

Garnet and diopside-bearing diamondites (framesites)

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Summary

Rocks consisting almost entirely of diamonds (diamondites) that contain minor amounts of silicates were analyzed for trace element abundances in the silicates by Laser Ablation ICP Mass Spectrometry for the first time. Diamondites, previously described as polycrystalline diamond “aggregates” and “framesite”, extend the range of monomineralic rocks known from the Earth's upper mantle. Our samples are intergrowths of diamonds with abundant open cavities and some interstitial silicates. The most common silicate is pyrope which occurs in two different colors (and chemical compositions): orange and lilac similar to garnet inclusions in diamonds and garnets known from upper mantle eclogites and garnet peridotites, respectively. In our sample, the “peridotitic” garnet is accompanied by Cr-rich diopside whereas the “eclogitic” garnet is unaccompanied. Trace element abundances suggest that both types of garnet formed from upper mantle fluids of similar origin which were rich in a carbonatitic component. The diamondites likely formed from the same fluids. Diamonds precipitated first and – in smaller amounts – contemporaneously with the silicates. Major upper mantle minerals like olivine, orthopyroxene and omphacite are missing, possibly indicating that these minerals behaved as refractory phases and were not mobilized by fluids. The chemical composition of “eclogite” and “peridotite” garnets differ in Cr and high field strength elements contents but not in the moderately compatible elements. They also have the same low Fe/Mg ratio which indicates a peridotitic source for the fluids. The compositional difference in minor and trace elements appears to be the result of different fluid processing rather than of a different source, i.e., peridotite or eclogite.

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Zusammenfassung

Granat- und Diopsid-führende Diamantite (Framesite)

Silikat-führende Gesteine aus Diamanten (Diamantite) wurden erstmals mittels Laser Ablation ICP Massenspektrometrie auf ihre Gehalte an Spurenelementen analysiert. Diese ursprünglich als polykristalline Diamant-“Aggregate” und Framesite beschriebenen Diamantite werden den monomineralischen Gesteinen des Erdmantels zugeordnet. Unsere Proben sind Verwachsungen von Diamanten mit verbreitet offenen Hohlräumen und wenig interstitialen Silikaten. Das verbreitetste Silikat ist Pyrop, welcher zwei verschiedene Farben und chemische Zusammensetzungen hat: orange und fliederfarben, ähnlich den Granat-Einschlüssen in Diamanten und den Granaten aus Erdmantel-Eklogiten und Peridotiten. In unserer Probe ist der “peridotitische” Granat von Cr-Diopsid begleitet, der “eklogitische” Granat ist unbegleitet. Die Spurenelement-Häufigkeiten in beiden Granaten machen es wahrscheinlich, daß diese von Erdmantel-Fluiden gebildet wurden, die reich an einer karbonatitischen Komponente waren und aus ähnlichen Quellen stammten. Die Diamanten wurden wahrscheinlich von denselben Fluiden gebildet. Diamanten wurden zuerst ausgefällt und wuchsen – in geringerem Ausmaß – auch gemeinsam mit den Silikaten. Hauptminerale des Erdmantels wie Olivin, Orthopyroxen und Omphazit fehlen. Möglicherweise verhielten sich diese Minerale refraktär und wurden von den Fluiden nicht mobilisiert. Die chemische Zusammensetzung von “eklogitischem” und “peridotitischem” Granat unterscheidet sich in den Gehalten an Cr und den Elementen, welche Ionen hoher Feldstärke bilden, aber nicht in den moderat kompatiblen Elementen. Die beiden Granate haben auch das gleiche niedrige Fe/Mg-Verhältnis, welches auf eine peridotitische Quelle für die Fluide hinweist. Die Unterschiede in der Häufigkeit von Neben- und Spurenelementen in den Granaten könnte auf verschiedene Entwicklung der Fluide zurückzuführen sein und wahrscheinlich nicht auf eine Herkunft der Fluide aus verschiedenen Quellen, wie Peridotiten oder Eklogiten.

Introduction

Diamonds are commonly found as xenocrysts in kimberlites, lamproites, and less commonly as accessory mineral in upper mantle and crustal metamorphic rocks (see reviews by *Gurney*, 1989; *Kirkley et al.*, 1991a; *Bulanova*, 1995; *Sobolev and Shatsky*, 1990). Beside single crystals, diamond forms fibrous pseudo-crystals (fibrous overgrowths on single diamond crystals) or concentric fibrous objects (commonly spheres = ballas) and polycrystalline “aggregates” (see *Orlov*, 1977). The best known polycrystalline diamonds are the so-called carbonados, black rocks consisting of fine-grained diamonds and containing a variety of rare phases (*Trueb and de Wys*, 1969; *Subarnarekha et al.*, 1998). Their genesis, however, is likely to be related to crustal environments and processes.

In the upper mantle, three relationships of diamonds with silicate phases (from the wall rocks or co-precipitates) are known:

- (1) silicate inclusions in single crystal diamonds (e.g., *Meyer*, 1987; *Bulanova*, 1995),
- (2) diamond as accessory and occasionally even minor phase in upper mantle ultramafic xenoliths (e.g., *Gurney et al.*, 1969; *Sobolev*, 1973; *Dawson and Smith*, 1975; *McCallum and Egglar*, 1976; *Robinson*, 1977; *Shee et al.*, 1982) and

- (3) silicates in polycrystalline diamond “aggregates” (*Gurney and Boyd, 1982; Kirkley et al., 1991b*).

