Inclusions in Sublithospheric Diamonds:
Glimpses of Deep Earth

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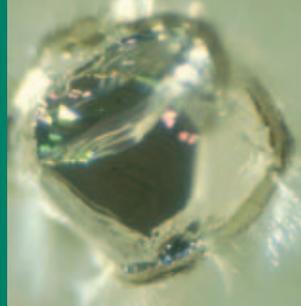
A 400-micron wide ferropericlase inclusion in a diamond from the São Luiz alluvial deposits of Brazil. PHOTO BY JEFFREY W. HARRIS.

Diamonds originate in the deep roots of ancient continental blocks (cratons) that extend into the diamond stability field beneath about 140 km. Over the last two decades, rare diamonds derived from even greater depths—the deep upper mantle, the transition zone (410–660 km), and the lower mantle—have been recognized. Inclusions in diamonds from the deep upper mantle and the transition zone document sources of basaltic composition, possibly related to subduction of old oceanic crust back into Earth's mantle. Diamonds from the lower mantle carry inclusions that largely confirm predictions of the composition and mineralogy of the deep mantle based on a "pyrolite" (primitive peridotitic) composition of silicate Earth. For some inclusions, however, the chemical evidence again points to a connection with subducting oceanic slabs, possibly ponding at the top of the lower mantle.

Keywords: diamond inclusion, majorite, perovskite, phase transition, transition zone, lower mantle, subduction, megalith

INTRODUCTION

The vast majority of diamonds mined from primary deposits in kimberlite and lamproite pipes and from secondary deposits derived through erosion and redeposition originated from a narrow depth window between about 140 and 200 km, as indicated by calculations of temperature and pressure of formation of their silicate inclusions. The top end of this depth range corresponds to the transition of graphite to diamond at conditions in Earth's mantle; the bottom end appears to coincide with the "normal" maximum thickness of lithosphere, the non-convecting uppermost portion of our planet (FIG. 1). Such substantial thicknesses of lithosphere are only achieved beneath the oldest parts of continents, the cratons; this explains the observation that primary diamond deposits are generally limited to areas where the last major tectonothermal event occurred at least 2.5 billion years ago—this is the essence of the so-called "Clifford's Rule".

Mineral inclusions in diamonds are overwhelmingly derived from the two principal rock types occurring in the deep lithosphere, peridotite and eclogite (e.g., Meyer 1987). Although peridotitic diamonds dominate, the relative abundance of eclogitic diamonds generally increases with larger stone sizes, giving them great economic importance. The study of lithospheric diamonds has proven to be a valuable tool complementary to similar research on fragments of mantle rocks (xenoliths) found in volcanic rocks of deep origin. The inclusions are typically 0.1–0.2 mm in size, rarely 0.5 mm, and are found using an optical microscope. If necessary, they can be identified in situ using Raman spectroscopy and characterized structurally using X-ray diffraction. For chemical analysis, mineral inclusions are released by crushing or burning their diamond hosts. The inert nature and presumed old ages of diamonds make their inclusions particularly useful for studying the origin and evolution of ancient lithosphere.

Important observations over the last two decades have shown that hidden among the dominant lithospheric diamonds are samples derived from even greater depths, extending to at least 700 km. Xenoliths of mantle material from beneath the lithosphere are extremely rare, and the few examples appear to have equilibrated to lithospheric conditions (e.g., Sautter et al. 1991). Our knowledge of the mineralogy and chemical composition of the sublithospheric mantle, therefore, is derived indirectly, using high-pressure experiments, seismic data, and cosmochemical and isotopic constraints. Mineral inclusions in ultradeep diamonds are the only direct samples from the deep mantle available for study and allow us to test the models derived from geophysical and experimental studies.

Discontinuities in the velocity of compressional and shear waves discovered in seismic studies point to layering in Earth's mantle. High-pressure experiments by A.E. Ringwood and coworkers (including W.O. Hibberson, T. Irifune, L. Liu, and A. Major) showed that these seismic discontinuities coincide with phase transitions affecting important mantle minerals. Based on these data, the mantle is subdivided into three major layers (see FIGS. 1 AND 2):

1 **The upper mantle (<410 km)** It is thought to consist predominantly of olivine and low-Ca pyroxene. In the present paper, we use the term "asthenosphere" for the entire convecting upper mantle beneath the lithosphere (see glossary p. 70).

