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Are euhedral microdiamonds formed during ascent and decompression of kimberlite magma? Implications for use of microdiamonds in diamond grade estimation

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Abstract—The relationship between euhedral microdiamonds (<1 mm in maximum dimension) and macrodiamonds is problematic. A major paradox is that euhedral microdiamonds, by virtue of their small size, should be especially susceptible to resorption compared to macrodiamonds, whereas the opposite is commonly observed. We discuss difficulties with published mechanisms for euhedral microdiamond formation and eruption, most of which involve two separate, possibly unrelated, events: first, euhedral microdiamond crystallization (by a variety of possible processes), and second, later entrainment in erupting kimberlitic or lamproitic magma.

We propose an alternative hypothesis based on published experimental studies showing there is a significant decrease in the C-bearing volatile content of kimberlite magma as pressure decreases. During ascent of the kimberlite magma, this may result in a pressure-related transition from conditions at depth at which diamond is unstable in fluid-undersaturated kimberlite magma to shallower-level conditions at which diamond becomes stable (or metastable) as the magma reaches fluid saturation. In this scenario macrodiamond xenocrysts (of an early generation), entrained at asthenospheric or deep lithospheric depths, may partially or totally dissolve into the undersaturated magma upon disaggregation of their host rocks; upon ascent of the magma to shallower depths, and under appropriate oxidation conditions, the lowered capacity of the magma to dissolve C-bearing volatiles may result in euhedral microdiamond precipitation, probably immediately before final eruption. Although framed in qualitative terms, our hypothesis has testable consequences which we discuss. In view of these considerations, and the multiple possible relationships within and between microdiamonds and macrodiamonds in individual deposits, we suggest that the use of microdiamond abundances from small samples as a guide to economic macrodiamond grade is problematic as an exploration strategy.

INTRODUCTION

Microdiamond is a term used for natural diamonds found in either kimberlite or lamproite that are smaller than 1.0 mm in their largest dimension (e.g., Gurney, 1989; Mitchell, 1991; McCandless *et al.*, 1994; but <0.5 mm in the diamond exploration literature, e.g., Deakin and Boxer, 1989; Lee *et al.*, 1994), regardless of their origin. Microdiamonds have been used in two ways during exploration for larger, economic diamonds once a kimberlite or lamproite has been discovered (Deakin and Boxer, 1989; Jennings, 1990; Rombouts, 1994): (1) to confirm the presence of diamonds in a pipe; (2) to estimate the grade (carats/tonne) of macrodiamonds in the pipe from relatively small samples (20–100 kg; Jennings, 1990). The basis for using microdiamonds in the above ways stems from the following observations: (a) microdiamonds (whatever their origin, see below) are generally more abundant in diamondiferous pipes than macrodiamonds, i.e., in any given volume of rock there will generally be more small diamonds than large ones; (b) the concentrations of microdiamonds and macrodiamonds in at least one pipe (Argyle, Australia) appears to define a single size distribution population (log-normal; Deakin and Boxer, 1989;

Rombouts, 1994), indicating that the proportion of microdiamonds to macrodiamonds may be relatively uniform.

Whereas the first use of microdiamonds is uncontroversial, the universal application of the second use is more controversial, as shown in the summer of 1994 by the poor economic macrodiamond grades of several kimberlite pipes in the Northwest Territories, Canada, that showed high microdiamond counts in relatively small samples (see below). Consequently, it appears that the relationship between microdiamonds and macrodiamonds is not completely understood.

The microdiamonds of concern in this paper occur as clear, well crystallized, euhedral octahedra that show little or no sign of resorption; henceforth they are referred to as euhedral microdiamond(s). Resorption is used in the manner of Otter and Gurney (1989) (p. 1043) "... for describing a non-specific process which has, subsequent to diamond growth, diminished the size of the diamond, whether it be by oxidation, graphitization or some other mechanism." Associated macrodiamonds (diamonds >1.0 mm in largest dimension) have variable clarity and transparency and are typically characterized by varying degrees of resorption, often occurring with a rounded, dodecahedral to tetrahexahedroid morphology, i.e., a
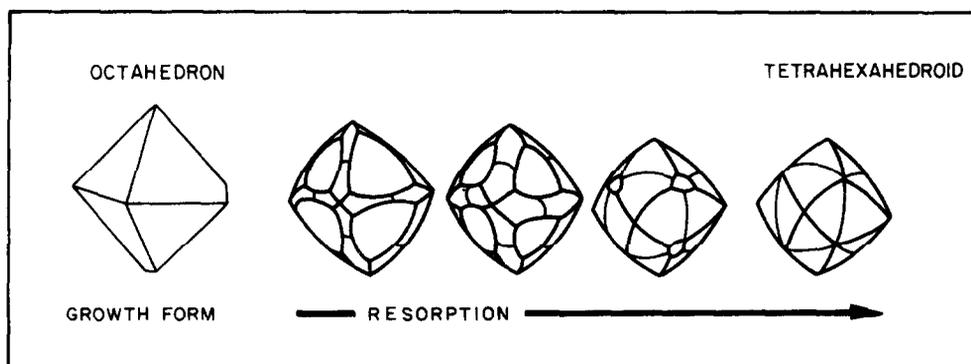
Fig. 1. Stages in the conversion of a diamond octahedron to a tetrahexahedroid. From Robinson *et al.*
(1989).

tetrahexahedral shape with rounded faces (Fig. 1). The resorption features are generally interpreted to result from resorption of originally euhedral macrodiamond octahedra by kimberlite or lamproite magma, implying that macrodiamonds are unstable in such magmas (Robinson, 1978; Harris, 1987; 1992; Robinson *et al.*, 1989; Mitchell, 1991; Gurney *et al.*, 1993; McCandless *et al.*, 1994; McCallum *et al.*, 1994; Otter *et al.*, 1994), although possibly not under all conditions (e.g., Haggerty, 1990; Arima *et al.*, 1993; see below). A major paradox is that the small size of euhedral microdiamonds would make them particularly susceptible to resorption in a magma by comparison with the macrodiamonds (Boyd, 1989). Based on their euhedral morphology, however, their apparent susceptibility to resorption is the opposite to that expected (Boyd, 1989; Harris *et al.*, 1994; Meyer *et al.*, 1994).

At any one deposit it is possible to have, in the same size range (< 1 mm), various proportions of euhedral microdiamonds, resorbed diamonds, and diamond fragments, in addition to macles, irregular crystals and polycrystalline aggregrates (e.g., Harris, 1992; Harris *et al.*, 1994; McCandless *et al.*, 1994). The term euhedral microdiamond, as used here, does not apply to small fragments of diamond if such have formed by any type of fragmentation of larger diamonds, even if they are in the same size range (< 1 mm) as defined above and are found in kimberlite or lamproite. Similarly, it does not apply to small (< 1 mm) rounded diamonds whose morphology is the result of resorption of larger diamonds, although we discuss this type of small diamond later in the paper. The term microdiamond has also been used for diamonds in meteorites, impact craters, and interstellar material and they, likewise, are not considered here.