Silicates and other phases associated with or included in diamond have been studied by a variety of analytical methods and have produced the only quantitative data so far on the deeper part of the upper mantle. However, for reasons unknown to us, the silicates associated with “polycrystalline” diamond have not been studied accordingly. In this contribution we report for the first time trace element abundances for silicates associated with polycrystalline diamond. Our data show that silicates and diamonds very likely grew from the same fluid. We thus suggest that “polycrystalline diamonds” should be regarded as rocks and, therefore, be classified as diamond rocks (diamondites) rather than as diamond “aggregates”. This takes also into consideration that “aggregates” are formed by aggregation of grains, a process for which the grains must have mobility, a quality which is probably not available in the sub-solidus upper mantle.

Diamondites extend the compositional range of monomineralic rocks known from the upper mantle such as pyroxenites, garnetites, olivinites, plagioclasites, chromitites, hornblendites and others. This is the first attempt to constrain the formation conditions of monomineralic diamond rocks on the basis of trace element abundances in silicates.

Samples

From several kilograms of pure diamond rocks (diamondites, polycrystalline diamonds) offered to the Natural History Museum in Vienna by a Viennese diamond dealer we extracted 20 rock fragments that contained either garnet or garnet plus Cr-diopside. The majority of rocks contains garnet of a honey-brown to orange color typical of garnets from eclogites as described in the literature. Two rocks contain garnets of a strong lilac color associated with deep green Cr-diopside, a mineral association typical for garnet peridotites. For this first study we selected two diamondites; one has a lilac garnet plus green clinopyroxene (cpx) silicate assemblage (Dia 012) and the other contains orange garnets only (Dia 016).

The locality from which the diamondite samples were derived is unknown but must be in Africa, presumably Botswana, because similar samples have previously been described from there only (*Gurney and Boyd, 1982; Kirkley et al., 1991b*). Also, large diamonds of hexahedral (“cubic”) habit sold together with the diamondites point towards such an origin.

Sample preparation and analytical techniques

In the very first attempt we tried to cut a diamondite with a high energy laser which, however, caused total melting of the silicates at the level of interest, the flat cut surface. Consequently, we changed the approach and ground and polished small, more or less flat, planes onto the rough rock. Although many silicates plucked out during this harsh procedure, some stayed in place and could finally be polished. The polished surfaces were investigated by optical microscopy and scanning electron microscopy. Mineral phases were analyzed by electron

microprobes (ARL SEMQ and Cameca) operated at 15 kV acceleration potential and 15 nA sample current.

About 30 trace elements were determined *in situ* in the minerals by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland. The laser ablation system used in this study is described in detail in Jackson et al. (1992), Jenner et al. (1994) and Horn et al. (1997). The laser beam of a Q-switched Nd: YAG laser operated at 266 nm in the ultraviolet region was focused onto the sample surface through the optics of a petrographic microscope. The pulse energy of the laser beam was 0.4–0.6 mJ and the diameter of the ablation pits were about 40–50 μm . The ablated material from the sample cell is carried by an Ar gas flow into the plasma torch of a Fisons VG PQ2 + ICP-MS instrument. All measurements were carried out using “time resolved analysis” data acquisition software operating in fast, peak-jumping mode; this allows us to monitor the progress of the laser ablation, and detect inclusions and heterogeneities. Spiked silicate glass NIST 612 was used for calibration and BCR-2 glass was used as secondary standard. Calcium was used as an internal standard to correct the ablation yield differences between the individual analyses. Data reduction was made using the LAMTRACE[©] spreadsheet software written in-house by S. Jackson.

Results

Petrography

The two selected samples are about 1.5 cm in their longest dimension (Fig. 1) and consist of complex intergrowths of anhedral (Dia 012) or anhedral and euhedral (Dia 016) diamonds with abundant cavities. The grain size varies between 200 and 600 μm in sample Dia 016 (Fig. 2b) while Dia 012 has a finer-grained (mainly < 100 μm) and more porous texture (Fig. 2a). Open cavities contain euhedral diamond crystals; they are usually sharp-edged octahedra in Dia 016 (Fig. 3c), contact-twins or terraced octahedra or highly porous fibrous cubes (parallel intergrown tubes, hopper crystals) in sample Dia 012 (Figs. 3e, f). Silicates are mostly interstitial (Figs. 3b, d) or occupy the space in cavities and often contain inclusions of euhedral diamonds (Figs. 3a, c, e). Garnet and clinopyroxene in Dia 012 have complex relationships. Garnet occurs either as lamellae in the pyroxene or as separate grains mantled by clinopyroxene at garnet/diamond interfaces. A few small garnets are also present in intergranular positions between diamonds.

Major element mineral chemistry

Major element contents of the silicate phases are given in Table 1. Minerals are chemically homogeneous. Clinopyroxene in Dia 012 is Mg and Cr-rich ($\text{Cr}_2\text{O}_3 = 2.3 \text{ wt}\%$) and has a relatively high Na_2O content (3.1%) and traces of K_2O (around 0.04 wt%). The molecular $\text{Mg}/(\text{Mg} + \text{Fe})$ ratio (the mg #) is 0.92. The calculated mineral formula has 2.0 Si a.p.f.u. (atoms per formula unit based on six oxygens) indicating that all Al resides in the octahedral lattice positions.

