25. PRIMARY DIAMOND DEPOSITS

25.1 Kimberlite-hosted diamond

25.2 Lamproite-hosted diamond

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INTRODUCTION

Diamonds are lithologically widely distributed, and are found in unconsolidated and consolidated sediments (placers and paleoplacers), various igneous rock types of deep-seated origin (kimberlite, orangeite, lamproite, alnoite, aillikite, picritic monchiquite, alkali basalt), high pressure mantle xenoliths, high pressure metamorphic rocks, and also meteorites and their impact structures. Of these, only diamond-bearing kimberlite, orangeite, and lamproite, plus associated placers and paleoplacers, are economically viable. Prior to 1960, more than 80% of all diamonds were derived from secondary deposits; by 1990, this figure was less than 25% (Levinson et al., 1992).

Diamond is the only mineral commodity extracted from kimberlite- or lamproite-hosted deposits. Diamonds are subdivided into industrial, near-gem, and gem quality stones. However, they are also described as being either 'cuttable' or 'industrial' (Levinson et al., 1992). Based on 1992 world production figures, approximately 50% by weight of a total production of 105 Mc (where Mc = million metric carats; c = metric carat = 0.2 g) was industrial grade, the remainder being cuttable. Industrial grade stones are used for a variety of purposes, but compete with synthetically produced industrial diamonds (estimated 1993 production 450-500 Mc; G.T. Austin, pers. comm., 1994).

Only primary diamond deposits are discussed here. These have been subdivided into two groups on the basis of their host rocks, which are either kimberlites or lamproites. In addition to their host rock differences, these deposits also differ in morphology, mineralogy, and other respects. These differences between the two types are discussed in the summary accounts that follow.

25.1 KIMBERLITE-HOSTED DIAMOND[1]

B.A. Kjarsgaard

IDENTIFICATION

In kimberlite-hosted deposits, diamonds occur mainly as sparsely dispersed, mantle-derived xenocrysts and diamondiferous mantle xenoliths in the kimberlite matrix. Economic quantities of diamond are mainly found in kimberlite diatremes. Kimberlites with preserved crater facies rocks are much rarer, but are in a few cases important high grade and high tonnage deposits.

The best examples of diamond-bearing kimberlites in Canada are several pipes in the Lac de Gras field, Northwest Territories. Grades established during current drilling and bulk sampling associated with pipe evaluation include A-154 south pipe (450 c/100 t), Misery pipe (419 c/100 t), Panda and Koala pipes (95 c/100 t), Leslie pipe (33 c/100 t) and the Fox pipe (27 c/100 t). These grades (as well as per cent gem quality stones) from preliminary samples are similar to those at producing mines (see below). Exploration and grade establishment also continues in the Attawapiskat and Kirkland Lake fields, Ontario and the Fort à la Corne and Candle Lake fields in Saskatchewan. Published grades for pipes from the Kirkland Lake and Fort à la Corne fields range from 1-23 c/100 t (Brummer et al., 1992; Northern Miner, 1995). These and other Canadian kimberlite localities are shown in Figure 25.1-1.

World class examples of kimberlite-hosted diamond deposits include the Orapa (67-130 c/100 t) and Jwaneng (154 c/100 t) pipes in Botswana, the Venetia (120 c/100 t) and Premier (35 c/100 t) pipes in South Africa, and the Mir (200 c/100 t) and Udachnaya (100 c/100 t) pipes in Yakutia.

IMPORTANCE

There is no past or current production of diamonds from kimberlite-hosted deposits in Canada. If diamond grade and stone quality from large bulk samples currently being extracted from the Lac de Gras pipes match results from smaller samples taken previously (see above), production decisions could be made by late 1996, with mining commencing in 1998. Diamond is an important mineral commodity, with many uses, including gemstones, abrasives, semiconductors, scientific instruments, surgical instruments, machine cutting tools, and drill bits. Before 1980, all production of diamonds was derived from kimberlite and related placer and paleoplacer deposits. Currently, this has decreased to about 65% (by weight; 93% by market value); the remainder is derived from lamproite and related placer deposits.

Kjarsgaard, B.A.
1996: Kimberlite-hosted diamond; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 560-568 (also Geological Society of America, The Geology of North America, v. P-1).

SIZE AND GRADE OF DEPOSIT

In kimberlite pipes, the grades and qualities of diamond vary considerably. Approximately 1% of all kimberlite pipes worldwide are economic. There are about 5000 kimberlites worldwide; fifty were mined at some time or another, twenty are active, and fifteen are major producers. The viability of any deposit is dependent upon a number of variables, including stone quality, stone size, grade (c/100 t), tonnage, extraction method (open pit versus underground), and processing costs, as well as local tax structure, environmental legislation, and infrastructure. An important economic parameter utilized is average US$/carat, determined from large (5000+ carats) parcel(s) of stones. The highly variable character of producing mines is illustrated by the ranges of the following parameters: size (1-150 ha), grade (4-600 c/100 t), average carat value (10-400 US$/c). Typical grades of economic kimberlites are listed throughout this paper.

In simple terms, deposit size is related to the erosional level of the pipe, coupled with its original shape (see Fig. 25.1-2A, B) and geology. The maximum long axis for near-surface craters is 1.5-2 km and their surface extent ranges from 200-40 ha. Examples include M1, Botswana (216 ha); Mwadui, Tanzania (146 ha); Pioneerskaya, Arkhangel, Russia (40 ha); and Orapa (106 ha). Very large kimberlites occasionally form due to multiple pipe coalescence; examples include the Jwaneng (52 ha) and Premier (32 ha) triple pipes and the Udachnaya (22 ha) and Frank Smith-Weltevreden, (South Africa, 8 ha) double pipes. Usually, however, at upper diatreme levels the maximum long axis is no more than 700 m. Examples of large diatremes include the Zarnitsa, Siberia (25 ha) and Letseng, Lesotho (16 ha, but the ore zone is only 4 ha in area) pipes. Due to the downward tapering of the diatreme, at root zone level (see Fig. 25.1-2A) diameters may only be tens of metres (e.g., Kimberley and De Beers mines, South Africa).

Grade (c/100 t) combined with stone value (US$/c) (Fig. 25.1-3A) illustrates the ore value for a number of economic pipes worldwide. An approximate 'in ground value' in US$billion to 120 m depth (Fig. 25.1-3B) can be calculated from deposit size to 120 m (Mt) combined with ore value (US$/t). Figure 25.1-3B illustrates that most economic pipes have 'values' of US$0.5-5 billion, exceptionally rich pipes have 'values' of US$10-17 billion. In practice, many pipes are mined to 1 km depth or more and with this increased tonnage theoretical mine 'values' can be upwards of $75 billion. The life spans for individual mines range from 25 years to more than 100 years (e.g. the Kimberley area Dutoitspan, Bulfontein, and Wesselton mines)

[1] Two types of kimberlite have been recognized (Wagner, 1914; Smith, 1983): 'basaltic' or 'Group I' kimberlite, hereafter termed kimberlite, and; 'micaceous' or 'Group II' kimberlite, hereafter termed orangeite (Mitchell, 1991). These latter rocks have only been recognized in South Africa, and therefore will not be discussed in greater detail.

GEOLOGICAL FEATURES

Setting and associated structure

Kimberlites are restricted to continental shield areas and are not associated with rift valleys. Economic kimberlites are found within Archean (>2.5 Ga) cratons. Kimberlites generally occur in clusters of two to twenty pipes; a kimberlite field (being approximately 50 km in diameter), consists of one to a number of separate kimberlite clusters of similar age. Kimberlite provinces consist of one or more fields. The Yakutia kimberlite province consists of twenty kimberlite fields; magmatism occurred in five distinct episodes from the Late Ordovician to the Late Jurassic. The initiation of kimberlite magmatism is deep seated, and correlation of this magmatism with hotspots or plate tectonic processes (transform fault extensions, subduction zones, etc.) has not been satisfactorily demonstrated on a worldwide basis. No viable theory exists which can predict the location of kimberlite fields within a craton. However, at the scale of a kimberlite field, individual pipes are believed to be located upon linear or arcuate trends related to major crustal fracture zones. These structural features provide an easily exploitable route for the ascent of deep-seated kimberlite magmas (Mitchell, 1991). The worldwide distribution of kimberlite pipes in relation to Archean cratons is shown in Figure 25.1-4.