2 **The transition zone (410–660 km)** The 410-km seismic discontinuity coincides with the experimentally observed conversion of olivine (α-phase) into spinel-like wadsleyite (β-phase), with roughly an 8% increase in mineral density. A further 100 km down, wadsleyite transforms to ringwoodite (γ-phase), which has a true spinel structure and is another 2% denser. This latter phase transition has been linked to a mild seismic discontinuity in the mid-transition zone (at about 520 km).

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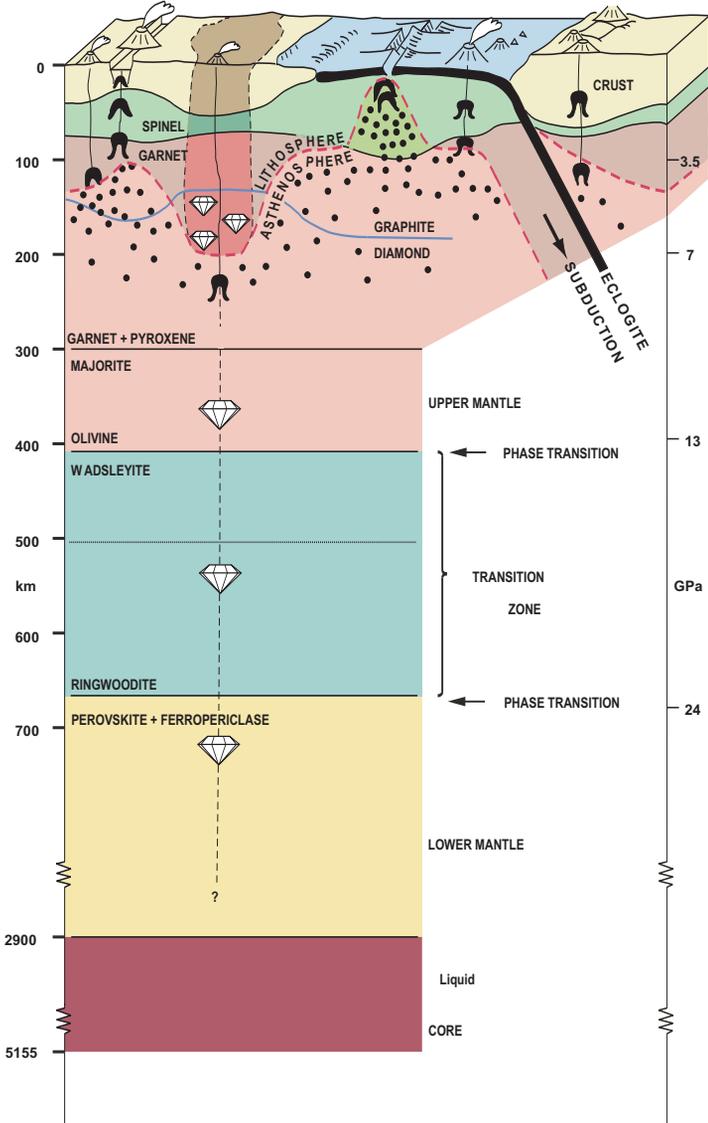
FIGURE 1 Vertical section through Earth's crust, mantle and core. The upper mantle, underlying the crust (shown in light yellow) is separated into two main mineralogical layers, spinel facies (green) and garnet facies (pink). The uppermost, non-convecting portion of Earth including the crust and part of the upper mantle is called the lithosphere, and the underlying convecting part the asthenosphere. Beneath ancient cratons the lithosphere may extend to about 200 km depth. In cooler regions of Earth's mantle the graphite/diamond transition occurs at shallower depth. Beneath cratons, therefore, there is a region where lithosphere and diamond stability overlap and this is the main source region of diamonds worldwide. Rare ultradeep diamonds may come from (i) the deep upper mantle, where majorite garnet becomes stable, (ii) the transition zone, characterized by the stepwise isochemical conversion of olivine first to wadsleyite and then to ringwoodite, and (iii) the lower mantle. These ultradeep diamonds are the only direct samples available from the deep interior of our planet.