The relationship between euhedral microdiamonds and macrodiamonds is unclear and controversial (e.g., Gurney, 1989; Boyd, 1989). Mitchell (1991) noted that hypotheses deduced for the origin of macrodiamonds may not apply to microdiamonds. Compared to macrodiamonds, relatively little research has been done on euhedral microdiamonds, most likely because: (1) their sub-economic (or at best industrial)

value does not justify their collection; (2) there appears to be reluctance on the part of mining companies to release authenticated and representative suites for study.

The purposes of this paper are to: (1) summarize contrasts between euhedral microdiamonds and macrodiamonds based on information available in the literature; (2) assess published theories of euhedral microdiamond formation; (3) suggest an alternative, testable hypothesis for euhedral microdiamond formation consistent qualitatively with the features in (1) and with experimental data; (4) use these considerations to caution against the use of microdiamond abundance in general, and euhedral microdiamond abundance in particular, as a guide to macrodiamond grade in kimberlite or lamproite pipes. Although the dangers of using microdiamond abundances as a guide to macrodiamond grades may have been recognized by some workers, our hypothesis for euhedral microdiamond formation provides an additional reason for caution in applying this technique. A secondary purpose of the paper, given the limited availability of published objective, statistical information on euhedral and other microdiamonds, is to suggest a testable hypothesis for euhedral microdiamond formation that may stimulate further research on this topic.

OCCURRENCE OF EUHEDRAL MICRODIAMONDS

The presence and abundance of euhedral microdiamonds in most kimberlite and lamproite pipes, whether or not they contain macrodiamonds, is not well documented. They have been reported in certain kimberlite and lamproite pipes/districts, sometimes in great abundance, e.g., Murfreesboro, Colorado-Wyoming State Line, and several pipes in South Africa and China (Wagner, 1914; Tolansky and Rawle-Cope, 1969; Tolansky, 1972; McCallum *et al.*, 1979; Harris, 1992; Harris *et al.*, 1994; McCallum *et al.*, 1994; McCandless *et al.*, 1994; Viljoen *et al.*, 1994). Nevertheless, in many of these cases, there are deficiencies in the information that is provided. For

example, Tolansky (1972) stated that he examined over 10,000 carats (representing some 10 millions of particles, including fragments and breakage chips) of fine-mesh tailings from several South African mines. From the Premier mine tailings, he selected 10,951 crystals for N-type studies (see below) that were predominantly euhedral microdiamonds. Unfortunately, there is no indication of how many tonnes of kimberlite had to be processed to yield this quantity, the kimberlite phase(s) from which they were obtained, nor the ratio of, or relationship between, euhedral microdiamonds, rounded (resorbed) microdiamonds and macrodiamonds in the kimberlite.

We have been unable to find any information on the occurrence of euhedral microdiamonds in the deposits in Botswana, India, Swaziland, Tanzania or Zaire; however, this lack of published information does not necessarily mean that they do not exist. Similarly, only 2 short articles in the Russian literature (Varshavskii and Bulanova, 1975; Bilenko and Zhikhareva, 1979) mention euhedral microdiamonds from Siberia. Recent visitors to Siberia saw what they estimated to be hundreds of carats of euhedral microdiamonds (Dr E. A. Schiller, pers. commun., 1994) but, again, we have no indication of the abundance of this material relative to macrodiamonds. F. Kaminsky (1995, pers. commun.) informed us that there are abundant euhedral microdiamonds in the Arkhangelsk deposits, Russia.

CONTRASTS BETWEEN EUHEDRAL MICRODIAMONDS AND MACRODIAMONDS

General characteristics

Apart from size difference, and the differences in morphology, clarity, and resorption mentioned above, macrodiamonds and euhedral macrodiamonds show a number of other contrasting characteristics and properties. Euhedral microdiamonds are widely reported in the groundmass of some diamondiferous kimberlites and lamproites (see above for localities). Most macrodiamonds are also found in the groundmass, but some macrodiamonds, as well as some small diamonds in the euhedral microdiamond size range, occur in xenoliths of eclogite and peridotite (e.g., Gurney, 1989; Viljoen et al., 1994). The degree of resorption of macrodiamonds is greater when they occur in kimberlite/lamproite groundmass than when they occur in xenoliths, suggesting that the xenolithic material protected the diamonds from corrosive kimberlitic/lamproitic magma (e.g., Shee et al., 1982; Harris, 1987; 1992; Harris et al., 1994; Viljoen et al., 1994).

Whereas a variety of peridotitic and eclogitic mineral inclusions, including silicates, oxides and sulphides, have been reported in macrodiamonds (e.g., Meyer, 1987; Gurney, 1989; Mitchell, 1991), there are few published accounts of mineral inclusions

in euhedral microdiamonds. Studies which have reported inclusions in what are tentatively classified as euhedral microdiamonds include Otter and Gurney (1989), Sloan kimberlite; Meyer et al. (1994), China; Lee et al. (1994), Australia. This situation may indicate either a lack of detailed study, or a genuine lack of mineral inclusions in euhedral microdiamonds.

Numerous C isotopic studies of macrodiamonds from both kimberlites and lamproites (e.g., Deines et al., 1989) have revealed contrasts between macrodiamonds of peridotitic and eclogitic affinity; in contrast, the only C isotope studies on microdiamonds of which we are aware are by McCandless et al. (1994) on some euhedral microdiamonds from Arkansas lamproites (discussed below), and Lee et al. (1994) on fibrous cube-shaped microdiamonds from Coanjula, Australia.

Nitrogen types

Diamonds are classified into 2 main types on the basis of the presence or absence of N: Type I, N present (range of 10–3000 ppm; Evans and Harris, 1989); Type II, N absent (see Robinson, 1978, Gurney, 1989, Evans and Harris, 1989, and Fritsch and Scarratt, 1992 for further details). This distinction is in part a function of the sensitivity of the analytical techniques employed. For example, Tolansky and Rawle-Cope (1969) and Tolansky (1972) used an ultraviolet absorption analytical technique (see discussion in Bilenko and Zhikhareva, 1979), whereas infrared spectroscopy is used today (Fritsch and Scarratt, 1992).

Type I diamonds are subdivided into Type Ia, in which N atoms occur in a variety of aggregated forms within the diamond lattice, and Type Ib, in which N occurs as single, substitutional atoms in the lattice. Type Ia diamonds are further subdivided on the basis of increasing complexity of aggregation types: 2 N atoms on adjacent sites (Type IaA); 4 N atoms plus a vacancy (Type IaB); N aggregates as 'platelets'; and some others (Evans and Harris, 1989). Type II diamonds are subdivided into Type IIa, containing no measurable substituting atoms of any type, and Type IIb, in which B is present. Although detailed studies have shown that many diamonds are a mixture of different types (e.g., Milledge et al., 1989), one type generally predominates. The majority of natural macrodiamonds, estimated at about 98%, are Type I, most of which are Type Ia (Wilks and Wilks, 1991); most extremely large diamonds (e.g., Cullinan) are Type IIa; and Type IIb (blue in colour) are extremely rare. All commercially-available synthetic diamonds are Type Ib (Wilks and Wilks, 1991).