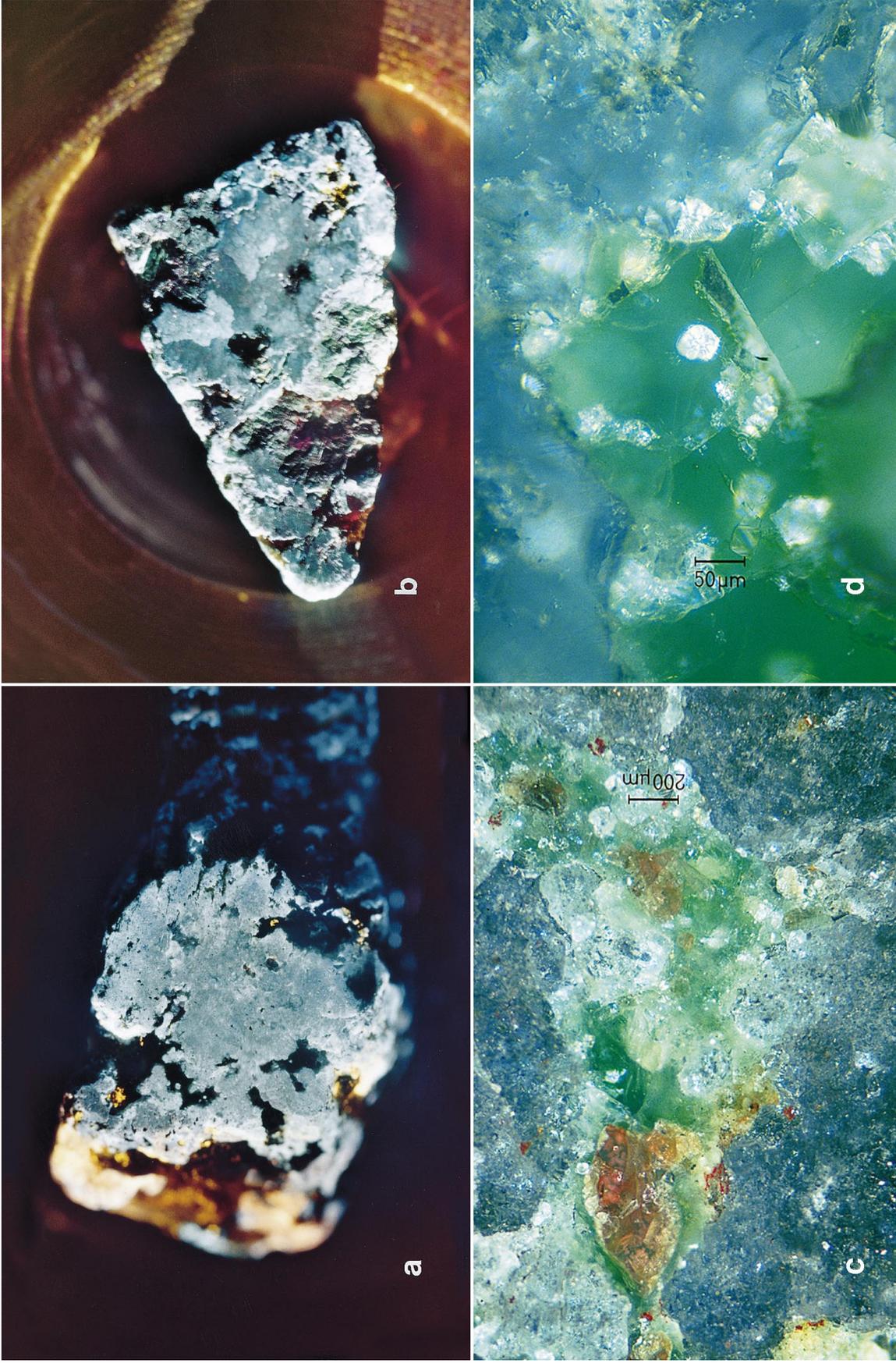


Fig. 1. Cathodoluminescence of polished surfaces of diamonds Dia 012 (a) and Dia 016 (b). Diamond shows different shades of blue, dark are mostly silicates. Note the difference in diamond grain size in the samples. Length of pictures is about 2 cm. c Garnet (red) and clinopyroxene (green) in diamondite Dia 012. Diamond shows all shades of gray. Note the intimate intergrowths of all three phases. Optical image, x polarizers. d Clinopyroxene (green) in diamondite Dia 012. Note abundant, mostly euhedral, diamonds included in clinopyroxene. Optical image, x polarizers

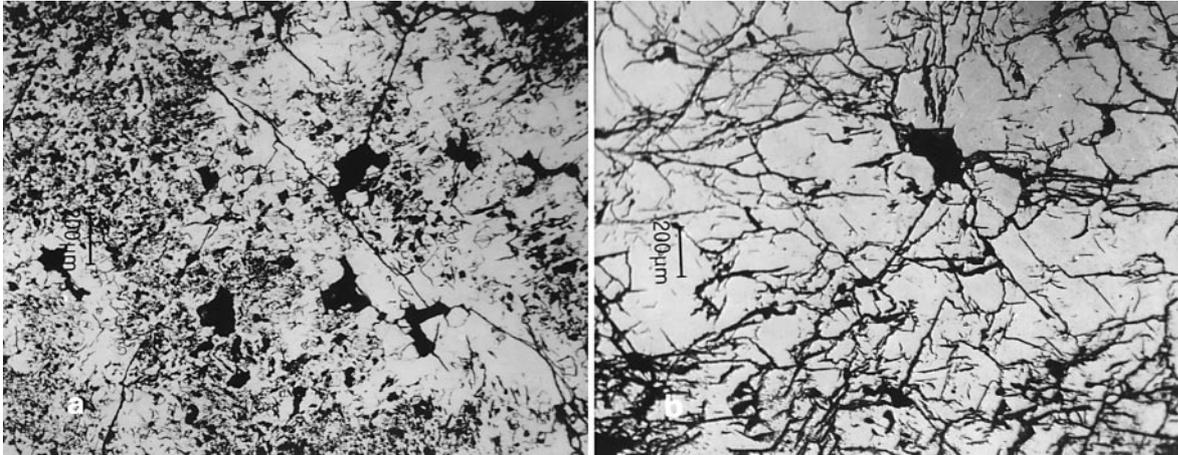


Fig. 2. Reflected light images of polished surfaces of diamondites Dia 012 (a) and Dia 016 (b). Black are silicates and holes. Note the differences in grain size, inclusion size, and distribution of holes between the samples