The discovery of ultradeep inclusions in diamonds was not a stepwise recognition of increasingly deeper origins. Rather, it began unexpectedly in 1984 with a small paragraph in a paper by Scott Smith et al. (1984) on kimberlite dikes near Orroroo in South Australia. These authors noted that if ferropericlase (see glossary p. 70) inclusions in diamonds from this occurrence and the Koffiefontein Mine in South Africa were indeed syngenetic, then, because of an apparent association with inclusions of orthopyroxene chemistry, they may indicate diamond formation in "deeper levels of the mantle" (i.e., the lower mantle). Not much attention was given to this discovery till more compelling evidence for lower-mantle diamonds was found at Rio São Luiz in the Juina area of Brazil (reviewed in Harte et al. 1999).

The next stage was the recognition of inclusions of majorite garnet (see glossary p. 70) in diamonds from the Monastery mine, South Africa (Moore and Gurney 1985), which indicated formation in the asthenosphere and the transition zone. The most recent discoveries of ultradeep inclusions came from Snap Lake (Canada), in the form of subcalcic, high-Cr majoritic garnet (Pokhilenko et al. 2001) and from Yubileynaya (Siberia), where Sobolev et al. (2004) report wehrlitic, high-Cr majorite garnet.
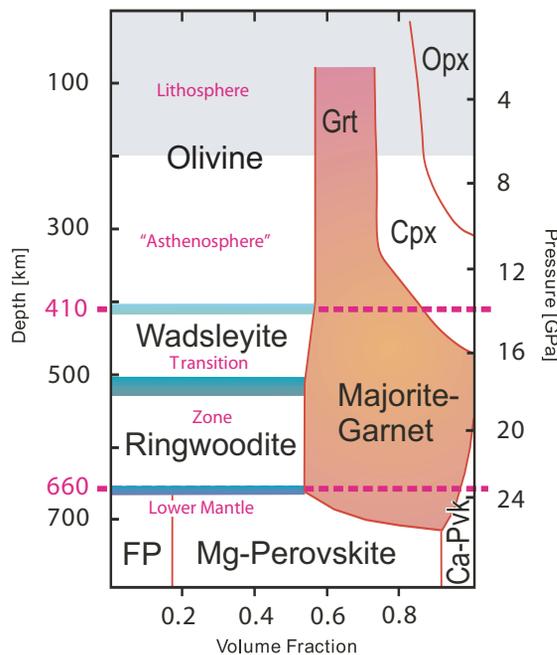
FIGURE 2 Relative mineral proportions and phase transitions in Earth's mantle (after Ringwood 1991; Agee 1998; Wood 2000). FP: ferropericlase; Grt: garnet; Cpx: clinopyroxene; Opx: orthopyroxene; Mg-perovskite: MgSi-perovskite; Ca-Pvk: CaSi-perovskite.

3 **The lower mantle (660–2900 km)** In contrast to the upper mantle, which is made up of silicate minerals based on various combinations of SiO_4-tetrahedra, silicon is octahedrally coordinated with oxygen in the lower mantle. The dominant phases are CaSi- and MgSi-perovskites, in addition to the oxide phase ferropericlase. The nature of the 660-km discontinuity is still not fully understood, with conflicting experimental, geochemical, and geophysical evidence as to whether it represents an impediment to whole mantle convection or not (cf. Agee 1998).

Although individual inclusions of "ultradeep" origin are by now quite common, so far only five localities have yielded many sublithospheric diamonds. Of these five localities, four have yielded diamonds with majoritic garnet inclusions: Monastery, Jagersfontein (both South African), Juina (Rio São Luiz, Brazil), and Kankan (Guinea). The principal sources of diamonds with lower-mantle parageneses are Juina, Kankan, and the Lac de Gras region of Canada. Studies on diamonds from these five occurrences (for references see Stachel 2001) form the basis of the review given here.

ASTHENOSPHERE AND TRANSITION ZONE

Important Phase Transitions

All four major minerals occurring in peridotite, the principal rock type in the upper mantle, are affected by phase transitions and reactions over the depth range in this zone. First, at around 300 km depth, orthopyroxene is eliminated by a structural conversion to monoclinic low-Ca pyroxene. At similar depths, garnet increasingly dissolves pyroxene as a majorite component to give a garnet-structured, high-pressure form with pyroxene stoichiometry. For a predicted primitive composition of the Earth's mantle ("pyrolite" of Ringwood 1962a and 1962b), all pyroxene would be dissolved in majorite garnet at about 450 km depth (Fig. 2). At about 550 km depth, the majorite component of garnet begins to decrease through exsolution of CaSi-perovskite. Magnesium-rich olivine, the most important constituent of the upper mantle, is eliminated at the top of the transition zone through conversion to wadsleyite, which in turn converts to spinel-structured ringwoodite in the middle of the transition zone. So, in the mid-transition zone, the typical four-phase peridotite of the upper mantle will have converted to a two-phase rock composed of silicate spinel and majorite garnet.