Only a few suites of euhedral microdiamonds have been investigated for their N types and in these the microdiamonds appear to be less predominantly of Type I compared to macrodiamonds. Tolansky (1972) found that 70% of the microdiamonds from the

Premier mine, South Africa (all clear, transparent crystals, mostly octahedra but some twinned octahedra and dodecahedra) are Type II, whereas about 2% of the microdiamonds from the Finsch mine are also of this type. Regrettably, Tolansky did not distinguish between the a and b varieties of either types. Tolansky (1972) noted that dodecahedral microdiamonds are mainly Type I and that Type II microdiamonds are predominantly of euhedral, octahedral morphology. In a preliminary study, Taylor et al. (1990) found that cubic microdiamonds from northern Australia were nearly 100% Type IaA. Meyer et al. (1994) examined sharp, colourless diamond octahedra in the microdiamond size range from Shandong, China, and similarly found they were largely Type IaA.

The contrasting N aggregation characteristics of diamonds carry implications for different crystallization and heating/cooling histories of the diamonds. Nitrogen is interpreted to be dispersed on an atomic basis (Type Ib) during the initial growth of a natural diamond, after which the dispersed N migrates to produce the various types of N aggregates (Type IaA, IaB, platelets) during the residence of the diamond in the high temperature mantle environment (Evans and Harris, 1989; Taylor et al., 1990). Consistent with this view is the fact that synthetic diamonds are all of Type Ib, due to rapid quenching from the high temperature conditions under which they were synthesized. Based on the kinetics of aggregation of Type Ib dispersed N atoms to Type IaA N aggregates, Evans and Qi (1982) estimated that Type Ib diamonds could not have spent more than between 2 and 10^5 years in the upper mantle at temperatures of 1000–1400°C because the isolated N atoms characteristic of this type would have aggregated to the point that the diamonds would be of Type IaA (Harris, 1987). Evans and Harris (1989) suggested that conversion of Type IaA to Type IaB N aggregations at temperatures of 1200–1300°C would also occur at geologically rapid rates (tens of Ma). Alternatively, occurrence of Type IaA or Type Ib diamonds may indicate formation and residence at lower temperatures (e.g., 800°C), where the kinetics are too slow to effect more substantial N aggregation regardless of the time available (Evans and Qi, 1982). The implication of these studies is that because preservation of Type IaA and Type Ib diamonds is expected to be relatively short lived at mantle temperatures, such diamonds were formed at relatively low temperatures and/or were transported to the surface at the time of, or shortly after, their formation. Taylor et al. (1990) noted that their nearly 100% Type IaA microdiamond population was consistent with short-term mantle storage and possibly magmatic crystallization.

DISCUSSION OF PREVIOUS THEORIES ON THE ORIGIN OF EUHEDRAL MICRODIAMONDS

Although the presence of euhedral microdiamonds

in kimberlites has been known for about a century (Wagner, 1914), relatively few explanations for their formation have been offered. Many researchers agree that they may have a different origin from macrodiamonds (e.g., Gurney, 1989; Boyd, 1989). Below, some published theories are described and discussed. In the ensuing discussion, the term 'fluid' is used to refer to a supercritical, predominantly volatile phase which may nevertheless contain appreciable dissolved solids, whereas the term 'magma' is used to refer to a predominantly silicate- and/or carbonate-rich liquid phase which may nevertheless contain appreciable dissolved volatiles.

Oxidation–reduction of mantle-derived volatiles

Haggerty (1986) proposed a metasomatic infiltration mechanism for euhedral microdiamond formation. In his model, C-containing volatile-rich fluids percolate upwards from relatively oxidized asthenospheric upper mantle (estimated by Haggerty to be between the wüstite–magnetite and fayalite–magnetite–quartz O buffers) and, upon encountering the base of the cooler, relatively reducing lithosphere (estimated by Haggerty to be between the Fe-wüstite and wüstite–magnetite O buffers), the fluids are reduced, leading to microdiamond precipitation. Haggerty described this process as 'redox cracking', and viewed the euhedral microdiamonds as condensates from these fluids (high pressure 'soot') that were formed only shortly before subsequent entrainment in an eruptive kimberlite magma. Haggerty (1986) predicted that such euhedral microdiamonds might be expected to be of Type Ib or Type IIa, owing to spontaneous nucleation and growth from a volatile fluid phase and rapid quenching (see discussion above). An unstated assumption in this prediction is that the kimberlite magma that ultimately transported the euhedral microdiamonds to the surface passed through the appropriate rocks and picked up the newly formed euhedral microdiamonds very shortly after they crystallized.

In an expansion of his 1986 model, Haggerty (1994) speculated that microdiamonds may have been formed in this manner at the heads of mantle plumes, the latter focusing the infiltration of the carbonaceous fluids into the lithosphere. Both Haggerty's 1986 and 1994 models for euhedral microdiamond formation involve 2 events: first, formation of microdiamonds by infiltration metasomatism, and second, entrainment of microdiamonds as xenocrysts in a later, but possibly unrelated, erupting kimberlitic/lamproitic magma. Contentious aspects of Haggerty's models are: (1) his estimation that the lithosphere is more reducing than the asthenosphere, a view disputed by some workers (e.g., Taylor and Green, 1989; Ballhaus and Frost, 1994 and references therein; see below); (2) his assumption that free fluids are present in the mantle lithosphere and asthenosphere, a point dis-

puted by some owing to the fact that $P-T$ conditions in these regions may be above the peridotite solidus such that the fluid would be dissolved in a melt phase (e.g., Eggler, 1989; Falloon and Green, 1990; Ballhaus and Frost, 1994).

Contrary to most current opinion (e.g., Robinson *et al.*, 1989; Gurney, 1989; Mitchell, 1991; Harris, 1992; Harris *et al.*, 1994; McCallum *et al.*, 1994), Haggerty discounted the possibility that resorbed macrodiamonds result from interaction with transporting kimberlite magma, stating (Haggerty, 1986, p. 36) that macrodiamond resorption "... is unlikely because the event is transient and it is inconsistent with the ubiquitous presence in kimberlite of microdiamonds, which would be totally resorbed given their high surface-to-volume ratio". We suggest below a possible mechanism by which euhedral microdiamond formation can be reconciled with macrodiamond resorption by the magma.

Wyllie (1987) suggested a mechanism for euhedral microdiamond formation based on the idea that kimberlitic magmas would crystallize and de-volatilize at the point where the geothermal gradient crosses the peridotite–C–O–H solidus (*ca* 160–190 km depth). Subsequent reduction of the released volatile fluids (*cf* Haggerty, 1986) might result in diamond crystallization. Although this mechanism might form euhedral microdiamond, substantial crystallization of the magma at the solidus would lead to freezing without eruption (Eggler, 1989), so that entrainment of the euhedral microdiamonds to the surface would require a second, through-going kimberlite. Thus, as in Haggerty's (1986) model, at least 2 separate events are required: first, to form the euhedral microdiamonds and second, to transport them to the surface, moreover without resorbing them.

