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Radiohalos and Diamonds: Are Diamonds Really for Ever?

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Abstract

Radiohalos were first reported in diamonds more than a decade ago. Since that time little work has been done to locate other radiohalo-bearing diamonds, to explain the origin of the radiohalos, or evaluate their significance. We conducted a search for such diamonds secured from a variety of sources and identified radiohalos containing one, three and four rings, as well as strange features in the form of twisted crystalline "tubes." New data suggest a radiohalo annealing temperature in diamond above 620°C. We offer an explanation for the radiohalos and for the "tubes" in these diamonds in terms of a hydrothermal fluid transport model for Po radiohalo formation.

Keywords

Radiohalos, Diamonds, Diamond inclusions, Zircons, Polonium, Kimberlite, Hydrothermal fluids, Cleavages

Introduction

Diamonds are probably the most intensely sought after of all the mineral gems known to man. India was the earliest producer of diamonds in the sixth century, with monarchs as their primary customers. Diamonds remained very rare and only a privileged few had them, until the first commercial diamond mine was opened in the late 1860s in South Africa (Meyer, 1985). It was Marilyn Monroe who in 1953 immortalized the phrase, "Diamonds are a girls' best friend" in a song from the movie, "Gentlemen Prefer Blondes". Of course, it had already become accepted practice for a marriage proposal to be secured with a diamond ring. It was DeBeers, a privately owned commercial enterprise, and still the largest seller of diamonds in the world with revenues of US$65 billion in 2005 alone, who in 1947 launched the successful "A Diamond is Forever" marketing campaign (Wikipedia, 2007). The unmatched brilliance of the sparkle of diamonds, their sizes and colors make them desirably attractive, but it is their unique hardness and resistance to physical weathering that give them their durability. Today, over 130 million carats (US$10–13 billion) of diamonds are mined annually (Wikipedia, 2007).

Tiny, microscopic radioactive halos (or radiohalos for short,) were first reported in diamonds only a decade ago (Armitage, 1993, 1995). This discovery elicited some brief discussion (Armitage, 1998; Gentry, 1998; Wise, 1998), but little has been done since to elucidate their enigma. The purpose of this study was to find additional diamonds containing radiohalos and to investigate in greater depth how they might have formed.

Diamonds

Diamonds are classified into two major categories—Type I, which contain nitrogen, and Type II, which do not (Meyer, 1985). There are four generally recognized sub-categories based on the form and placement of the nitrogen, and the presence or absence of boron. Type Ia diamonds, for example, which may comprise over 98% of the world's natural diamonds, contain from 200 ppm up to a maximum of 5500 ppm nitrogen distributed in small clusters or aggregates of nitrogen atoms through the diamonds (Evans, 1992). Diamonds in this category are normally colorless, light yellow or brown. Type Ib diamonds, which comprise around 1% of natural diamonds, are yellow and contain lesser atoms (150–600 ppm) of nitrogen in individual carbon substitution sites. Normal colors of this type range from light to bright yellow or even amber. Type IIa diamonds comprise less than 1% of all diamonds and contain very small concentrations of nitrogen atoms in the range of 4–40 ppm (undetectable or barely detectable by infrared spectroscopy). These diamonds are generally colorless or brown. Some of the world's very large diamonds are in this category. Type IIb diamonds, the rarest and purest type, contain up to around 20 ppm boron and even less nitrogen. These are usually blue or grey in color, and are electrically conductive.

The origin and formation of diamonds is not yet completely understood, but it is generally accepted

that diamonds crystallized from a liquid melt in the earth's upper mantle at depths of between 150 and 300 km (Kirkley, Gurney, & Levinson, 1991). At these depths the temperatures range from 1100–2900° C and the pressures range from 50–100 kilobars, as calculated and confirmed by laboratory studies of the minerals in rock fragments brought up from the earth's upper mantle with the diamonds in volcanic rocks (Mitchell, 1991). Some diamonds may even have formed at depths of 450 km below the earth's surface, because of the great temperatures and pressures required for certain mineral inclusions in them to form (Meyer, 1987).

Most natural diamonds so far discovered are thought to have crystallized between 1 and 3 billion years ago in mantle rock containing relatively high concentrations of magnesium and iron (Meyer, 1985; Stachel, Banas, Muehlenbachs, Kurszlaukis, & Walker, 2006). The processes of diamond formation are inferred on the basis of what is known of conditions in the earth's upper mantle at 150–300 km depth (Rice, 2003; Shirey, Richardson, & Harris, 2004; Tappert, Stachel, Harris, Muehlenbachs, Ludwig, & Brey, 2005). The origin of the carbon source for diamonds is also still very much debated (Banas, Stachel, Muehlenbachs, & McCandless, 2007; Gunn & Luth, 2006; Rice, 2003). Once formed, the diamonds seemed to have resided for hundreds of millions up to 2 billion years in the upper mantle beneath the Archean keels of the continental Precambrian cratons. The diamond phase of carbon, once crystallized, remains stable there, because of the high temperatures and pressures.

