

DIAMONDS AND ASSOCIATED HEAVY MINERALS IN KIMBERLITE: A REVIEW OF KEY CONCEPTS AND APPLICATIONS

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ABSTRACT

Kimberlite, a variety of ultramafic volcanic and sub-volcanic rock, is the dominant source of diamonds worldwide. It is widely accepted that the majority of diamonds are not formed within the kimberlite and much evidence points towards an ancient origin for most diamond in the deep lithospheric keels of Archaean cratons. The kimberlites, therefore, are transporting agents that “sample” deep, occasionally diamond-bearing, mantle material and rapidly convey it to surface. The dominant source rocks for diamond are highly depleted peridotite (harzburgite or dunite) and high-pressure eclogite. These are minor components of the mantle lithosphere, which is dominated by less-depleted peridotite (primarily lherzolite) and lesser amounts of non-diamondiferous eclogite. While other diamond sources are known, these rarely contribute significantly to diamond populations in kimberlite. Despite the limited range of source lithologies, diamond population characteristics in any given kimberlite are typically highly complex and indicative of several distinct populations, most likely formed in discrete events occurring at different times, ranging from the Archaean to the age of kimberlite emplacement.

In addition to rare diamond, disaggregation of mantle rocks sampled by kimberlite yields relatively large quantities of other mantle minerals, commonly referred to as kimberlitic indicator minerals. From an exploration point of view, the most important indicator minerals are garnet, chromite, ilmenite, Cr-diopside and olivine. Several of these minerals display diagnostic visual and compositional characteristics, making them ideal pathfinders for kimberlite. The more chemically resistant minerals (garnet, ilmenite and chromite) are particularly useful due to their greater ability to survive weathering in the surface environment. Thus, sampling of surface materials to recover kimberlitic indicator minerals and tracing these back to their source is a key component of most diamond exploration programs.

Studies of diamond inclusions and diamond-bearing xenoliths permit geochemical characterisation of diamond source materials and have led to major advances in the understanding of the relationship between diamond and its host rock in the mantle.

Keywords: indicator-mineral; exploration; geochemistry; peridotite; eclogite; garnet; chromite; ilmenite; clinopyroxene

1. INTRODUCTION

Kimberlite is an ultramafic, alkaline igneous rock of deep-seated origin that can contain significant quantities of diamond (Mitchell, 1986). It is by far the most important primary source of these gems, accounting for more than 70% of world diamond production by value in 2003 (based on data in Willmott, 2004). The only other commercially significant primary diamond source is olivine lamproite, an ultramafic, ultrapotassic rock similar in certain respects to kimberlite (Mitchell, 1995). This rock type currently provides ~5% by value (~20% by weight) of world diamond production, with the balance of production deriving from secondary deposits in alluvial and marine sediments. The development of laboratory processes to produce diamonds (Bundy et al., 1973), and subsequent refinements that enable the mass manufacture of a superior product for industrial purposes, has had a major effect on the world market for natural diamonds which is now predominantly reliant for revenue on the global jewellery market.

It has been apparent for some years that kimberlite and lamproite are merely transporting agents carrying diamond from its source region in the upper mantle to the crust. Whether diamond remains at the end of the journey depends on whether it was present in the mantle rocks sampled and disaggregated by the kimberlite and on whether or not the diamonds were preserved (Gurney, 1984). A very high-grade kimberlite or lamproite might contain 5 carats (1 carat = 0.2 g) of diamonds per tonne of host rock, translating to a concentration of 1 part per million.

The proven diamond source rocks in the mantle are various types of peridotite (Dawson and Smith, 1975; McCallum and Egger, 1976; Pokhilenko et al., 1977; Shee et al., 1982), certain high pressure eclogite assemblages (e.g., Rickwood et al., 1969; Sobolev, 1974; Reid et al., 1976; Robinson et al., 1984) and closely associated websterites (e.g., Gurney, 1989), and the ultra-high pressure mineral majorite (Moore and Gurney, 1985). With the exception of majorite (a very rare association believed to be sourced from the asthenosphere), these diamond-bearing sources occur only in the deep portions of the thick lithosphere developed under Archaean cratons. Thus, all known significantly diamondiferous kimberlites occur within regions underlain by Archaean crust and/or mantle.

Minerals derived from the diamond source rocks described above are present in all kimberlites with significant concentrations of diamond. However, even in highly diamondiferous kimberlite, they are typically subordinate to ubiquitous mantle-derived minerals from rock types that do not have a clear association with diamond. In addition, most kimberlite intrusions do not contain significant concentrations of diamond, indicating that diamond is rare and sporadically distributed even in its original source region within the mantle.

Mantle-derived minerals sampled and brought to surface by kimberlite (and other similar rock types) are typically referred to as kimberlitic indicator minerals. The most important of these are garnet, ilmenite, chromite, Cr-diopside and olivine. Orthopyroxene (enstatite) is a key component of the lithospheric mantle but is highly reactive with the kimberlite magma and is, therefore, commonly absent or only preserved in trace amounts (Seifert and Schreyer, 1968). Similarly, omphacitic clinopyroxene, which makes up a significant proportion of mantle eclogite, is highly unstable at low pressure and it typically breaks down on ascent to the surface. Thus enstatite and omphacite are rarely useful as kimberlitic indicator minerals. The other mantle-derived minerals are commonly present in significant concentrations in most kimberlites and, even in highly diamondiferous bodies, are typically three or four orders of magnitude more abundant than diamond. As a result, indicator minerals provide an invaluable exploration tool, firstly as pathfinder minerals for locating kimberlites and, secondly, as indicators of the diamond potential of their host intrusion.

In this contribution, we review some important concepts relating to the origin of diamond and its association with other mantle minerals. These concepts form the basis for a tried and tested approach to the application of indicator mineral geochemistry in kimberlite exploration.

2. DIAMOND: PETROLOGICAL ASSOCIATIONS AND GENESIS

2.1. *Multiple Diamond Populations*

In both kimberlites and lamproites, diamonds range in size from microcrystals smaller than 50 μm to macrocrystals occasionally over 1 cm in size. It is clear that the full diamond suite in any given deposit incorporates several overlapping populations with diverse origins. Evidence for more than one population of eclogitic or peridotitic diamonds has been presented for several localities (Moore and Gurney, 1985, 1989; Deines et al., 1987; Otter and Gurney, 1989). In a study of diamonds from the low-grade Letseng La Terai locality in northern Lesotho, McDade and Harris (1999) detected 10 different diamond parageneses. Developing the same theme, Gurney et al. (2004) have described widely disparate diamonds recovered from various kimberlites on the Slave Craton (Fig. 1). These include flat-faced sharp-edged octahedra, fibrous cubes, coated stones, diamonds of various colours, cloudy stones, deformed crystals and extensively resorbed diamonds. It has been suggested that these also have been produced by a number of different diamond-forming processes in the mantle. It is apparent, therefore, that diamonds recovered from kimberlite generally reflect a variety of processes and most likely represent several different diamond sources.

2.2. *Peridotite and Eclogite: Key Diamond Sources*

Every diamond-bearing locality, for which a reasonable body of data exists, has diamonds of eclogitic and peridotitic paragenesis, as judged by mineral inclusions in the diamonds and often confirmed by the finding of diamond-bearing xenoliths



Fig. 1. Diamonds from kimberlites in the Ekati property, Slave province, Canada. These diamonds were recovered from geographically closely associated kimberlites in the Slave craton but are also broadly representative of diamonds from kimberlite worldwide. Examples of most of these diamond types can be found in any given kimberlite of the Ekati property. (A) Colourless, flat-faced octahedra from Fox. (B) Colourless, flat-faced octahedron from Fox, showing a characteristic imperfectly developed crystal termination. (C) Light brown octahedra from Grizzly. (D) Colourless, step-faced octahedron from Koala. (E) Colourless contact-twinning octahedral (macles) from Fox. (F) Brown, step-faced octahedron from Misery. (G) Dark brown octahedron from Koala. (H) Fibrous-coated, flat-faced octahedron from Panda. (I) Remnant fibrous coat on surface of a flat-faced octahedron from Panda; the coat has been sufficiently resorbed at the edges and corners to reveal a colourless, gem-quality interior. (J) Translucent lemon yellow cube from Sable. (K) Opaque, fibrous cubes from Grizzly. (L) Colourless cubo-octahedra from Piranha; the diamonds have a translucent core and transparent rims. (M) Light brown, rounded resorbed diamond from Fox with relict octahedral surfaces. (N) Colourless dodecahedron from Koala. (O) Light brown, rounded resorbed dodecahedron from Misery with well-developed curvilinear faces acquired during resorption. (P) Dark brown rutted and rounded dodecahedron from Misery. Diamonds in (A) through (G) have primary shapes and are expected to be old by analogy to other studies; (H) and (I) are primary old diamonds coated with young fibrous diamond; (J) may be a Type Ib, very young diamond; (K) are young fibrous cubes; (L) are intermediate between (A) through (G) and (K); (L) through (O) are all resorbed forms of diamonds anticipated to be old. [Reproduced from Gurney et al., (2004), Fig. 2, p. 29; permission by Elsevier, 2007.]

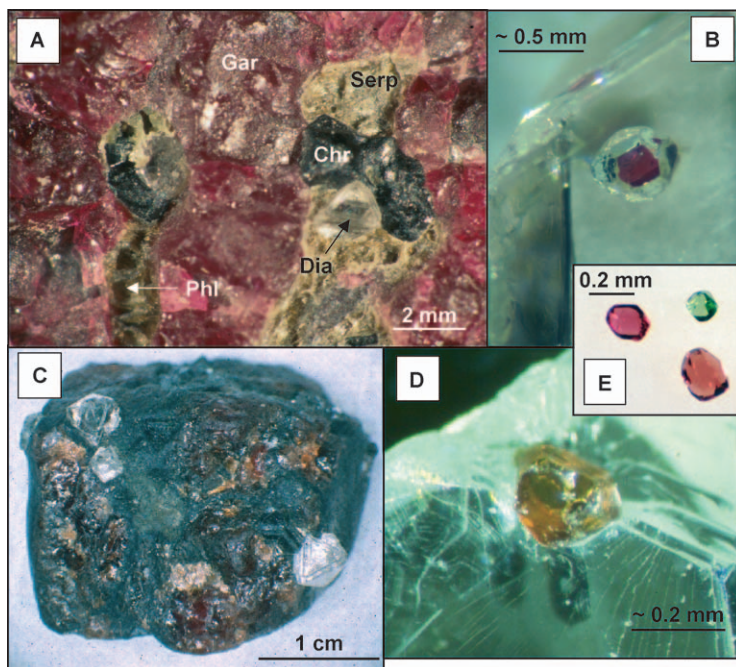


Fig. 2. (A) Diamondiferous sub-calcic garnet harzburgite xenolith from Newlands kimberlite, South Africa. Minerals present: garnet (Gar), chromite (Chr), phlogopite (Phl), serpentinized orthopyroxene and olivine (Serp), diamond (Dia). (B) Peridotitic garnet inclusion in diamond. (C) Diamondiferous eclogite xenolith from the Ardo kimberlite, South Africa; three colourless diamonds feature prominently on the surface; careful visual inspection of the hand specimen reveals three more diamonds on that surface and, taking all surfaces into account, 12 diamonds can be seen in this xenolith; other minerals are fresh garnet and partially altered clinopyroxene; prominent diamonds at lower right weigh ~ 0.3 carat. (D) Eclogitic garnet inclusion in diamond. (E) Comparison of harzburgitic G10 garnet (purple, upper left), lherzolithic G9 garnet (red, lower right) and diopside (green) inclusions liberated from two generations of peridotitic diamonds from the 1.2 Ga Premier kimberlite, Kaapvaal craton. [Photographs A, C and E reproduced from Gurney et al., (2005), Fig. 4, p. 158 with permission from the Society of Economic Geologists.]

(Fig. 2). Eclogite is a high-pressure rock type of broadly basaltic composition that is dominated by magnesium-rich but relatively chrome-poor garnet (pyrope) and sodic clinopyroxene (omphacite). Diamond-bearing eclogites are relatively common in diamondiferous kimberlite, particularly at some of the localities where eclogitic diamonds are common such as Orapa in Botswana. These xenoliths are not cognate to the host volcanic rock, but have clearly been sampled in the upper mantle and transported to the earth's surface fairly rapidly. This diamond source is also commonly represented as xenocrysts of low-Cr garnet with compositions similar to those of garnets in diamond-bearing eclogite and eclogitic garnet inclusions in diamond (see below).