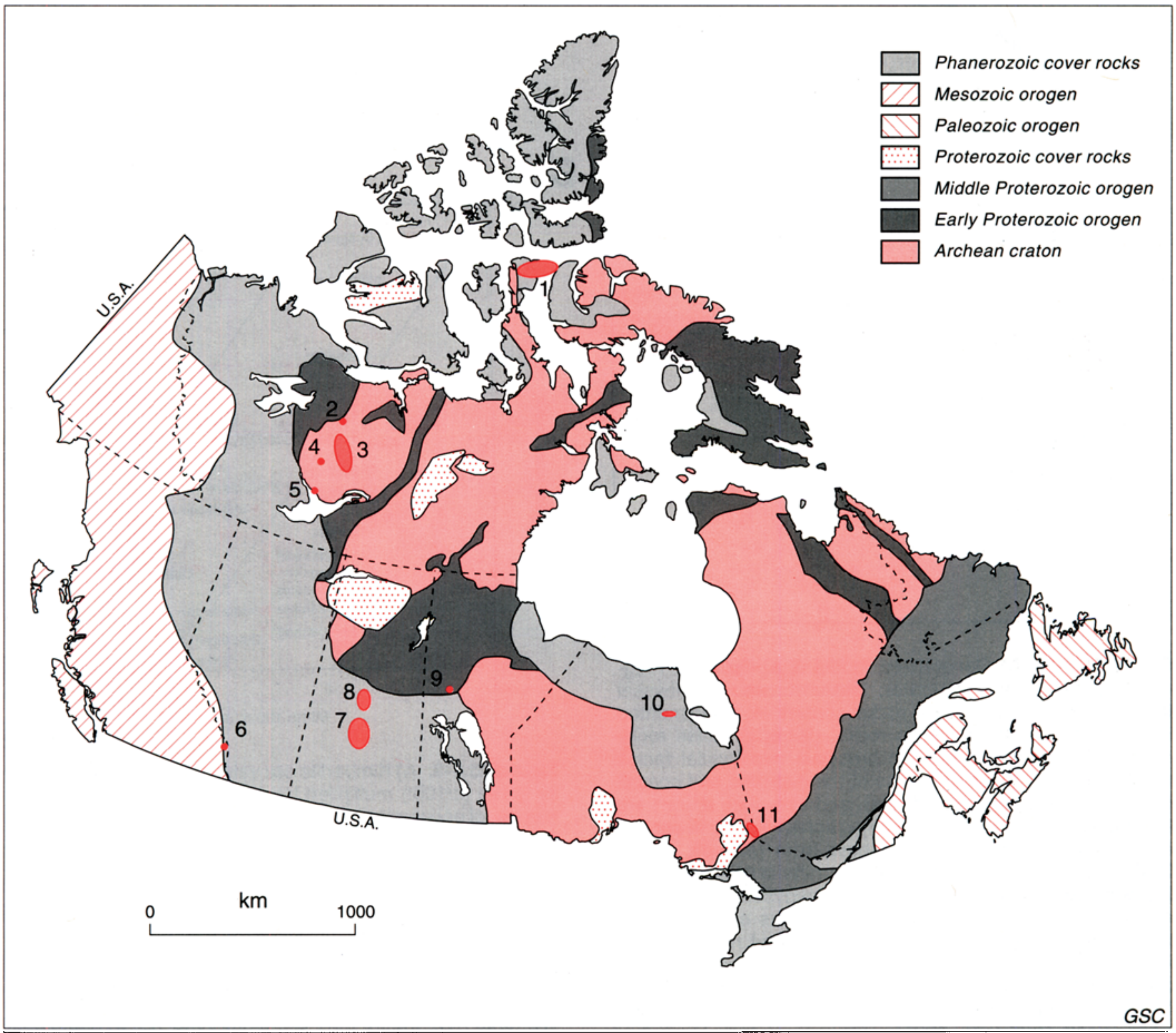

Figure 25.1-1. Location map of kimberlites in Canada: 1) Somerset Island field; 2) Ranch Lake; 3) Lac de Gras field; 4) Cross Lake; 5) Dry Bones Bay; 6) Crossing Creek; 7) Fort à la Corne field; 8) Candle Lake field; 9) Snow Lake-Wekusko; 10) Attawapiskat field; 11) Kirkland Lake/Timiskiming fields.

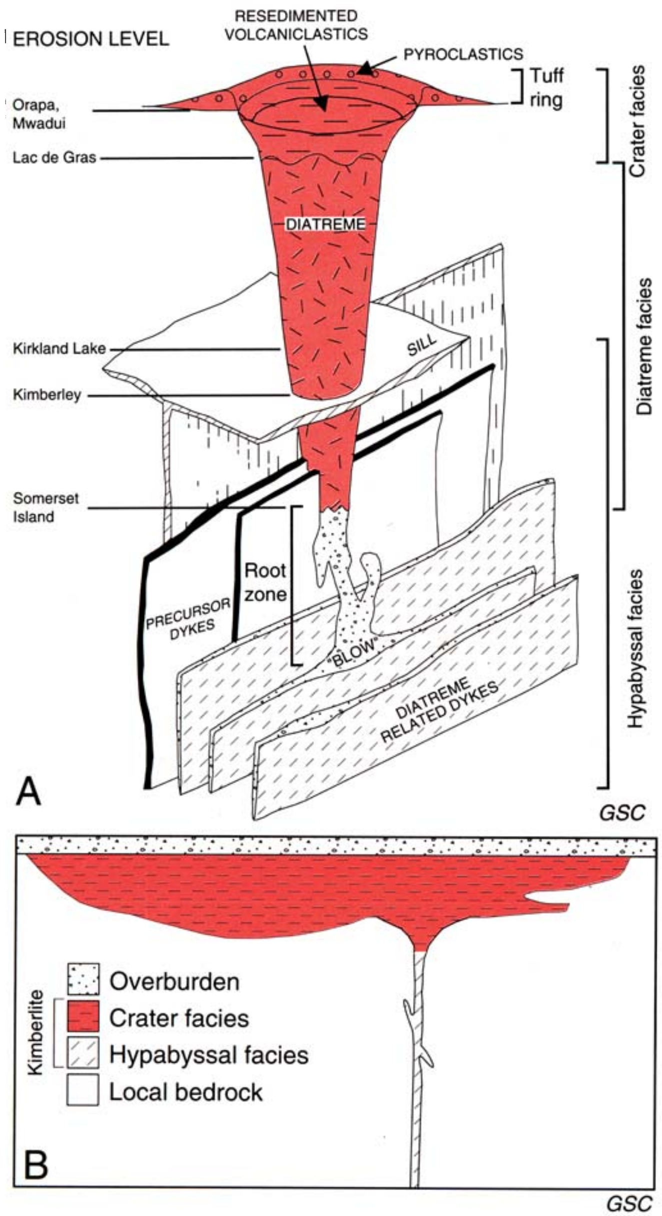

Figure 25.1-2. A) Generalized model of a kimberlite magmatic system, showing crater, diatreme, and hypabyssal facies rocks. Crater facies rocks consist of resedimented volcaniclastic and pyroclastic rocks; diatreme facies rocks consist dominantly of tuffisitic breccias; hypabyssal facies rocks are found in the root zone of the diatreme and consist of dykes, blows (enlarged dykes), and sills. Also shown are the present erosion levels of some representative economic and Canadian kimberlites (adapted from Mitchell, 1986), **B)** Generalized model of a kimberlite crater in which diatreme facies are absent. Thin (metre scale) hypabyssal feeder dykes are not necessarily observed. These craters are dominated by a wide variety of different pyroclastic and resedimented volcaniclastic rock types. Examples of this type of kimberlite crater include Mbuji Maye, Zaire; and Fort à la Corne, Saskatchewan (adapted from Meyer de Stadhelhofen, 1963 and Lehnert-Thiel et al., 1992).