Taylor and Green (1989) provided an analysis of the role of C–O–H fluids in the mantle and their influence on partial melting and C (diamond, graphite) precipitation in the system peridotite–C–O–H, laying special emphasis on the importance of fugacity of O_2. They noted, as have many others, that there is considerable controversy over the variation of fugacity of O_2 with depth in the mantle (e.g., see contrasting views of Haggerty, 1986; 1990; Blundy *et al.*, 1991; Luth, 1993; Eggler and Lorand, 1994; Ballhaus and Frost, 1994), making modelling problematic. Taylor and Green (1989) inferred an overall gradation with depth from a relatively oxidized lower lithosphere and asthenosphere (*ca* magnetite–wüstite) to a more reduced lower mantle (below Fe-wüstite), a view supported by the calculations of Ballhaus and Frost (1994) but opposite to that of Haggerty (1986). In their model, reduced CH_4–H_2 fluids from the relatively deep mantle become progressively oxidized as they rise through the more oxidized upper mantle. At some depth in the upper mantle, the fluids reach solid C saturation, and precipitate diamond ('asthenospheric diamonds', which we interpret to mean macrodiamonds), resulting in an increase in H_2O

content of the fluid. If, during continued ascent of the fluid, $P-T$ conditions were such that the peridotite solidus was exceeded, melting would be induced (e.g., Wyllie, 1987), producing kimberlite-like magmas. Taylor and Green (1989) predicted that precipitation of diamond from the fluid ('lithospheric diamond', which they suggested could represent euhedral microdiamonds) would accompany melting.

A difficulty with the Taylor and Green (1989) model is that there is no provision for entrainment and resorption of macrodiamond xenocrysts by the kimberlitic magma, owing to kimberlite (and euhedral microdiamond) generation at shallower depths than their speculated levels of macrodiamond formation. Consequently, as with the Haggerty (1986) and Wyllie (1987) models, a later through-going magma is required to bring the euhedral microdiamonds to the surface. In all of these models, the timing of euhedral microdiamond release into the magma and/or the rate of magma ascent must be such that there is little time for N aggregation and resorption of the delicate microdiamond forms, even though euhedral microdiamonds are sometimes found in the same intrusions as resorbed macrodiamonds.

Disaggregation of xenoliths

In contrast to euhedral microdiamonds having formed shortly before or at the same time as kimberlite eruption, Haggerty (1986) noted that a different and older type (relative to kimberlite eruption) of euhedral microdiamond might exist provided such were protected from resorption, or did not undergo grain-size coarsening to form macrodiamonds. Such euhedral microdiamonds might have resided in xenoliths prior to kimberlite eruption.

In a similar vein, McCandless (1989) and Otter *et al.* (1994) suggested that euhedral microdiamonds from the Sloan kimberlite may have originated from xenoliths which were disaggregated during final kimberlite emplacement, a view supported by Jaques *et al.* (1994) for some small octahedral diamonds from Ellendale, Australia. Such a mechanism would minimize the time the euhedral microdiamonds were in contact with the kimberlite/lamproite magma, potentially resulting in little to no resorption. McCandless *et al.* (1994) made a similar case for euhedral, octahedral microdiamonds from several Arkansas pipes, noting a variety of incipient, non-uniformly distributed resorption features on the otherwise euhedral microdiamonds that they interpreted to be due to a short residence period in the magma immediately prior to eruption.

Supporting this hypothesis is the fact that euhedral microdiamonds (and small macrodiamonds up to 2 mm in diameter) have been recovered from peridotitic (McCallum and Eggler, 1976) and eclogitic (McCandless and Collins, 1989) xenoliths in the Colorado-Wyoming State Line district in the past. Euhedral

microdiamonds (and small macrodiamonds up to 1.8 mm in diameter) have also been reported in xenoliths from other localities, e.g., the Finsch and Roberts Victor kimberlites in South Africa (Shee *et al.*, 1982; Viljoen *et al.*, 1994). We suggest that these older euhedral microdiamonds might be expected to be of Type Ia, owing to longer periods of time available for N aggregation.

A difficulty in accepting the disaggregation model for all euhedral microdiamond occurrences is that one would expect that euhedral macrodiamonds, in addition to euhedral microdiamonds of the same age and paragenesis, would be released from the disaggregated xenoliths, and would therefore account for a portion of the macrodiamond population. This does not appear to agree with observations from many pipes containing euhedral microdiamonds. For example, McCandless *et al.* (1994) reported that all of the macrodiamonds in the euhedral microdiamond-bearing pipes from Arkansas show moderate to strong degrees of resorption (dodecahedral and tetrahexahedroidal forms). They demonstrated that although most of the microdiamonds they studied were unresorbed fragments and probably derived from disaggregated xenoliths, a significant population of exclusively unresorbed octahedra existed, which we suggest may represent a separate and distinct mode of formation. Lee *et al.* (1994) noted a sharp division between morphological types of macrodiamonds and microdiamonds in kimberlites from Africa, Australia and North America, which they argued was inconsistent with the microdiamond population being entirely due to protection inside xenoliths. F. Kaminsky (1995, pers. commun.) informed us of a similar situation at the Arkhangelsk deposit, Russia, where there is a sharp morphological division between macrodiamonds, over 80% of which were rounded, and microdiamonds, over 90% of which are flat-faced euhedra.

Although some deposits, e.g., Wesselton, Mir (see below), contain relatively high proportions of euhedral macrodiamonds, information on the abundance and morphology of microdiamonds is unfortunately lacking. In general, if it is assumed that kimberlitic or lamproitic magma is always corrosive to diamond, one might expect euhedral microdiamonds formed by this mechanism to be relatively rare owing to the special set of circumstances and timing required for their release from xenoliths and subsequent preservation in the magma.

Precipitation from mantle melts

Experimental data and observations from natural fibrous and coated diamonds and diamond inclusions suggest that diamond may not be uniformly unstable in kimberlitic magma. Gurney (1989) suggested that although most macrodiamonds are probably xenocrysts, Type Ib diamonds (size not specified), fibrous

coats on macrodiamonds and euhedral microdiamonds may be associated with crystallization from the host magma (i.e., phenocrysts) or from magmatically-related fluids.

Experiments by Arima *et al.* (1993) showed that diamond can be stable in kimberlitic melt at 1800–2200°C and 7.0–7.7 GPa. Although they recognized that these temperatures and pressures are considerably higher than those generally attributed to the growth of most natural diamonds (800–1500°C, 3–6 GPa, Finnerty and Boyd, 1987), their experiments nevertheless showed that diamond might be stable under certain conditions in kimberlite magma.

