

Department of Geochemistry, University of Cape Town,
Rondebosch, South Africa.

Introduction

The most striking new information about diamonds in the past decade has been the evidence of their ancient origins first brought to notice by Kramers (1977) in a study of composited sulphide diamond inclusions for the Finsch, Kimberley and Premier Mines. Results with similar implications were reported by Takaoka and Ozima (1978), Melton and Giardini (1980), Evans and Qi (1982) and Ozima et al (1983, 1984). Very old ages for peridotitic garnet inclusions in diamonds from the cretaceous Finsch and Bultfontein kimberlite pipes were then demonstrated by Richardson et al (1984). Whilst these measurements are not yet sufficiently detailed to demonstrate that all diamonds are very old there is conversely less quantitative information to suggest that their formation can be contemporaneous with pipe emplacement.

Regional Diamond Distribution

In this light the confined distribution of primary diamond deposits to ancient crust and the similar if somewhat more diffuse spread of placer deposits seems to be of more fundamental importance than was formerly recognised.

Ages of Diamond Deposits

Diamond has been intermittently carried to the Earth's crust throughout a long period of the Earth's history with the oldest well documented diamonds being those found in the Witwatersrand conglomerates (\pm 2.6 billion years). Most of the younger diamondiferous deposits are also sedimentary, many being of quaternary age. The oldest well documented diamondiferous volcanic diatreme is the Premier Kimberlite in South Africa with a preferred age of 1250 m.y. (Welke et al 1974). The youngest are the diatremes at Ellendale, West Australia, with ages between 20 and 25 m.y. (Hall and Smith 1984). The volcanic emplacement of diamonds in the Earth's crust is also clearly episodic. Polar wandering curves provide some evidence of an association between this volcanism and plate motions (Hargraves and Onstott 1980). Most kimberlites are Phanerozoic and most placer deposits are Cenozoic but this is probably related to the effects of erosion and secondary weathering rather than to any increase in the rate of formation of diamond deposits with age of the earth.

Diamond Distribution within Kimberlite Clusters

It has been observed that if one kimberlite within a closely spaced petrographically and chemically linked group of kimberlites is diamondiferous then all the other kimberlites within that grouping will also carry diamonds. It is also clear that diamond grades may vary substantially from one occurrence to another. In many cases the diamond populations found in kimberlites within the same cluster have very similar overall characteristics of size shape and colour. Diamond paragenesis may also be similar but there is a recorded instance where the ratio of eclogitic to peridotitic diamonds in two diatremes from the same group are quite substantially different. There is evidence that the size distribution of diamonds within kimberlites in the same group may not be identical (Sutton 1928).

Diamond Distribution within Kimberlite Diatremes

Kimberlite pipes develop three characteristic morphological zones formed by different processes and reflected by predominantly epiclastic, tuffisitic and hypabyssal rocks respectively (Hawthorne 1975). Diamond concentrations within these three zones can fluctuate widely. The tuffisitic rocks show the greatest degree of homogenisation. The overall diamond distribution within and between the three zones does not show any simple well developed pattern. Individual intrusions may show a steadily declining

grade with depth whilst others do not show this feature. Changes in diamond recovery parameters, periods of "high grading", lack of concise records and the effects of geological processes all combine to prevent a really precise assessment of grade variations with depth (Clement 1982). Calculations for kimberlite mines over extended periods sometimes show roughly constant grades. On the other hand there is strong evidence from other occurrences that diamond content can decline quite rapidly with depth of mining and this appears to be most apparent when mining commenced in the epiclastic rocks. Pronounced long term increases in grade are unknown. In kimberlite dykes which presumably act as the feeders to major diatremes and are typically less than 1m wide, there is no evidence for consistent variations of grade with depth over mined sections in excess of 500 metres.

Diamond Distribution in Placer Deposits

The outstanding feature of alluvial diamond deposits is the improvement in average quality of the diamonds with distance from the primary source due apparently to the preferential breakage of inferior crystals. Alluvial diamonds do not show marked abrasion features but frequently many and sometimes all of the population are slightly worn (Robinson 1979). Breakage therefore presumably takes place chiefly by impact. Coastal diamonds having suffered wave damage show between two and three times more percussion marks than deposits inland (Robinson 1979). Industrial stones are very efficiently destroyed. No evidence is available about how many gem stones are broken by the same mechanisms.