Peridotites are a group of ultramafic rocks that are characterised by significant amounts of olivine (forsterite) in combination with varying quantities of

orthopyroxene (enstatite) and clinopyroxene (Cr-diopside). Chrome-rich pyrope garnet and/or chromite are important minor phases in many mantle-derived peridotites. Diamond-bearing peridotite xenoliths are much scarcer than diamond eclogites. It is clear from studies of inclusions in diamonds, however, that peridotitic diamonds are as abundant as those formed in eclogite. Compensating for the lack of xenoliths, xenocrysts of disaggregated peridotites are always found in diamondiferous kimberlite. Some of these xenocrysts have compositions consistent with derivation from diamond-bearing garnet harzburgites (Gurney, 1984). This rock is considered to be preferentially disaggregated on sampling and transport to the surface because of the presence of a carbonate-rich phase that dissociates in response to pressure reduction while temperature remains relatively high (Boyd and Gurney, 1982; Wyllie et al., 1983). The constituent minerals of the diamond peridotites are, therefore, mostly introduced as dispersed phases into the host volcanic magma. Other peridotitic diamonds are derived from garnet lherzolites, but such source rocks appear to be much less significant than the harzburgites, and their constituent minerals have not been shown to have diamond diagnostic compositions.

Lithospheric harzburgite is a highly depleted ultramafic rock type that forms initially as the residue after extraction of large amounts of partial melt from fertile mantle peridotite. Eclogite is a high-pressure rock of broadly basaltic composition and the mantle eclogite sampled by kimberlite is generally interpreted to represent subducted mafic oceanic crust (Helmstaedt and Schulze, 1989; Helmstaedt and Gurney, 1995). Although eclogite could be generated by partial melting of mantle leaving a depleted peridotitic residuum, it is clear that the eclogitic minerals associated with diamonds cannot be derived by the partial melting processes that produce diamond-bearing harzburgite residue. For instance, high rare earth element (REE) concentration and light-REE enrichment patterns in harzburgite garnets (Shimizu and Richardson, 1987) are quite irreconcilable with the low-garnet REE concentrations and heavy-REE enrichment patterns in eclogitic diamonds at Finsch (Shimizu, unpublished data). Harzburgitic and eclogitic diamonds, therefore, are quite clearly unrelated populations; this is confirmed by different model ages and carbon isotope characteristics. Therefore, at least two unrelated source rocks (eclogitic and peridotitic) for diamond are sampled by all well-studied primary occurrences.

The diamond content of these host rocks appears to vary widely, as indicated by the disparate abundances of diamond in eclogite xenoliths found at mines such as Orapa and Roberts Victor (Hatton and Gurney, 1979; Shee and Gurney, 1979). Eclogites also show large disparities in diamond content even within different portions of the same xenolith (Hatton and Gurney, 1979; Fig. 2). Furthermore, the diamond-bearing rocks may form minor lenses and pods in the mantle, as suggested by evidence from the Beni Bouchera high temperature peridotite (Slodkevich, 1983). Here, octahedral graphite (formerly diamond) is irregularly distributed in lenses of igneous garnet pyroxene cumulate rocks of minor extent. Locally the original diamond content could have been as high as 15–20%. Only small amounts of such rocks need be disaggregated to provide the total diamond content of a typical diamondiferous kimberlite, usually <1 ppm.

Based on diamond inclusion studies, the relative proportions of eclogitic to peridotitic diamonds in one locality can vary widely, from at least 90% eclogitic (Orapa,

Botswana: Gurney et al., 1984) to at least 99% peridotitic (Mir, U.S.S.R.: Yefimova and Sobolev, 1977). Worldwide, peridotitic and eclogitic diamonds are the dominant recognisable parageneses and appear to have a similar overall abundance to each other.

2.3. *Isotopic Composition of Diamond*

Eclogitic diamonds display a wide range of carbon isotope compositions ($-34 < \delta^{13}\text{C} < +3$; Sobolev et al., 1979). This range could be derived from an upper mantle that has retained a primary heterogeneity (Deines et al., 1987), or from crustal sources subducted into the mantle (Helmstaedt and Gurney, 1984; Helmstaedt and Schulze, 1989; Kirkley et al., 1991). Most of the eclogitic range can be found at a single locality (Sloan: Otter et al., 1989), which is difficult to explain unless at least some eclogitic diamonds are related to recycling processes active during subduction, such as those associated with ophiolite formation (Taylor and Anand, 2004). In contrast, peridotitic diamonds have a more restricted range in carbon isotope composition ($-9 < \delta^{13}\text{C} < -2$), which is thought to be derived from a more homogeneous asthenospheric source for the carbon. However, most peridotitic diamonds appear to be of Archaean age (see below) and it is possible that the smaller range of carbon isotope ratios result from the lack of advanced life forms at that time and that the carbon is also subduction related (Westerlund, 2005).

2.4. *Age-Constraints on Diamond Formation*

There is abundant evidence of the old age of both eclogitic and peridotitic diamonds. Some of the more persuasive observations are radiogenic isotope measurements on diamond inclusions (Kramers, 1977, 1979; Richardson et al., 1984, 1990; Richardson, 1986, 1989; Smith et al., 1989; Menzies et al., 1999; Westerlund, 2005). These studies point to harzburgitic diamonds being Archaean, and eclogitic diamonds being younger and spanning an age range from the Archaean through at least most of the Proterozoic.

Since isotope studies can be controversial to interpret, evidence supporting an old age for diamond is important. Diamonds are found in xenoliths of peridotite and eclogite where they are in general well preserved, showing predominantly growth forms. This indicates that the diamonds were formed in their original host rock prior to incorporation by the kimberlite. Many diamonds show direct evidence that they have been deformed under mantle conditions in a plastic manner, reflecting stress under conditions of grain boundary contact (Robinson, 1979) and, again, indicating residence in the mantle for a significant period prior to incorporation into the kimberlite. Finally, most diamonds show complex nitrogen aggregation patterns that would appear to need more than 10^9 years to develop at mantle temperatures and pressures (Evans and Harris, 1989). Thus all these lines of evidence point towards an ancient origin for the majority of diamonds. The reason that diamonds are associated with ancient continental cratons may be because they are predominantly formed and preserved in very old rocks.

The processes by which diamonds form are a subject of much debate (Bulanova, 1995; Harte et al., 1999; Taylor and Anand, 2004; Westerlund et al., 2004). However,

in general, available information suggests formation of most peridotitic diamonds by a major worldwide event at $\sim 3.3 \pm 0.3$ Ga that produced diamonds in a metasomatised garnet/chromite bearing harzburgite (Gurney et al., 2005). The metasomatising fluids are likely to have been generated by subduction processes (Westerlund, 2005). Eclogitic diamond formation has also been documented to be related to metasomatic activity associated with subduction (Westerlund et al., 2004). This has been identified to occur at various times in the Proterozoic and Archaean (~ 1 – 2.9 Ga), on a more localised basis than the widespread 3.3 Ga harzburgitic event, in mafic oceanic crust recycled into the upper mantle during ancient subduction events (Richardson et al., 2001).

2.5. Other Diamond Associations

In addition to the dominant harzburgitic and eclogitic diamond associations described above, other upper mantle lithologies that can contain diamond include lherzolite and websterite. The former is a common variety of peridotite (in fact the dominant rock type in the upper mantle) whereas the latter is a pyroxene-rich rock similar to eclogite but with a higher Cr and Mg content. In rare cases, diamonds have been found with inclusions of majorite, a very high-pressure mineral with a garnet structure but containing pyroxene in solid solution. Majorite is stable only at great depths (~ 200 – 450 km) indicating that at least some diamonds originate in the asthenospheric mantle. Websteritic, lherzolititic and majoritic diamonds are very subordinate in abundance overall, but may be locally significant, such as lherzolititic diamonds at Premier Mine, South Africa (Gurney et al., 1985; Richardson et al., 1993), the majoritic diamonds at Monastery (Moore and Gurney, 1985) and Jagersfontein mines (Deines et al., 1991), South Africa, and the websteritic association at Victor kimberlite project, Canada (Armstrong et al., 2004).

All the above associations are older than and non-cognate to their host magma. At some localities, fast-grown younger diamonds, at most only slightly older than the host magma, have been noted. These occur as low value fibrous cubes, fibrous coats on older diamonds or unusual diamond distinguished by complex crystal forms, a distinctive amber colour and single nitrogen atom substitution for carbon in the diamond lattice (1b diamonds). The fibrous diamonds may be abundant (e.g., Mbuji Mayi, Democratic Republic of Congo) but are of very low commercial value. The 1b diamonds are very rare and have shapes that are not amenable to manufacturing of cut gemstones. The paragenesis of these younger diamonds is not well-established. Both varieties have been found to be associated with eclogite (Hills and Haggerty, 1989; McKenna et al., 2003), whereas only the slenderest of evidence associates fibrous diamond with peridotitic minerals (Talnikova, 1995). No diamond deposits worldwide are known to have a commercially significant population of 1b diamonds and, although fibrous diamonds are abundant at a few locations, they are of very low value (per carat) and do not sustain mining operations on a commercial basis. These younger diamonds have, like majorite, academic rather than economic significance. Relatively little is known about the processes that produce them and tracing them receives little or no attention in prospecting for diamond deposits.

2.6. *Diamond Resorption and the Relationship Between Macrodiamonds and Microdiamonds*

It has been comprehensively proven that many diamonds are partially resorbed en route to the earth's surface from the upper mantle (Robinson, 1979; Robinson et al., 1989), primarily by oxidation. This process is sufficiently common and significant to deduce that many diamonds assume a round-dodecahedral morphology from their original octahedral shape, implying a weight loss of the order of at least 45%. Under such oxidising conditions it is considered probable that many microdiamonds (>0.5 mm) would be completely resorbed and therefore disappear. This, in turn, has led to the proposal that the microdiamonds that do occur in kimberlite may be mainly a separate population, crystallising just prior to kimberlite emplacement and unrelated to macrodiamond populations, which appear to be much older (Haggerty, 1986). However, microdiamonds appear to carry similar inclusions to macrodiamonds and have similar nitrogen aggregation characteristics (Trautman et al., 1997) indicating that they have the same ancient origins. Nonetheless, resorption may well affect the size distribution of the overall diamond population in a particular deposit, which is in any case, a composite of diamonds formed by several mantle processes.

2.7. *Significance to Diamond Exploration*

In terms of diamond exploration, the important factors known about diamond genesis can be summarised as follows.

- (1) The macrodiamonds in economic deposits are derived from pre-existing, sometimes highly diamondiferous, ultrabasic and basic rocks that formed in the lithospheric upper mantle.
- (2) Both peridotitic and eclogitic diamonds occur in every known diamond deposit worldwide.
- (3) Peridotitic diamonds can be subdivided into harzburgitic and lherzolitic types. Harzburgitic diamonds are common to all diamondiferous kimberlites and are interpreted to be of Archaean age (~3.3 Ga). Lherzolitic diamonds are subordinate to harzburgitic diamonds and represent another, somewhat younger population, which at the Premier Mine is 1.9–2.0 Ga in age (Richardson et al., 1993).
- (4) Eclogitic diamonds show a range of ages from 0.99 to 2.9 Ga, except for the rare instances of younger diamonds described above.
- (5) As diamonds are released into the host magma by disaggregation of pre-existing diamond-bearing mantle rocks, other constituent minerals of those rocks are incorporated with the diamonds. Quite small volumes of these, sometimes richly diamondiferous, mantle rocks can provide the concentrations of diamond (generally <1 ppm) found in economic kimberlites.
- (6) In a single kimberlite intrusion, it is reasonable to expect a roughly linear relationship between the amount of diamond present and the abundance of fragments of the host diamondiferous rocks from the mantle.
- (7) In different kimberlites, such comparisons can never be expected to be as quantitative because of variations in the diamond grade of the eclogite and peridotite sources, the superimposed reductions in diamond content by

- resorption, and more speculatively because of assimilation of the diamond source rock in the magma, which may be particularly relevant in lamproites.
- (8) Microdiamond counts in a kimberlite or lamproite are, in general expected to correlate broadly with macrodiamond abundance, but in certain cases may not give good correlations with the grade of commercially sized stones (> 1 mm) because of the decoupling effects of resorption followed by subsequent growth of another population of microdiamonds.
 - (9) The relationship described in (6) can be used to predict the presence of diamond with a high degree of certainty and can give a semi-quantitative estimate of diamond abundance with some success.
 - (10) The heavy mineral geochemistry approach can give the first signal about the diamond potential of the source in an exploration program.
 - (11) The approach is perhaps more likely to go wrong in terms of predicting the presence of diamonds that are not there, than to miss out on predicting their presence when they are there.
 - (12) Macrodiamonds are likely to be found in regions of the earth with thick cool lithospheric keels where old rocks are preserved. Consequently, continental cratons may be prime targets if they are thick enough. Complex structural settings where over-thrusting will allow old keels to survive underneath younger rocks are not ruled out of contention (Gurney et al., 2005).
 - (13) In order to provide diamonds in appropriate size ranges and abundance for economic exploitation, transport to the surface from depths of diamond stability must be rapid and thus far has proven to involve volatile-rich, ultrabasic volcanics, with only minor exceptions (Gurney et al., 2005).