Tentative support for the conclusions of Arima *et al.* (1993) can be found in the preliminary work of Taylor *et al.* (1990) N-types of some cubic microdiamonds from northern Australia (see discussion above). Further support comes from the work of Navon *et al.* (1988), Schrauder and Navon (1994) and Schrauder and Koeberl (1994), who determined the compositions of fluids trapped in fibrous diamonds from Zaire and Botswana. They suggested that the fluids bear many similarities to kimberlitic magma, falling on mixing lines between carbonatitic and solute-rich hydrous endmembers. Schrauder *et al.* (1994) noted that these diamonds, in addition to some others from Yakutia and India, are of Type IaA and Ib, consistent with minimal residence time in the mantle environment or relatively low temperature crystallization. Opaque fibrous cubes from Coanjula, Northern Territory, Australia, described by Lee *et al.* (1994), are similiar in many ways to those described by Navon *et al.* (1988) and Schrauder and Navon (1994) in that they contain potassic silicate melt inclusions which Lee *et al.* (1994) attributed to trapping during diamond growth.

Another example in which natural diamonds were inferred to have crystallized from kimberlite melt is the study of Leung *et al.* (1990), who found coexisting SiC and diamond in one of the Fuxian kimberlites. Sino-Korean craton. The SiC shows what the authors described as vesicular textures, which Leung *et al.* (1990) suggested might have been due to growth during fluid liberation from a depressurized kimberlitic magma. They ascribed the metastable persistence of SiC to quenching due to rapid ascent of the magma, which would also favour preservation of euhedral microdiamond.

AN ALTERNATIVE HYPOTHESIS: CRYSTALLIZATION OF EUHEDRAL MICRODIAMONDS DURING ASCENT AND DECOMPRESSION OF KIMBERLITIC MAGMA

Rationale for proposed mechanism

We suggest an alternative, testable hypothesis for the formation of euhedral microdiamonds, other than those which may have been released from xenoliths,

that may reconcile the apparent paradox of macro-diamond resorption and euhedral microdiamond preservation in kimberlites/lamproites. Owing to ongoing debate over a number of aspects of kimberlite genesis and mantle petrology that bear on this topic (e.g., oxidation conditions; see above), our hypothesis is framed in largely qualitative terms, although it is based on inferences from theoretical and experimental studies.

Our proposed mechanism is based on 2 generally agreed upon observations/inferences: (1) macrodia-monds in kimberlites/lamproites are typically resorbed, suggesting that at some point they were unstable in the transporting magma; (2) the occur-rence of euhedral microdiamonds, sometimes in the same intrusion or pipe as resorbed macrodiamonds, is the reverse of what would be expected if the magma were uniformly corrosive to diamond. From these observations we deduce that (a) euhedral microdia-monds are younger than the resorbed macrodia-monds, and (b) there was a transition from conditions in which diamond was unstable in the magma to conditions in which it became stable (or possibly metastable).

We propose a scenario in which euhedral micro-diamonds may be formed from the kimberlitic magma that transports them to the surface, either: (1) directly from the melt as phenocrysts, or (2) as condensates from fluids that were liberated from the C-bearing magmas due to decompression on ascent (vesicula-tion). In this scenario, euhedral microdiamonds are predicted to be essentially the same age as the eruptive event, with rapid crystallization and quenching result-ing in small size and a Type IaA or Ib N distribution (cf Haggerty, 1986). Where our scenario differs from that of Haggerty (1986) is our idea that the euhedral microdiamonds are formed from the same magma as that which transports them to the surface, rather than involving an earlier metasomatic infiltration event (which formed the euhedral microdiamonds) and a later, possibly unrelated, kimberlite event (which transported the euhedral microdiamonds as xeno-crysts to the surface).

Microdiamond precipitation by magma decompression and the importance of oxidation conditions

The basis for our proposed mechanism is the decrease in magma volatile content as a function of decreasing pressure. Burnham (1979) provided a general discussion of the variations in solid-melt-fluid equilibria as a function of pressure, temperature and volatile content using the albite–water system as an analogue. Of special note is the delineation of mainly pressure-dependent isopleths of the melt-volatile saturation surface for different melt volatile contents (Fig. 16-6 of Burnham, 1979). For a given volatile content, melts at higher pressures than the saturation surface are fluid-undersaturated, whereas

at lower pressures they become fluid saturated and will liberate fluid even if the solidus has not been reached.

For fluid liberation to occur during decompression prior to reaching the solidus, the melt must retain some proportion of its initial (relatively high) volatile concentration. This situation may prevail during rapid, adiabatic ascent of segregated magma, such as is envisioned for kimberlites. Adiabatic gradients are limited by 2 end members: the isentropic gradient and isenthalpic gradient (Waldbaum, 1971). The isentro-pic gradient is the most commonly assumed adiabatic gradient for kimberlite ascent (e.g., Wyllie, 1987), and involves minor temperature decrease as pressure drops. In contrast, the isenthalpic adiabatic gradient (Waldbaum, 1971) typically involves moderate tem-perature increase as pressure decreases. Natural adiabatic gradients are expected to follow a path between these two limiting cases (Waldbaum, 1971). Wyllie (1987) noted that the actual P–T evolution of any individual magma may lie between an adiabatic gradient and the geothermal gradient of the rock through which the magma passes.

Brey et al. (1991) found that the solubility of CO_2 in kimberlitic melt in the presence of an H_2O–CO_2 fluid decreases substantially from 20–30% at 5–6 GPa to about 5 wt% at 2 GPa. On this basis, they argued that fluid liberation from a fluid-saturated kimberlitic melt could occur at deep lithospheric conditions due to simple pressure decrease (such as described above). We suggest that release of C from the melt might additionally result in precipitation of euhedral micro-diamonds either directly from the saturated melt as phenocrysts (cf Arima et al., 1993; Navon et al., 1988), or from a C-bearing fluid phase that evolved from the rising, devolatilizing magma (e.g., Leung et al., 1990). Whether microdiamonds would precipitate would depend on the evolution in oxidation conditions of the magma during ascent (cf Taylor and Green, 1989; Ballhaus and Frost, 1994), the oxidation conditions of the rocks through which the magma passes (e.g., Luth, 1993; Taylor and Green, 1989), and the degree of interaction between the two. Sunagawa (1984) used similar reasoning to account for increasing degrees of C supersaturation to explain the development of the fibrous rims on coated diamonds (see below). As noted by Brey et al. (1991), fluid liberation would facilitate rapid upward transport of the kimberlitic magma through the overlying lithosphere, possibly due to crack propagation (Wyllie, 1989). This mechanism in principle might provide simultaneously for crystallization of euhedral microdiamonds from the kimberlite magma and facilitation of kimberlite eruption.

In contrast to the relatively oxidized CO_2-rich kimberlitic magmas considered by Brey et al. (1991), in which C is likely to occur in the melt as CO_3^{2-} complexes, Ballhaus and Frost (1994) speculated that highly reduced kimberlitic melts (in association with CH_4-rich fluids) might dissolve elemental (uncom-plexed) C, such that simple decompression due to

ascent might induce solid C (diamond or graphite) precipitation from the melt with little or no change in oxidation of the magma. The observations and inferences of Leung *et al.* (1990) on coexisting diamond and SiC in one of the Fuxian kimberlites are consistent with this view.