Diamonds may be sorted by size and shape within a single deposit or dispersion train. Whilst this is usually a product of hydrodynamic processes in rivers and the sea it has been most impressively developed in an aeolian environment. Diamondiferous gravels in rivers and palaeo stream beds are usually of sub-economic grade. Diamonds are generally concentrated rapidly into a bed rock layer which is seldom very thick and frequently covered with overburden of finer grained sediments. Higher diamond contents are found in favourable trap sites and in some cases extreme enrichment combined with the high quality of the diamonds leads to the development of very rich deposits. This situation can be enhanced even further in the sea where grades in excess of 250 ct./c.m. of gravel have been reported and on sand sea deflation surfaces where significant diamond recoveries have been made by hand in the past. Throughout the world with some minor but no major exceptions lithified gravels are uneconomic to mine because of their low average grade and higher costs of mining.

Diamond Morphology

Diamonds with minor exceptions grow in the octahedral and cubic forms. The vast majority of natural diamond crystal surfaces show no growth features. The tetrahexahedroid is most commonly a shape produced by a major amount of resorption which must be a significant factor in controlling the diamond content of volcanic host rocks. There is an approximate correlation between diamond grade and the proportion of primary growth shapes in the diamonds from kimberlites in southern Africa. Diamonds in eclogite and peridotite xenoliths are characteristically well preserved and have clearly been protected from severe resorption. Diamond dissolution has been inferred to occur in the transporting magma. Lamination lines are often observed as positive features on the surfaces of resorbed diamonds. The deformation which produces these features and can make the diamonds pink or brown in colour is likely to have occurred in the mantle (Harris et al 1975, Robinson 1979).

Topographic studies of rare single crystal diamonds with minimal resorption features indicate that they grew by a spiral mechanism from a solution phase of low supersaturation through the incorporation of atomic growth units. It is thought highly improbable that they grew in metamorphic environments. Polycrystalline aggregates grew more quickly under rather higher supersaturation conditions (Sunagawa 1982).

Green spots can be caused on diamonds particularly in alluvial deposits by alpha particle damage. Experimental results show that these spots become brown at $+550^{\circ}\text{C}$. Brown spotted natural diamonds may therefore have passed through amphibolite facies metamorphic events (Vance et al 1973). However in detail occurrences of diamonds with brown spots cannot always be reconciled with such a sequence of events.

Diamonds

Diamonds have been classified into type 1 and type 2 on the basis of the presence or absence of detectable nitrogen (Robertson et al 1934). Type 1 diamonds represent about 98% of the total (Dyer et al 1965).

Type 1 diamonds can be subdivided on the basis of the aggregation states of nitrogen in the diamond lattice which in turn is related to temperature. Evans and Qi (1982) estimated that Type 1A diamonds remained in the upper mantle for periods in excess of 200 m.y. years at temperatures between 1000 and 1400°C, whilst the rare Type 1B diamond might have been present for as little as 50 y. if temperatures exceeded 1000°C.

Diamonds have a wide range of $\delta^{13}\text{C}$ values from +5 to -34 ‰. There is a marked mode between -5 and -6 ‰ (Harris 1986). Diamonds of both eclogitic and peridotitic parageneses contribute to this mode. Peridotitic diamonds have a restricted range of $\delta^{13}\text{C}$ values (Deines et al 1984), so that the isotopically light and heavy diamonds are either eclogitic or of unknown paragenesis. Since many of the latter are polycrystalline aggregates (Vinogradov 1966, Galimov and Kaminsky 1982) it can be inferred that they are likely to be eclogitic also. Studies of carbon isotopic variation within individual diamonds have found only minor $\delta^{13}\text{C}$ variations (Kaminsky et al 1978) except for diamonds from Zaire where variations of up to 5.2 ‰ have been reported (Swart et al 1983, Javoy et al 1984). Zairian diamonds show evidence for episodic growth in that clear diamond is frequently coated with fibrous diamond rich in impurities. At Roberts Victor a small data set available for eclogitic diamonds is bimodal suggesting two distinct environments of diamond crystallisation. One population has a primary mantle signature of $\delta^{13}\text{C}$ at approximately 5.6 ‰ and the other a $\delta^{13}\text{C}$ of approximately -15.5 ‰ is possibly related to the recycling of subducted lithosphere (Deines et al 1986).