3. KIMBERLITIC INDICATOR MINERALS AS A TOOL FOR DIAMOND EXPLORATION

3.1. *Mantle Minerals as Indicators of the Presence of Kimberlite*

From the above discussion, it is clear that kimberlites (and certain related rock types) generally contain significant amounts of high-pressure minerals (including diamond) derived by sampling of mantle rock types. The presence of such minerals as xenocrysts in kimberlite or lamproite is the product of disaggregation of these mantle rocks sampled at depth and transported into the crust by the host magma. Processes contributing towards the disaggregation of mantle material include: precursor intrusive and/or metasomatic activity which locally weakens the lithospheric mantle prior to kimberlite emplacement; physical stoping and partial melting/assimilation during the early stages of kimberlite emplacement; attrition associated with ascent of the kimberlite through the lithosphere via narrow conduits and explosive eruption of the kimberlite or lamproite at surface. Field evidence indicates that the emplacement of volcanic kimberlite or lamproite pipes occurs as a series of highly explosive eruptions, whereas the magmatic feeders are thin (often < 1 m wide) dykes. In accordance with the latter observation, upper mantle xenoliths in kimberlite have been observed to occasionally approach but never exceed a meter in largest dimension. The above-described intrusion and eruption processes are an efficient mechanism for

the disaggregation of mantle rocks such as peridotite, eclogite, websterite and megacryst assemblages (see below), causing the release of numerous individual mineral grains into the host magma.

These mantle-derived minerals commonly display visual and compositional characteristics that permit their distinction from minerals of crustal derivation. In addition, several of the key mantle minerals are relatively resistant to chemical weathering and are commonly dispersed into the secondary environment by sedimentary processes. Thus, they provide ideal pathfinders for kimberlite and are typically referred to as kimberlitic indicator minerals.

As mentioned previously, the most important indicator minerals for kimberlite exploration are garnet, chromite, ilmenite, Cr-diopside and olivine (Fig. 3). Cr-diopside and olivine break down rapidly in most surface environments and, other than in frigid arctic or sub-arctic conditions, are generally not transported significant distances from their source kimberlite. In contrast, garnet, chromite and ilmenite are resistant and may be dispersed considerable distances away from their

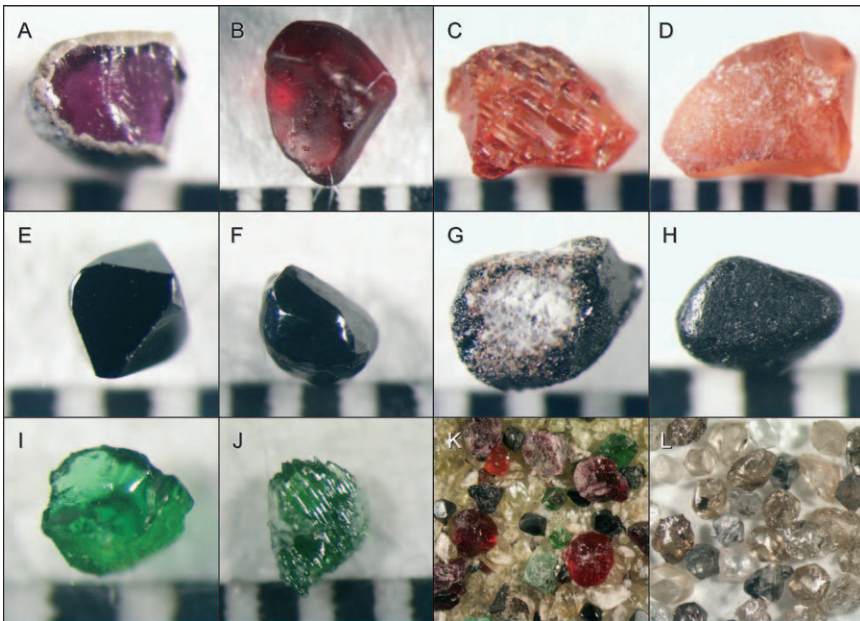


Fig. 3. Photomicrographs of typical kimberlitic indicator minerals and microdiamonds recovered from kimberlite. Scale bar division in A to J = 1 mm. (A) Mauve peridotitic garnet with primary alteration rim (kelyphite). (B) Red peridotitic garnet with finely frosted (sub-kelyphitic) surface. (C) Orange low-Cr garnet displaying “sculpted” surface due to crystallographically controlled dissolution of grain in kimberlite. (D) Orange low-Cr garnet displaying sub-kelyphitic surface texture. (E) Euhedral chromite. (F) Subhedral chromite. (G) Ilmenite with primary alteration rim (mostly perovskite). (H) Unaltered ilmenite. (I) Cr-diopside with conchoidal fracture. (J) Cr-diopside with “sculpted” surface. (K) Typical kimberlite concentrate showing abundant pale yellowish-green olivine plus garnet, Cr-diopside, chromite and ilmenite (grain size ranges to ~ 1.5 mm). (L) Microdiamonds derived by dissolution of kimberlite and visual sorting of residue (grains size ranges to ~ 0.5 mm).

point of origin. Thus these minerals typically form the focus of stream-sediment and soil sampling programs aimed at detecting kimberlites. The indicator minerals in kimberlite show a very wide range of sizes, from less than 0.5 mm to in excess of 20 mm. However, most grains are less than 2 mm in size and, in surface sediments, by far the majority of them are recovered in the fine and medium sand fractions.

Techniques for sampling and recovery of these indicator minerals rely largely on their relatively high density (Gregory and White, 1989; Muggeridge, 1995). In environments that are rich in heavy minerals of crustal origin, magnetic separation methods can be used to help concentrate the kimberlitic indicator minerals. The latter are then extracted from the concentrate by visual sorting processes, typically undertaken with binocular microscopes. Mantle-derived garnet, Cr-diopside, ilmenite and chromite have visual characteristics that permit their distinction, with varying degrees of confidence, from similar minerals of crustal origin. However, with the exception of peridotitic garnet, there is a considerable amount of overlap, and confirmation of visual classifications by compositional analysis is usually advisable.

In general, kimberlitic indicator minerals are characterised by Mg- and commonly Cr-rich compositions. Garnets from peridotite are Cr-pyropes with compositions that do not overlap with crustal garnet types. Eclogitic garnets are also typically Mg-rich pyropes, but they are poor in Cr and range to relatively Fe-rich and Ca-rich compositions that overlap with certain crustal almandines and grossulars. Nonetheless, eclogitic garnet from kimberlite is generally compositionally distinguishable from most crustal varieties with a reasonable degree of confidence. Ilmenite (commonly of megacrystic origin, see below) from kimberlite is diagnostically Mg-rich (picroilmenite) and is reliably distinguished from non-kimberlitic varieties using a combination of Mg and Ti content (Wyatt et al., 2004). Mantle-derived chromites (from chromite peridotite) show near complete compositional overlap with those from a variety of crustal sources and reliable identification of grains from kimberlitic sources generally requires careful study of population trends (Gurney and Zweistra, 1995). Fortunately, chromite also occurs as a phenocryst phase in kimberlite and this variety (commonly recovered in prospecting samples) displays diagnostic Cr–Ti relationships (Grütter and Apter, 1998). “Kimberlitic” Cr-diopside and olivine, derived from mantle peridotite, show compositional ranges similar to those of equivalent minerals from ultramafic crustal sources. While portions of the compositional spectrum seen in kimberlitic olivine and Cr-diopside are unique, in certain cases, unequivocal confirmation of a kimberlitic origin may not be possible.

Numerous approaches based on chemical composition have been proposed for the classification of kimberlitic indicator minerals (Dawson and Stephens, 1975; Danchin and Wyatt, 1979; Jago and Mitchell, 1989; Schulze, 2003; Grütter et al., 2004). For the most part, these focus on distinguishing different varieties of mantle-derived garnet. The most recent classification scheme by Grütter et al. (2004) provides a relatively simple, practical scheme for application by diamond explorers.

The use of kimberlitic indicator minerals to provide evidence for the proximity of potentially diamondiferous source rocks has been in practice for more than 100 years, virtually since kimberlite was first recognised as a host for diamond in South Africa (Draper and Frames, 1898). In the past three decades, application of indicator mineral techniques has progressed considerably, particularly through advent of electron microprobe technology. This has led to significant improvements

in the recognition of kimberlite-derived minerals and, perhaps more importantly, to the development of advanced indicator-mineral-based techniques for the assessment of diamond potential in kimberlite source rocks (Gurney et al., 1993; Griffin and Ryan, 1995).

3.2. Assessing Diamond Potential Based on Indicator Minerals: Principles

In this contribution we present an overview of the use of indicator mineral geochemistry in the evaluation of the diamond potential of kimberlites. This approach was developed primarily on the basis of studies of kimberlites and has been successfully applied to all major kimberlite provinces worldwide. The principles are nonetheless applicable to lamproites and other magma types that have sampled the upper mantle, although the precise relationship between kimberlitic indicator mineral criteria and diamond content in these rock types may vary.

The model on which the method is based considers that macrodiamonds are xenocrysts in the volcanic kimberlites from which they are recovered, and that they are derived from disaggregated mantle-equilibrated rocks that pre-date the age of emplacement of the volcanic intrusion. This is consistent with evidence reviewed earlier.

The validity for this approach rests on the fact that some diamonds contain mineral inclusions that can clearly be assigned to an eclogitic or peridotitic source and, as discussed above, diamonds are occasionally found in xenoliths of eclogite, or more rarely peridotite. The unequivocal assignation of the paragenesis of most diamonds is, however, not possible because they are recovered as single crystals and are commonly without any definitive inclusions. It is assumed that these diamonds have similar origins to the minority that can be defined. On the basis of carbon isotope measurements in inclusion-free diamonds compared to those of known paragenesis, this seems reasonable (Jaques et al., 1989; Gurney, 1990).

The amount of diamond the volcanic host-rock contains will depend on at least six variables:

- (a) the quantity of diamond peridotite that it sampled;
- (b) the average grade of the diamond peridotite;
- (c) the quantity of diamond eclogite that it sampled;
- (d) the grade of the diamond eclogite;
- (e) the degree of preservation of diamonds during transportation and
- (f) the efficiency with which the diamonds were transported to the earth's surface.

The amount of diamond peridotite or diamond eclogite that has been sampled (a and c) should be reflected in the amount of disaggregated mineral grains and/or xenoliths in the kimberlite. If these can be identified, it should be possible to forecast whether diamond could be present or not. Identification of garnets and chromites that have specific compositions has indeed turned out to be a useful diamond indicator (Gurney, 1989; Gurney et al., 1993; Lee, 1993; Fipke et al., 1995; see also below).

Forecasting accurately the diamond content of a rock that is in the mantle and cannot be directly sampled is unfortunately impossible, so that variations in source-rock grade (b and d) cannot be quantified in any rigorous way. Fortunately, the diamond indicator minerals can be identified by certain compositional parameters

and the higher the abundance of these minerals in kimberlites, the better the diamond content of the body usually is. However, there are exceptions to this, as must be expected from considerations (a–e) above.

3.3. *Geochemical Criteria for Recognition of Diamond-Associated Minerals*

Recognition of diamond-associated indicator minerals is based largely on relatively simple compositional criteria derived from studies of diamond inclusions and mineral compositions in diamond-bearing xenoliths. Fortunately for the diamond explorer, these minerals define characteristic compositional fields that show only limited overlap with mineral compositions from non-diamondiferous mantle lithologies. This simple empirical approach has been refined over the last decade or so to incorporate recent developments in geothermobarometry and an improved understanding of the pressure–temperature–composition (P–T–X) relationships in specific diamond source rocks. These refinements have to a large extent been incorporated into the recent garnet classification scheme of Grütter et al. (2004).

3.3.1. *Peridotitic minerals associated with diamond*

In the peridotitic diamond paragenesis three sub-groupings are apparent: garnet harzburgite/dunite, chromite harzburgite and garnet lherzolite. The harzburgites and dunites are depleted in calcium relative to the lherzolites in three ways: the absence of a Ca-saturated phase (diopside); a low bulk-rock Ca content and a low mineral content of Ca (i.e., sub-calcic garnet). As with most classification schemes, there is overlap between categories. For example, chromite and garnet can occur in the same harzburgite and chromite can be present in a lherzolite. Other features are incompatible: a sub-calcic garnet, for instance, cannot be in equilibrium with diopside and is, therefore, never found in a lherzolite. It has been established that the relative importance with respect to diamonds is: garnet harzburgite/dunite > chromite harzburgite >> garnet lherzolite, i.e., diamonds are highly preferentially associated with peridotite of depleted composition. Garnet lherzolite is not a major component of the diamond inclusion suite at any locality yet described. This is fortunate since garnet lherzolite is the most common mantle rock type found in kimberlite, and there is no simple way to differentiate between a diamond-bearing and a barren garnet lherzolite (Gurney, 1984). The preferential association of diamond with depleted peridotite is highlighted by comparison of peridotitic garnets found as inclusions in diamonds or in diamond-bearing xenoliths with those present in “average” lithospheric mantle sampled by kimberlite (i.e., as reflected in the xenolith and xenocryst suites of large numbers of kimberlites). Approximately 85% of peridotitic garnets directly associated with diamond are sub-calcic in composition (e.g., Gurney, 1984), indicating derivation from depleted mantle harzburgite or dunite. In contrast, studies of xenoliths and garnet xenocryst populations from kimberlites indicates that the peridotitic mantle is dominated by relatively “fertile” (i.e., undepleted) lherzolite, which yields garnets with more calcium-rich compositions. For example, sub-calcic garnets make up only ~15% of the peridotitic component of kimberlite xenocryst suites in the Kaapvaal craton (Herman Grütter, personal Communication, 2003).