The lilac garnet coexisting with clinopyroxene is rich in Mg and Cr ($\text{Cr}_2\text{O}_3 = 5.2 \text{ wt}\%$) and has minor amounts of TiO_2 (0.27 wt%) and Na_2O (0.08 wt%). The orange-brown colored garnet from Dia 016 has a low Cr content ($\text{Cr}_2\text{O}_3 = 0.7 \text{ wt}\%$) and – apart from some minor differences (in Na_2O and TiO_2 contents) – its composition is very similar to that of the Dia 012 garnet (Table 1). The mg# of the garnets from Dia 012 and Dia 016 are about the same, 0.82 and 0.84, respectively. Both garnets have excess Si above the theoretical 3 a.p.f.u in their calculated formulae (Table 1). This excess Si is accompanied by high totals of the low charge cations (Fe^{2+} , Mn, Mg, Ca and Na) and low totals of the trivalent and tetravalent cations (Al, Ti, Cr and Fe^{3+}) relative to the standard stoichiometric formula.

Trace element mineral chemistry

Trace element contents of the minerals are given in Table 2 and are graphically presented in Figs. 4 and 5. In the chondrite-normalized abundance pattern for the rare earth elements (REEs), clinopyroxene from diamondite Dia 012 has a sinuous pattern with an abundance maximum at Nd and Pr (Fig. 4b). That pattern converts into a concave upwards pattern in the graphical representation of the normalized elemental abundances in Fig. 5a where the elements are arranged in order of increasing compatibility. The pattern is smooth except for small negative abundance anomalies of Ti, Zr and Ta relative to the neighboring REEs resulting in a fractionated, subchondritic Zr/Hf ratio. The relatively high Ba content is probably the result of fluid inclusion contamination (see below).

The chondrite-normalized REE pattern for the peridotitic garnet from diamondite Dia 012 shows a relatively flat heavy REE (HREE) pattern at about $8 \times \text{Cl}$ with a little hump at Eu and Gd and decreasing abundances of the LREE from Sm to La (Fig. 4a). In the chondrite-normalized trace element diagram (Fig.

