctica has a high diamond production potential, although at present technological problems and international agreements prevent mining on this continent.

4. The Origin of Diamond

The origin of diamond is still far from thoroughly understood. Contrary to past belief, only in certain cases does diamond seem to have crystallized directly from the host kimberlitic magma. This possibly applies to many microdiamonds, but certainly does not to most of the commercial-sized macrodiamonds that constitute the fortune of any exploitable diamond deposit.

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Biographical Sketch

Paolo Nimis graduated in Geological Sciences in 1990 and took a Ph.D. in Earth Sciences in 1994 at the University of Padua, Italy. He obtained a two-year post-doctoral fellowship in 1995 at the same University. In 1997 he was a visitor researcher at the Research School of Earth Sciences, Australian National University, Canberra, with the financial support of an Italian C.N.R. fellowship. In 1998 he became Researcher in Ore Deposits at the Department of Mineralogy and Petrology of the University of Padua. His main fields of interest have concerned the development of thermobarometric methods and their application to natural rocks. His current lines of research involve the evaluation of the pressures and

temperatures of equilibration of high-pressure ultramafic rocks and diamond inclusions and the development of mineralogical methods for assessment of diamond potential. Part of his present research activity is devoted to the study of hydrothermal massive sulfide deposits.