This indicates an approximately 32-fold preferential association of carbon with depleted harzburgite or dunite. Therefore garnets of lherzolitic composition have to

be discriminated against in an exploration program, and the method described by Gurney (1984) has repeatedly proved to be useful in exploration programs on several continents. In addition, it needs to be emphasised that, by definition, Cr-diopside does not occur in depleted harzburgite and, therefore, is not useful as a diamond indicator mineral. Under certain circumstances, however, it can yield very useful pressure and temperature information. This is discussed further below.

The minerals closely associated with diamonds have well-defined ranges in composition (Meyer, 1987). For harzburgitic diamonds, the garnets are high in Mg and Cr and low in Ca (Gurney and Switzer, 1973; Sobolev, 1974; Gurney, 1984). The component of diamonds derived from garnet harzburgite is assessed by considering both the number of sub-calcic garnets found in a kimberlite and their degree of calcium depletion. While not strictly in accord with the Dawson and Stephens (1975) classification, these garnets have been referred to as “G10” garnets, while lherzolitic garnets have been referred to as “G9”. The compositional fields for these garnet types are defined in Fig. 4. More recently, the field designated G10 has been called the “diamond in” field and the G9 field “diamond out” for reasons developed by Gurney and Zweistra (1995). In the case of G10 garnets it has been noticed

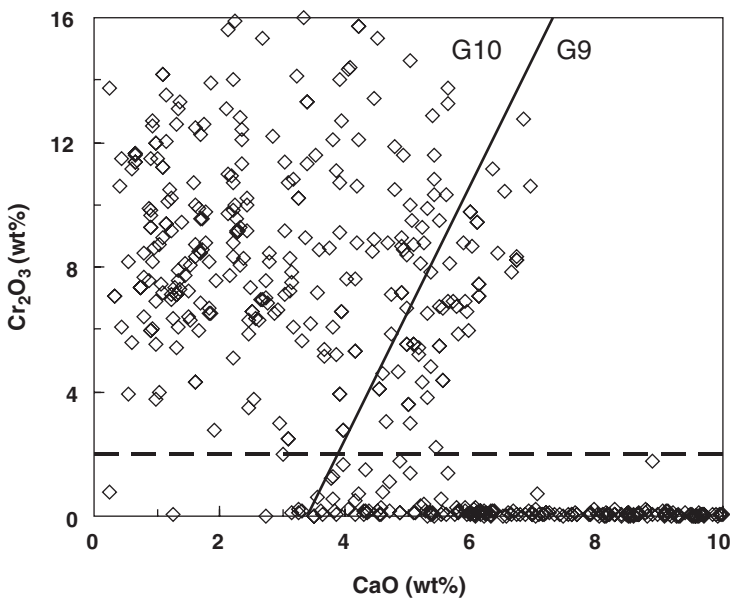


Fig. 4. Plot of Cr_2O_3 versus CaO for diamond inclusion garnets from worldwide localities. The diagonal line distinguishing sub-calcic “G10” garnets from calcium saturated “G9” garnets was defined by Gurney (1984) on the basis that 85% of peridotitic garnets associated with diamond plot in the G10 field. The horizontal line drawn at 2 wt.% Cr_2O_3 is used as an arbitrary division between eclogitic (< 2 wt.% Cr_2O_3) and peridotitic (> 2 wt.% Cr_2O_3) garnets. Diamond inclusion data represent 49 kimberlite, lamproite and alluvial localities in southern Africa, West Africa, Russia, Australia, South America, North America and China. [Sourced from the KRG Database, Department of Geology, University of Cape Town, South Africa.]

empirically that richer kimberlites with abundant harzburgitic diamonds tend to have more sub-calcic and chromiferous G10 garnets.

Chromites associated with diamond show a high average Cr_2O_3 content, characteristically in excess of 62.5 wt.% (Lawless, 1974; Sobolev, 1974; Dong and Zhou, 1980; Fig. 5). Chromite is used in a manner similar to garnet to provide an indication of the amount of diamond in the kimberlite derived from disaggregated chromite harzburgite.

Over the last two decades, it has become apparent that not all garnets falling in the G10 “diamond in” field are indicators of the presence of diamond. This stems from the fact that, although they have a very strong association with mantle carbon, garnets of this compositional range do not necessarily equilibrate within the diamond stability field.

3.3.2. Pressure, temperature and diamond stability

There are several approaches to determine whether G10 garnets are associated with graphite or diamond. The basis for all of these methods is a clear understanding of the relationship between geothermal gradient and diamond stability in the lithosphere. Diamond stability is dependent on oxygen fugacity, pressure and temperature. Typical cratonic lithosphere is relatively reducing (McCammon et al., 2001) and thus, in the absence of oxidizing events (e.g., metasomatism), carbon will occur

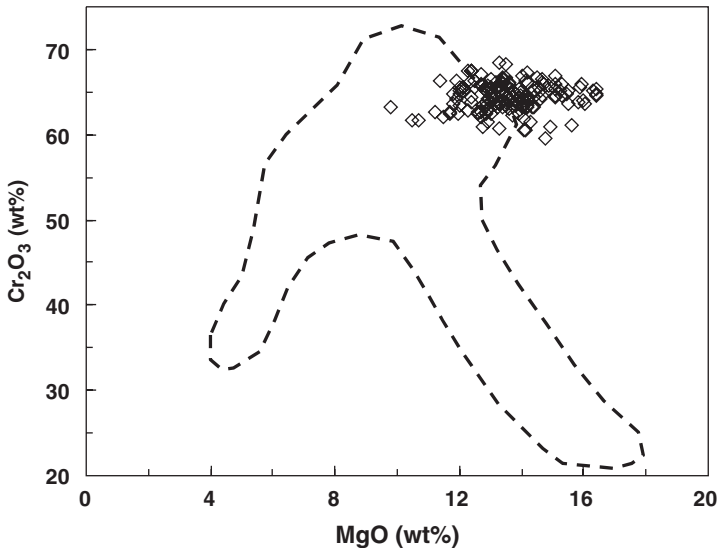


Fig. 5. Plot of Cr_2O_3 versus MgO for chromite diamond inclusions from worldwide localities shown in relation to the compositional range observed for chromites from samples of kimberlite concentrate (dashed line). Note the highly restricted Cr- and Mg-rich character of the inclusions. Diamond inclusion data represent 22 kimberlite localities in southern Africa, West Africa, Russia, South America and China. [Sourced from the KRG Database, Department of Geology, University of Cape Town, South Africa.] The concentrate chromite composition field is based on data for 28 kimberlite localities in southern Africa, Russia and North America (Mineral Services, internal database).

in the form of diamond or graphite (as opposed to carbonate). The boundary between the stability fields of these two carbon polymorphs is illustrated in Fig. 6 relative to a series of reference geothermal gradients (“geotherms”). The latter represent the change in temperature with depth in the lithosphere and the curves shown in Fig. 6 illustrate conductive models (Pollack and Chapman, 1977) applicable to surface heat flows of 35, 40, 45 and 50 mW/m². Old, thick, stable cratonic regions have low geothermal gradients, equivalent to models for surface heat flows of ~35–41 mW/m². Under these conditions, diamond is stable in the deep lithosphere over a relatively wide range of pressure and temperature. Under hotter geothermal conditions associated with younger, thinner lithosphere or a thermal perturbation of old lithosphere, the upper boundary of the diamond stability field shifts to greater pressures and temperatures, thereby substantially reducing the size of the diamond window. Depending on the thickness of the lithosphere, geotherms exceeding

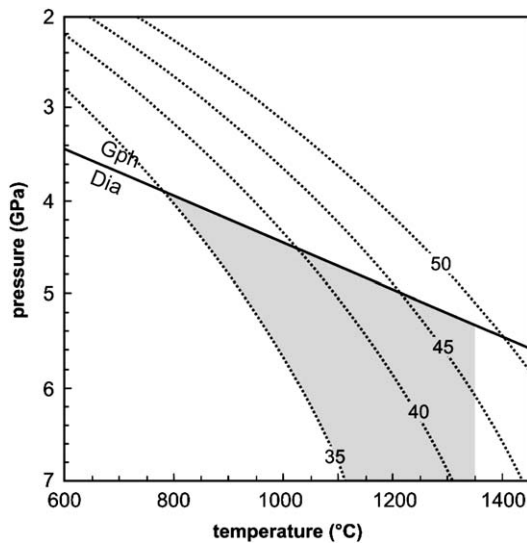


Fig. 6. Plot of pressure against temperature illustrating the concept of geothermal gradients (geotherms), diamond stability and the diamond window. The boundary between the stability fields of diamond and graphite (Kennedy and Kennedy, 1976) is shown as a solid line. Curved dotted lines represent model conductive geotherms for surface heat-flows of 35, 40, 45 and 50 mW/m² (Pollack and Chapman, 1977). Pressure is directly proportional to depth (e.g., 40 kb \approx 130 km), thus the geotherms represent the change in temperature with depth in the lithosphere. Undisturbed Archean cratons typically have geothermal gradients that correspond with geotherm models of 35–41 mW/m². For any given section of lithosphere, the “diamond window” (the zone within which diamond can form and be preserved) is represented by the portion of the geotherm that lies below (i.e., at greater pressure than) the graphite/diamond phase boundary and above the base of the lithosphere. The latter typically occurs at temperatures of between 1250 and 1400 °C. The shaded region on the plot illustrates the potential extent of the diamond window for geotherms exceeding 35 mW/m² and assuming a temperature at the base of the lithosphere of 1350 °C. It is evident that, as the geotherm increases, the potential depth range for diamond stability within the lithosphere is substantially reduced.

$\sim 44 \text{ mW/m}^2$ may not intersect the diamond stability field at all, because diamond cannot be formed and/or preserved in the lithosphere in this case.

Geothermal conditions at the time of kimberlite emplacement can be determined using mineral geothermometers and geobarometers applied to fragments of mantle rocks (Rudnick and Nyblade, 1999). Most of these require analysis of equilibrated mineral pairs and, therefore, are only applicable to mantle xenoliths with appropriate mineralogy. However, Nimis and Taylor (2000) developed a method for determining pressure and temperature from single grains of Cr-diopside, thereby permitting determination of the geotherm based on concentrate grains derived from kimberlite (i.e., without the occurrence of xenoliths being required).

In order to determine whether a garnet is derived from the diamond stability field, it is necessary to determine its pressure and temperature of equilibration. The temperature of equilibration can be determined based on the Ni content of individual peridotitic garnet grains using the Ni-in-garnet geothermometer (Griffin et al., 1989; Canil, 1994; Ryan et al., 1996). An alternative approach allows temperature information to be derived from the Mn content of peridotitic garnet (Grütter et al., 1999, 2004). This has the advantage of being applicable to electron microprobe data (Ni content occurs in trace amounts and typically requires analysis by laser ablation mass spectrometry or proton probe) but is susceptible to analytical error and is significantly less precise than the Ni thermometer. Consequently, Mn thermometry is best applied to garnet populations rather than individual grains.

There is no direct method available for determining the equilibration pressure of a single garnet grain. However, if the geotherm at the time of kimberlite emplacement is known, the pressure or depth of origin of the garnet grain can be determined by projecting the Ni-temperature onto this geotherm. Alternatively, because the cut-off temperature of diamond stability is fixed and known for any given geotherm, the calculated equilibration temperature allows one to directly determine whether a garnet grain equilibrated in the diamond or graphite stability field.

Graphite-associated G10 garnets can occur in regions with cool geotherms as a result of sampling of relatively shallow, low-temperature harzburgite (e.g., Fig. 7), or in cases where the kimberlite has sampled mantle that equilibrated on a hot geotherm (Shee et al., 1989). Clearly, a high proportion of such garnets will substantially downgrade or eliminate the potential for peridotitic diamonds in a kimberlite or lamproite.