The Problem of Retrograde Phase Transitions

Based on these phase transitions, it might be expected that recognition of inclusions in diamonds from the deep asthenosphere and transition zone would be fairly straightforward and could be based on phase identification (X-ray diffraction, Raman spectroscopy). In fact, exhumation converts these high-pressure minerals to lower-pressure phases or assemblages. This happens because diamond deforms plastically at the high temperatures of the Earth's mantle, and thus high internal pressure on inclusions is relaxed during ascent. Even rapid ascent from the point of diamond formation is not sufficient to prevent retrograde conversion of ringwoodite or wadsleyite to olivine and of low-Ca clinopyroxene to orthopyroxene. The only exception is the retrograde reaction of majorite to "normal" garnet plus pyroxene, as this conversion is not an isochemical phase transition and leaves the telltale signature of an extra phase if reequilibration proceeds. The onset of pyroxene exsolution from majorite garnet has been documented for inclusions in diamonds from Juina by Wilding (1990).

Because of the polymorphic transitions, chemical fingerprinting appears to be the only way to detect former single-phase low-Ca clinopyroxene, wadsleyite, and ringwoodite inclusions. High-pressure experiments on pyrolite compositions show elevated Al contents in wadsleyite and (even more so) in ringwoodite relative to olivine (Akaogi and Akimoto 1979). From experiments, wadsleyite in equilibrium with a primitive mantle contains ≥0.3 wt% Al_2O_3, which is also true for ringwoodite. As 0.1 wt% is the highest Al_2O_3 content for all of the 700 olivine inclusions analyzed from diamonds worldwide, we can exclude wadsleyite or ringwoodite as precursors.

Majorite Garnet

The only samples recognized so far as being from the asthenosphere and transition zone are inclusions of majoritic garnet. Experimental studies have found a near linear increase in "excess" silicon with increasing pressure for the pressure range of about 7–15 GPa, thus suggesting the possibility of using the majorite component in garnet as a geobarometer. Here we provide an interpretation using the 1200°C experimental data of Akaogi and Akimoto (1979) and Irifune (1987) for pressure estimates, though bulk chemical effects are not accounted for and experi-

mental data sets of other authors would lead to somewhat different results. Figure 3 shows the compositional spread of majorite inclusions in diamonds from worldwide sources. The bulk of the inclusions show majorite contents that translate to an asthenospheric depth of origin of about 250–350 km. A few majorites, however, come from greater depths, probably extending even into the transition zone. For the one inclusion from Jagersfontein showing the highest majorite component yet observed, even the most conservative pressure estimates (e.g., Gasparik 2002) imply an origin beneath the 410-km discontinuity.

Diamond Growth in the Transition Zone

A surprising feature of majoritic garnet inclusions is their paragenetic association with eclogite as inferred from their major-element composition. Earth's mantle is generally assumed to have a chemistry matching primitive peridotite ("pyrolite") with a very minor component (probably <1%, cf. Schulze 1989) of eclogite, the high-pressure metamorphic equivalent of basalt. Yet, only 10% of the about 90 majoritic garnet inclusions analyzed so far belong to the peridotitic suite. These peridotitic majorites are so high in chromium (up to 14 wt% Cr_2O_3) that they do not correspond chemically to pyrolitic mantle but to non-convecting lithospheric mantle with a history of melt extraction (cf. Pokhilenko et al. 2004). The Cr-rich majorites show that at some stage during Earth's history, the lithosphere may have locally extended to a depth of about 300 km, which is significantly deeper than what we observe today based on the record from mantle xenoliths.