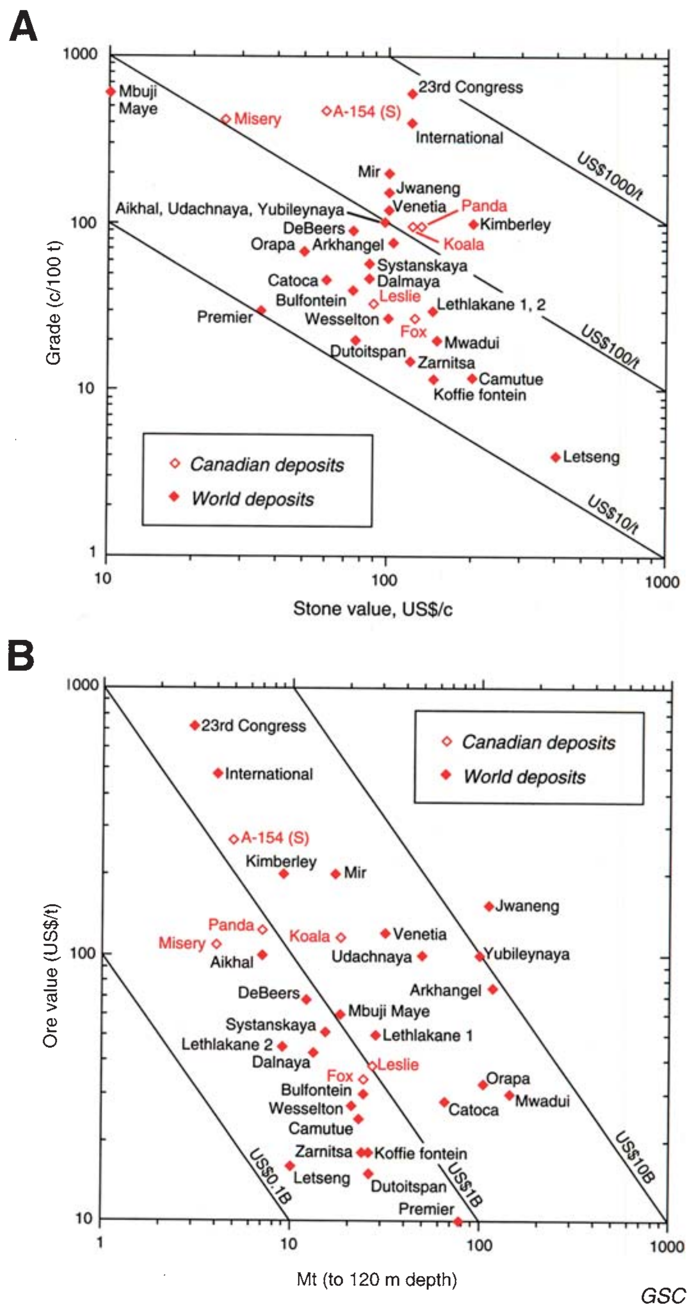

Figure 25.1-3. A) Kimberlite ore value (US$/t) as determined by grade (c/100t) multiplied by diamond value (US$/c) for a number of economic kimberlite pipes worldwide (labelled filled diamonds; data from Janse, 1993) as compared to the Northwest Territories pipes (labelled open diamonds; data from various press releases). **B)** 'In ground kimperlite pipe value' (in US$B to a depth of 120 m) as determined by deposit size (Mt to a depth of 120 m) multiplied by average value per tonne (US$/t) for a number of economic kimberlite pipes worldwide (labelled filled diamonds; data from Janse, 1993) as compared to the Northwest Territories pipes (labelled open diamonds; ore value from Figure 25.1-3A; tonnage to 120 m depth estimated by the author).

Age of host rocks and diamond

Intrusion ages of economic kimberlite pipes range from the Mesoproterozoic (Middle Proterozoic) to the Middle Eocene (Table 25.1-1). The presence of diamonds (and associated kimberlite indicator minerals) in the Witwatersrand Conglomerates (ca. 2.9-2.7 Ga) is taken as evidence for kimberlite volcanism of Archean age. Consistent with these Archean ages are syngenetic diamond inclusions which have been dated at or have model ages of 3.3-0.6 Ga, inferred to be the formation ages of the diamonds. Examples in which both kimberlite host rock age and diamond formation age have been determined illustrate that the diamonds are 3.2 Ga to 1 Ma older than the host rocks.

Relationship of diamond to host rock

Age determinations on diamonds and their kimberlite hosts (see above) are consistent with other evidence suggesting that kimberlite-derived diamonds (specifically macro-diamonds: >1 mm) are xenocrysts. Kimberlites act as transportation agents only, bringing diamonds or diamond-bearing mantle xenoliths from within the diamond stability field (>4.5 GPa or 150 km depth) to the surface. In general, diamonds are disseminated throughout the kimberlite host, although 'intact' diamond-bearing mantle xenoliths are also found. Diamond inclusion silicate minerals and silicate mineral assemblages in diamond-bearing mantle xenoliths indicate that macro-diamonds can be of either eclogitic (E-type) or peridotitic (P-type) paragenesis. Diamond inclusion studies illustrate that the proportion of E-type to P-type stones at different mines is variable. At Wesselton the diamond population consists of 2% E-type and 98% P-type stones, whereas at Orapa, 85% of the stones are E-type and only 15% are P-type (Gurney, 1989). Grades reported for diamondiferous mantle xenoliths have been extrapolated to suggest that mantle source rocks are moderately to highly diamondiferous; inferred grades range from 0.5-650 c/100 t for peridotitic mantle to 17-37 000 c/100 t for eclogitic mantle.

Form of deposit and diamond distribution

In kimberlites which have preserved crater facies rocks, two distinct types of craters have been recognized. The most common type consists of resedimented volcaniclastic and rare pyroclastic rocks that overlie diatreme facies kimberlite (e.g., Mwadui and Orapa; see Fig. 25.1-2A). Crater walls dip inward at angles ranging from 25° to 75°. Craters of the other type are extremely rare and have only recently been recognized. These consist mainly of pyroclastic kimberlite with associated resedimented volcaniclastics (Fig. 25.1-2B). Contacts are horizontal to shallowly (0° to 35°) dipping. Diatreme facies rocks are absent and the feeder dyke(s) are

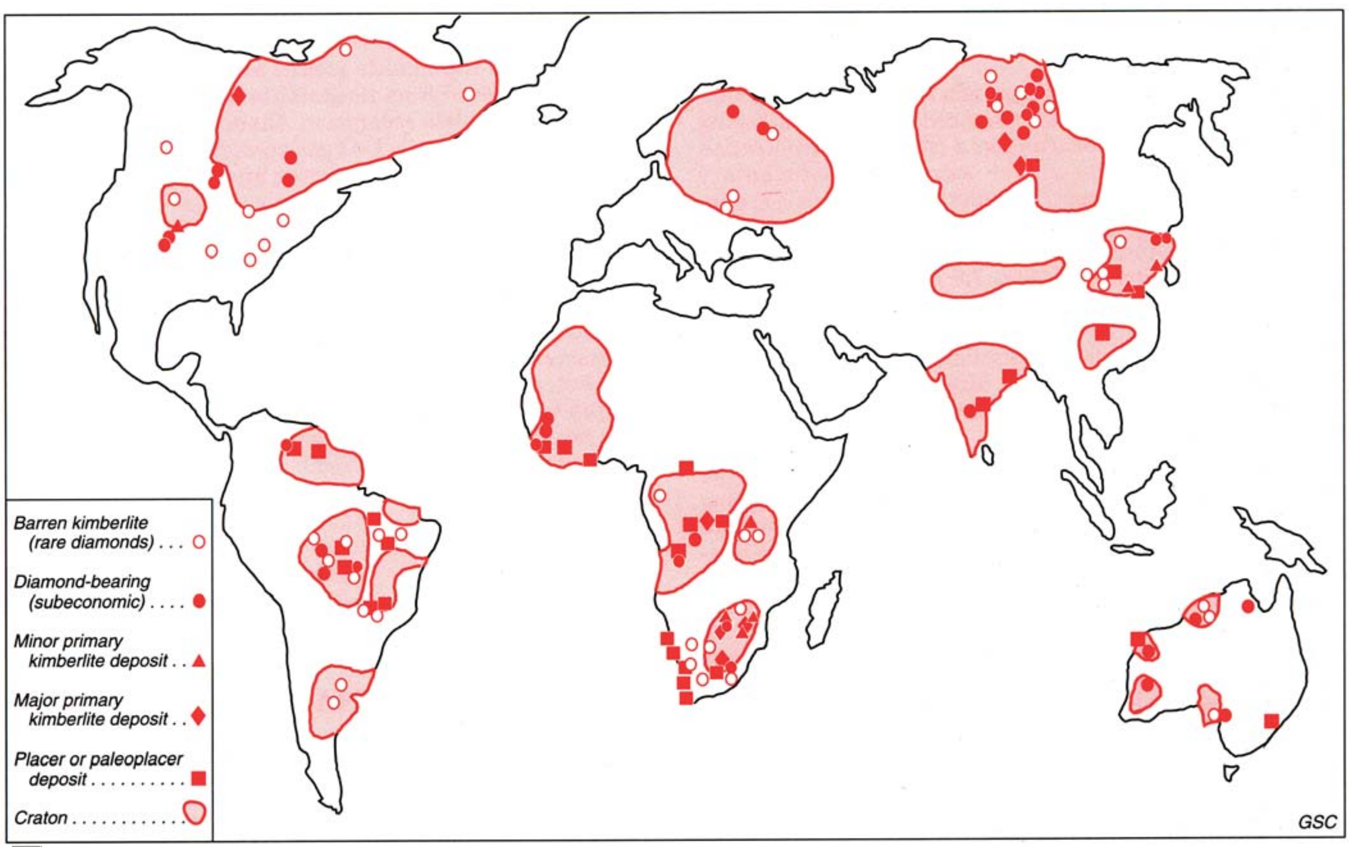

Figure 25.1-4. Distribution of kimberlites worldwide in relationship to Archean cratons. (Adapted from Janse, 1984; Atkinson, 1989; Gurney, 1989; Helmstaedt, 1993; and Janse, (pers. comm., 1994).