The importance of oxidation conditions (Taylor and Green, 1989; Ballhaus and Frost, 1994) in controlling euhedral microdiamond formation by this decompression mechanism is indicated by the fact that most kimberlites and lamproites are not diamondiferous, even though their mineralogy (e.g., carbonate minerals) indicates they formed from C-bearing volatile-rich magmas like their diamond-bearing counterparts. In such situations, it may be that these magmas were more oxidized than the diamond-bearing magmas, or that there was a less effective or prolonged interaction of kimberlitic magma with relatively reducing mantle rocks en route to the surface, such that C in the magma and/ or released fluids was not of the appropriate oxidation state to crystallize diamond even though fluid liberation occurred. An implication is that the oxidation state of diamond-bearing kimberlites may in general be lower than in other kimberlites.

Coexistence of resorbed macrodiamonds and euhedral microdiamonds

The above mechanism does not account for the resorbed nature of macrodiamond xenocrysts that coexist with euhedral microdiamonds in some deposits. Based on experimental kimberlite liquidus studies and *P–T* estimates from entrained xenoliths, Eggler (1989) noted that common temperature estimates for kimberlitic magmas are 1200–1500°C, significantly higher than the fluid-saturated peridotite solidus (*ca* 1000–1100°C, Falloon and Green, 1989). Such magmas must be fluid under-saturated (Eggler, 1989). Depending on oxidation conditions (*cf* Taylor and Green, 1989; Ballhaus and Frost, 1994), macrodiamonds entrained from mantle depths might therefore wholly or partially dissolve into, i.e., release C into, the fluid-undersaturated magma. Ascent and depressurization of the magma might result in a transition from conditions of fluid undersaturation of the magma in which macrodiamonds were unstable (dissolving) to conditions of fluid (and possibly C) saturation of the magma at lithospheric depths (Eggler, 1989; Brey *et al.*, 1991), possibly leading to euhedral microdiamond formation as described above. Incomplete resorption of the macrodiamonds entrained at depth could therefore result in a mixture of resorbed macrodiamonds and euhedral microdiamonds in a single kimberlite pipe. Alternatively, relatively oxidizing kimberlitic magma, initially corrosive to entrained macrodiamond xenocrysts, might undergo reduction through interaction with more reduced mantle or lithospheric rocks to conditions at

which solid C (diamond, graphite) became stable in the magma (analogous to Haggerty's (1986) model except involving magmas rather than volatile fluids). Situations can also be envisaged in which entrained macrodiamonds are completely destroyed through oxidation in kimberlitic magma, with no subsequent precipitation of euhedral microdiamonds.

Depth of fluid liberation with respect to the diamond stability field

The depth at which fluid liberation occurs is a function of the volatile content of the kimberlitic magma (Burnham, 1979) and the *P–T* path followed by the rising magma (Waldbaum, 1971; Wyllie, 1987), and could vary considerably. Eggler (1989) estimated that expected depths of fluid liberation of vapour-undersatured kimberlitic magmas, assuming ascent along an isentropic adiabatic gradient, might be in the 1–2 GPa (30–60 km depth) range, which falls well within the graphite rather than diamond stability field. For our mechanism to be feasible for such magmas, metastable nucleation and growth of euhedral microdiamond would be required. The possibility that such a process may occur is supported by: (1) the delineation of metastable regions of coexisting diamond and graphite in the C phase diagram (Bundy, 1963); (2) the extensive literature on low-pressure chemical vapour deposition processes (Sato and Kamo, 1992). McCandless (1995, pers. commun.) suggested that microdiamonds might form under conditions approaching those of chemical vapour deposition during sudden depressurization of fluids released from erupting kimberlitic magma, possibly related to episodic bursts of magma upward through the brittle crust. Leung *et al.* (1990) inferred that the SiC and diamonds from the Fuxian kimberlite formed at pressures of 2–3 GPa (60–90 km depth), which is within the graphite stability field.

Progressively more fluid-saturated kimberlitic magmas would vesiculate at progressively greater depths. Brey *et al.* (1991) suggested depths of 120–150 km for fluid liberation from volatile-rich kimberlitic magmas, which would be closer to the diamond stability field than in Eggler's (1989) scenario. In summary, there may be a wide range of conditions, not all in the diamond stability field, under which fluid liberation and solid C precipitation could occur, with kinetic factors potentially being important in controlling whether or not diamond precipitates (*cf* Bundy, 1963).

Euhedral microdiamond growth versus overgrowths on precasting nucleii

If our suggested mechanism of euhedral microdiamond formation is operable, a possible paradox is the apparent absence of overgrowths on resorbed

macrodiamonds contained in the same pipe as euhedral microdiamonds. Numerous examples of coated diamonds, consisting of a crystalline core with fibrous rims, have been reported (e.g., Sunagawa, 1984; Navon et al., 1988; Schrauder and Navon, 1994). Coated stones must have experienced changes in environmental conditions in their growth histories. The fibrous coatings have been ascribed to super-saturation of the magma with C (Sunagawa, 1984), resulting in rapid growth of fibrous diamond on pre-existing crystalline diamond nucleii. Sunagawa (1984) suggested that the most likely scenario for this phenomenon would involve 'uprift' of the magma leading to an increase in effective supersaturation (essentially the same mechanism as we are proposing for euhedral microdiamond formation).

In contrast to overgrowths on pre-existing nucleii, nucleation and growth of a mineral as new crystals rather than as overgrowths on preexisting grains of the same mineral has been documented in various igneous and metamorphic rocks. An example from the igneous petrological literature is the study of Nelson and Montana (1994) on crystallization of plagioclase in volcanic rocks; their Fig. 1 shows abundant euhedral plagioclase microphenocrysts in the ground-mass of a volcanic rock containing large, resorbed plagioclase phenocrysts of an earlier generation that show no sign of overgrowths. An explanation that could account for the phenomenon of concern in this paper is the probable short duration of euhedral microdiamond precipitation in response to decom-pression and supersaturation. This period of time might be too short for effective transport of C to the relatively few and scattered resorbed macrodiamond crystals in the magma, leading to spontaneous nucleation of numerous small crystals instead. Another factor is the nature of the surfaces of the resorbed macrodiamond crystals, which might not always be favourable for attachment of new C atoms and consequent development of overgrowths. Finally, it may also be that there has been a lack of recognition of subtle overgrowth forms on ostensibly rounded macrodiamonds.