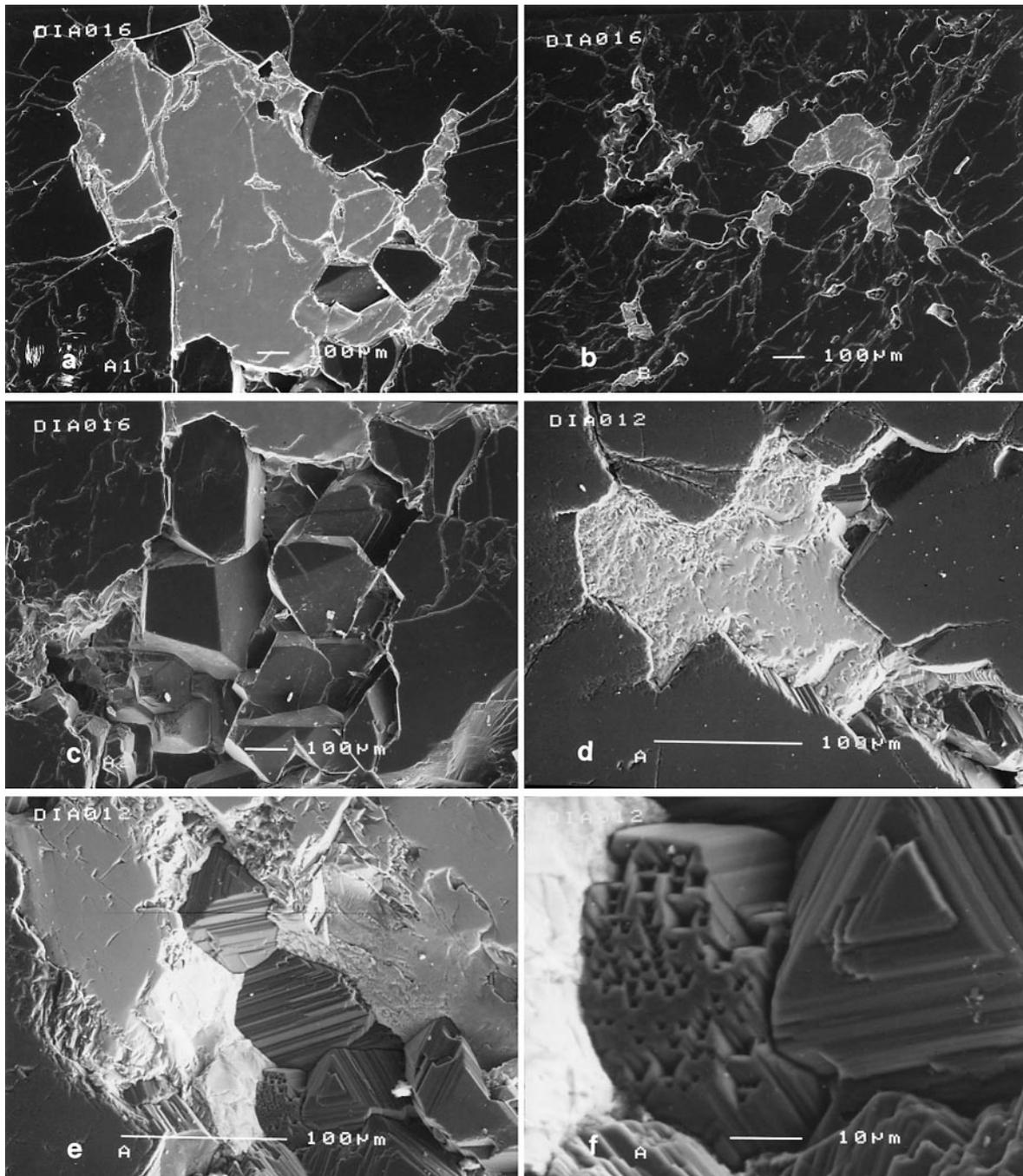


Fig. 3. Secondary scanning electron microscope images of diamondites: **a** Dia 16, large eclogitic garnet (gray) in diamondite (black). The polycrystalline garnet has diamond inclusions. **b** Dia 16, small eclogitic garnets (gray) interstitial to diamonds (dark) in diamondite. **c** Dia 16, open cavity with euhedral diamonds adjacent to and intergrown with garnet (gray) in Fig. 3a. **d** Dia 012, clinopyroxene (light) intergrown with diamond (dark); note euhedral diamond inclusion in clinopyroxene (upper right) and growth steps on diamond wall (lower center). **e** Dia 012, octahedral diamonds with growth steps in clinopyroxene (gray). **f** Dia 012, detail from Fig. 3e, octahedral diamond with growth steps and a twin of hexahedral crystals with abundant parallel cavities of square cross section (fibrous diamond) in center, all in clinopyroxene (white)

Table 1. *Major element composition of clinopyroxene and garnet in diamondites (in wt%)*

Rock	Dia 012 Clinopyroxene	Dia 012 Garnet	Dia 016 Garnet
SiO ₂	56.0	42.2	43.2
TiO ₂	0.33	0.27	0.61
Al ₂ O ₃	3.5	19.5	21.5
Cr ₂ O ₃	2.27	5.2	0.71
FeO	2.44	7.8	7.0
MnO	0.08	0.35	0.28
MgO	15.6	20.8	22.2
CaO	17.1	4.4	3.7
Na ₂ O	3.1	0.08	0.12
K ₂ O	0.04	–	–
Total	100.66	100.60	99.32
Formulae No. Oxygens	6	12	12
Si	2.000	3.010	3.062
Al ^{IV}	–	–	–
Al ^{VI}	0.146	1.639	1.793
Ti	0.009	0.014	0.033
Cr	0.064	0.294	0.040
Fe ³⁺	–	0.030	0.000
Fe ²⁺	0.073	0.434	0.416
Mn	0.002	0.021	0.017
Mg	0.831	2.212	2.343
Ca	0.653	0.335	0.281
Na	0.213	0.011	0.016
K	0.002	–	–
Sum 3+, 4+		1.987	1.927
Sum 2+, 1+		3.013	3.073
mg #	0.917	0.820	0.844

5a) a slight positive anomaly of Zr, a slight negative anomaly of Ti and a strong negative anomaly of Sr can be observed relative to the REE abundances. The Zr-Hf fractionation in the garnet (superchondritic Zr/Hf ratio) is the opposite to that of the co-existing clinopyroxene. Niobium and Ta have much higher normalized abundances than La and the Ba content is high and probably also affected by fluid contamination.

The eclogitic garnet of Dia 016 has heavy REE (HREE) abundances very similar to that of the peridotitic one (between 8 and 10 × Cl) but REE abundances continuously decrease from Lu to La with the slope steadily increasing towards La (Fig. 4a). The negative Sr anomaly (Fig. 5a) and the elevated Nb and Ta abundances relative to the light REEs (LREEs) are similar to those in the lilac garnet. However, Dia 016 garnet has also strong positive abundance anomalies of Ti, Zr and Hf relative to the REEs with comparable compatibility.

Table 2. Average minor and trace element contents of silicates in diamondites (in ppm)

	Dia 012 Clinopyroxene	Dia 012 Garnet	Dia 016 Garnet
Sc	35	145	94
Ti	2100	1800	2220
V	380	220	240
Cr	15700	39000	4800
Mn	770	3250	2870
Co	38	71	68
Ni	630	100	120
Zn	46	55	57
Ga	8.0	9.0	10.5
Sr	199	0.83	0.42
Y	3.9	9.9	10.4
Zr	63.8	26.6	37.1
Nb	2.24	0.78	0.24
Ba	11.0	0.76	1.02
La	3.9	0.036	0.014
Ce	14.9	0.38	0.135
Pr	2.6	0.14	0.040
Nd	12.6	1.26	0.36
Sm	3.1	0.98	0.40
Eu	0.99	0.42	0.20
Gd	2.2	1.2	0.81
Tb	0.27	0.22	0.20
Dy	1.2	1.7	1.5
Ho	0.18	0.37	0.38
Er	0.34	1.2	1.4
Tm	0.041	0.21	0.26
Yb	0.20	1.4	1.8
Lu	0.028	0.27	0.39
Hf	3.2	0.43	1.2
Ta	0.127	0.033	0.012
Th	0.088		
U	0.095		

Both garnets and the clinopyroxene are rich in fluid inclusions that were revealed during analysis by high trace element signals (Fig. 6a). In fact, it was difficult to obtain clean silicate analyses. Trace element signals changed abruptly when inclusions were ablated and therefore most of the analyses were contaminated by inclusion or grain boundary fluids (or precipitates from such fluids). The fluid precipitates are rich in LREE (La, Ce, Pr, Nd), Sr, Ba, U, Th, Rb, Nb and Ta and these elements are overabundant in the mixed fluid-garnet and fluid-clinopyroxene analyses. The medium REE (MREE), HREE, Ti, Zr, Hf and Y abundances are relatively unaffected and similar to those in the “clean” mineral analyses. The contaminating phase has fractionated Nb/Ta ($Nb_N > Ta_N$) and U/Th ($U_N < Th_N$ or $U_N > Th_N$) ratios.