It is generally postulated that localized melting of the mantle subsequently occurred to produce a magma rich in CO_2 and H_2O, either a kimberlite or lamproite. This volatile-rich magma then began rising explosively through the mantle areas containing the diamonds and transported the diamonds through the crust to the earth's surface at speeds of 10–30 km per hour via propagating cracks in the mantle and the crust above (Kelley & Wartho, 2000; Snelling, 1994). The kimberlite and lamproite magmas cooled as they approached the earth's surface and therefore hardened, so the resultant explosive eruptions often shattered the solidified magmas in what were cold volcanic eruptions. What remained in the conduit and the material that settled back into it after the eruptions contains the diamonds in pipe-like structures. If these kimberlite and lamproite magmas did not ascend catastrophically from the upper mantle to the earth's surface within 8–24 hours, the diamond crystals would have become unstable at the changing pressure and temperature conditions during their passage and would have reverted to graphite. At the earth's surface these kimberlite and lamproite pipes weather and are eroded so the diamonds are shed into alluvial deposits in river systems, deltas and along coastlines. The diamonds that remain in the pipes may be mined, often from great depths. For some diamond deposits no formation process has been proposed (Banas et al, 2007; DeStefano, Lefebvre, & Kopylova, 2006; Leost, Stachel, Brey, Harris, & Ryabchikov, 2003; Stachel, Viljoen, McDade, & Harris, 2004).

Efforts to produce gem-grade synthetic diamonds, though intensive, have produced only meager results. In 1955 researchers at General Electric successfully synthesized tiny industrial-grade diamonds over several weeks of extreme laboratory temperatures and pressures over intervals of several weeks (Koskoff, 1981). Since then many small industrial-grade diamonds have been produced (some estimates are as high as 100,000 carats per year). In order to produce these diamonds, carbon must be subjected to very high pressures and temperatures in the presence of transition metals (or some other "seed") to get the reaction started (Gunn & Luth, 2006; Langenhorst, Poirier, & Frost, 2004; Zhou, Jia, Chen, Guo, & Li, 2006). Although gem quality diamonds as large as 5 carats have been produced, the cost of production generally remains prohibitively high. DeBeers claims that their equipment can detect the difference between synthetic and natural diamonds; but that claim is highly disputed. Synthetic gemstones larger than 1 carat are not readily produced or available.

Diamonds are mentioned in several places in the Scriptures. A diamond was among the 12 gemstones on the high priest's breastplate representing the 12 tribes of Israel before God (Exodus 20:18; 39:11). Diamonds were thus looked upon by God as things of beauty, purity and value. Indeed, in reference to the "anointed cherub" in Ezekiel 28:13–14, his covering in "the garden of God" and "upon the holy mountain of God" was "every precious stone" including the diamond. This implies that diamonds, along with other gemstones, were present in and on the earth after God created it, so if diamonds are really as "old" as claimed, then they may date back to the original creation. Their presence in the earth's crust today and at the earth's surface may then largely be due to the subsequently eruption of kimberlite and lamproite magmas during the Flood. Diamonds and their origin have occasionally featured in creationist news reports and literature (Baumgardner, 2005; Brown, 1997; Chaffin, 1986; DeYoung, 1982; Oard, 2004; Sarfati, 2006; Snelling, 1994, 1996).

Inclusions in Diamonds

Natural diamonds (and many other crystalline materials) often encase smaller grains or crystals of other minerals within their crystalline matrices, and these are known as inclusions. Twenty to thirty

different minerals have been described as inclusions inside natural diamonds, along with 58 different types of impurities, including uranium and thorium (Meyer, 1987). Synthetic diamonds also suffer from inclusions, but these are mostly metal fragments introduced in the manufacturing process (Langenhorst et al, 2004). In the case of the natural diamonds, these included minerals must have been present at the time the diamonds formed to be incorporated within the diamond matrix. As far as has been ascertained, diamonds are almost completely chemically inert and extremely resistant to any contamination or chemical exchange within their crystal lattice. This means they would have traveled from the earth's upper mantle and through the crust to the earth's surface carrying these inclusions completely intact and unchanged during the 150–300 km ascent (Baumgardner, 2005; Dobrzhinetskaya, Green, Bozhilov, Mitchell, & Dickerson, 2003; Meyer, 1985; Promprated, Taylor, Anand, Floss, Sobolev, & Pokhilenko, 2004; Tappert et al., 2005). Therefore, these inclusions represent tiny "capsules" of mantle materials captured under mantle conditions that have been safely delivered from the upper mantle to the earth's surface. Yet there are some as yet unexplained mysteries concerning the types of inclusions found in diamonds. For example, it is well known that sulfides represent the most common inclusions in diamonds, implying that these sulfides formed in the mantle. Yet many mantle xenoliths brought from the upper mantle to the earth's surface by volcanic eruption contain only small quantities of sulfides (Westerlund, Guknhy, Caklson, Shirey, Hauri, & Richardson, 2004). Furthermore, it is puzzling as to how saline liquids and water, plus gases, are often encapsulated as fluid inclusions within diamonds at such depths (and pressures).

Inclusions consist of, but are not limited to, apatite, calcite, carbonates, chromite, smaller diamonds, garnet, hematite, iron, mica, pyrite, pyroxene, silicates, sulfides, zircon, and, as mentioned, liquids (such as liquid CO_2, water and even brine) and gases (Anonymous, 2001, 2003; Bizzarro & Stevenson, 2003; Jacob, Kronz, & Viljoen, 2004; Klein-BenDavid, Izraeli, Hauri, & Navon, 2007; Navon, Izraeli, & Klein-BenDavid, 2003; Promprated et al., 2004; Stachel et al., 2004, Tappert et al., 2005; Tomlinson, Jones, & Harris, 2006; Westlund & Gurney, 2004).