Macrodiamonds as a possible source of C for euhedral microdiamonds

Dissolution of macrodiamonds entrained from depth will contribute to the amount of dissolved carbon in the magma. Owing to substantial degrees of resorption implied by some macrodiamond forms (Robinson et al., 1989; Fig. 1), this might provide a source of C of the appropriate oxidation state for the later process of euhedral microdiamond formation. Gurney (1989) and McCallum et al. (1994) noted that diamonds lose about 45% of their mass going from an octahedral to a tetrahexahedroid form. However, given that diamonds are modally minor phases even in the richest diamond-bearing kimberlites (1–2 ppm),

it seems that C from macrodiamond dissolution would make only a small contribution to the total C content of kimberlite/lamproite magmas; for example, many non-diamondiferous kimberlites and lamproites contain substantial modal amounts of carbonate and other C-bearing minerals presumed to have originated from the magma on final crystallization. Eggler and Lorand (1994) estimated that CO_2 and H_2O contents of kimberlitic magmas would be on the order of a few hundred ppm. On the other hand, the relative proportions of C-bearing compounds or species, as controlled by bulk composition of the magma and oxidation conditions (e.g., Taylor and Green, 1989; Ballhaus and Frost, 1994), may ultimately be more important in controlling diamond precipitation than the total C content.

Testing the hypothesis

Although the above hypothesis for euhedral micro-diamond formation is clearly speculative and framed in qualitative terms, it has a number of testable consequences. A difficulty in evaluating the hypothesis is the lack of representative data of appropriate scope on microdiamonds, and the lack of consensus over P–T-oxidation conditions in the lithosphere and asthe-nosphere that would allow a more quantitative treatment of solid fluid-melt evolution in kimberlite magma as a function of depth and volatile content. Below we suggest several types of data that would provide tests for our ideas:

(1) Nitrogen type of euhedral microdiamonds. Infra-red absorption studies of euhedral microdiamonds focusing on their N type compared to macrodiamonds (e.g., Taylor et al., 1990; Meyer et al., 1994) represent possibly the most important test of our ideas, especially where both euhedral microdiamonds and macrodiamonds occur in the same intrusion and intrusion phases. Our hypothesis predicts that the euhedral microdiamonds will be predominantly of Types IaA, Ib and IIa, compared to more aggregated types for macrodiamonds (see above). The preliminary studies of Tolansky (1972), Taylor et al. (1990), Meyer et al. (1994) and Schrauder et al. (1994) may be consistent with our hypothesis.

(2) Morphology and surface features of microdiamonds. Further detailed studies on the microscopic morphology and surface features of macrodiamonds and euhedral microdiamonds from the same intrusion, such as performed by McCandless et al. (1994), might provide further insight into the interaction of resorption, overgrowth and nucleation processes on diamonds in kimberlite or lamproite magma. Evidence for or against subtle overgrowth features on macroscopically rounded macrodiamonds that occur in the same intrusion as euhedral microdiamonds would be especially interesting.

(3) Inclusion studies of euhedral microdiamonds.
Both solid (e.g., Meyer, 1987; Lee *et al.*, 1994) and
fluid inclusion (e.g., Navon *et al.*, 1988; Schrauder and
Navon, 1994; Lee *et al.*, 1994) studies of euhedral
microdiamonds would allow comparison with results
from macrodiamonds. Possible contrasts between
solid and fluid inclusions in macrodiamonds and
euhedral microdiamonds might reveal contrasts in
the *P–T*-oxidation conditions, indicating separate
modes of formation.

(4) Carbon isotopes. There have been relatively few
C isotope studies of euhedral microdiamonds from
kimberlites/lamproites, in contrast to the situation
for macrodiamonds (e.g., Deines *et al.*, 1989).
Comparison of C isotope analyses between euhedral
microdiamonds and macrodiamonds from the same
pipe or intrusion might indicate whether or not there is
a genetic relationship between the resorbed
macrodiamonds and the euhedral microdiamonds.
One such study was performed by McCandless *et al.*
(1994) on macrodiamonds and diamonds from the
Prairie Creek lamproites in Arkansas: they concluded
that at least 2 generations of microdiamonds were
indicated, and that 8 of the 10 euhedral
microdiamonds shared a common C reservoir with
the macrodiamonds. Lee *et al.* (1994) determined the
C isotopic compositions of 31 opaque fibrous cubes
(some with transparent cores) and 18 single crystalline
microdiamonds (both sharp and resorbed
octahedrons, and irregular shapes) from Coanjula,
Australia. Although the results were problematic (e.g.,
the fibrous exterior and clear interior of the stones
were not analyzed separately), they were able to
suggest that the fibrous overgrowths appear to have
formed in a different environment from the
transparent cores.

(5) Experimental studies. Experiments such as those
of Arima *et al.* (1993) could be extended to examine
diamond/graphite stability in kimberlitic melts at
asthenospheric and deep lithospheric pressures and
temperatures (e.g., 3–7 GPa, 900–1300°C) and a range
of oxidation conditions. Experiments at a series of
successively lower *P–T* conditions, defining arrays
appropriate to adiabatic and geothermal gradients,
would help delineate regions of fluid liberation and
possible diamond precipitation.

POTENTIAL PITFALLS IN THE USE OF
EUHEDRAL MICRODIAMOND ABUNDANCE AS A
GUIDE TO ECONOMIC DIAMOND GRADES

The above considerations carry implications for the
use of microdiamond abundance as a guide to
economic macrodiamond grades in kimberlites or
lamproites. The technique entered the public domain
as a result of the publication of Deakin and Boxer
(1989) who described in detail how the method

(discussed above) is used for macrodiamond grade
estimation at the exceptionally diamond-rich (average
6.8 carat/tonne) Argyle lamproite pipe, Australia, the
only pipe for which a detailed study has been reported.
Rombouts (1994) discussed the statistical basis for this
concept. The method was put into use only after the
mine had been in production long enough to establish
that the technique was viable, primarily because the
pipe apparently has one stable size distribution and,
therefore, the number of macrodiamonds can be
predicted from the number of microdiamonds present.
Deakin and Boxer (1989) noted that the stable size
distribution may be due to the fact that the diamonds
that were recovered are essentially of one paragenesis
(most of the recovered diamonds are predominantly
resorbed, rounded dodecahedra, which they inter-
preted to be due to early entrainment and resorption
in the lamproitic magma), eliminating problems that
would be introduced if there were more than one
paragenesis for different diamond types.

This technique, or modifications thereof, attained
prominence in exploration and evaluation of dia-
mondiferous kimberlites in the Northwest Territories,
Canada, where, as of mid-1994, over 100 kimberlite
pipes were discovered of which at least 35 were
diamondiferous (Levinson *et al.*, 1992; Pell, 1995).
Microdiamond counts were used as an indication of
macrodiamond grades based on the assumption that
the more microdiamonds there are, the better the
economic diamond grade will be (Deakin and Boxer,
1989; Jennings, 1990; Rombouts, 1994). In general,
quantitative application of such schemes to other
pipes for exploration purposes (i.e., in the absence of
knowledge of the diamond population systematics
such as at Argyle) fails to recognize the fact that every
diamond pipe has its own unique set of diamond
parageneses, transportation characteristics and
depositional patterns, leading to complex local varia-
bility. Our analysis of the genesis of euhedral micro-
diamonds suggests further reasons why this approach
may be flawed, particularly if the source of the C for
euhedral microdiamonds is due partially to resorption
of macrodiamonds; in this latter case, microdiamond
and macrodiamond abundance might show an inverse
relationship.