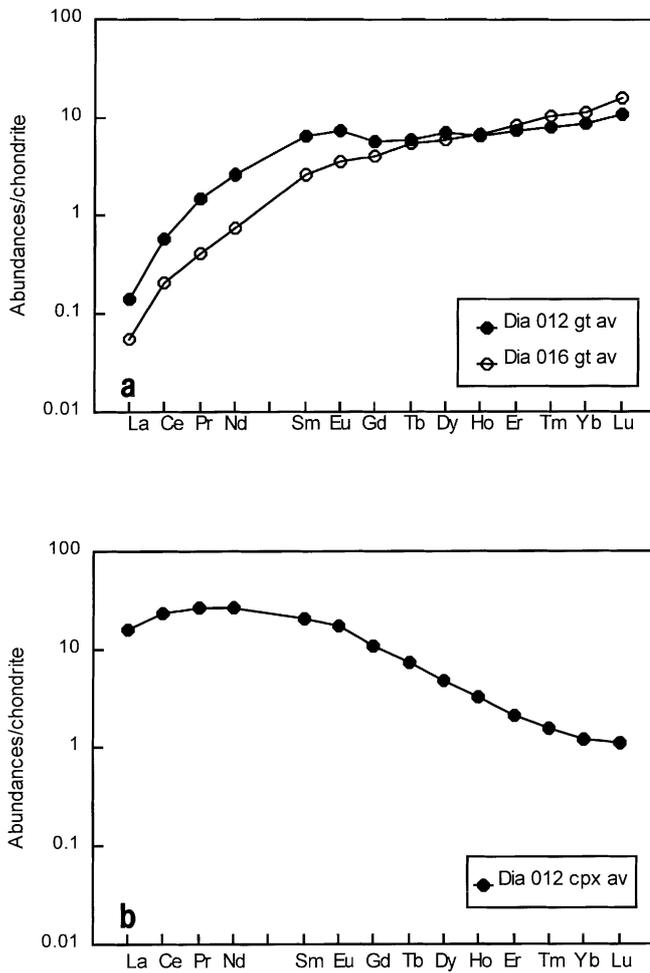


Fig. 4. Chondrite-normalized (*Palme, 1988*) REE abundances in garnets from diamondites Dia 012 and Dia 016 (a) and in coexisting clinopyroxene from Dia 012 (b)

Discussion

Monomineralic upper mantle rocks like pyroxenites, hornblendites, olivinites, garnetites, etc., very likely crystallized from fluids mostly as veins in upper mantle peridotites (compare e.g., *Hess, 1960; Loomis and Gottschalk, 1981; Schiffries and Skinner, 1987; Kurat et al., 1993*). The monomineralic character of the diamondites also supports a non-magmatic, fluid precipitate origin. During LA-ICP-MS analysis of all silicates we encountered severe contamination by fluid inclusions (Fig. 6). The incompatible trace element abundances in this fluid are very high and comparable to those described by *Navon et al. (1988), Schrauder et al. (1996), and Bulanova et al. (1998)*. The amounts of fluid mobilized by the laser were very different indicating highly variable amounts of trapped fluid.

Diamondites have high porosity with abundant open cavities the walls of which are lined with octahedral diamond crystals. The open cavities possibly were originally filled with carbonates rather than high pressure fluids. In fact, carbonates have been found to fill vugs and interstitial space in some framesites/diamondites (*Kirkley et al., 1991b*). Silicates also crystallized into cavities and interstitial