3.3.3. The “graphite–diamond constraint” and the Cr/Ca barometer

Although it is not possible to reliably determine the depth of equilibration of single grains of garnet, the Cr/Ca content of garnet in garnet-chromite peridotite is sensitive to pressure, i.e., increased Cr/Ca concentration correlates with increased pressure. This relationship has been used to determine lines of equal pressure (isobars) based on the Cr_2O_3 and CaO content of peridotitic garnets that coexist with chromite (Grütter et al., 2006). The isobars are fixed for a given geothermal gradient and Grütter et al. (2006) show that, for common cratonic geothermal conditions, the graphite–diamond transition occurs at 4.3 GPa and is represented on a garnet Cr–Ca plot by the relationship $\text{Cr}_2\text{O}_3 = 5.0 + 0.94 \times \text{CaO}$ (Fig. 8). This is referred to as the graphite–diamond constraint (GDC), and it forms a convenient reference with which to characterise Cr-pyrope garnets that occur in heavy mineral concentrates. An important proviso is that the relationship between Cr/Ca in peridotitic garnet and

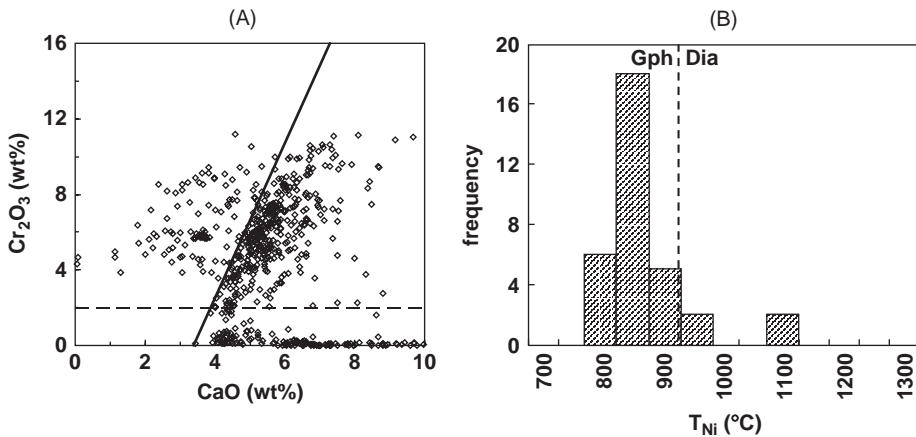


Fig. 7. Plot of Cr_2O_3 versus CaO (A) and T_{Ni} histogram (B) for garnets from a kimberlite locality in the central Slave Province, Northwest Territories, Canada. The Cr–Ca plot shows all garnet grains recovered from the kimberlite sample and indicates a relatively high proportion of G10 grains. The T_{Ni} histogram illustrates the distribution of equilibration temperatures (determined using the nickel thermometer of Ryan et al., 1996) for a compositionally representative selection of 33 G10 garnets. The majority of these grains equilibrated at temperatures of $<900^\circ\text{C}$. This places them in the graphite (Gph) stability field (for the $\sim 38 \text{ mW/m}^2$ geotherm applicable to this locality) signifying that, for this kimberlite, the majority of G10 garnets are not indicative of a diamond association.

pressure assumes equilibrium with chromite. Where chromite is not present, the Cr/Ca content provides a minimum pressure estimate. Thus, in the case of garnet grains from kimberlite heavy mineral concentrates where coexistence with chromite cannot be confirmed, the Cr-pyrope compositions yield minimum-pressure estimates. Where a minimum-pressure estimate exceeds 4.3 GPa (i.e., the garnet compositions have higher Cr than the GDC), the grain is clearly derived from within the diamond stability field. Garnet compositions with lower Cr indicate minimum-pressures of less than 4.3 GPa, i.e., they cannot be unequivocally assigned to the diamond or graphite stability field. For these garnets, it is necessary to determine temperature of equilibration (as described above) in order to establish whether they are associated with diamond or graphite (see Grütter et al., 2004).

The P–T–X relationships for garnet \pm chromite peridotite are evaluated in more detail by Grütter et al. (2006), who develop the concept of a garnet Cr/Ca barometer and demonstrate its use to estimate pressure and lithospheric thickness based on the Cr–Ca compositions represented in peridotitic garnet populations. These concepts are illustrated with numerous examples from kimberlite and related-rock localities worldwide.

3.3.4. Eclogitic minerals associated with diamond

As for peridotite, studies of eclogitic mineral inclusions in diamond and minerals from diamond-bearing eclogite reveal distinctive compositional features that are useful for distinguishing diamond-associated minerals from those derived from

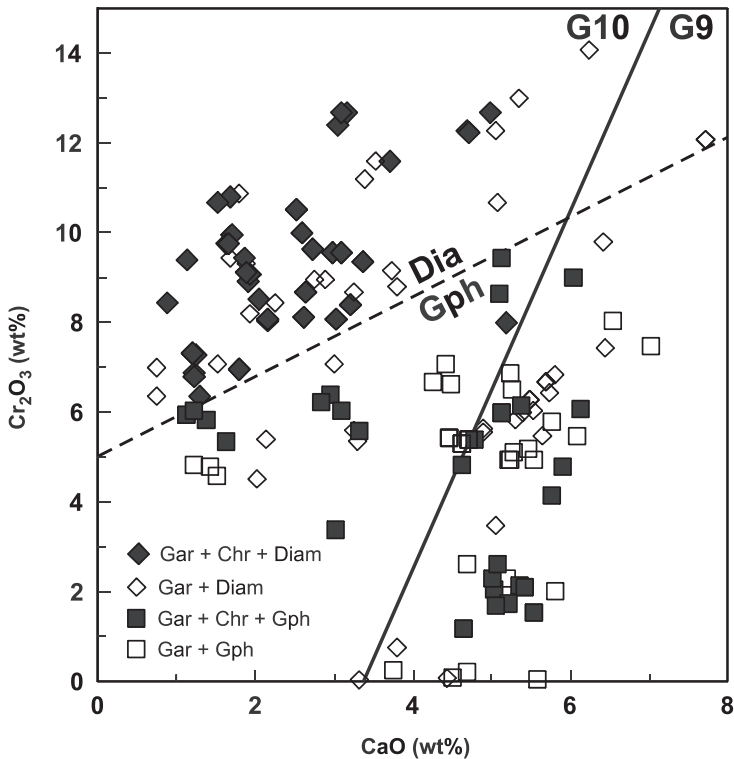


Fig. 8. Cr_2O_3 – CaO compositions of garnets in graphite-bearing (Gph, square symbols) or diamond-bearing (Dia, diamond symbols) peridotite xenoliths, with coexisting chromite (Chr, filled symbols), or lacking coexisting chromite (unfilled symbols). Under Cr-saturated conditions the graphite–diamond constraint (GDC, dashed line) of Grütter et al. (2004, 2006) separates graphite-facies from diamond-facies conditions for common cratonic geotherms. Garnets with Cr content higher than the GDC are derived from pressures within the diamond stability field (i.e., filled and unfilled diamond symbols). Garnets with lower Cr than the GDC are derived from graphite-facies pressures if they are known to coexist with chromite (i.e., filled square symbols), or potentially from higher pressures if chromite coexistence is indeterminate (e.g., unfilled diamond symbols). [Diagram modified after Grütter et al. (2006).]

non-diamondiferous eclogite. Eclogitic garnet is particularly important because it is a resistant mineral commonly recovered in kimberlitic concentrate and shows diagnostic compositions. It can be readily distinguished from peridotitic garnet by its orange to orange-brown colour and significantly lower Cr content (Grütter et al., 2004). The most diagnostic feature of eclogite garnets associated with diamonds are elevated trace amounts of Na ($\text{Na}_2\text{O} > 0.07$ wt.%), first noted by Sobolev and Lavrent'yev (1971) and expanded on by McCandless and Gurney (1989). These garnets also show slightly higher Ti levels relative to non-diamondiferous eclogite (Danchin and Wyatt, 1979). The composition of eclogitic garnets associated with diamonds worldwide with respect to these two key oxides is presented in Fig. 9. These compositional features are characteristic of a texturally distinct, coarse-grained variety of eclogite classified as Group 1 (McCandless and Gurney, 1989).

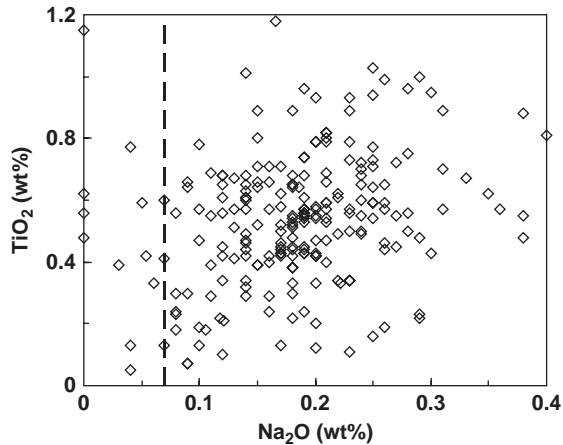


Fig. 9. Plot of TiO_2 versus Na_2O for eclogitic diamond inclusion garnets from worldwide localities. Note that the elevated levels of both of these elements is characteristic of eclogitic garnets associated with diamonds. In exploration applications, garnets with $\text{Na}_2\text{O} > 0.07$ wt.% (dashed line) are generally considered significant (see text for further discussion). Diamond inclusion data represent 45 kimberlite, lamproite and alluvial localities in southern Africa, West Africa, Russia, Australia, South America, North America and China. [Sourced from the KRG Database, Department of Geology, University of Cape Town, South Africa.]

Group 2 eclogites are finer-grained, do not show elevated Na or Ti contents, and do not appear to be associated with diamond.

In contrast to the peridotite association in which the presence of diamond or graphite is strongly related to the bulk composition of the host rock, diamonds (and graphite) occur within the full compositional range displayed by mantle eclogite (Grütter and Quadling, 1999) and the diagnostic elevated trace Na contents reflect high pressures of equilibration appropriate for diamond formation. However, Na concentration in garnet is also dependent on the bulk composition of the host eclogite (Grütter and Quadling, 1999). Thus, while the empirically determined value of 0.07 wt.% Na_2O provides a useful threshold for identifying the majority of diamond-associated eclogitic garnets, predictions of eclogitic diamond potential may be improved by allowing for a variable Na_2O threshold value, dependent on the bulk composition of the host eclogite, as reflected in the garnet composition.

The clinopyroxene (omphacite) in diamond-eclogite has been shown to have elevated concentrations of K_2O (McCandless and Gurney, 1989) relative to that in non-diamondiferous eclogite. However, due to the instability of omphacite at low pressure, it is rarely preserved in kimberlitic concentrate (unlike Cr-diopside which is common in unaltered kimberlite) and hence, is not commonly used to assess diamond potential.

3.3.5. The megacryst suite of minerals

Many kimberlites contain a suite of closely related very coarse-grained (often > 2 cm, occasionally > 20 cm) mantle-derived minerals, commonly referred to as megacrysts. These include olivine, orthopyroxene, garnet and clinopyroxene, all

commonly occurring together with megacryst ilmenite. Ilmenite can also occur on its own and in various combinations with phlogopite, zircon and possibly carbonate. The megacryst minerals are not genetically related to diamond. Geochemical and isotopic data show that the entire megacryst suite recovered from any given kimberlite locality can form in one magmatic event. Radiogenic isotopic evidence shows that the megacrysts remain an open system until the host kimberlite event, and their formation is interpreted to be closely related to that intrusion. Geothermobarometry indicates an association between megacrysts and a layer of highly deformed, high-temperature garnet lherzolite at the base of the cratonic lithosphere, below the primary diamond bearing strata. In fact, the megacrysts are thought to represent pegmatitic vein systems within these deformed garnet lherzolite host rocks. Megacrysts can be identified compositionally and are useful indicators of the presence of kimberlite. The vast majority of ilmenite recovered in exploration programs are megacrystic in origin. Megacryst phlogopite and zircons are excellent and reliable minerals for dating of kimberlite intrusive events.

Megacryst garnets are visually similar to garnet from eclogite. They also show similar low-Cr compositions and commonly contain trace levels of Na₂O that overlap with those of garnet from potentially diamondiferous (Group 1) eclogite. The Na content of megacryst garnets is sensitive to pressure and they can be used to monitor craton thickness. However, since megacryst garnets are not related to diamond, they must be discriminated against when assessing the diamond potential of a kimberlite. This can be very effectively done using geochemical parameters such as TiO₂, CaO, MgO and FeO contents (Grütter *et al.*, 2004).

At each locality the contribution of each of the garnet harzburgite, chromite harzburgite and eclogite parageneses is assessed by establishing the abundance of the garnets and chromites derived from disaggregation of the mantle host rock. These three diamond sources are additive and a really good contribution from any one of them could be sufficient to provide an economic grade in a kimberlite. Clearly, it is necessary to establish both the compositions of the indicator minerals and their relative abundances.

3.4. Geochemical Criteria Related to Diamond Preservation

Having sampled diamondiferous rocks in the mantle, an igneous intrusion must carry them to the surface. En route, conditions within the magma must eventually be outside the diamond stability field. Providing that reaction kinetics are sufficiently rapid, diamond may be converted to graphite or, more frequently, to CO₂. The latter will happen more rapidly as a result of higher oxygen activity in the magma. The effect of this resorption on the diamond content of an intrusion can be large.