Frequently mineral inclusions contain radioactive nuclides such as uranium or thorium incorporated within the crystalline lattice of the inclusion. These radioactive nuclides eject alpha particles as a normal part of the radioactive decay process. Alpha-particles travel some distance in the mineral (and then into the surrounding host) depending on the energy at which they were ejected from the nucleus of the nuclide as well as the characteristics of the crystalline material(s). The crystalline lattice structure of inclusions, including zircons, may tend to become somewhat amorphous over time if sufficient self-irradiation takes place (Nasdala, Wenzel, Andrut, Wirth, & Blaum, 2001; Nasdala, Wildner, Wirth, Groschopf, Pal, & Moller, 2006).

The presence of zircons in diamonds is considered rare, but they have been previously reported (Kinney & Meyer, 1993, 1994). It may be that few reports of zircon inclusions have appeared because zircons are not expected to be at depths in the mantle where diamonds are thought to form (Meyer, 1985). The consensus is that zircons exist predominately in the earth's crust. Because of their extreme hardness, it is unlikely that diamonds can incorporate zircons from the crust during their ascent from the mantle to the earth's surface (J. Baumgardner, personal communication, April 2, 2007). Nevertheless, zircon inclusions occur within diamonds and have been reported (Kinney & Meyer, 1993, 1994). Furthermore, there have even been reports of diamond inclusions within zircons (Dobrzhinetskaya et al., 2003; Kinney and Meyer, 1994; Menneken, Nemchin, Geisler, Pidgeon & Wilde, 2007), but these are microdiamonds formed under ultrametamorphic conditions in the earth's crust (Dobrzhinetskaya et al., 1995; Snelling, 1996).

Zircons are known to contain radioactive nuclides (such as described above) and they are also well known in their role as radiocenters for ^{238}U radiohalos, which have been observed in biotite, chlorite, cordierite, fluorite, sapphire, quartz and other minerals (Coenraads, Sutherland, & Kinney, 1990; Gentry, 1973; Ion, Ion-Mihai, Ion, & Sandru, 2003; Nasdala et al., 2001, 2006; Pal, 2004; Snelling, 2000, 2005a). One well-known researcher commented, however, that he was not aware of any report describing uranium in diamond (K. N. Bozhilov, personal communication, June 16, 2006). Nevertheless, zircon inclusions in sapphires are known to contain uranium, the parent radionuclide for polonium (Coenraads, Sutherland, & Kinney, 1990) and others have described such radioactive elements in other rocks from diamond-bearing kimberlites (Kramers, 1979).

Radiohalos are minute circular areas (in cross-section) of discoloration and darkening caused by damage from α-particle radiation emanating from a tiny central inclusion containing radioactive elements such as U and Th (Gentry, 1973; Snelling, 2000). The damage is mostly from point vacancies produced in the crystal lattice of the host mineral by the α-particles. The identity of the isotopic species responsible for a given ring in the darkened region can be determined from the ring's diameter, which is proportional to the energy of the alpha particles emitted by the isotopic species. The rare element polonium (Po) is

momentarily produced as three isotopes in the ^{238}U decay chain—^{218}Po, ^{214}Po and ^{210}Po. Whereas a ^{238}U radiohalo consists of eight rings, radiohalos are also found with only three, two and one rings, resulting from, respectively, the α-decay of these three Po isotopes. Such ^{218}Po, ^{214}Po, and ^{210}Po radiohalos had to have been produced with the respective Po isotopes exclusively present in their radiocenters. It has been estimated that each radiohalo requires between 500 million and 1 billion α-particles to form it (Gentry, 1988).

Doubts have been raised concerning whether radiohalos interpreted as polonium radiohalos have been correctly identified. For example, Moazed, Spector, and Ward (1973) and Moazed, Overbey, and Spector (1975) claim that single, double, triple and quadruple ring radiohalos can clearly and unambiguously be shown to have been generated by the ^{238}U and ^{232}Th decay chains, rather than by "parentless" polonium isotopes as proposed by Gentry (1974, 1984, 1986, 1988). This claim is based partly on the issue of potential uncertainties in the ion microprobe analyses of the halo radiocenters. However, Gentry (1974, 1986) and Gentry, Hulett, Cristy, McLaughlin, McHugh, and Bayard (1974) have refuted this claim, demonstrating that due care was taken in these analyses, and other techniques were employed for comparison to rule out such uncertainties. Furthermore, most of the many others that disagree with Gentry's model for the formation of these polonium radiohalos have accepted their correct identification (for example, Damon, 1979; Dutch, 1983; Wakefield, 1988; Wilkerson, 1989; York, 1979). Indeed, Collins (1992) goes further and specifically includes the Moazed, Overbey, and Spector (1975) claim in his list of attempts to explain Gentry's conundrum that are not fully satisfactory. In any case, Meier and Hecker (1976) have conclusively shown that polonium radiohalos are sometimes associated with polonium bands generated by the polonium being transported by hydrothermal fluids along fractures. Thus the overwhelming consensus is that the polonium radiohalos have been correctly identified.