There is considerable compositional overlap between eclogitic majorite garnet inclusions and lithospheric eclogitic garnet inclusions. This suggests that diamonds with eclogitic inclusions from within and beneath the cratonic lithosphere grew in similar source rocks. This compositional overlap seems to support the extreme view that the sub-lithospheric upper mantle is composed of eclogite (cf.
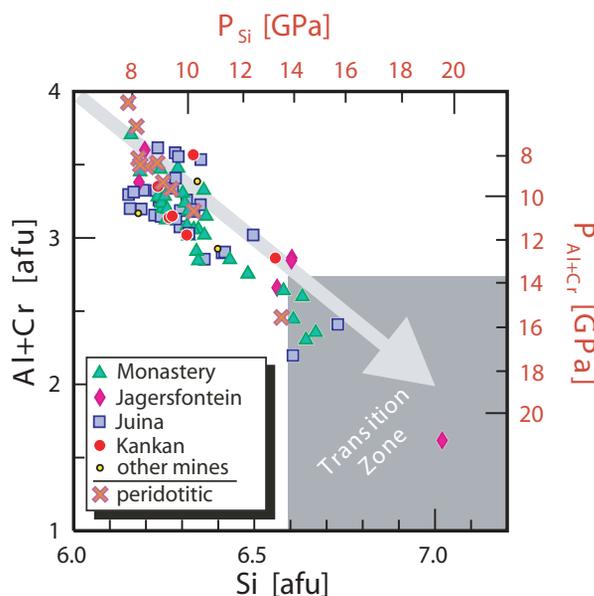
FIGURE 3 Majoritic garnet inclusions in diamonds from worldwide sources. An increasing majorite component with increasing pressure corresponds to increasing Si and decreasing Al+Cr. P_{Si} and P_{Al+Cr} (given in giga-Pascal) are obtained via linear regression of experimental data (1200°C) of Akaogi and Akimoto (1979) and Irifune (1987) and are approximate values only. The transition zone, beginning at about 410 km (or 13.7 GPa) is indicated in grey. Except for crosses, which have peridotitic sources, all majorites shown are eclogitic in paragenesis. [afu] is atoms per fomula unit.

Gasparik 2002). However, plate tectonics, the standard model in Earth sciences, provides a mechanism in accord with the petrological, geochemical, and geophysical constraints on the composition of Earth's mantle and the evidence against the long-term survival of extreme compositional stratification. Plate tectonics predicts that old and therefore dense oceanic lithosphere is subducted back into the mantle (Fig. 1) where it sinks through the asthenosphere and transition zone to the top of the lower mantle and in part even farther, to the core–mantle boundary, as seen from seismic tomography. The former basaltic oceanic crust in such sinking slabs could well be the source of eclogitic majorite inclusions in diamonds.

But why would diamond formation in the asthenosphere and transition zone be restricted to down-going slabs? Carbon is a trace element in a peridotitic mantle (≤0.04 wt%). For the growth of macrodiamonds, a local enrichment mechanism for carbon is needed. Within the lithosphere, this is probably accomplished by redox fronts, where reducing fluids encounter oxidized rocks or vice versa. The deep asthenosphere and transition zone are expected to be fairly well mixed and more reduced than the lithospheric mantle, making the presence of redox fronts unlikely. A sinking oceanic slab, however, will at least locally be oxidized through seawater alteration and provide redox gradients where reduced hydrocarbon-bearing fluids may precipitate diamond. In addition, thermally stable carbonates in subducting slabs may become reduced to diamond by virtue of a crystal chemistry-induced decrease in oxygen fugacity with increasing pressure. Strong support for a subduction model comes from the rare-earth elements in some majoritic garnets where europium is depleted relative to its neighboring rare-earth elements (REEs). Eu (as Eu^{2+}), unlike the other REEs, follows calcium and fractionates into the low-pressure mineral plagioclase. It is removed from the basaltic rocks during crystal–melt fractionation prior to being transformed into eclogite during subduction.
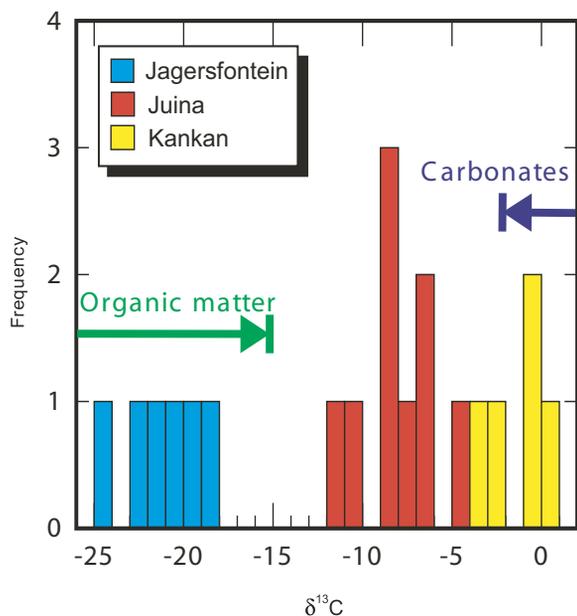
FIGURE 4 Carbon isotopic composition of diamonds with majoritic inclusions (all mines with less than two analyses were excluded). Kankan diamonds with majorites show similarities to the carbon isotopic composition of carbonates, Jagersfontein diamonds (Deines et al. 1991) resemble organic matter. At Juina (Hutchison et al. 1999) the carbon isotopic composition extends from the mantle value (about -5‰) to more negative values (i.e. isotopically lighter compositions), which may be due to a fractionation process affecting a primordial fluid.