The least radiogenic terrestrial helium isotope ratio which is 226 times the present day atmospheric ratio was measured in a diamond by Ozima and Zashu (1983). In this and subsequent work it has been inferred that some diamonds are nearly as old as the earth. At the same time a wide range in helium isotope ratios was measured in diamonds from both known and unknown sources. Amongst these and at the other extreme a framesite diamond with a $\delta^{13}\text{C}$ value of -29.7 ‰ contained extremely radiogenic helium leading to the suggestion that framesite formed in or from subducted crustal carbon.

Inclusions in Diamonds

Excluding sulphides which are a common inclusion in diamonds and in isolation do not have an obvious paragenesis peridotitic and eclogitic minerals are the only common primary inclusions in diamonds world wide, irrespective of source. Sulphides, olivine and orthopyroxene are the predominant peridotitic minerals with lesser abundances of garnet and chromite, rare clinopyroxene and very rare ilmenite, zircon, native iron and magnesio-wustite. Garnet, clinopyroxene and sulphides form the bulk of eclogitic inclusions with minor kyanite, rutile, corundum, coesite, ilmenite, sanidine, zircon and mica. Amphibole magnetite, apatite, ferro-periclase and moissanite have also been occasionally reported in diamonds, whilst inclusions of diamond in diamond bring the total number of minerals up to 22.

A similar number of epigenetic minerals have been reported.

Overall peridotitic inclusions predominate, but the eclogite/peridotite ratio has been shown to increase with larger sizes of diamond at one locality whilst at another variations of this ratio are even more complex. Both the peridotite and eclogite associations can show bimodal chemical characteristics suggesting that several diamond populations may be represented in the same kimberlite. The inclusions are generally interpreted to be syngenetic or occasionally protogenetic in origin and each isolated crystal or group of crystals is considered to be a closed system within the diamond. Numerous measurements including isotope ratios support this conclusion. Both parageneses are present at every locality so far studied in any detail. The relative proportions vary widely and are unrelated to the geochemical or isotopic signature of the host rock, to its age of emplacement or to the tectonic setting. In general

discrete mineral grains trapped inside the diamond are in equilibrium with each other. However this is not always true particularly where central inclusions in larger diamonds are compared with inclusions towards the margins of the host crystal (Bulanova 1985). The most graphic examples of this disequilibrium have been eclogitic. Examples of "crossed paragenesis" are extremely rare, but there are now at least four independent descriptions of eclogitic and peridotitic minerals having been found in the same diamond (Prinz et al 1975, Hall and Smith 1984, Otter and Gurney 1986, Moore and Gurney 1986). Some inclusions in diamonds have primitive isotope ratios which suggest archaean ages which are much older than the host diatreme. The peridotitic diamond inclusions have very refractory highly magnesian compositions but also show direct evidence of enrichment in light rare earth elements and alkalis which it has been suggested could have been present together with CO₂ in an interstitial fluid phase (Richardson et al 1984). The eclogitic diamond inclusions are characterised by trace amounts of sodium in garnet and potassium in clinopyroxene. The latter can only be expected at high pressures outside the stability field of phlogopite.

The calculation of equilibration conditions for co-existing mineral pairs in diamonds show that the majority of peridotitic inclusions formed within the diamond stability field under conditions that lie close to the predicted ambient shield geotherm and to the peridotite solidus. Calculated equilibration pressures correspond approximately to the highest pressures calculated for coarse grained garnet peridotite xenoliths from kimberlite. Eclogitic inclusions have similar ranges of equilibration temperature. Crystallisation for the majority of both the peridotitic and eclogitic diamond inclusions close to the base of the lithosphere at depths between 150 and 200 kilometres appear to be predicted.