Table 25.1-1. Radiometric ages of selected economic kimberlites worldwide, plus additional Canadian examples. Data sources are from the bibliography and cited references of this paper (Ages indicated by * from L. Heaman and B.A. Kjarsgaard, unpub. data).

	Age (Ma)	Localities
Middle Eocene	52 55-50	Lac de Gras, Canada Mwadui, Tanzania
Late Cretaceous	71 73* 84 93 95	Mjubi Maye, Zaire Lac de Gras, Canada Dutoitspan, South Africa Orapa, Botswana Kimberley pool, South Africa
Early Cretaceous	99* 99*	Fort à la Corne, Canada Somerset Island, Canada
Late Jurassic	155*	Kirkland Lake, Canada
Early Triassic	250-235 250-240	Jwaneng, Botswana Crossing Creek, Canada
Late Devonian	361	Mir, Yakutia
Mesoproterozoic	1180	Premier, South Africa

not always observed. Examples include the Mbuji Maye pipe in Zaire, and kimberlite pipes in the Fort à la Corne field, Saskatchewan.

The concentrations of diamonds in craters facies kimberlite are in some cases enhanced due to weathering (denudation of tuffs, resulting in a residual concentration of resistant minerals) and/or associated sedimentary reworking (fluvial, lacustrine, marine processes). Exceptionally high diamond grades of 660 c/100 t are reported for the Mbuji Maye kimberlite, although more than 95% of the stones are industrial quality. At Mwadui, it has been inferred that the resedimented volcaniclastic rocks were richer in diamonds (both grade and stone size) than the diatreme facies rocks below. Similarly, the surface (crater) grade at Orapa is 132 c/100 t, almost twice the reported subsurface (diatreme) grade of 64-69 c/100 t. The grade of the Jwaneng crater is 154 c/100t.

Usually kimberlites manifest themselves as cone-shaped diatremes (see Fig. 25.1-2A), with steeply dipping (75°-85°) country rock contacts. Diatreme facies rocks consist mainly of tuffisitic kimberlite breccias, which are relatively uniform compared to crater or hypabyssal facies rocks. Although a diatreme can be comprised of ten to twenty separate, identifiable types of kimberlite, grades are relatively uniform throughout the diatreme. This is envisaged as a result of mixing processes involved in diatreme formation (Mitchell, 1991). Grades reported from mined kimberlite diatremes are highly variable, i.e. 4 c/100 t (Letseng), 60 c/100 t (Systanskaya, Yakutia), 120 c/100 t (Venetia, South Africa), 400 c/100 t (International, Yakutia). Very high grades may be encountered in weathered diatreme facies kimberlite at the surface. Wagner (1914) observed at the Premier pipe that surface grades (highly weathered kimberlite) were initially more than 150 c/100 t but after four years of mining were less than 50 c/100 t and after 15 years of mining were 32 c/100 t (the present day grade). Although official grades are unavailable for the Russian pipes, at Mir surficial diatreme facies kimberlite grades of 300-400 c/100 t are inferred to be much higher than subsurface diatreme facies rock which grades 60-200 c /100 t.

With increasing depth, kimberlite diatremes grade into root zones (see Fig. 25.1-2A), consisting of multiple intrusions of kimberlite forming dykes, blows (enlarged dykes), and sills. Pipes which have been eroded to the level of the root zone are usually not economic (Mitchell, 1991). However, extraction of root zone kimberlite may be viable if mining continues after the diatreme facies rocks are exhausted (e.g., pipes in the Kimberley cluster, South Africa). In the root zone of a kimberlite pipe, several distinct intrusive phases of hypabyssal kimberlite occur. Grades of different intrusive phases within a root zone are variable: e.g., 1.6 - 17.8 c/100 t at Dutoitspan and less than 10 c/100 t to more than 40 c/100 t for the W3 kimberlite at Wesselton.

Alteration

Porous kimberlite crater and diatreme facies rocks are highly susceptible to alteration by weathering processes after emplacement. This alteration leads to the development of 'yellow' and 'blue' ground, whose properties (e.g., resistivity) can be used in exploration programs. Diamonds, however, are not affected by these surficial weathering processes and therefore surface grades may be much higher (see previous discussion of Premier and Mir) due to kimberlite volume loss. During transport by the kimberlite magma from the mantle source area to the surface, diamond is removed from its stability field and may undergo partial or complete resorption. Diamond can be converted to either graphite or a C-O gas species (CO, CO_2), depending upon magma fO_2 and reaction kinetics (P-T dependent). At low fO_2 diamond is very stable. It has been suggested that resorption of octahedral macro-diamonds to stones with tetrahexahedroid morphology implies a weight loss on the order of 45 to 60% (Gurney, 1989). Kimberlite-derived magnesian-ilmenite compositions are utilized as a monitor of redox conditions to indicate the potential for diamond preservation. In general (if the kimberlite is diamond-bearing) ilmenites with low Fe^{3+}/Fe^{2+} ratios (i.e., low fO_2) are associated with higher diamond contents, whereas diamonds are not found in association with high Fe^{3+} (i.e. high fO_2) ilmenites that are low in MgO.

Ore mineralogy

Diamond is the only 'ore' mineral extracted from the kimberlite host. The associated minerals are discussed below.

DEFINITIVE CHARACTERISTICS

Kimberlite is a volatile-rich ultrabasic rock that has an enriched incompatible (Sr, Zr, Hf, Nb, REEs) and compatible (Ni, Cr, Co) element signature similar to, but distinct from, lamproites. Kimberlite often appears hybrid in nature, as they may contain mantle xenoliths, xenocrysts, and macrocrysts (large crystals 1-20 cm in size), plus crustal xenoliths in a matrix crystallized from kimberlite melt.

Contents

The following definition of kimberlite has been adapted from Clement et al. (1984) and Mitchell (1986). Kimberlites are CO_2- and H_2O-rich ultrabasic rocks that have a distinctive inequigranular texture due to the presence of large, rounded, anhedral macrocrysts (i.e., megacrysts and xenocrysts) plus euhedral to subhedral phenocrysts set in a finer grained groundmass. The macrocryst suite of minerals includes minerals derived from disaggregated mantle xenoliths plus olivine (the essential macrocryst), Mg-ilmenite, Ti-Cr-pyrope garnet, clinopyroxene, phlogopite, enstatite, and zircon of the megacryst suite. Primary matrix minerals include second generation euhedral olivine phenocrysts/microphenocrysts, and one or more of the following: spinels, ilmenite, perovskite, monticellite, apatite, phlogopite-kinoshitalite$_{ss}$ mica, carbonates, and serpentine. Primary groundmass microcrystalline diopside has been observed only in crustally contaminated rocks. Commonly, macrocrysts and both early- and late-formed matrix minerals (e.g., monticellite) are replaced by deuteric serpentine and calcite.

The diverse mineralogy and associated mineral chemistry of kimberlites are reflections of the unusual major and trace element composition of these rocks. In this respect, combined petrographic, mineral chemistry, and whole-rock geochemical studies can usually discriminate kimberlites from other rock types of similar mineralogy (e.g., alnoite, aillikite, and other lamprophyres) and magmatic style (Mitchell, 1986). Chemical zoning trends observed in minerals such as phlogopite (plots of Al_2O_3-FeO and Al_2O_3-TiO_2) and spinel (reduced and oxidized spinel prism plots) can be particularly useful in constraining the identification of an unknown rock type (Mitchell, 1986).

Peridotite and eclogite xenoliths, plus minerals derived from their disaggregation are also observed in kimberlites. Eclogite xenoliths are characterized by pyrope-almandine garnet and omphacitic pyroxene, as well as accessory rutile, kyanite, corundum, coesite, and diamond. Peridotite xenoliths are olivine-rich with variable amounts of orthopyroxene, clinopyroxene, spinel, and garnet plus accessories (e.g., phlogopite, amphibole, rutile, and diamond).

Kimberlite typically occurs as small (<1 km diameter), steep walled (75°-85° dips), carrot-shaped diatremes occurring in clusters. Complex root zones consisting of hypabyssal kimberlite are found at the base of the diatreme. Large (to 2 km) craters are rarely preserved. Kimberlite-filled craters have shallowly dipping (0°-75°) contacts and may resemble vents formed by hydrovolcanic processes (see also subtype 25.2, "Lamproite-hosted diamond"). The greatest potential for diamonds is found in pipes with preserved diatreme and/or crater facies kimberlite. Unfortunately, these rocks are highly susceptible to alteration and weathering, and either do not outcrop (e.g., under lakes) or form poor outcrops in low or swampy ground.