The formation of Po radiohalos has thus been somewhat enigmatic, given the short half-lives of the three Po isotopes—3.1 minutes, 164 microseconds and 138 days, respectively. Conventionally the Po radiohalos have been called "a very tiny mystery" without further explanation (Dalrymple, as quoted by Gentry, 1988, p. 122). The mystery in question is how these polonium isotopes could have been derived and separated from a nearby source of ^{238}U to then be concentrated in radiocenters to produce the Po radiohalos, all within ten half-lives of these Po isotopes, corresponding to their effective life-spans (1.64 milliseconds in the case of ^{214}Po). Therefore, Gentry (1974, 1984, 1986, 1988) proposed that the polonium had to have been primordial, created in place in the radiocenters and then nearly instantaneously produce the Po radiohalos. Furthermore, he maintained, if the Po was primordial, then the host crystals and rocks (for example, biotite flakes and their host granites) also had to have been created at the same time. However, as pointed out by Wise (1989) and Snelling (2000), many granites that contain Po radiohalos appear from their geologic contexts to have been formed during the Flood, and therefore cannot have been primordial (that is, created) granites. This in turn implies that the Po which generated the Po radiohalos in those granites could not have been primordial Po. Indeed, Snelling and Armitage (2003) studied three specific Po-radiohalo-bearing granite plutons that they demonstrated had to have been generated and formed during the Flood. Therefore, Snelling and Armitage (2003) and Snelling (2005a) proposed a hydrothermal fluid transport model for Po radiohalo formation, which has been tested and verified by subsequent studies (Snelling, 2005b, 2006, 2008; Snelling & Gates, 2008).

Mendelssohn, Milledge, Vance, Nave, and Woods (1979) reported finding radiohalos on the outer surfaces of opaque diamonds using cathodoluminescence. Armitage (1993, 1995), however, was the first to report optically-visible, multi-ringed internal radiohalos in a Type Ia diamond. Despite the fact that exact size matching with the radiohalos observed in biotites was difficult because of the greater density of the diamond's carbon structure reduces the penetration distance of the α-particles, these radiohalo rings were nevertheless identified as produced by ^{218}Po, ^{214}Po, ^{210}Po, and ^{222}Ra. Furthermore, these radiohalos were found along rod-like structures and at the termini of strange hollow tubes that were bent repeatedly at right angles within the diamond. Wise (1998) suggested that these structures represented fluid conduits along which the radioisotopes responsible for parenting these radiohalos had been transported into the diamond, but both Armitage (1998) and Gentry (1998) maintained that this interpretation was not viable due to the diamond's unfractured internal crystal structure. They insisted instead that the short half-lives of the radioisotopes responsible for the rings in the radiohalos suggested a primordial origin for the radioisotopes and thus the diamond. Nevertheless, Vicenzi, Heaney, Snyder, and Armstrong (2002) reported radiation halos 25 micrometers in diameter in alluvially deposited polycrystalline diamonds (carbonados) from the Central African Republic, which they maintained were generated as a result of uranium deposition from a single pulse of fluids infiltrating the diamonds following their formation. Furthermore,

whereas J.W. Harris (personal communication, May, 2007) has claimed, "over decades of looking at millions of diamonds I have only once seen a green set of haloes inside a stone," jewelers and gemologists in southern California testify to having regularly seen radiohalo inclusions in diamonds and other gemstones (Armitage, personal communications with jewelers in southern California, April, 2007; May, 2007).

Diamonds Examined

Sixty-nine small diamonds and diamond chips from diamond mines in Kimberley (South Africa), Jwaneng (Namibia), and Orapa (Botswana), and from alluvial diamond deposits in Namibia and Guinea, were examined for radiohalos. These diamonds were in the possession of Dr. John Baumgardner at the Institute for Creation Research in Santee, California. The two diamonds with radiohalos in them examined in this study were on loan from the Gemological Institute of America laboratory (GIA), Carlsbad, California, courtesy of Dr. John Koivula and Thor Strom. The first of these diamonds was a 0.06 carat, faceted stone from an unknown source. The other was described as a 0.11 carat diamond macle (or oddly shaped crystal) from the Diamantina mines, Gerias, Brazil.

The diamonds of interest were photographed with film on a Zeiss Jena dissecting light microscope configured with multiple fiber optic illuminators and an Olympus SLR film camera body. Illumination of radiohalos proved difficult particularly since both specimens had been carbon-coated for examination with scanning electron microscopy (SEM), but SEM was not performed in this study. Prints of the negatives made were digitally scanned.

Twenty different jewelry stores in three counties in southern California were visited over a period of several weeks. Jewelers and gemologists at those stores were interviewed. Half of the proprietors stated that they had seen such radiohalo inclusions in diamonds and other gemstones previously but none of the twenty had any gemstones available for examination.

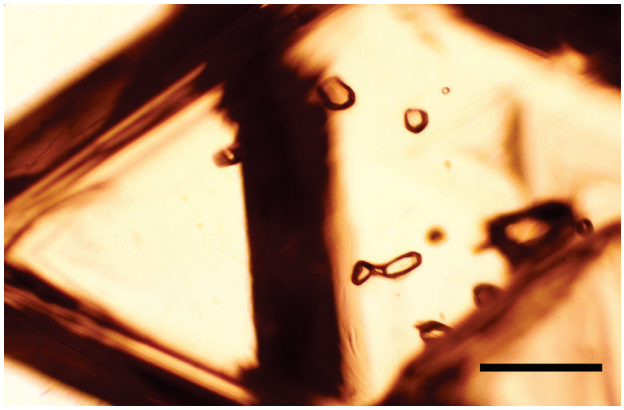

Figure 1. Small inclusions in diamond from Orapa mine, Africa. Magnification 250×. Scale bar = 300 microns.

Results

No radiohalos were found in any of the African diamonds. However, large numbers of various inclusions (including possible zircons) were found in them and some in the Orapa diamond were photographed (Figure 1).