Carbon isotopic data on diamonds containing majorite garnet inclusions (FIG. 4) exist for only three occurrences, Jagersfontein, Juina, and Kankan, and appear to support multiple origins for ultradeep diamonds: (i) subducted carbonates (high $\delta^{13}C$, Kankan), (ii) mantle fluids (at about –5‰) combined with minor isotopic fractionation (Juina), and (iii) subducted organic matter or strong isotopic fractionation (low $\delta^{13}C$, Jagersfontein) (see glossary p. 70).

LOWER MANTLE

Phase Transitions at the 660-km Discontinuity

The present understanding of Earth predicts that mantle of the deep transition zone should be approximately 60 vol% ringwoodite and 40 vol% majorite. At about 660 km, ringwoodite breaks down to an Al-poor MgSi-perovskite and ferropericlase (FIGS. 1 AND 2). Majorite garnet begins to exsolve CaSi-perovskite at a depth of ~550 km, and from the 660-km discontinuity down to ~700 km, the garnet gradually reacts to form aluminous MgSi-perovskite and expels some more CaSi-perovskite. If the lower mantle is richer in iron then assumed by the pyrolite model, stishovite, the high density polymorph of SiO_2, would also be present.

Diamond Inclusions from the Lower Mantle

Ferropericlase: The most prominent lower-mantle inclusion mineral in diamond is ferropericlase [(Mg,Fe)O]. It is easy to recognize by its peacock-like play of colors under the microscope. Ferropericlase is preserved during exhumation because it is stable over the entire pressure range of the mantle. However, when raised above the depths of the lower mantle and in the presence of low-Ca pyroxene, ferropericlase should react to form olivine (or wadsleyite or ringwoodite). The absence of ferropericlase from "normal" upper mantle rocks, therefore, appears to indicate that all ferropericlase inclusions in diamonds are of lower-mantle origin. However, there is evidence that local regions within the upper mantle have low silica abundances; thus, the presence of single inclusions of ferropericlase in diamonds does not automatically prove a lower-mantle origin. It is only the coexistence in the same diamond of ferropericlase with non-touching inclusions of perovskite chemistry that unarguably reveals a lower-mantle origin.

Experimental studies on pyrolite compositions predict that ferropericlase in the lower mantle should have an Mg-number [100Mg/(Mg+Fe)] of 84–85. Ferropericlase inclusions recovered from diamonds show a prominent mode in Mg-number at 85–88, indicating either a slightly more depleted or a slightly hotter source than modelled in experiments. Ferropericlase inclusions from Juina differ significantly from this fairly uniform picture by showing a very large range in Mg-numbers, from 36 to 87, and a polymodal distribution, with the majority of analyses falling between 60 and 82. The ferrous nature of the inclusions from Juina (in this case, correctly termed magnesiowüstite) led Harte et al. (1999) to speculate about a possible origin from Fe-enriched mantle regions near the core–mantle boundary (2900 km). Alternatively, these inclusions may reflect much shallower but non-pyrolitic lower-mantle sources, for example ancient subducted oceanic crust.

Stishovite: This high-pressure SiO_2-phase should be stable together with ferropericlase in the lower mantle at elevated iron contents (and possibly also in the transition zone at unusually high T); otherwise the two phases would combine to form MgSi-perovskite. Harte et al. (1999) constrained the magnesium-iron ratio for this reaction using the compositions of inclusions in diamonds from Juina and

found that stishovite coexists with ferropericlase and MgSi-perovskite at Mg-numbers as high as 70 for the former and 86 for the latter. Compared with high-pressure experiments, these ferropericlase and perovskite Mg-numbers are relatively high. The other four occurrences of stishovite plus ferropericlase in diamonds worldwide all reflect even more magnesian compositions and, therefore, should not exist in equilibrium. Disequilibrium seems the most straightforward explanation, but considering the relative "abundance" of these samples, some doubts are justified.