GENETIC MODEL

Thermobarometric calculations on mineral assemblages from diamondiferous mantle xenoliths and polymineralic diamond inclusions are consistent with diamond existing in regions of the mantle at depths greater than150 km. It is rarely possible to establish precise constraints on the formation of macro-diamonds; igneous, metamorphic, and metasomatic origins have all been suggested. On the basis of carbon isotope studies of eclogitic diamonds, it is inferred that the carbon for at least some of these stones originated at or near the Earth's surface and was transported into the mantle via subduction processes. In contrast to eclogite paragenesis diamonds, peridotitic diamonds have a restricted range of carbon isotopic compositions, consistent with a juvenile (mantle) source of the carbon. Macro-diamonds are transported from the mantle to the surface by kimberlite magmas (see Fig. 25.1-5).

Kimberlites occur in a restricted tectonic setting and are observed only in ancient continental shield regions older than 1.5 Ga (Clifford, 1966). The most favourable tectonic environment for kimberlite pipes is a thick, old craton with low heat flow values; economic kimberlites are restricted to Archean cratons (>2.5 Ga; see Fig. 25.1-4). The initiation of kimberlite magmatism is deep seated, and magma generation is poorly understood. Correlation of this magmatism with hotspots or plate tectonic processes (transform fault extensions, subduction zones) cannot be satisfactorily demonstrated on a worldwide basis. Kimberlite magmas are thought to form by the partial melting of carbonated peridotite source regions (Eggler, 1989). However, Ringwood et al. (1993) have proposed an alternate model in which kimberlite magma is generated by partial melting in the transition zone (400-650 km depth). Ultra-high pressure majorite garnets that occur as inclusions in diamonds (Moore and Gurney, 1985) and in mantle xenoliths (Haggerty and Sautter, 1990) are consistent with kimberlite magma formation at depths of at least 300 km.

The range in diamond contents of kimberlites is dependent upon the amount of diamond-bearing mantle material entrained by the ascending magma, the proportions of various mantle lithologies (eclogite and peridotite; eclogite often contains higher modal diamond content) sampled and the degree to which resorption and mechanical sorting of this entrained material occurs during transport to the surface. Kimberlites probably ascend through the mantle at substantial velocities (10-30 kilometres per hour; Eggler, 1989) by crack propagation processes. Near the surface, vent velocities of several hundred kilometres per hour may be possible, due to rapid CO_2 degassing from the magma. Highly explosive, near surface volcanism is consistent with the formation of kimberlite diatremes and craters as well as the entrainment of large amounts of angular crustal material. This can cause dilution of grade which in some cases is significant. Crater and diatreme facies kimberlite contain the highest diamond grades, hypabyssal rocks generally have low diamond tenors.

RELATED DEPOSIT TYPES

Lamproite (see subtype 25.2, "Lamproite-hosted diamond") and orangeite form the only other important primary diamond deposits with established economic potential. Associated with primary deposits are secondary (placer and paleoplacer) deposits. The distribution patterns of important secondary deposits closely mimics primary distribution (i.e., closely associated with stable cratonic nuclei; Gurney, 1989). Diamonds in these deposits are inferred to be dominantly kimberlite-derived, although in South Africa orangeite-derived diamonds are also important.

The alluvial diamond deposits of Sierra Leone and along the Zaire-Angola border region, as well as the marine terrace deposits in Namaqualand and southwest Africa-Namibia, are examples of economic secondary deposits.

The Namibian eolian deposits are thought to be reworked marine terrace deposits. Diamonds from placer deposits in general have a very high proportion of gem-quality stones; this improvement is thought to be due to the preferential breakage of inferior crystals (Gurney, 1989). Extreme secondary enrichment of diamonds (grades of 1000 c/m^3) have been reported from favourable trap sites in placers and paleoplacers.

The primary sources for some secondary diamond fields remain unknown. Secondary diamond deposits (of unknown source) which have yielded significant quantities of diamonds are located in Brazil, India, southeast Australia, China, and western Transvaal, South Africa (Gurney, 1989). In the Great Lakes region of North America, more than 80 diamonds of as much as 21 carats in weight (most are less than 1 carat) have been recovered from glacial drift. Although the primary source of these stones is unknown (Brummer, 1978), they are possibly derived from kimberlites of the Kirkland Lake or Attawapiskat fields. Many 'sourceless' lone diamonds have been recovered from diverse regions of the globe, but this is not surprising in light of the inherent hardness and chemical stability of diamond. These diamonds, however, must have had a primary source, likely a kimberlite or lamproite.

EXPLORATION GUIDES

Economic kimberlites are found in old (>2.5 Ga) stable cratons characterized by thick crust and low geothermal gradients. Various methods are used to locate kimberlites, depending upon local conditions: i.e., type of country rock, climate, and overburden. The main exploration techniques used are: 1) indicator mineral sampling (heavy mineral separates from stream sediment sampling, soil sampling, and till sampling); 2) remote sensing (LANDSAT, airphoto interpretation); 3) geophysical surveys (magnetic, gravity, electrical, radiometric, seismic profiling); and 4) geochemical. Biogeochemical methods have also been utilized. Atkinson (1989) provided a recent general summary of exploration techniques.

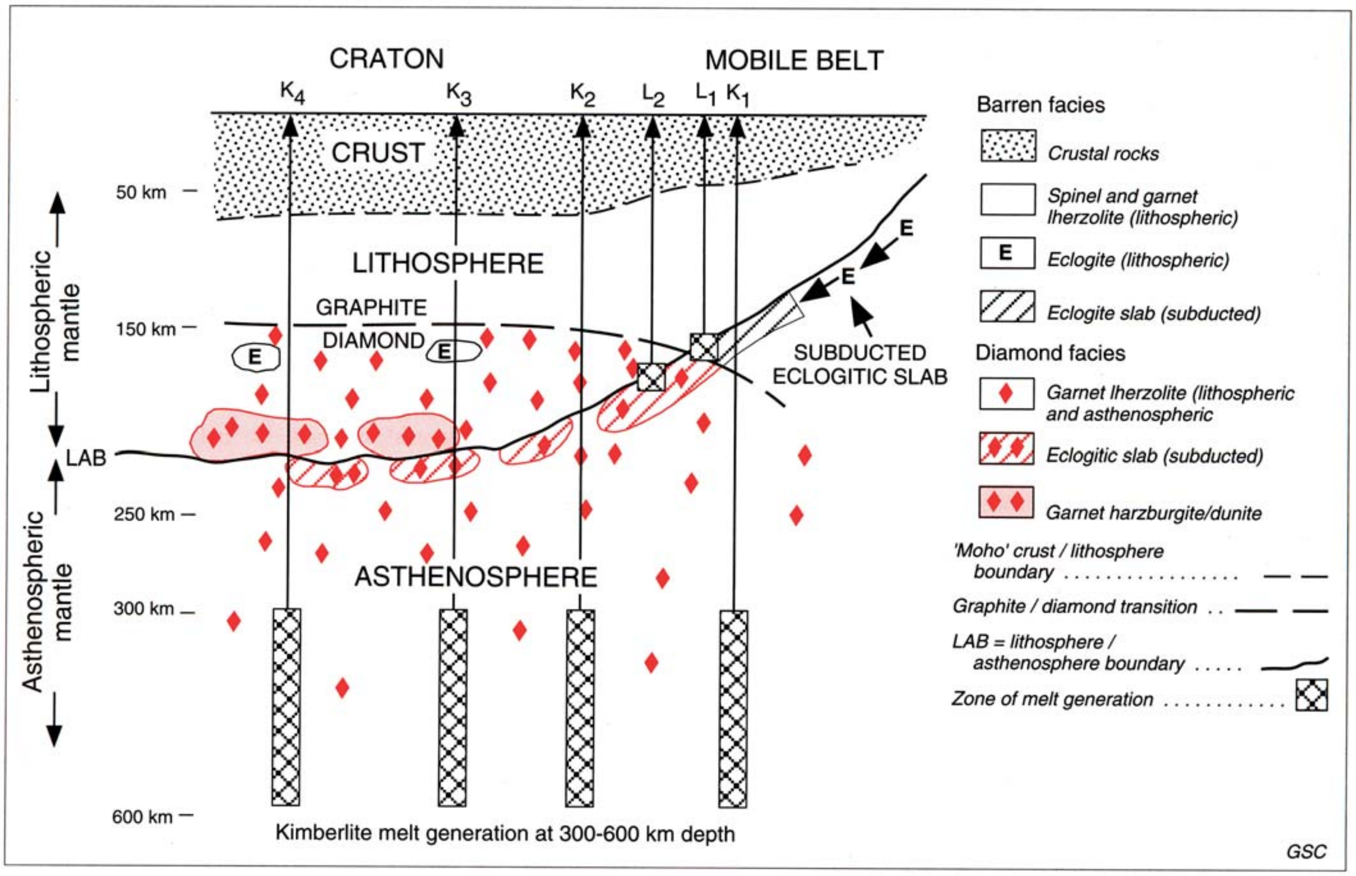

Figure 25.1-5. Schematic model illustrating magma source regions and the relationship between the ascent of these magmas and diamond source rocks in an Archean craton and surrounding mobile belt. Salient points on this diagram are described in the figure key. Kimberlites (asthenospheric source), depending upon the nature of the mantle they ascend through may contain: no diamonds (path K1); diamonds from lithospheric and asthenospheric garnet lherzolite (path K2); diamonds predominantly from eclogites, plus minor contributions from garnet harzburgite/dunite and garnet lherzolite (path K3); diamonds predominantly from garnet harzburgite/dunite, plus minor contributions from eclogite and garnet lherzolite (path K4). Lamproite (lithospheric source: see subtype 27.2) ascent routes are shown as path L1 (barren) and L2 (diamondiferous). Modified from Mitchell (1991).