Radiohalos with one, three, and four rings were found in the GIA diamonds. The round brilliant cut 0.06 carat diamond from an unknown source contained dozens of radiohalos and "etch trails" (Figures 2–4). Documentation was provided with this diamond. It described "etch trails" which intersected with the radiocenters of each halo sharply bent at differing angles (see Figure 4). These "etch trails" did not extend to the surface. Therefore, the diamond girdle was ground away by GIA personnel until contact with the etch trails was made (see ground girdle on Figures 4–5). The text stated that inclusions were solid (crystalline?) and that "they appear to have a hexagonal outline." These radiohalos (both 3 and 4 ring varieties) were measured with a calibrated ocular micrometer to 50 micrometers diameter.

The diamond macle (oddly shaped crystal) from Brazil (Figures 7–8) contained dozens of radiohalos, but only of the single ring variety. This documentation supplied with this specimen stated "this 0.11 carat diamond macle is from Diamantina mines, Gerais, Brazil. Its radiation spots with central 'cores' are from some unknown substance. These spots started out green and changed to brownish orange when the diamond was heated to 620 °C. The first change in spot color was noticed at 590–600 °C." These radiohalos (single ring only) were measured with a calibrated ocular micrometer to 30 micrometers diameter.

Discussion

The crucial factor in the occurrence of the radiohalos within these two diamonds is the temperature at which radiohalos are annealed. At the annealing temperature the vibrations of the atoms in the crystal structure have increased sufficiently to repair the point vacancies caused by the previous α-particle bombardment, such that the darkening, and thus the radiohalos, are erased. In biotites, radiohalos are erased above 150 °C (Laney & Laughlin, 1981). This annealing temperature was determined using samples taken from a drill-hole in which present in situ temperatures had been measured, and so could be interpreted as having been determined under natural conditions. In contrast, Armitage and Back (1994) placed biotite flakes containing radiohalos in an oven, heating them at temperatures up to 700 °C for up to five hours. They found erasure of radiohalos occurred

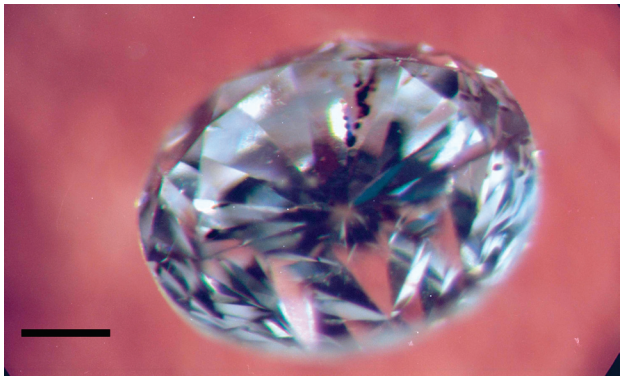

Figure 2. Round, brilliant cut diamond. Note radiohalos at 12 o'clock position. Scale bar = 0.3 mm

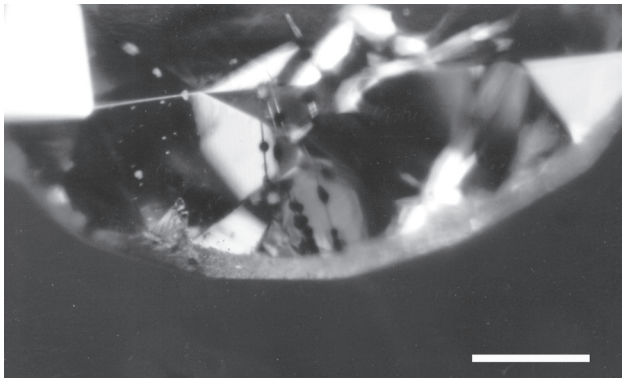

Figure 3. Radiohalos in round diamond. Magnification 80×. Scale bar = 450 micrometers.

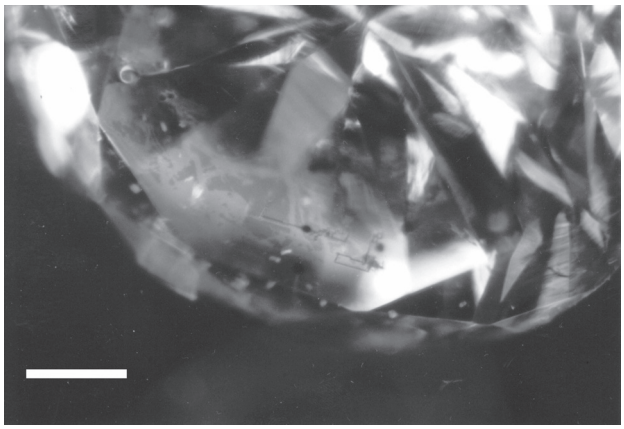

Figure 4. Radiohalos in round diamond. Note right and sharp angles made by crystalline tubes. Magnification 80×. Scale bar = 450 micrometers.