TAPP: One of the surprising discoveries made by the Edinburgh-Glasgow group on Juina diamonds was the occurrence of inclusions with a garnet-like composition but a tetragonal structure, hence called "TAPP" for Tetragonal Almandine–Pyrope Phase. TAPP is chemically distinct from "normal" peridotitic garnet because it is essentially Ca free (≤ 0.1 wt% CaO) (FIG. 5). Because TAPP is less dense than garnet at appropriate pressure–temperature conditions, it was suggested that TAPP represents a retrograde phase, possibly stabilized by high Fe^{3+}/Fe^{2+} ratios. This explanation is supported by a TAPP sample in a lower-mantle diamond from Kankan, which clearly resulted from a reaction that occurred during ascent through the mid-transition zone.

MgSi-perovskite: Compositionally, MgSi-perovskite is a high-pressure equivalent of orthopyroxene. Crystallographic studies of inclusions show that presumed perovskites inverted to pyroxene during exhumation. Nickel content is the chemical indicator used to determine whether an inclusion originally formed as orthopyroxene or MgSi-perovskite. In the lower mantle, all nickel is partitioned into ferropericlase, and MgSi-perovskite consequently has less than 300 ppm NiO, as opposed to typical orthopyroxene from the upper mantle which has >1000 ppm NiO.

Seventeen out of 20 MgSi-perovskite inclusions discovered worldwide have Al_2O_3 contents below 3 wt%. As discussed above, experiments indicate that garnet dissolves gradually into MgSi-perovskite in the uppermost 50 km of the lower mantle, as the solubility of Al in perovskite increases with pressure. If models for the composition of the lower mantle are correct, then MgSi-perovskite with such low Al contents should occur only in the topmost ~20 km of the lower mantle. Only three MgSi-perovskites from Juina show high Al contents (about 10 wt% Al_2O_3) and thus may be derived from the deeper lower mantle.

CaSi-perovskite: Being almost pure $CaSiO_3$, CaSi-perovskite is compositionally distinct from minerals occurring in typical upper-mantle and transition zone rocks. It should
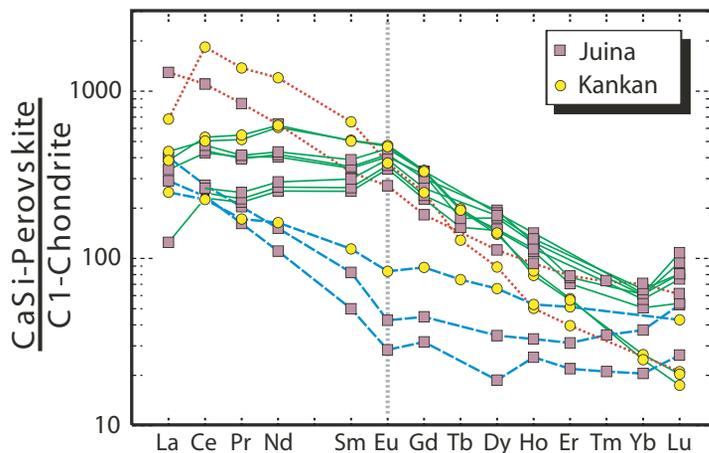
FIGURE 6 The concentrations of rare-earth elements (REEs) in CaSi-perovskite inclusions in diamonds from Juina and Kankan normalized to C1-chondrite as a "primitive" reference material. CaSi-perovskites generally show high concentrations in light REEs (left side of figure). Different types of REE patterns may be distinguished (shown as green, red and blue lines). The three groups also differ in the behavior of Eu, which shows positive spikes for the "green group", negative spikes for the "blue group" and normal behavior for the "red group". Negative Eu-anomalies are usually attributed to feldspar fractionation and positive anomalies to feldspar accumulation, making former oceanic crust that subsequently became subducted into the lower mantle a likely protolith.

be a high-pressure phase in both peridotitic and eclogitic parageneses. Despite the fact that the perovskite structure is never preserved—primary CaSi-perovskite inclusions are either amorphous or converted to the less dense walstromite structure—the discovery of $CaSiO_3$ inclusions was a crucial piece of evidence at Juina that established for the first time a lower-mantle origin for some diamonds.