Because kimberlites are rare rocks which generally form poor outcrops, exploration methods (like those for many other ore deposits) must be capable of finding a hidden target. While the geophysical signature of kimberlites is not unique, it is unusual and can be discerned by low-level aeromagnetic and EM surveys. Numerous kimberlite pipes in the Arkhangel region (Russia) and the central Kalahari in Botswana were located by aeromagnetic surveys. This technique is most effective in areas with a uniform and low magnetic background. Combined aeromagnetic and electromagnetic surveys have been used with a high success rate in the Lac de Gras field, Northwest Territories. A recent, comprehensive review of geophysical techniques as applied to kimberlite exploration can be found in Urquart and Hopkins (1993).

The unique mineralogical signature of kimberlites enables the application of indicator mineral sampling exploration techniques. The identification of resistant minerals that can indicate the potential presence of a kimberlite has been widely and successfully applied as an exploration technique in South Africa, Yakutia, and Canada. However, it is extremely important to note that these so-called kimberlite indicator minerals are also found in many other rock types that do not contain diamonds. Kimberlite indicators include minerals derived from the kimberlite (spinel, olivine, ilmenite, and perovskite), all the macrocryst minerals (olivine, spinel, low-Cr Ti-pyrope, Mg-ilmenite, Cr-diopside, enstatite, and zircon), as well as minerals from disaggregated mantle xenoliths (olivine, enstatite, Cr-diopside, chrome pyrope garnet, Cr-spinels, pyrope-almandine garnet, omphacitic pyroxene, and diamond). In Canada, application of the indicator mineral method to stream sediment sampling is problematic due to Quaternary glaciation. However, success in locating kimberlite pipes has been obtained by esker and till sampling in the Lac de Gras, and Kirkland Lake areas. A combination of alluvial and stream sediment sampling coupled with ground magnetics was utilized in the discovery of pipes at Attawapiskat.

Because diamond is a rare mineral in kimberlite, (0-1.4 ppm), a subset of the indicator minerals, termed 'diamond indicators' is used to indicate the potential presence of diamond in these rocks. This is based on studies of silicates and oxide inclusions in diamond and minerals from diamond-bearing mantle xenoliths (Gurney, 1989). Specific diamond indicator minerals (with xenolith-paragenesis type in brackets) include subcalcic Cr-pyrope (garnet-bearing harzburgite/dunite source), Cr-pyrope garnet (garnet-bearing lherzolite source), high-Cr-Mg chromite (chromite-bearing harzburgite/dunite source), and high-Na-Ti pyrope-almandine garnet (eclogite source). It is important to note that these minerals (and xenoliths) are not definitive of kimberlite volcanism, as they can be observed in other rock types of deep-seated origin (e.g., ultramafic lamprophyres). Furthermore, these minerals are not an infallible indicator of the presence of diamond in kimberlite; the Skerring (Australia) and Zero (South Africa) kimberlites both contain subcalcic Cr-pyrope garnet, but lack diamonds (Gurney, 1989).

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Critical reviews by Barbara Scott-Smith and Roger Mitchell on an early version of the manuscript greatly improved the content. Comments by R.I. Thorpe, O.R. Eckstrand, D.F. Sangster, and A.N. LeCheminant on later versions were quite helpful. The final version was capably reviewed by A.J.A. Janse, whose comments clarified a number of points.

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25.2 LAMPROITE-HOSTED DIAMOND

B.A. Kjarsgaard

IDENTIFICATION

In lamproites, as in kimberlites, diamond occurs as sparsely dispersed xenocrysts in the matrix. Economic quantities of diamonds are found mainly in lamproite pyroclastic rocks, but rarely also in dykes. Diamonds have yet to be found in lamproite lavas. Viable lamproite diamond deposits are all hosted by vent facies olivine lamproite tuffs; examples include the Argyle AK1 mine, Australia and the Majhgawan mine, India.

No lamproites have yet been found in Canada, although they are known in the U.S.A. (e.g., Leucite Hills, Wyoming; Prairie Creek, Arkansas).

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1996: Lamproite-hosted diamond; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 568-572 (also Geological Society of America, The Geology of North America, v. P-1).

IMPORTANCE

Initially, the Argyle deposit was considered to be kimberlitic (Atkinson et al., 1984). The importance of lamproite as a diamond host rock has only been recognized since 1984, a result of the landmark studies of Scott-Smith et al. (1984, 1989). They determined that some 'anomalous' diamond-bearing kimberlites are actually lamproites (e.g. Prairie Creek; Majhgawan mine; Kapamba, Zambia). The Argyle AK1 mine in Australia, discovered in 1979, is of vast economic importance. This deposit currently produces just over one third (by weight) of all diamonds mined (38.4 Mc/a), 400% more than the most productive kimberlite mine (Jwaneng, Botswana; 9.4 Mc/a). In value, however, Argyle stones represent only 7% of world production, as 95% of the diamonds mined are either industrial grade or poor quality gemstones.

In Canada, rocks of the lamproite type are unknown and there is no past or current production of diamonds from this deposit type.

SIZE AND GRADE OF DEPOSIT

The Argyle AK1 mine has a surface area of approximately 46 ha. The reported grade for 1987 for a variety of tuffs ranged from 100 to 680 c/100 t (Grice and Boxer, 1990). Hyalo-olivine lamproite lapilli tuffs at the Majhgawan mine (9 ha surface area), have diamond grades of 8 to 15 c/100 t (Scott-Smith, 1989). The Prairie Creek vent has a surface area of 27 ha, and grades approximately 13 c/100 t. At present, this deposit is not mined (it is now a state park), but is being re-evaluated. Approximately 100 000+ carats of diamond were mined from 1907 to 1933 (Waldman and Meyer, 1992). The Ellendale 4 vent, Australia (surface area 84 ha) grades 3 to 25 c/100 t, but is a sub-economic deposit.

Established grades for diamond-bearing lamproites (<1-680 c /100 t) are similar to those of kimberlites. However, the exceptionally high grade of the Argyle AK1 mine is anomalous with respect to other lamproites. Typical reported grades for other diamondiferous olivine lamproites range from <1 to 30 c /100 t, lower than most economic kimberlites. The economic viability of any diamond-bearing lamproite is dependent upon a variety of factors, such as grade, tonnage, average $/carat etc. (see also subtype 25.1, "Kimberlite-hosted diamond").

GEOLOGICAL FEATURES

Setting and associated structure

Diamond-bearing lamproites occur in a wide variety of geological and tectonic settings. This precludes the formulation of a universal model constraining the geotectonic setting in which they were emplaced. The following diamondiferous lamproites illustrate this variety. The Argyle and Ellendale lamproites are in Mesoproterozoic mobile belts at the margins of the Archean/Paleoproterozoic