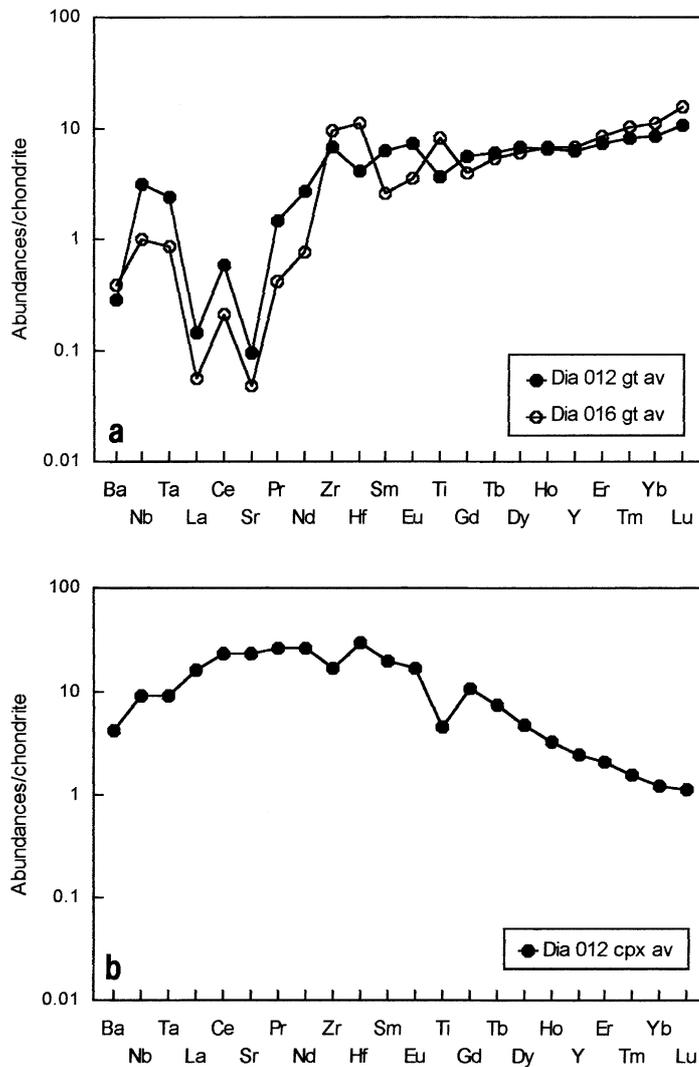


Fig. 5. Chondrite-normalized (*Palme, 1988*) trace element abundances in garnets from diamondites Dia 012 and Dia 016 (a) and in coexisting clinopyroxene from Dia 012 (b). The elements are arranged in order of increasing compatibility in clinopyroxene

diamond grain boundaries. This indicates that the silicates crystallized after the diamond; however, the common presence of small, euhedral free-floating diamond inclusions in both garnet and clinopyroxene suggests that some diamond crystallized together with the silicates. This defines a genetic link between the diamond and the silicates which – similar to silicate inclusions in diamond – can be used in the characterization of the geochemical environment of diamond crystallization. An alternative could be that diamonds were intergrown with a pre-existing phase which in a metasomatic event was replaced by garnet and/or clinopyroxene. However, as we do not see any trace of such a phase, we shall prefer the first interpretation. Diamonds included in clinopyroxene and lining the cavity walls in Dia 012 have growth steps on their octahedral faces or are parallel

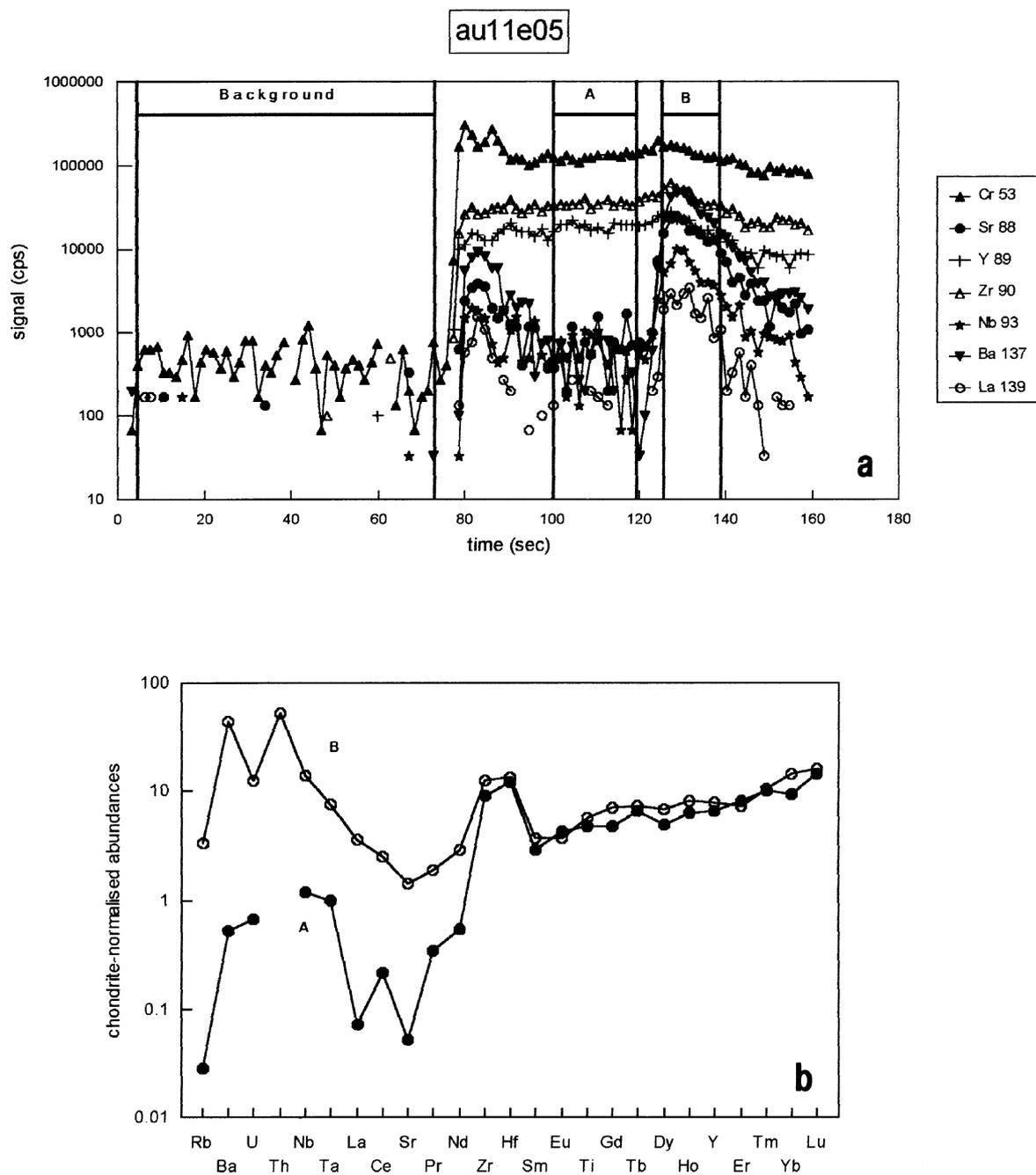


Fig. 6. **a** Selected time resolved trace element signals as obtained by the LA-ICP-MS for a typical analysis of Dia 016 garnet. Note the abrupt increase in count rate at about 125 seconds. The counts selected for analyses of garnet and fluid-rich garnet are marked A and B, respectively. **b** Chondrite-normalized (*Palme, 1988*) trace element abundances as calculated for fluid-poor (A) and fluid-rich (B) garnet in Dia 016 from analysis cycles as chosen in Fig. 6a. The fluid is very rich in highly incompatible elements (Nd to Rb)

intergrowths of tubes (hopper crystals, Figs. 3d–f). Both features are typical for vapor-grown crystals (e.g., *Givargizov*, 1987); this lends further support to our chemical evidence for a fluid origin of the diamondites (and their silicates).