A very few diamond inclusions could be derived from greater depths. Eclogitic garnets included in diamonds from the Monastery and Jagersfontein Mines show pyroxene solid solution and therefore appear to have a particularly deep origin. Rare inclusions of iron, moissanite, ferro-periclase and magnesio-wustite are additional possible ultra high pressure phases, all of which could be derived from the asthenosphere.

Diamond Indicator Minerals

Diamondiferous Type 1 and Type 2 kimberlites can usually be recognised by the presence of macrocrysts of high chrome chromites, subcalcic G10 garnets and high sodium eclogitic garnets, which appear to be related to the peridotitic and eclogitic parageneses defined by diamond inclusions. Rare examples where these indicator minerals are present and diamonds are absent could be due to the complete resorption of diamonds and may correlate with redox conditions of the transporting magma.

Diamondiferous Xenoliths

Diamondiferous eclogites, frequently with very high diamond contents, are found with sufficient frequency to be qualitatively compatible with the idea that diamonds of eclogitic provenance are entirely derived from disaggregated eclogite xenoliths.

Relationships between the compositions of the minerals in the xenoliths and the eclogitic inclusions in diamonds from the same volcanic source are complex and are not well understood. Diamondiferous eclogites show the sodium enrichment in garnet and potassium enrichment in clinopyroxene which is characteristic of the diamond inclusions. Several pieces of evidence suggest that eclogitic diamonds like peridotitic diamonds can be much older than the diatreme in which they are found.

Diamond bearing peridotites also occur but in contrast to the relative abundances of inclusions in diamonds, are much rarer than eclogite xenoliths. G10 garnets and high chrome chromites are so common in kimberlite by comparison to xenoliths containing minerals of the same composition and diamond peridotites are so rare that it has been suggested that diamondiferous peridotites self-destruct after sampling by the kimberlite due to decomposition of magnesite or to devolatilisation of a volatile rich interstitial fluid (Wyllie et al 1984, Boyd and Gurney 1982).

In a study based on southern African samples arguments have been advanced on chiefly isotopic grounds that there are two varieties of kimberlite. Group I have an asthenospheric origin. Group II are derived from sub-continental lithosphere (Smith 1983). This sub-division of two groups is not reflected in diamond paragenesis. All diatremes studied to date from both groups and indeed from lamproites contain diamonds with eclogitic and peridotitic mineral inclusions with widely variable apparently random relative proportions. Similar isotopic and trace element signatures to those seen in the kimberlites are generated in the south Atlantic by hotspots which can be recognised as having two "end member" types (Allegre and Turcotte 1985). One results from the up-welling of primordial mantle across an asthenosphere-mesosphere boundary and the second from a mesosphere boundary layer of recycled (subducted oceanic lithosphere) (Hofman and White 1982, Ringwood 1982) or of delaminated sub-continental lithosphere (McKenzie and O'Nions 1983). Extending the ideas of Duncan et al (1978) and Crough et al (1980) it has been suggested that both Group 1 and Group 2 kimberlites can be generated in the asthenosphere by hotspot activity. This would avoid having to derive spatially juxtaposed kimberlites of only slightly differing ages from two tectonically different source regions (le Roex 1986). Assuming a xenocrystic origin for diamonds then such a model will allow both kimberlite types to sample diamondiferous rocks from the same sources in the asthenosphere, lithosphere and perhaps most importantly the interface between the two which forms an integral part of the model proposed by Haggerty (1986).

References and Acknowledgments

It is impossible to acknowledge the contributions of more than a fraction of the researchers who in one way or another have a legitimate claim to having contributed through their hard work and ideas to this extended abstract. The vast majority are fully referenced in two excellent current reviews by H.O.A. Meyer and J.W. Harris in "Mantle Xenoliths" Ed. P.H. Nixon, Wiley and Sons (1986). Others will be found at the back of the Proceedings of the 3rd International Kimberlite Conference. Personal acknowledgments are due also to F.R. Boyd, J.B. Dawson, P. Deines, A.J. Erlank, S.E. Haggerty, J.W. Harris, B. Harte, J.B. Hawthorne, H. Helmstaedt, M. Kurz, R.O. Moore, M.L. Otter, R.S. Rickard, S.H. Richardson, C.B. Smith and N.V. Sobolev for all manner of contributions through what have in some cases been quite lengthy associations.