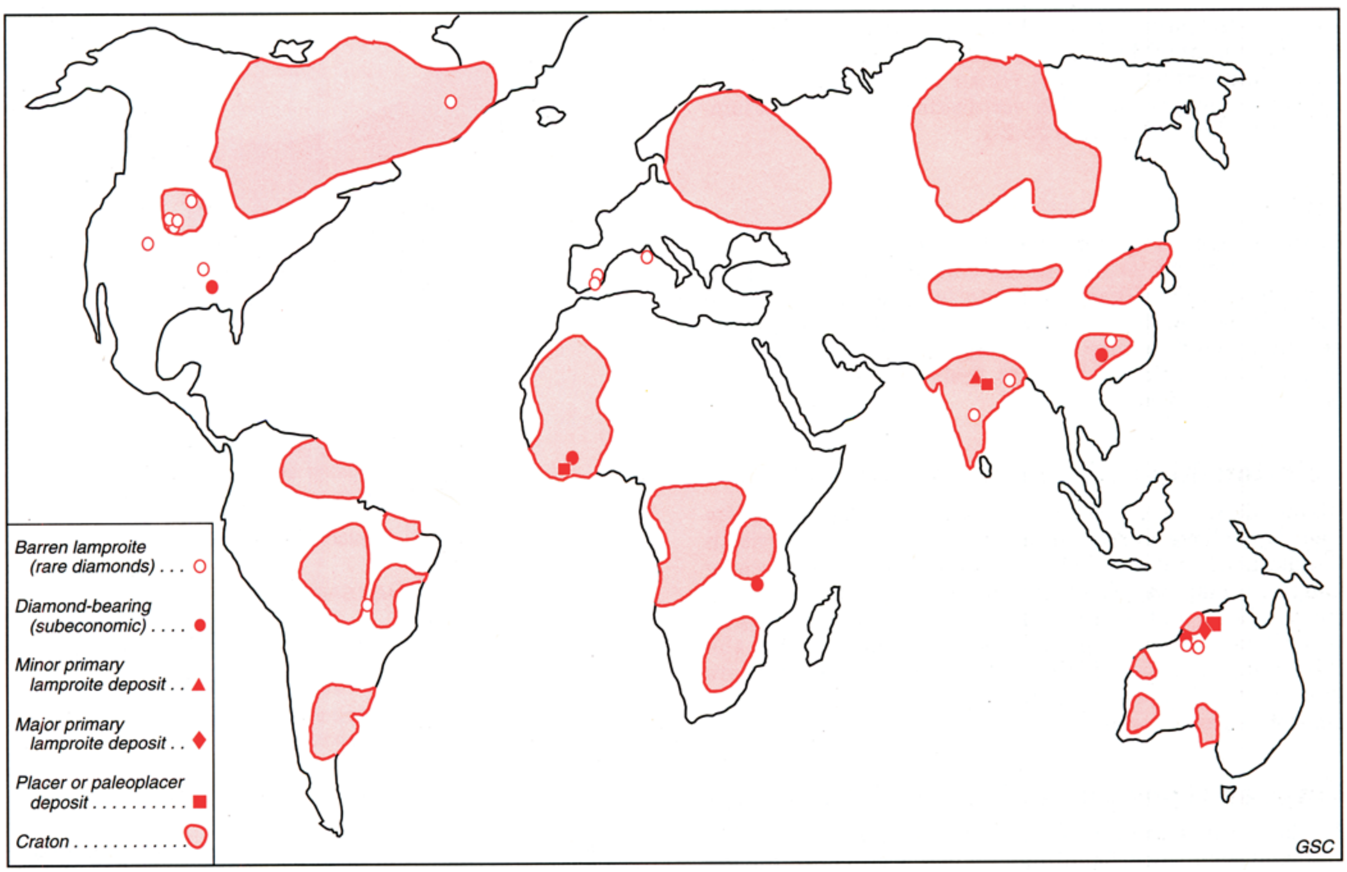

Figure 25.2-1. Distribution of lamproites worldwide in relationship to Archean cratons. Barren lamproites in Antarctica are not shown. Localities from Mitchell and Bergman (1991), Helmstaedt (1993), and Janse (pers. comm., 1994).

Table 25.2-1. Radiometric ages of diamondiferous lamproites worldwide. Data from Mitchell and Bergman (1991).

	Age (Ma)	Location
Tertiary	22-18	Ellendale, Australia
Cretaceous	106-97	Prairie Creek, U.S.A.
Late Triassic	≈220	Kapamba, Zambia
Mesoproterozoic	1170-1140 1178-1126 1455-1150	Majhgawan, India Argyle, Australia Bobi, Ivory Coast

(Early Proterozoic) Kimberley block. Their emplacement appears to have been strongly controlled by major fracture zones that represent lithospheric lines of weakness. The Prairie Creek vent (which lies well off craton) was emplaced near the intersection of the Reelfoot rift and the southeastern edge of the Phanerozoic Ouachita orogenic belt (marginal to the 1.7-1.6 Ga Mazatzal-Pecos structural province). The Kapamba lamproites are located in the Luangwa graben, an extension of the East African Rift (Scott-Smith et al., 1989). This graben occurs in the Proterozoic Irumide and Mozambique tectonic belts, to the south of the Archean Tanzanian craton. The Bobi dykes (Ivory Coast) have intruded Archean-Paleoproterozoic granitic basement of the West African Shield. Lamproites are also found within stable Archean cratons (e.g., Leucite Hills, Wyoming craton). The worldwide distribution of lamproites is shown in Figure 25.2-1.

Age

Intrusion ages of the lamproite host rocks span the range from the Mesoproterozoic to the Late Pleistocene. Typical radiometric ages of diamondiferous lamproites are listed in Table 25.2-1. As for kimberlites, diamonds in lamproites are interpreted to have formed during the Early Archean to the Proterozoic, previous to their entrainment in the lamproite host magma.

Relationship of diamond to host rock

Diamonds in lamproites are considered to be xenocrysts (see "Age" above) derived from regions of the mantle within the diamond stability field and brought to the surface by lamproite magmas. Diamonds are disseminated throughout the host, and also found in diamond-bearing mantle xenoliths. Mineral inclusions in diamond from the Ellendale, Argyle, and Prairie Creek lamproites indicate that macro-diamonds (>1 mm) are of both eclogite and peridotite paragenesis.

Form of deposit and diamond distribution

For lamproites, subeconomic to commercial quantities of diamond have been found mainly associated with olivine lamproite vents. Figure 25.2-2A illustrates the typical form of a champagne glass-shaped lamproite vent (e.g. Ellendale field vents, Prairie Creek). Figure 25.2-2B illustrates the funnel-shaped form of the lamproite vents observed at

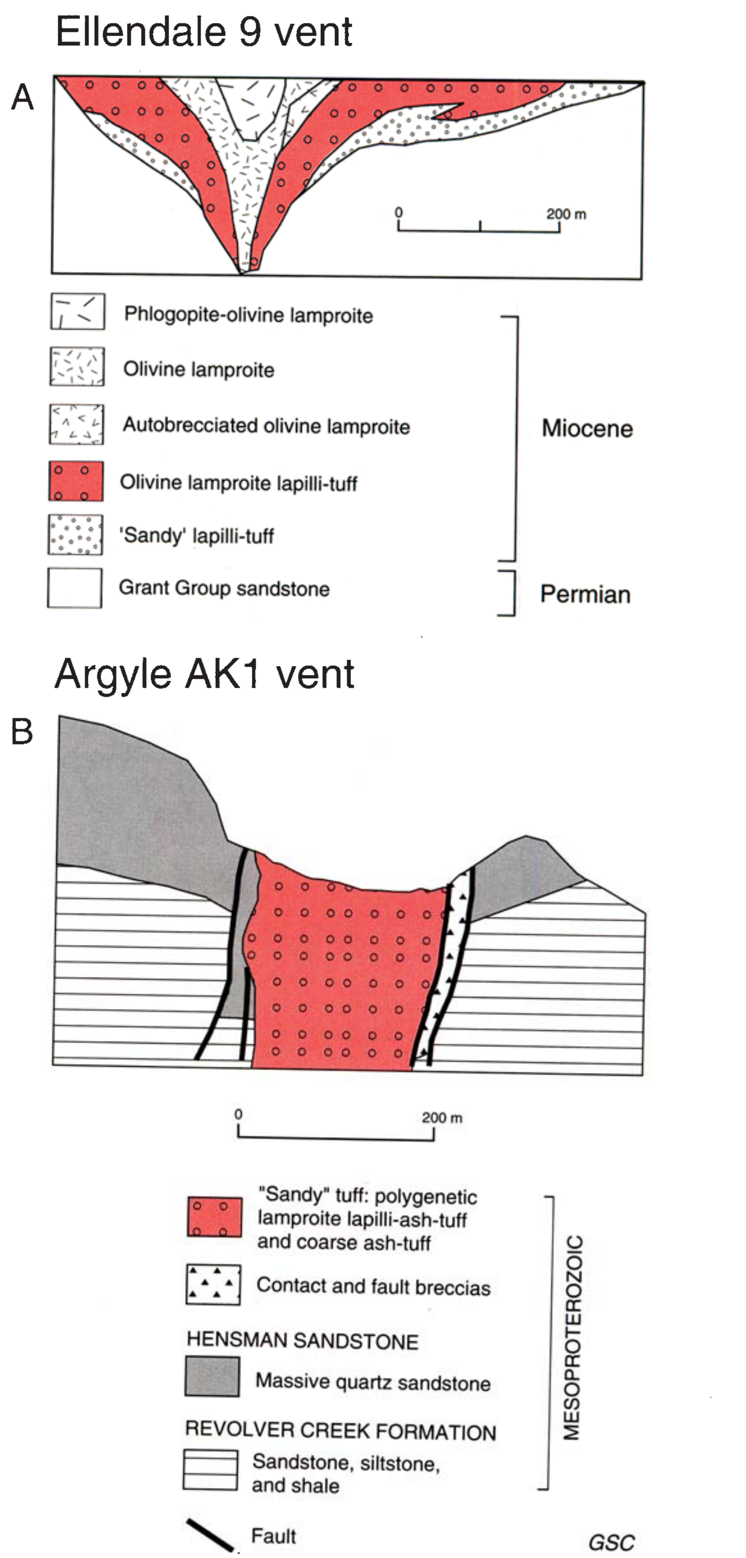

Figure 25.2-2. **A)** Simplified cross-section of the champagne-glass shaped Ellendale 9 lamproite vent (adapted from Jacques et al., 1986); **B)** Simplified cross-section of the funnel-shaped Argyle lamproite vent (adapted from Jacques et al., 1986).