In the model developed for southern Africa, it appears that ilmenite compositions give some measure of these redox conditions. Ilmenites with low Fe³⁺/Fe²⁺ ratios are associated with higher diamond contents than those with more ferric iron (Fe³⁺). In kimberlitic ilmenites, high Fe³⁺ is associated with low MgO. High Cr³⁺ can be found in either association but is only a positive factor when it occurs with high Mg. Favourable and unfavourable trends can be seen readily on simple MgO/Cr₂O₃ plots or ternary diagrams, such as that presented by Haggerty and Tompkins (1983). This is illustrated in Fig. 10, taken from Horwood (1998). Young, fast-grown fibrous

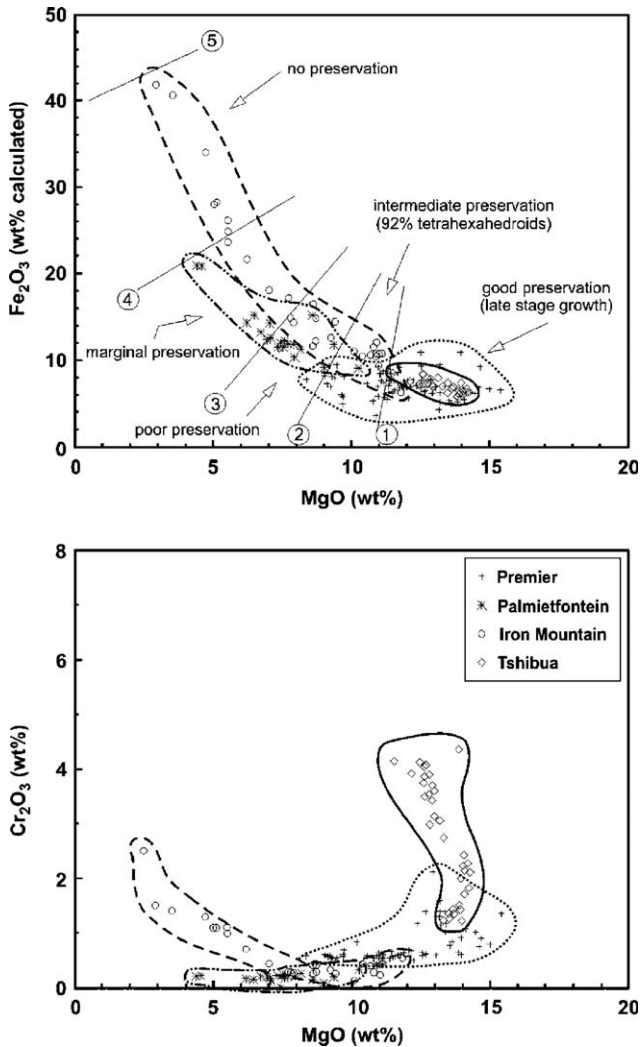


Fig. 10. Plots of Fe_2O_3 versus MgO and Cr_2O_3 versus MgO illustrating the composition of ilmenites from four kimberlite localities. [Reproduced from Horwood, 1998.] The ilmenites define a trend from MgO -rich and Fe_2O_3 -poor to Fe_2O_3 -rich and MgO -poor compositions. This trend corresponds with a gradual increase in oxygen fugacity and associated reduction in diamond preservation potential. Compositional fields 1–5 are from Horwood (1998) and illustrate the interpreted correlation between ilmenite composition and the extent of diamond preservation.

diamond is associated with ilmenite of very high Mg, high Cr, and very low Fe^{3+} content. Very resorbed diamonds, on the other hand, are found in kimberlites that have megacryst ilmenites high in Fe^{3+} and lower in Mg. Hence, megacryst ilmenite composition appears to provide an index of diamond preservation potential.

In addition to resorption processes taking place in the host magma, it has been suggested that metasomatism of the mantle lithosphere, at some time prior to

kimberlite emplacement, may be detrimental to diamond preservation (Griffin and Ryan, 1995). Such processes are reflected in the composition of peridotitic garnet and in certain instances appear to be associated with significant increases in oxygen fugacity, suggesting increased potential for diamond resorption (McCammon et al., 2001). In general, the effects of these metasomatic processes on the diamond potential of a kimberlite are likely to be accounted for by the compositional criteria described above. For example, metasomatism generally increases the Ca content and will reduce the proportion of G10's present in any given peridotitic garnet population. Similarly, peridotite that has been subjected to significant melt metasomatism (Griffin and Ryan, 1995) will manifest as Ca-saturated, Ti-rich garnet that is discounted when determining the potential diamond budget of a kimberlite. Nonetheless, understanding the "signatures" associated with metasomatic processes as well as the potential effect of such processes on diamond preservation helps to constrain the history of the lithosphere sampled by a kimberlite or lamproite and, therefore, is an important aspect of indicator mineral geochemistry.

4. APPLICATION OF INDICATOR MINERAL METHODS IN DIAMOND EXPLORATION AND EVALUATION

Flow charts summarising how indicator minerals and diamonds are used in exploring for and evaluating primary diamond deposits are provided in Figures 11 and 12.

Different diamond provinces appear to obey different sets of rules particularly with respect to preservation. For instance, at most kimberlite localities on the Kalahari Craton, resorption of diamonds is a very significant process (Robinson, 1979). In the Malo-Botuoba and Daldyn-Alakhit regions of the Siberian Platform, which include the Mir, Udachnaya and Jubilee kimberlites, resorption is of minor significance. In Zaire and Sierra Leone, late stage fibrous coats on numerous diamonds suggest that the last event in the diamond history in those regions was a period of diamond growth. Variations in the eclogitic to peridotitic ratio of the diamonds may also be regional. The three kimberlite mines in Botswana for instance show higher than average proportions of eclogitic diamonds, which is also the case for the described primary diamond resources in Australia (Hall and Smith, 1984; Jaques et al., 1989). In contrast, diamonds from kimberlites in the Kimberley region of South Africa have a preponderance of peridotitic inclusions and minimal eclogitic minerals. As with most geochemical approaches to mineral exploration, an orientation survey within a prospective area is a necessary prerequisite and the interpretations must be continuously adapted to the database compiled.

A vital question is how much reliance to place on diamond potential forecasts based on the geochemistry of indicator minerals. To reach its full potential, the method needs to be rigorously applied, taking into consideration all of the factors described above. If that is done, most "anomalies" can be accounted for, and it is clear that the system can be a major aid to exploration programs. In Botswana, where an early version was applied by Falconbridge Exploration to several tens of kimberlites discovered under Kalahari cover in the early 1980s, the heavy mineral

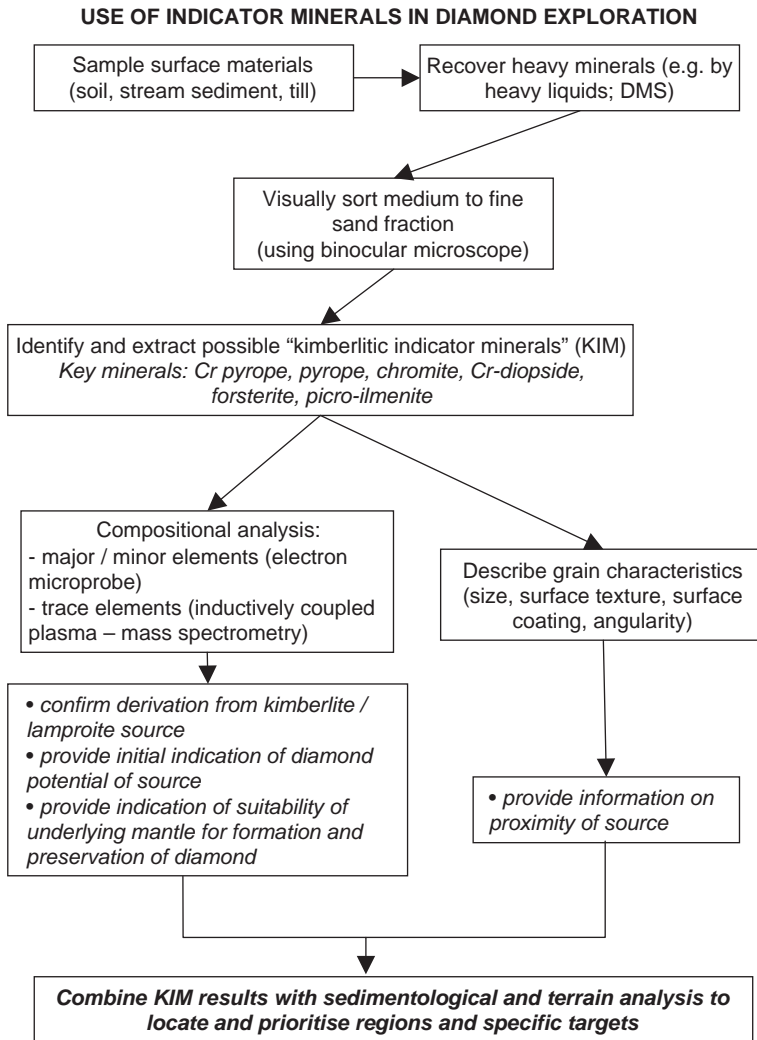


Fig. 11. Flow-chart summarising key aspects of the application of indicator mineral studies in diamond exploration.

analyses correctly identified all the barren kimberlites and all the diamond-bearing kimberlites. Notably, the method flagged the best ore-bearing body found (GO25) as soon as the first batch of heavy minerals from that source passed in front of the microprobe. In this environment of hidden ore bodies, it was an unqualified success (Lee, 1993). Subsequently the method was a major factor in the early stages of prospecting for the Ekati kimberlites by DiaMet and in the subsequent evaluation and development of the Ekati diamond mine by the BHP/DiaMet/Fipke/Blusson consortium (Fig. 12) (Fipke et al., 1995).

In a Venezuelan stream sampling program in 1975, the presence of G10 garnets from a nearby diamond source was picked up in the Guaniamo region where the

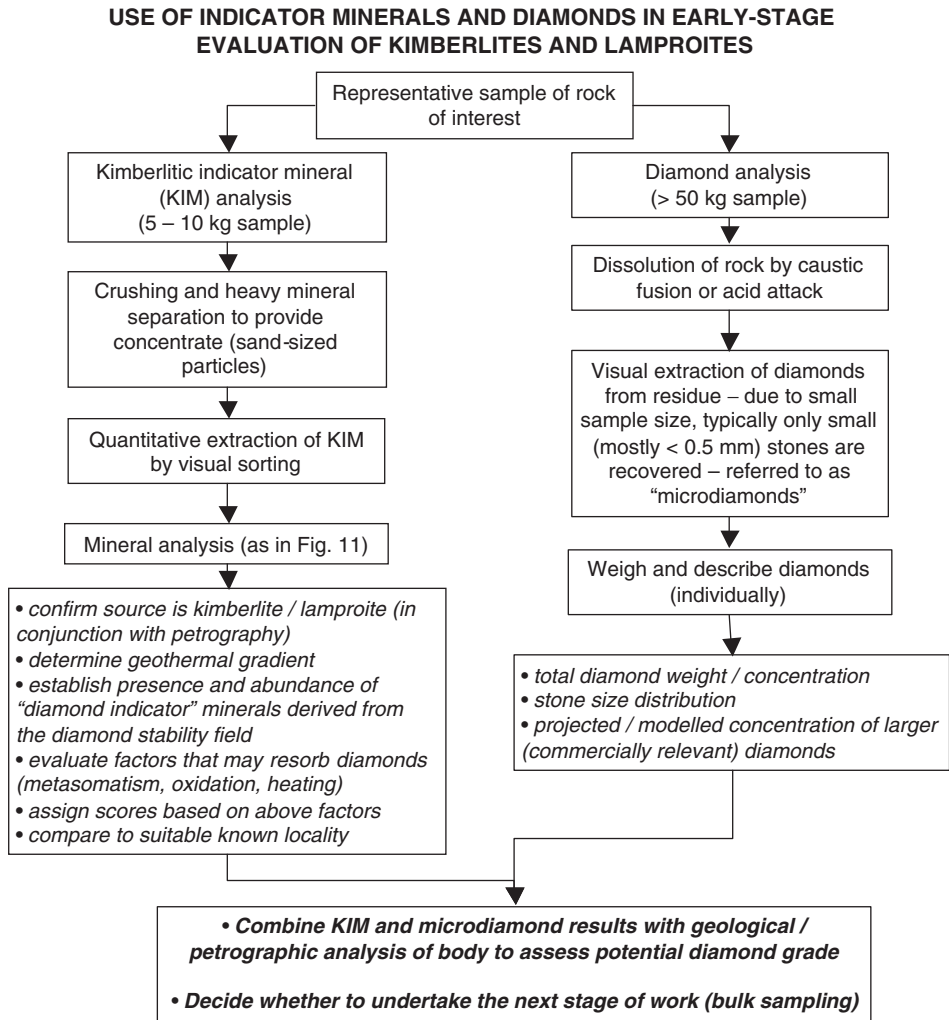


Fig. 12. Flow-chart summarising key aspects of the application of indicator mineral and microdiamond studies in the early-stage evaluation of kimberlite or lamproite deposits.

primary source of some of the alluvial diamonds has now been found (Nixon et al., 1989). Earlier, the system demonstrated the proximity of a then unknown primary source (Dokolwayo) to the Hlane alluvial diamonds in Swaziland.