The Lac de Gras area, Northwest Territories, Canada

Table 1 is a compilation of data on micro- and
macro-diamonds from the Lac de Gras kimberlites.
The data are from core samples (<314 kg in weight)
obtained during early stages of exploration between
1991 and 1993. All diamonds greater than 0.5 mm in
their maximum dimension were classified as macro-
diamonds. The microdiamond contents of the Point
Lake, Tli Kwi Cho and the Torrie kimberlites (Table
1) appear high and made them particularly interesting
economically. Unfortunately, relatively little informa-
tion is available on the nature of the microdiamonds

Table 1. Example of the use of microdiamond and macrodiamond counts in diamond exploration in the Lac de Gras area, Northwest Territories, Canada

Pipe name	Sample weight (kg)	Number of macrodiamonds	Number of microdiamonds	Macro/micro ratio	Number per 100 kg	
					Macro	Micro
Point Lake	59.0	16	65	0.25	27	110
BHP 92-C	161.4	10	28	0.35	6	17
Tli Kwi Cho	313.7	96	299	0.32	31	95
North Lobe	265.2	16	62	0.26	6	23
DHK-93(DO-41)	122.1	–	1	–	–	1
Ranch Lake	208.1	6	38	0.16	3	18
Torrie	162	39	152	0.26	24	94

These data were obtained from core samples during early stages of exploration during 1991–1993 in which relatively small samples are used (largest sample in this selection is 313.7 kg). Microdiamonds are <0.5 mm in maximum dimension. Source: Diamonds and the Northwest Territories, Canada, Department of Energy, Mines and Petroleum Resources, Government of the Northwest Territories, Yellowknife, December, 1993.

from the kimberlites in the Northwest Territories, particularly whether or not they are primarily euhedral octahedral microdiamonds or other types (e.g., resorbed macrodiamonds, fragments), which could be significant given our discussion of microdiamond origins.

In mid-1994, when large bulk samples were analysed from the Tli Kwi Cho (4261 tonnes) and the Torrie (21 tonnes) pipes, the anticipated macrodiamond counts were well below those expected empirically based on the microdiamond content in Table 1, to the point where the pipes were deemed uneconomic. In this case, the use of microdiamond abundance (i.e., counts) alone as a guide to economic diamond grade failed, possibly for some of the reasons noted above.

Contrasts in microdiamond–macrodiamond abundances and morphological relations from Siberia, South Africa and Colorado–Wyoming

A number of diamond deposits show a relatively high proportion of well-formed, unresorbed macrodiamond crystals. For example, in several Siberian kimberlite pipes, macrodiamonds are noted for their excellent shape for cutting, characteristically occurring as regular, sharp-edged, flat-faced octahedra showing little to no evidence of resorption. At Mir in Siberia, diamonds up to 1 cm are unresorbed (Harris et al., 1994). Production from the Mir and Udachnaya in Siberia yield 21% and 12%, respectively, of well formed, unresorbed macrodiamonds (Cotty and Wilks, 1971). As noted earlier, there is little information on microdiamonds in the Siberian pipes. Cotty and Wilks (1971) noted that the Wesselton Mine in South Africa yields the world's highest percentage of excellent macrodiamond octahedra (30%); unfortunately, there is no published information on the relative abundance and morphological nature of microdiamonds compared to macrodiamonds in this mine.

In general, a relatively high abundance of well-formed, euhedral macrodiamonds relative to resorbed macrodiamonds in individual deposits appears to be uncommon (Cotty and Wilks, 1971): for example, in other areas of Siberia, e.g., the Upper Muna diamond-iferous region, most of the production consists of dodecahedral and other resorbed forms (Cotty and Wilks, 1971). Compared to the Wesselton Mine, other mines in South Africa are characterized by a higher proportion of highly resorbed stones (Cotty and Wilks, 1971).

At the opposite end of the spectrum from the rare examples noted above, in which euhedral macrodiamonds are relatively abundant, are the kimberlite pipes in the Sloan district (e.g., McCallum et al., 1979; 1994; McCandless, 1989; Otter et al., 1994) and the lamproite pipes at Murfreesboro, Arkansas (McCandless et al., 1994), which have macrodiamonds that are characteristically small and resorbed. Notably, in all of these deposits, euhedral microdiamonds are abundant and well documented, although all additionally contain some other microdiamond types (e.g., rounded, tetrahexahedroid) in variable amounts (see references above).

Implications for diamond grade estimation from microdiamonds

Resorption can potentially lead to the reduction of large euhedral macrodiamonds to the size of resorbed microdiamonds, and all sizes and degrees of resorption in between (Fig. 1). Significant resorption might result in a significant number of resorbed, non-euhedral microdiamonds (formerly macrodiamonds), such as in the Argyle deposit (Hall and Smith, 1984). Taken to the extreme, it is possible that resorption will be complete and any macrodiamonds originally entrained in a kimberlite may have been consumed to extinction by the magma (e.g., Mitchell, 1991). Conversely, kimberlites or lamproites which never

entrained diamond xenocrysts or in which diamond xenocrysts were consumed to extinction might precipitate euhedral microdiamonds by the mechanism described above; in such situations, small samples yielding high microdiamond abundances could lead to unjustified optimism regarding expected economic macrodiamond grades.

If a significant source of C for euhedral microdiamond formation is resorbed macrodiamond, it may be that if a deposit is characterized by predominantly well-formed, unresorbed macrodiamonds, then microdiamonds will be in low abundance or absent (e.g., possibly some Siberian pipes), whereas if macrodiamonds are highly resorbed, then the content of well-formed microdiamond octahedra may be high (e.g., Colorado–Wyoming, Murfreesboro). Intermediate situations can be envisaged in which 2 types of microdiamonds (resorbed macrodiamonds and euhedral microdiamonds) are present together in the same pipe. In such pipes, the two different types of microdiamond might be recognized by contrasts in morpology, C isotopes and/or N type. Finally, situations can be envisaged in which 3 types of microdiamonds may be encountered: the 2 mentioned previously as well as euhedral microdiamonds released during xenolith disaggregation (cf McCandless, 1989; 1994).

What seems clear is that the relationships between the abundance and morphology of macrodiamonds and microdiamonds are complex and vary from deposit to deposit, a point that has been recognized for some time. Any individual model is probably oversimplified because in any one kimberlite pipe there are frequently several intrusions and intrusion phases of varying character that contain their own grade and morphological, textural and color characteristics of diamonds (e.g., Harris, 1992; Gurney, 1989; Mitchell, 1991). These variables, in addition to the ones raised above, are expected to result in multiple relationships between microdiamonds and macrodiamonds. Consequently, the results of any individual scheme involving microdiamond abundance or microdiamond/macrodiamond ratios as a guide to economic macrodiamond grades in pipes other than the one from which the scheme was devised should be viewed suspiciously.

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