CaSi-perovskite is particularly interesting among lower-mantle phases because it acts as a sink for incompatible trace elements e.g., strontium (0.03–0.73 wt%), zirconium (0.01–0.22 wt%), and total REEs (0.03–0.22 wt%). FIGURE 6 is a concentration diagram (normalized to C1-chondrite as a "primitive" reference material) for the REEs in CaSi-perovskites from Juina and Kankan. The analysed perovskites fall into three groups (see different line colors) with contrasting REE distributions. For each of these groups, the behaviour of Eu is different, with positive Eu anomalies for all perovskites with fairly flat slopes from La to Sm and negative anomalies for the three perovskites with the lowest total REEs. As discussed before, differences in the behaviour of Eu relative to neighbouring Sm and Gd are interpreted as a response of protolith composition to addition or extraction of plagioclase (which readily accommodates Eu^{2+} compared to the other trivalent REEs, including Eu^{3+}) at low pressure.

Formation of Lower-Mantle Diamonds

From the low Al contents of the MgSi-perovskites, it appears that the bulk of the lower-mantle diamonds are derived from the topmost ~20 km of the lower mantle. This characteristic, combined with the trace-element composition of CaSi-perovskites (with their positive or negative Eu anomalies), suggests that the diamonds were not derived from primitive mantle but from former oceanic slabs that accumulated at the top of the lower mantle (the "megalith model" of Ringwood 1991, see FIG. 7). As in the asthenosphere and transition zone, redox conditions in the lower mantle may generally be too reducing for the formation of
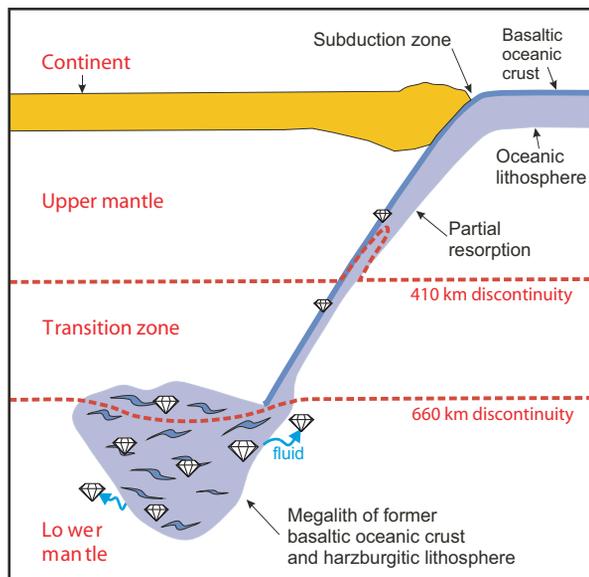
FIGURE 7 According to the "megalith model" of Ringwood (1991), subducting oceanic slabs may become buoyant at the top of the lower mantle. The resulting pile of subducted lithosphere is called a "megalith". The evidence for diamond formation at the top of the lower mantle, in combination with crustal signatures in lower-mantle diamonds containing CaSi-perovskite, suggests that megaliths may well be the primary source. Oxidizing fluids coming out of the subducted lithosphere may cause diamond formation in highly reducing "normal" lower mantle. The formation of diamonds with inclusions of majoritic garnet may occur earlier during the subduction process, in the deep upper mantle and transition zone. Exhumation of ultradeep diamonds may occur through mantle plumes or in the course of normal mantle convection.

macrodiamonds without the assistance of oxidized slab material or oxidizing fluids emanating from subducted material (FIG. 7) to provide the necessary redox gradients.

In conclusion, inclusions in ultradeep diamonds have turned out to be an excellent tool for testing mantle models based on high-pressure experiments and geophysical data. We have gained glimpses of the fate of subducting slabs passing through the asthenosphere and transition zone, and overall we observe good consistency with compositional models for the lower mantle. However, no studies involving radiogenic isotopes have yet been undertaken on ultradeep diamonds, and our knowledge of lower-mantle diamonds is largely based on only two occurrences. The search for more ultradeep material is therefore guaranteed to continue.

ACKNOWLEDGMENTS

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