Accurate forecasts about the presence or absence of diamonds have also been made for Brazilian kimberlites and for numerous localities in southern Africa, both barren and diamond-bearing. The method has been successfully applied in the Banankoro region in Guinea, West Africa. In North America, it was used to prioritise the sampling of the Georges Creek dyke in the Colorado/Wyoming State Line District (Carlson and Marsh, 1989). It provided acceptable forecasts for the nearby Schaffer and Sloan 2/5 intrusions, predicted the absence of diamonds at Iron Mountain, Garnet Ridge, Moses Rock and Green Knobs, and was successfully

applied to diamond exploration in the North American Cordillera (Dummett et al., 1986). The heavy mineral assessment of the kimberlites in the Upper Peninsula, Michigan is again in good accord with the known facts in that area (McGee, 1988). Even the Twin Knobs lamproite in Arkansas conforms to the general pattern (Waldman et al., 1987). The fact that diamonds are being (or can be) traced by association with fragments of the mantle rocks from which they have been originally released by disaggregation is such a fundamental association that whatever geological vehicle has been used to convey them to the surface, there is a chance that semi-quantitative relationships may hold. Where they do not, further geochemical or petrological detective work may reveal relevant clues. The diamonds may not have been preserved en route to surface, the lithosphere may not have been thick enough or the geothermal gradient sufficiently low to permit diamond formation and/or storage to have occurred. The apparently necessary metasomatic activity that may have a particularly important role in the formation of peridotitic diamonds may never have occurred and a suitable carbon source may, therefore, not be available. Clues may come from the major and trace element contents of other mantle minerals that occur in the intrusion under investigation. Given the wide range of uncertainties, a balanced view has to be permissive of exceptions to the rules since these are certain to occur.

ACKNOWLEDGEMENTS

The development of this geochemical approach to assessing the diamond potential of volcanic ore bodies has taken more than three decades of research and practical experience. The project profited greatly from the enthusiastic support of Hugo T. Dummett while he was employed by Superior Oil Company and BHP. A key early input was made by Dr. George Switzer from the Smithsonian Institution and by J. Barry Hawthorne, of De Beers Consolidated Mines in Kimberley. The method has been refined and greatly improved by the contributions of numerous scientists around the world whom we have hopefully correctly referenced in the text. Financial support during various phases of this period of time is gratefully acknowledged from De Beers Consolidated Mines, Falconbridge Explorations, Superior Oil and BHP Billiton Diamonds, Inc. The authors would also like to acknowledge Jon Carlson of BHP Billiton for supporting application and ongoing research of the methods described in this paper. Thanks to Herman Grütter for valuable input to aspects of the manuscript and to Meilanie Zamora for drafting several of the figures. Finally, we would like to thank Laurence Robb, John Dewey and Maria Mange for efficient and constructive reviews that have improved this manuscript.

REFERENCES

- Armstrong, K.A., Nowicki, T.E., Read, G.H., 2004. Kimberlite AT-56: A mantle sample from north central Superior craton Canada. *Lithos* 77, 695–704.
- Boyd, F.R., Gurney, J.J., 1982. Low-Calcium Garnets: Keys to Craton Structure and Diamond Crystallisation. *Carnegie Institute of Washington Yearbook*, vol. 81, Washington DC, U.S., pp. 261–267.

- Bulanova, G.P., 1995. The formation of diamond. *Journal of Geochemical Exploration* 53, 1–24.
- Bundy, F.P., Strong, H.M., Wentorf, R.H., 1973. In: Walker, P.L., Throver, P.A. (Eds.), *Chemistry and Physics of Carbon*. Marcel Dekker, New York, pp. 213–263.
- Canil, D., 1994. An experimental calibration of the “Ni-in-garnet” geothermometer with applications. *Contributions to Mineralogy and Petrology* 117, 410–420.
- Carlson, J.A., Marsh, S.W., 1989. Discovery of the George Creek, Colorado kimberlite dykes. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 1169–1178.
- Danchin, R., Wyatt, B.A., 1979. Statistical cluster analyses of garnets from kimberlites and their xenoliths. *Kimberlite Symposium II*, Cambridge, U.K., pp. 22–27.
- Dawson, J.B., Smith, J., 1975. Occurrence of diamond in a mica-garnet lherzolite xenolith from kimberlite. *Nature* 254, 580–581.
- Dawson, J.B., Stephens, W.E., 1975. Statistical classification of garnets from kimberlite and associated xenoliths. *Journal of Geology* 83, 589–607.
- Deines, P., Harris, J.W., Gurney, J.J., 1987. Carbon isotopic composition, nitrogen content and inclusion composition of diamonds from Roberts Victor kimberlite, South Africa: evidence for ^{13}C depletion in the mantle. *Geochimica et Cosmochimica Acta* 51, 1227–1243.
- Deines, P., Harris, J.W., Gurney, J.J., 1991. The carbon and nitrogen content of lithospheric and asthenospheric diamonds from the Jagersfontein and Koffiefontein kimberlites, South Africa. *Geochimica et Cosmochimica Acta* 55, 2615–2625.
- Dong, Z., Zhou, J., 1980. The typomorphic characteristics of chromites from kimberlites in China, and the significance in exploration of diamond deposits. *Acta Geologica Sinica* 4, 299–309.
- Draper, D., Frames, M.E., 1898. *The Diamond, with Hints to Prospectors in Search of these Gems*. Mathews and Walker, Johannesburg, 44pp.
- Dummett, H.T., Fipke, C.E., Blusson, S.L., 1986. Diamond exploration in the North American Cordillera. In: Elliot, I.L., Smee, B.W. (Eds.), *Joint Publication of the Association of Exploration Geochemists and the Geological Association of Canada*, pp. 168–176.
- Evans, T., Harris, J.W., 1989. Nitrogen aggregation, inclusion equilibration temperatures and the age of diamonds. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 1001–1006.
- Fipke, C.E., Gurney, J.J., Moore, R.O., 1995. Diamond exploration techniques emphasising indicator mineral geochemistry and Canadian examples. *Geological Survey of Canada, Bulletin* 423, 86.
- Gregory, G.P., White, D.R., 1989. Collection and treatment of diamond exploration samples. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 1123–1134.
- Griffin, W.L., Gurney, J.J., Ryan, C.G., Cousens, D.R., Sie, S.H., Suter, G.F., 1989. Trapping temperatures and trace elements in P-type garnets in diamonds: a proton microprobe study. *Extended Abstracts, Workshop on Diamonds, 28th International Geological Congress, Washington, DC*, pp. 23–25.
- Griffin, W.L., Ryan, C.G., 1995. Trace elements in indicator minerals: area selection and target evaluation in diamond exploration. *Journal of Geochemical Exploration* 53, 311–337.
- Grütter, H.S., Apter, D.B., 1998. Kimberlite- and lamproite-borne chromite phenocrysts with “diamond-inclusion”-type chemistries. *Extended Abstracts, 7th International Kimberlite Conference, Cape Town, South Africa*, pp. 280–282.
- Grütter, H.S., Apter, D.B., Kong, J., 1999. Crust-mantle coupling: evidence from mantle-derived xenocryst garnets. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H.

- (Eds.), Proceedings of 7th International Kimberlite Conference, vol. 1 (J.B. Dawson Volume). Red Roof Design, Cape Town, pp. 307–313.
- Grütter, H.S., Gurney, J.J., Menzies, A.H., Winter, F., 2004. An updated classification scheme for mantle-derived garnet, for use by diamond explorers. *Lithos* 77, 841–857.
- Grütter, H.S., Latti, D., Menzies, A.H., 2006. Cr-saturation arrays in concentrate garnet compositions from kimberlite and their use in mantle barometry. *Journal of Petrology* 47, 801–820.
- Grütter, H.S., Quadling, K.E., 1999. Can sodium in garnet be used to monitor eclogitic diamond potential? In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), Proceedings of 7th International Kimberlite Conference, vol. 1 (J.B. Dawson Volume), Red Roof Design, Cape Town, pp. 314–320.
- Gurney, J.J., 1984. A correlation between garnets and diamonds in kimberlites. In: Glover, J.E., Harris, P.G. (Eds.), *Kimberlite Occurrence and Origin: A Basis for Conceptual Models in Exploration*. Geology Department and University Extension, University of Western Australia, Publication, vol. 8. Blackwell Scientific Publications, Perth, pp. 143–166.
- Gurney, J.J., 1989. Diamonds. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 1. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 935–965.
- Gurney, J.J., 1990. The diamondiferous root zones of our wandering continents. *South African Journal of Geology* 93, 423–437.
- Gurney, J.J., Harris, J.W., Rickard, R.S., 1984. Silicate and oxide inclusions in diamonds from the Orapa mine, Botswana. In: Kornprobst, J. (Ed.), *Kimberlites II: The Mantle and Crust-Mantle Relationships*. Elsevier, Amsterdam, pp. 3–9.
- Gurney, J.J., Harris, J.W., Rickard, R.S., Moore, R.O., 1985. Premier mine diamond inclusions. *Transactions of the Geological Society of South Africa* 88, 301–310.
- Gurney, J.J., Helmstaedt, H.H., le Roex, A.P., Nowicki, T.E., Richardson, S.H., Westerlund, K.J., 2005. Diamonds: crustal distribution and formation processes in time and space and an integrated deposit model. *Society of Economic Geologists, 100th Anniversary Volume* 143–177.
- Gurney, J.J., Helmstaedt, H., Moore, R.O., 1993. A review of the use and application of mantle mineral geochemistry in diamond exploration. *Pure and Applied Chemistry* 65, 2423–2442.
- Gurney, J.J., Hildebrand, P.R., Carlson, J.A., Fedortchouk, Y., Dyck, D.R., 2004. The morphological characteristics of diamonds from the Ekati Property, Northwest Territories, Canada. *Lithos* 77, 21–38.
- Gurney, J.J., Switzer, G.S., 1973. The discovery of garnets closely related to diamonds in the Finsch Pipe, South Africa. *Contributions to Mineralogy and Petrology* 39, 103–116.
- Gurney, J.J., Zweistra, P., 1995. The interpretation of the major element compositions of mantle minerals in diamond exploration. *Journal of Geochemical Exploration* 53, 293–309.
- Haggerty, S.E., 1986. Diamond genesis in a multiply-constrained model. *Nature* 320, 34–38.
- Haggerty, S.E., Tompkins, L.A., 1983. Redox state of the earth's upper mantle from kimberlitic ilmenites. *Nature* 303, 295–300.
- Hall, A.E., Smith, C.B., 1984. Lamproite diamonds—are they different? In: Glover, J.E., Hams, G. (Eds.), *Kimberlite Occurrence and Origin: A Basis for Conceptual Models in Exploration*. Geology Department and University Extension, University of Western Australia, Publication, vol. 8, Blackwell Scientific Publications, Perth.
- Harte, B., Harris, J.W., Hutchison, M.T., Watt, G.R., Wilding, M.C., 1999. Lower mantle mineral associations in diamonds from Sao Luiz, Brazil. In: Fei, Y., Bertka, C.M., Myson, B.O. (Eds.), *Mantle Petrology: Field Observations and High-Pressure Experimentation: A Tribute to Francis R. (Joe) Boyd*, Chemical Society, Special Publication, vol. 6, pp. 125–154.

- Hatton, C.J., Gurney, J.J., 1979. A diamond-graphite eclogite from the Roberts Victor mine. In: Boyd, F.R., Meyer, H.O.A. (Eds.), *The Mantle Sample*. American Geophysical Union, Washington, DC, pp. 29–36.
- Helmstaedt, H., Gurney, J.J., 1984. Kimberlites of southern Africa—are they related to subduction processes? In: Kornprobst, J. (Ed.), *Kimberlites I: Kimberlites and Related Rocks*. Elsevier, Amsterdam, pp. 425–434.
- Helmstaedt, H.H., Gurney, J.J., 1995. Geotectonic controls of primary diamond deposits: implications for area selection. *Journal of Geochemical Exploration* 53, 125–144.
- Helmstaedt, H., Schulze, D.J., 1989. Southern African kimberlites and their mantle sample—implication for Archean tectonics and lithosphere evolution. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 1. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 358–368.
- Hills, D.V., Haggerty, S.E., 1989. Petrochemistry of eclogites from the Koidu kimberlite complex, Sierra Leone. *Contributions to Mineralogy and Petrology* 103, 397–422.
- Horwood, S.J., 1998. The use of upper mantle derived ilmenite to predict preservation of diamond parcels in kimberlite. Unpublished M.Sc. thesis. University of Cape Town, 154 pp.
- Jago, B.C., Mitchell, R.H., 1989. A new garnet classification technique: divisive cluster analysis applied to garnet populations from Somerset kimberlites. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 1. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 298–310.
- Jaques, A.L., Hall, A.E., Sheraton, J.W., Smith, C.B., Sun, S.-S., Drew, R.M., Foudoulis, C., Ellingsen, K., 1989. Composition of crystalline inclusions and C isotopic composition of Argyle and Ellendale diamonds. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 966–989.
- Kennedy, C.S., Kennedy, G.C., 1976. The equilibrium boundary between graphite and diamond. *Journal of Geophysical Research* 81, 2467–2470.
- Kirkley, M.B., Gurney, J.J., Otter, M.L., Hill, S.J., Daniels, L.R., 1991. The application of C isotope measurements to the identification of the sources of C in diamonds: a review. *Applied Geochemistry* 6, 477–494.
- Kramers, J.D., 1977. Lead and strontium isotopes in Cretaceous kimberlites and mantle-derived xenoliths from southern Africa. *Earth and Planetary Science Letters* 34, 419–431.
- Kramers, J.D., 1979. Lead, uranium, strontium, potassium and rubidium in inclusion bearing diamonds and mantle-derived xenoliths from southern Africa. *Earth and Planetary Science Letters* 42, 58–70.
- Lawless, J., 1974. Some aspects of the geochemistry of kimberlite xenocrysts. Unpublished Ph.D. thesis. University of Cape Town, South Africa, 193 pp.
- Lee, J.E., 1993. Indicator mineral techniques in a diamond exploration program at Kokong, Botswana. In: *Diamond: Exploration, Sampling and Evaluation*. Prospectors and Developers Association, Diamond Exploration Short Course Notes, pp. 1–21.
- McCallum, M.E., Egger, D.H., 1976. Diamonds in an upper mantle peridotite nodule from kimberlite in southern Wyoming. *Science* 192, 253–256.
- McCammon, C.A., Griffin, W.L., Shee, S.R., O'Neill, H.S.C., 2001. Oxidation state during metasomatism in ultramafic xenoliths from the Wesselton kimberlite, South Africa: implications for the survival of diamond. *Contributions to Mineralogy and Petrology* 141, 287–296.
- McCandless, T.E., Gurney, J.J., 1989. Sodium in garnet and potassium in clinopyroxene: criteria for classifying mantle xenoliths. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 827–832.