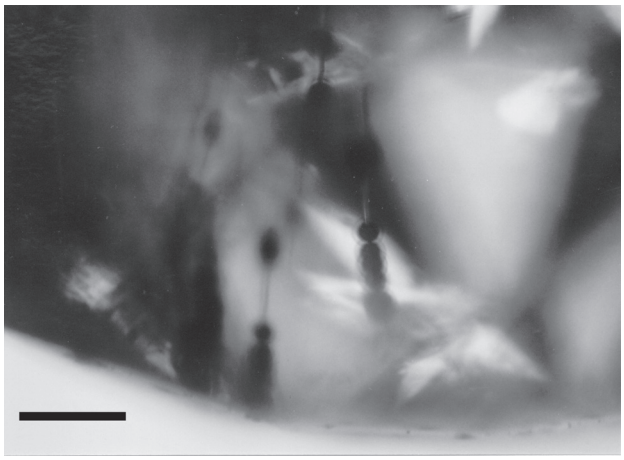

Figure 5. Radiohalos in round diamond. Magnification 100×. Scale bar = 160 micrometers.

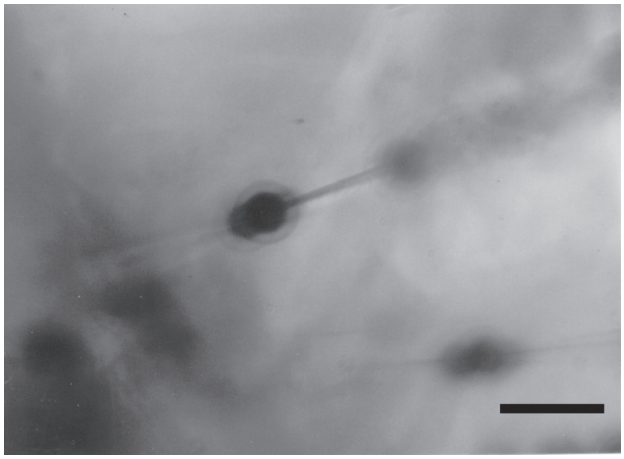

Figure 6. Radiohalos in round diamond. Magnification 200×. Scale bar = 75 micrometers.

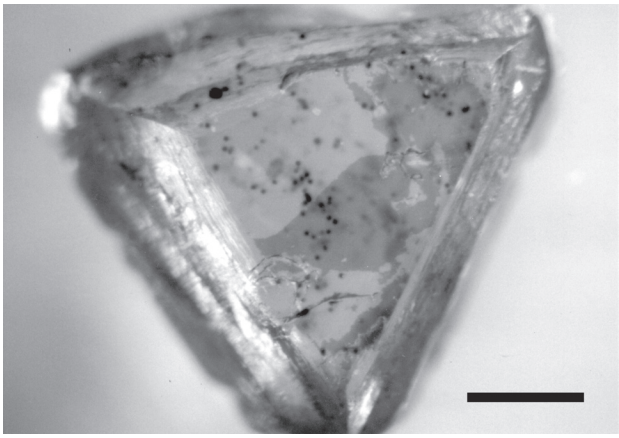

Figure 7. Radiohalos in macle diamond from Brazil. Magnification 200×. Scale bar = 1 mm.

after only an hour of heating at temperatures of 250–550 °C. However, it is not known whether radiohalos in diamonds are annealed at 150–250 °C. The Brazilian macle diamond was reported to have been heated to 620 °C without complete loss of radiohalos. This would seem to imply that the annealing temperature of radiohalos in diamonds is higher than 620 °C.

The temperatures at the 150–300 km depths in the upper mantle where diamonds are inferred to have formed are 1100–2900 °C. Of course, any radiohalos would only be generated in diamonds after the diamonds formed at those temperatures. If the annealing temperature of radiohalos in diamonds is

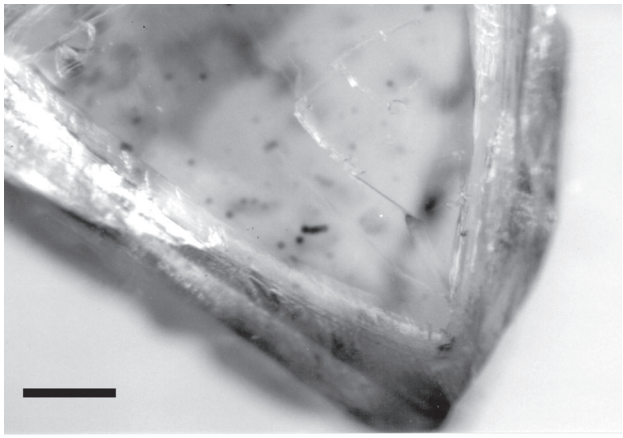

Figure 8. Radiohalos in macle diamond. Magnification 90×. Scale bar = 0.5 mm.

higher than 620°C, there is a greater temperature window (compared with the 150°C annealing temperature of radiohalos in biotites) in which magmatic and hydrothermal fluids could transport ^{238}U and its decay products into and within diamonds. This assumes that ^{238}U, its decay products, or tiny crystals of a mineral such as zircon hosting them, had not been included in diamonds when they formed. Zircon inclusions in diamonds are considered to be rare, but at the upper mantle temperatures at which diamonds have supposedly resided for hundreds of millions of years, before transport to the earth's surface by kimberlite and lamproite magmas, it is highly unlikely radiohalos would have formed around any zircon inclusions.