Argyle and Majhgawan. At Argyle, Ellendale, Majhgawan, and Prairie Creek, the earliest tuffaceous phases appear to have the highest diamond tenors (Mitchell, 1991). Diamonds are also found in economic quantities in olivine lamproite dykes (e.g., Bobi; the Lissadell Road dykes associated with the Argyle mine), although lamproite lavas are nondiamondiferous. Diamond grades can be highly variable in vent facies rocks. For example, at Argyle the sandy tuffs (pyroclastic rocks with as much as 60% xenocrystic quartz) contain as much as 680 c/100 t, but tuffs rich in juvenile clasts have much lower grades (100 c/100 t; Deakin and Boxer, 1989). In contrast, at Ellendale diamond grades increase from the earliest contaminated 'sandy' lapilli-tuff (1-4 c/100 t) to later uncontaminated olivine lamproite lapilli tuffs (3-30 c /100 t; Jacques et al., 1986).

Alteration

During transport by the lamproite magma from the mantle source area to the surface, diamond is removed from its stability field and may undergo graphitization or partial to complete resorption (conversion to CO_2). Although H_2O-rich lamproite magmas are thought to have higher intrinsic oxygen fugacities (i.e., high diamond resorption potential) than CO_2-rich kimberlite magmas (Mitchell, 1991), this is an oversimplification. Lamproite diamond populations from Argyle (high degree of resorption and graphitization, irregular stone shapes) and Ellendale (no or low degrees of resorption, preserved crystal shapes) illustrate this variability.

Ore mineralogy

Diamond is the only 'ore' mineral extracted from the lamproite host. The associated minerals are discussed below.

DEFINITIVE CHARACTERISTICS

Lamproite is defined as an ultrapotassic ($K_2O/Na_2O>3$), peralkaline ([Na+K]/Al>1) and typically perpotassic (K>Al) rock, ranging from ultrabasic to intermediate (37-64 wt.% SiO_2) in composition. These rocks have enriched incompatible (Rb, Ba, Sr, Zr, Hf, Ti, P, Nb, REEs, Y, Th, U) and compatible (Ni, Cr, Co, V, Sc) element abundances similar to, but distinct from, kimberlites. Lamproites are characterized by the occurrence of at least one of the following: olivine, leucite, richterite, diopside, and sanidine (± glass).

The following explicit definition of lamproite is adopted from Scott-Smith and Skinner (1984) and Mitchell and Bergman (1991). Lamproites contain the following typomorphic minerals (5-90 vol.%): Al-poor, Ti-rich phlogopite phenocrysts; poikilitic groundmass Ti-rich tetraferriphlogopite; Ti-K-richterite; forsteritic olivine; Al-Na-poor diopside; Fe^{3+}-rich leucite; Fe^{3+}-rich sanidine. Not all of the above phases are required for a rock to be termed a lamproite, as one or two minerals may be modally dominant and the others subordinate or absent. Lamproites are divided into five petrographic groups, based upon the modal dominance of olivine, leucite, richterite, diopside, and sanidine. Accessory phases include apatite, perovskite, Mg-chromite, Mg-Ti-chromite, Mg-Ti-magnetite, potassian barian titanates (priderite and jeppeite), and potassian zirconian or titanian silicates (wadeite, davanite, and shcherbakovite). Other typomorphic accessories include armalcolite, ilmenite, and enstatite. Common alteration and secondary phases include analcite (replacing leucite and/or sanidine), barite, quartz, TiO_2-polymorphs, Ba-rich zeolites, chlorite, and carbonates. Megacrysts of Ti-Cr-pyrope and Mg-ilmenite (typical of kimberlites) are very rare to absent in lamproites. Mantle peridotite and eclogite xenoliths, plus minerals derived from their disaggregation are also (rarely) observed in these rocks.

The diverse mineralogy and associated mineral chemistry of lamproites are reflections of the unusual major and trace element compositions of these rocks. In this respect, combined petrographic, mineral chemistry, and whole-rock geochemical studies can discriminate lamproites from other rock types of similar mineralogy (e.g., leucite basanites, potassic alkali basalts, kamafugites, minettes, ultramafic lamprophyres, kimberlites, and orangeites) and magmatic style (Mitchell and Bergman, 1991). Chemical zoning trends observed in specific minerals such as phlogopite (plots of Al_2O_3-FeO and Al_2O_3-TiO_2) and spinel (reduced and oxidized spinel prism plots) are particularly useful in arriving at an identification of an unknown rock type (Mitchell and Bergman, 1991).

Lamproites occur as extrusive, subvolcanic and hypabyssal rocks. Ponded magma which has formed a lava lake, and pyroclastic rocks are the most common form of lamproite. Lava flows are rare. Lamproite volcanism is similar in style to alkali basaltic volcanism and small magma volumes preclude the formation of large stratovolcanoes and calderas. In contrast to kimberlite volcanism, lamproites do not form diatremes or root zones, but rather vents and dyke-lava lake systems (see Fig. 25.2-2A, B). The greatest potential for diamondiferous lamproites is in olivine-phyric tuffs in champagne glass- or funnel-shaped vents.

GENETIC MODEL

Lamproites occur in a wide variety of tectonic and geological settings that may be either on or off Archean cratons. Specifically, all economic and near-economic lamproites are found in Proterozoic terranes. These magmas have commonly intruded crust that overlies lithospheric mantle affected by earlier subduction or rifting events (Mitchell and Bergman, 1991). Lamproite magmas are derived by partial melting of ancient, enriched (metasomatized, i.e., amphibole-, phlogopite- and apatite-bearing) upper mantle sources (lithospheric) which have previously been depleted in Na, Al, and Ca (leaving a residuum of harzburgitic composition). The source region for diamond-bearing olivine lamproites must be at a depth of more than 150 km; these magmas sample diamond-bearing mantle en route to the surface, transporting the ore as xenocrysts and diamond-bearing xenoliths. Vent-filling, olivine lamproite pyroclastic rocks contain the highest diamond grades. The formation of these vents is believed to be a result of hydrovolcanic processes (resulting in maars and tuff rings).

RELATED DEPOSIT TYPES

Important secondary (placer) diamond deposits are associated with primary lamproite diamond deposits. These are shown on Figure 25.2-1 and include the Smoke and Limestone Creek placers downstream from the Argyle pipe (with grades lower than the pipe; 70-140 c /100 t) the Bow River placer east of Argyle (27 c /100 t) and the Sequéla placers, Ivory Coast (derived from the Bobi dykes).

EXPLORATION GUIDES

Economic lamproites are found within Proterozoic terranes, which are usually adjacent to stable cratonic blocks characterized by thick crust and low geothermal gradients. Exploration methodologies used to locate lamproites are the same as those for kimberlites (see subtype 25.1; "Exploration guides"). However, it is noteworthy that the responses to these surveys and tests are not necessarily the same as those obtained for kimberlites (Atkinson, 1989).

The two most successfully used lamproite exploration techniques are stream sampling for indicator minerals and low-level airborne surveys. The Ellendale and Argyle lamproites were initially discovered by stream sampling; follow-up aeromagnetic work located additional vents in the Ellendale area. In contrast to kimberlites, airborne electromagnetic surveys do not appear to be particularly effective; no additional pipes were found in the Ellendale field by EM methods. As in kimberlites, diamonds are rare in lamproites, and thus concentrates are examined to identify associated minerals that belong to the 'lamproite indicator mineral suite'. This suite is similar to, yet distinct from, the kimberlite indicator mineral suite and has a finer grain size. Lamproite indicators include minerals from disaggregated mantle xenoliths (diamond, Cr-Al-Mg-Fe spinels, Cr-pyrope garnet, pyrope-almandine garnet, olivine, and rarely Cr-diopside and orthopyroxene) and lamproite liquidus phases (Cr-rich spinels, olivine, Ti-rich phlogopite and richterite, diopside, priderite, wadeite, perovskite). Megacrysts of Ti-Cr-pyrope and Mg-ilmenite (typical of kimberlites) are very rare to absent in lamproites.

As in the case of kimberlites, the specific compositions of certain indicator minerals can be used to assess diamond potential. Unfortunately, the well defined method of estimating diamond grade from extensive studies of low calcium, high chromium pyrope garnets in kimberlites (Gurney, 1989) is not reliably applicable to lamproites; studies based on kimberlite indicator minerals at both Argyle and Prairie Creek resulted in forecasts of low diamond potential due to the lack or near absence of such garnets.

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