- McDade, P., Harris, J.W., 1999. Syngenetic inclusion bearing diamonds from Letseng-la-Terai, Lesotho. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), *Proceedings of 7th International Kimberlite Conference*, vol. 2 (P.H. Nixon Volume). Red Roof Design, Cape Town, pp. 557–565.
- McGee, E.S., 1988. Potential for diamond in kimberlites from Michigan and Montana as indicated by garnet xenocryst compositions. *Economic Geology* 83, 428–432.
- McKenna, N., Gurney, J.J., Davidson, J.M., 2003. A study of the diamonds, diamond inclusion minerals and other mantle minerals from the Swartruggens kimberlite dyke swarm. *Extended Abstracts, 8th International Kimberlite Conference*, Victoria, BC, abstract 0054 (CD-ROM).
- Menzies, A.H., Carlson, R.W., Shirey, S.B., Gurney, J.J., 1999. Re-Os systematics of Newlands peridotite xenoliths: Implications for diamond and lithosphere formation. In: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H. (Eds.), *Proceedings of 7th International Kimberlite Conference*, vol. 2 (P.H. Nixon Volume). Red Roof Design, Cape Town, pp. 566–573.
- Meyer, H.O.A., 1987. Inclusions in diamond. In: Nixon, P.H. (Ed.), *Mantle Xenoliths*. Wiley, Chichester, pp. 501–522.
- Mitchell, R.H., 1986. *Kimberlites: Mineralogy, Geochemistry and Petrology*. Plenum Press, New York, 442pp.
- Mitchell, R.H., 1995. *Kimberlites, Orangeites, and Related Rocks*. Plenum Press, New York, 410pp.
- Moore, R.O., Gurney, J.J., 1985. Pyroxene solid solution in garnets included in diamond. *Nature* 318, 553–555.
- Moore, R.O., Gurney, J.J., 1989. Mineral inclusions in diamond from the Monastery kimberlite, South Africa. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 1029–1041.
- Muggeridge, M.T., 1995. Pathfinder sampling techniques for locating primary sources of diamond: recovery of indicator minerals, diamonds and geochemical signatures. *Journal of Geochemical Exploration* 53, 183–204.
- Nimis, P., Taylor, W.R., 2000. Single clinopyroxene thermobarometry for garnet peridotites: Part 1. Calibration and testing of a Cr-in-Cpx barometer and an enstatite-in-Cpx thermometer. *Contributions to Mineralogy and Petrology* 139, 541–554.
- Nixon, P.H., Davies, G.R., Condliffe, E., Baker, R., Baxter Brown, R., 1989. Discovery of ancient source rocks of Venezuela diamonds. *Extended Abstracts, Workshop on Diamonds, 28th International Geological Congress*, Washington, DC, pp. 73–75.
- Otter, M.L., Gurney, J.J., 1989. Mineral inclusions in diamonds from the Sloan diatremes, Colorado-Wyoming State Line kimberlite district, North America. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 1042–1053.
- Otter, M.L., Gurney, J.J., McCandless, T.E., 1989. The carbon isotope composition of Sloan diamonds. *Extended Abstracts, Workshop on Diamonds, 28th International Geological Congress*, Washington, DC, pp. 76–79.
- Pokhilenko, N.P., Sobolev, N., Lavrent'yev, Y.G., 1977. Xenoliths of diamondiferous ultramafic rocks from Yakutian kimberlites. *Extended Abstracts, 2nd International Kimberlite Conference*, Sante Fe, American Geophysical Union (unpaged).
- Pollack, H.N., Chapman, D.S., 1977. On the regional variation of heat flow, geotherms, and lithosphere thickness. *Tectonophysics* 38, 279–296.
- Reid, A.M., Brown, R.W., Dawson, J.B., Whitfield, G.C., Siebert, J.C., 1976. Garnet and pyroxene compositions in some diamondiferous eclogites. *Contributions to Mineralogy and Petrology* 58, 203–220.

- Richardson, S.H., 1986. Latter-day origin of diamonds of eclogitic paragenesis. *Nature* 322, 623–626.
- Richardson, S.H., 1989. Radiogenic isotope studies of diamond inclusions. Extended Abstracts, Workshop on Diamonds, 28th International Geological Congress, Washington, DC, pp. 87–90.
- Richardson, S.H., Erlank, A.J., Harris, J.W., Hart, S.R., 1990. Eclogitic diamonds of Proterozoic age from Cretaceous kimberlites. *Nature* 346, 54–56.
- Richardson, S.H., Gurney, J.J., Erlank, A.J., Harris, J.W., 1984. Origin of diamonds in old enriched mantle. *Nature* 310, 198–202.
- Richardson, S.H., Harris, J.W., Gurney, J.J., 1993. Three generations of diamonds from old continental mantle. *Nature* 366, 256–258.
- Richardson, S.H., Shirey, S.B., Harris, J.W., Carlson, R.W., 2001. Archean subduction recorded by Re-Os isotopes in eclogitic sulfide inclusions in Kimberley diamonds. *Earth and Planetary Science Letters* 191, 257–266.
- Rickwood, C., Gurney, J.J., White-Cooper, D.R., 1969. The nature and occurrence of eclogite xenoliths in the kimberlites of southern Africa. Geological Society of South Africa, Special Publication, vol. 2, pp. 371–393.
- Robinson, D.N., 1979. Surface textures and other features of diamonds. Unpublished Ph.D. thesis. University of Cape Town, South Africa, 221pp.
- Robinson, D.N., Gurney, J.J., Shee, S.R., 1984. Diamond eclogite and graphite eclogite xenoliths from Orapa, Botswana. In: Kornprobst, J. (Ed.), *Kimberlites II: The Mantle and Crust-Mantle Relationships*. Elsevier, Amsterdam, pp. 11–24.
- Robinson, D.N., Scott, J.A., Van Niekerk, A., Anderson, G., 1989. The sequence of events reflected in the diamonds of some southern African kimberlites. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 980–990.
- Rudnick, R.L., Nyblade, A.A., 1999. The thickness and heat production of Archean lithosphere: constraints from xenolith thermobarometry and surface heat flow. In: Fei, Y., Bertka, C.M., Myson, B.O. (Eds.), *Mantle Petrology: Field Observations and High-Pressure Experimentation: A Tribute to Francis R. (Joe) Boyd*, Chemical Society, Special Publication, vol. 6, pp. 3–12.
- Ryan, C.G., Griffin, W.L., Pearson, N.J., 1996. Garnet geotherms: pressure–temperature data from Cr-pyrope garnet xenocrysts in volcanic rocks. *Journal of Geophysical Research* B3, 5611–5625.
- Schulze, D.J., 2003. A classification scheme for mantle-derived garnet in kimberlite: a tool for investigating the mantle and exploring for diamonds. *Lithos* 71, 195–213.
- Seifert, F., Schreyer, W., 1968. Die Möglichkeit der Entstehung ultrabasischer Magmen bei Gegenwart geringer Alkalimengen. *Geologische Rundschau* 57, 349–362.
- Shee, S.R., Bristow, J.W., Bell, D.R., Smith, C.B., Alsopp, H.L., Shee, P.B., 1989. The petrology of kimberlites, related rocks and associated mantle xenoliths from the Kuruman province, South Africa. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 1. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 60–82.
- Shee, S.R., Gurney, J.J., 1979. The mineralogy of xenoliths from Orapa, Botswana. In: Boyd, F.R., Meyer, H.O.A. (Eds.), *The Mantle Sample*. American Geophysical Union, Washington, DC, pp. 37–49.
- Shee, S.R., Gurney, J.J., Robinson, D.N., 1982. Two diamond-bearing peridotite xenoliths from the Finsch kimberlite, South Africa. *Contributions to Mineralogy and Petrology* 81, 79–87.
- Shimizu, N., Richardson, S.H., 1987. Trace element abundance patterns of garnet inclusions in peridotite-suite diamonds. *Geochimica et Cosmochimica Acta* 51, 755–758.

- Slodkevich, V.V., 1983. Graphite paramorphs after diamond. *International Geology Review* 23, 497–514.
- Smith, C.B., Gurney, J.J., Harris, J.W., Robinson, D.N., Shee, S.R., Jagoutz, E., 1989. Sr and Nd isotopic systematics of diamond-bearing eclogite xenoliths and eclogitic inclusions in diamond from southern Africa. In: Ross, J. (Ed.), *Kimberlites and Related Rocks*, vol. 2. Geological Society of Australia, Special Publication, vol. 14. Blackwell Scientific Publications, Perth, pp. 853–863.
- Sobolev, N., 1974. Deep seated inclusions in kimberlites and the problem of the composition of the upper mantle. English Translation by Brown, D.A., 1977, American Geophysical Union, Washington, DC.
- Sobolev, N., Galimov, E.M., Ivanovskaya, I.N., Yefimova, E.S., 1979. Isotope composition of carbon of diamonds containing crystalline inclusions. *Doklady Akademii Nauk SSSR* 249, 1217–1220 (in Russian).
- Sobolev, N., Lavrent'yev, Y.G., 1971. Isomorphic sodium admixture in garnets formed at high pressures. *Contributions to Mineralogy and Petrology* 31, 1–12.
- Talnikova, S.B., 1995. Inclusions in diamonds of different habits. Extended Abstracts, 6th International Kimberlite Conference, Novosibirsk, Russia, pp. 603–605.
- Taylor, L.A., Anand, A., 2004. Diamonds: time capsules from the Siberian mantles. *Chemie der Erde* 64, 1–74.
- Trautman, R.L., Griffin, B.J., Taylor, W.R., Spetsius, Z.V., Smith, C.B., Lee, D.C., 1997. A comparison of the microdiamonds from kimberlite and lamproite of Yakutia and Australia. 6th International Kimberlite Conference, Novosibirsk, Russia, *Russian Geology and Geophysics* 38, 341–355.
- Waldman, M.A., McCandless, T.E., Dummett, H.T., 1987. Geology and petrography of the Twin Knobbs #1 lamproite, Pike County, Arkansas. In: Morris, E.M., Pasteris, J.D. (Eds.), *Mantle Metasomatism and Alkaline Magmatism*. Geological Society of America, Special Publication, vol. 215, pp. 205–216.
- Westerlund, K.J., 2005. A Geochemical Study of Diamonds, Mineral Inclusions in Diamonds and Mantle Xenoliths from the Panda Kimberlite, Slave Craton. Unpublished Ph.D. thesis. University of Cape Town. 170pp.
- Westerlund, K.J., Gurney, J.J., Carlson, R.W., Shirey, S.B., Hauri, E.H., Richardson, S.H., 2004. A metasomatic origin for late Archean eclogitic diamonds: implications from internal morphology of Klipspringer diamonds and Re-Os and S isotope characteristics of their sulfide inclusions. *South African Journal of Geology* 107, 119–130.
- Willmott, E., 2004. World diamond production. *Rough Diamond Review* 7, 28–30.
- Wyatt, B.A., Baumgartner, M., Anckar, E., Grütter, H.S., 2004. Compositional classification of “kimberlitic” and “non-kimberlitic” ilmenite. *Lithos* 77, 819–840.
- Wyllie, J., Huang, W.-L., Otto, J., Byrnes, A.P., 1983. Carbonation of peridotites and decarbonation of siliceous dolomites represented in the system CaO-MgO-SiO₂-CO₂ to 30 kbar. *Tectonophysics* 100, 359–388.
- Yefimova, E.S., Sobolev, N., 1977. Abundance of crystalline inclusions in diamonds of Yakutia. *Doklady Akademii Nauk SSSR* 237, 1475–1478 (in Russian).