Instead, it is far more likely that ^{238}U and its decay products infiltrated the diamonds during and after their ascent to the earth's upper crust. However, while kimberlite and lamproite magmas are volatile-rich, particularly with respect to CO_2, they contain very little water and so produce dry volcanic eruptions. Thus, as water is the likely transporter of ^{238}U and its decay products, the infiltration of water transporting ^{238}U and its decay products to form the radiohalos in diamonds would need to occur after the emplacement of the host kimberlite or lamproite at and near the earth's surface. Indeed, even though the kimberlite and lamproite magmas are considered dry, they are nonetheless very hot (>1,000°C) when emplaced, and their interaction with the ground waters in the immediately surrounding intruded strata would generate in situ hydrothermal fluids (Snelling & Woodmorappe, 1998). That such fluids are generated is confirmed by the ubiquitous hydrothermally produced minerals such as serpentine in kimberlites and lamproites. Such fluids would scavenge, dissolve, and concentrate ^{238}U and its decay products from both the intruded strata and the congealed, rapidly cooled, and explosively fragmented intruding magmas.

The next question has to be whether magmatic and hydrothermal fluids can infiltrate into diamonds. Both Armitage (1998) and Gentry (1998) insisted that fluid infiltration was not possible due to the unfractured, tight internal crystal structure of diamonds. However, Vicenzi et al (2002) maintained the radiohalos they found in alluvially deposited carbonados were generated as a result of uranium deposition from a single pulse of fluids having infiltrated those microcrystalline diamonds after their formation. The crystal structure of diamonds is cubic, and even though diamonds fracture conchoidally, they exhibit cleavage in four directions (octahedral) with one perfect cubic cleavage {111} (Mason & Berry, 1968). As in the case of the radiohalos in the diamond documented by Armitage (1994), many of the radiohalos in one of the diamonds in our study are centered along thin darkened straight lines within the diamond. These lines appear to follow the directions of the cleavages (Figures 3–5). Other radiohalos are at the termini of strange darkened tubes that turn and twist at right angles (Figure 4). Wise (1998) interpreted all these features as conduits along which fluids must have transported the ^{238}U and its decay products responsible for the radiohalos. This interpretation is supported by the observations made by Armitage and Back (1994) and in our study that the darkening along these linear features and twisted tubes is due to radiation staining. Furthermore, these linear features and the linear sections of the twisted tubes appear to follow the perfect cleavages within the diamonds. These cleavages are the natural weaknesses of the diamond crystal lattice along which infiltrating fluids might be expected to flow.

This interpretation raises several issues. Again, the intact crystal structure of diamonds, without clearly developed fracture surfaces along cleavages, would seem not to be capable of providing open avenues for fluid infiltration. However, this concern is based on observations of diamonds at ambient temperatures. By contrast, at the temperatures of 300–400°C at which magmatic and hydrothermal fluids might have infiltrated, the heat would likely have expanded the diamond crystal structure, thus opening cleavage planes to provide the necessary pathways for these fluids. Yet how are these darkened linear features and "tubes" produced by fluid infiltration when cleavage planes are two-dimensional surfaces? Given that the diamond crystal structure is normally tight (close-packed), if the cleavages within it are opened by heat and fluid pressures, the easiest, most open, pathways for fluids to infiltrate would be at the linear intersections of cleavage planes. It then follows that because there are essentially five cleavage planes in diamonds, the lines of intersection between them run in numerous directions, which would account for the twisted tubes.

It would also be precisely because of the tight crystal structure of diamonds that some of these tubes are twisted at right angles. Because all the cleavages are at varying angles only a few right angles would seem possible, but the cubic cleavage plane is regarded as perfect (Mason & Berry, 1968). Armitage (1998) described these strange twisted tubes as solid inclusions, rather than being hollow as previously thought (Armitage, 1994). A few of these twisted tubes were found to extend to the surface of the diamond (Armitage, 1994), and not all of them terminated at a radiohalo. Furthermore, in both the Armitage (1994) diamond and the cut diamond in our study, both the darkened linear tubes with radiohalos centered along them, and the twisted tubes terminating in radiohalos, usually do not reach the surfaces of these faceted stones. This would seem to argue against these tubes having been formed by fluid infiltration. However, the character of these tubes, and their containment of solid mineral inclusions, suggest their formation as mineral inclusions via precipitation from infiltrating fluids. These would have to have been trapped in the diamond crystal structure long enough for the mineral matter dissolved in them to precipitate.

It is thus envisaged that with the emplacement of the host kimberlite pipe, connate water in the surrounding intruded strata was heated by the cooling kimberlite, and the hydrothermal fluids thus generated infiltrated the still warm diamonds within the kimberlite, carrying ^{238}U and its decay products scavenged from the intruded strata. Heated diamonds expanded sufficiently to facilitate fluid infiltration along cleavage planes; but because of the tight diamond crystal structure, where the fluids met resistance within the diamonds because the cleavages would not open further, the fluids instead exploited any weakness along the intersections between other cleavage directions. Thus some of the linear fluid pathways became twisted repeatedly at right angles as the fluids infiltrated where cleavage intersections were sufficiently open to them. As the diamonds first cooled at their outer surfaces, the cleavages infiltrated by the fluids would contract and close first at their outer surfaces, locking the fluids into those cleavages where the contained elements and minerals then precipitated. Because ^{238}U and its decay products were dissolved in these infiltrating fluids, α-radiation tracks would be left along the cleavage pathways traversed by the fluids. The ^{238}U decay products in the fluids apparently became concentrated in nucleation or precipitation centers, where trace atoms such as Cl (present in diamonds) chemically attracted Po. These precipitated Po atoms then "parented" the now observed radiohalos. The half-lives of these radioisotopes are short (^{210}Po 138 days, ^{218}Po 3.1 minutes, and ^{214}Po 164 microseconds); but isolated ^{214}Po radiohalos may be accounted for by retention in the infiltrating fluid of the 27-minute half-life parent ^{214}Pb and the 20-minute half-life parent ^{214}Bi. Similarly, isolated ^{210}Po radiohalos may be accounted for by retention of the 22-year half-life parent ^{210}Pb and the 5-day half-life parent ^{210}Bi. A satisfactory explanation for the observed density ratios of polonium radiohalos awaits further study.

The single ring radiohalos in the Brazilian macle diamond, most probably ^{210}Po radiohalos, are dispersed randomly and sometimes apparently in clusters, and do not seem to be along any radiation-stained linear features (Figures 7–8). This does not mean the ^{210}Po was not transported into this diamond by fluid infiltration along cleavages. Rather, it suggests that the ^{210}Po transport was so rapid there was insufficient time for radiation staining to develop along the cleavages infiltrated by the fluids. Furthermore, the oddly shaped nature of this macle diamond has two other implications. First, its contraction accompanying cooling after emplacement would have been very rapid due to its likely less orderly crystalline structure; and thus fluid infiltration to produce these ^{210}Po radiohalos also needed to be very rapid. And second, the packing of its crystal structure would mean that its cleavages are not as well defined, and the infiltrating fluids would have more readily dispersed around the constituent components of its crystal lattice rather than along cleavages. This is consistent with its distribution pattern of ^{210}Po radiohalos. However, since only ^{210}Po radiohalos are present in this macle diamond, the infiltrating fluids likely only transported ^{210}Po scavenged from the host kimberlite and the intruded strata. The fluids which infiltrated the other diamond we studied had to have carried radioisotopes higher up the ^{238}U decay chain, at least up to 1,000 year half-life ^{226}Ra, which is readily soluble in most fluids.

All these considerations indicate time limits on the fluid infiltration process to generate the polonium radiohalos is the order of hours or weeks. This is consistent with the evidence of the rapid speed (within hours) at which diamond-bearing kimberlite pipes are explosively emplaced. Additionally, once emplaced, complete cooling of the fragmented congealing kimberlite magma is also rapid (within days or weeks) at the surface, and in the near-surface environment beneath where heated meteoric waters containing Ra, Rn, and Po scavenged from the host strata would rapidly penetrate into the kimberlite and mix with any magmatic and hydrothermal fluids. Rapid hydrothermal fluid transport of ^{210}Po in the natural environment has been documented (Snelling, 2000). Hussain, Church, Luther, and Moore (1995) found that the residence time of ^{210}Po in hydrothermal fluids venting on the ocean floor was of the order of

only a few minutes, and that the residence time of the hot fluids in the hydrothermal system was no more than 30 days. Furthermore, the hydrothermal fluids in geothermal and mid-ocean ridge vent systems are estimated to circulate through rock volumes of several cubic kilometers over distances of several kilometers (Lowell, Rona, & Von Herzen, 1995; Nicholson, 1994), transporting ^{210}Po within 20–30 days. Given the explosive emplacement of the hot kimberlite pipes and the rapid penetration into them of hydrothermal fluids transporting Ra, Rn, and Po, infiltration of hydrothermal fluids carrying Po into the diamonds within the hot fragmented kimberlite would have needed to be rapid to deposit the Po in time to generate the Po radiohalos before the whole system cooled rapidly, the diamond cleavages "closed," and hydrothermal fluid circulation ceased.

Conclusions

Even though the available data suggest the erasure temperature of radiohalos in diamonds may be above 620°C, the 1100–2900°C conditions in the mantle where diamonds form would be too severe for radiohalos to form there. Furthermore, the temperature of the kimberlite and lamproite magmas that transported diamonds to the upper crust, the short transit times, and the lack of water to transport radioisotopes into diamonds, would militate against radiohalos being formed during the ascent of diamonds from the mantle. Thus the radiohalos in the diamonds examined in this study must have formed after emplacement of their host kimberlite/lamproite pipes at or near the earth's surface.

The emplacement of the hot, dry kimberlite/lamproite magmas in pipes would result in heating of the connate water in the surrounding intruded (host) strata. The hydrothermal fluids thus produced would then scavenge and concentrate trace amounts of ^{238}U and its decay products, transporting them into the kimberlite/lamproite pipes via convective flow. Due to expansion of the still hot diamonds, these fluids would have infiltrated the diamonds along the cleavages within them. Where resistance was sometimes encountered because of the diamonds' tight crystal structure, the fluids exploited other cleavage directions, resulting in fluid pathways, which twisted repeatedly at right angles. The α-decay of the radioisotopes in the fluids often left dark radiation stains along these linear and twisted fluid pathways. Contraction of the outer surfaces of the diamonds would have closed termination of cleavages there, thus trapping the infiltrated fluids to precipitate the mineral matter that forms the observed tubes. Precipitation of ^{238}U decay products in nucleation centers along, and sometimes at the end of, these fluid infiltrated cleavages where chemical conditions were conducive produced concentrations that generated the observed polonium radiohalos. All considerations indicate severe time limits on the fluid infiltration process—on the order of hours or weeks.

Radiohalos in diamonds can be explained by the hydrothermal fluid transport model for Po radiohalo formation; but they cannot answer the question: are diamonds really for ever? However, as specified by the prophet Ezekiel, the anointed cherub was covered with every precious stone in the garden of God at the dawn of time (Ezekiel 28:13–14). According to Revelation 21:19, the foundations of the wall of the eternal city are decorated with all manner of precious stones. Hence, diamonds truly are for ever! More of them should be examined for radiohalos.

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