The silicate inclusions in diamonds have been classified into two series: the peridotitic series with olivine, orthopyroxene, Cr-rich pyrope and chrome-diopside and the eclogitic series with Cr-poor garnet (almandine–pyrope) and omphacitic pyroxene (*Meyer*, 1987). These inclusions have been interpreted by some as wall rock xenocrysts accidentally incorporated into the growing diamond (e.g., *Wang*, 1994). They thus are believed by some researchers to be indicators of the environment of diamond formation (diamond grew in peridotitic or eclogitic rocks). However, another point of view is to see the silicate inclusions as syngenetic with diamond (e.g., *Gurney and Boyd*, 1982; *Kirkley et al.*, 1991a; *Bulanova*, 1995; *Bulanova et al.*, 1998; *Stachel and Harris*, 1997). If this is the case, then the inclusions carry geochemical information about the fluids which precipitated the diamonds. A similar genesis has also been proposed for silicates associated with polycrystalline diamonds (*Gurney and Boyd*, 1982; *Kirkley et al.*, 1991b). This view is in agreement with our observations where silicates could not be accidental wall rock xenocrysts. Garnet and clinopyroxene include euhedral diamonds and must, therefore, have grown after the enclosed diamonds. If garnet and clinopyroxene were xenocrysts, samples of the most common rock-forming minerals in the upper mantle, namely olivine and omphacite should also be present, but they are missing. Thus, there is no compelling reason for the assumption that diamondite with peridotitic garnet crystallized in a peridotitic environment and the other in an eclogitic one.

At first glance, the lilac garnet and green chrome diopside in Dia 012 may correspond to the peridotitic inclusion series and the orange garnet in Dia 016 to the eclogitic series. The Dia 012 garnet projects into the Iherzolite field of *Sobolev et al.* (1973) and garnet Dia 016 has a non-peridotitic composition. This also holds for taxonomy based on some trace element abundances like the Sc/Cr ratio (e.g., *Hart et al.*, 1997). However, a close look at the composition of the silicates does not support this classification. The garnets from both samples have very similar major element (as previously recognized by *Kirkley et al.*, 1991b) and REE abundances apart from their different Cr/Al and Sc/Cr ratios (and Ti contents). The high mg# of the low-Cr “eclogitic” garnet in Dia 016 argues against an eclogitic origin because eclogitic garnets are richer in iron (*Reid et al.*, 1976; *Meyer*, 1987). The composition of garnet from Dia 016 is far outside the range reported for garnet compositions in diamondiferous eclogites and eclogitic garnets included in diamonds. However, *Hills and Haggerty* (1989) reported some rare Mg-rich garnet compositions from eclogite xenoliths from Koidu, Sierra Leone, the most Mg-rich of which are similar to the Dia 016 garnet composition, except for the Ti and Na contents, which are lower. However, their Mg-rich eclogite suite is strictly bimineralic and free of diamonds.

The trace element contents of garnets are also similar in the two samples. Both garnets have positive abundance anomalies for Nb, Ta, and Zr and a negative Sr anomaly. Garnet Dia 016 has in addition positive anomalies in the Hf and Ti abundances relative to REE. Fluids from which the diamonds and silicates of both samples precipitated probably had a similar origin or a similar source at least for

the elements which enter the silicates. The difference in the Cr/Al ratio in the two fluids can be explained by differences in the mobilization of chromium due to different physico-chemical conditions (in one case the fluid could mobilize Cr together with the other elements in the other case it could not), or as the result of fluid fractionation. Precipitation of chromite (i.e., formation of chromite porphyroblasts or chromitite veins) could effectively remove Cr from the fluid without changing the concentration of the other elements. Chromite associated with diamondites (polycrystalline diamond) has in fact been previously reported (Gurney and Boyd, 1982; Kirkley et al., 1991b).

The REE content of the garnets and clinopyroxene is similar to that in the phases of garnet lherzolites – e.g., the sheared garnet lherzolite xenoliths of Shimizu (1975). The garnet lherzolite REE pattern and the primitive (high) mg# of the garnets and pyroxene suggest that the fluid did not fractionate with respect to these elements. The positive abundance anomalies of HFSEs in both garnets indicate elemental partitioning with a carbonate or carbonatitic fluid/liquid. The different HFSE/REE ratio in the garnets from the two diamondite samples likely reflects carbonatite-silicate equilibria with different carbonate/silicate ratios. The fluid from which the garnets precipitated either was carbonatitic and preferentially kept REEs and Sr relative to the HFSE or it had lost these elements by carbonatite immiscibility or carbonate precipitation. Because carbonates accept REEs and Sr but not HFSEs the remaining fluid (and/or co-existing silicate) is enriched in the latter elements over the former (e.g., Green et al., 1992; Keller and Spettel, 1995). The observed co-existence of silicates and carbonate in “framesites” supports this interpretation (Kirkley et al., 1991b).

The possible formation of peridotitic and eclogitic garnet by fluids from the same source also offers a solution to the problem posed by some (rare) diamond crystals that contain minerals of both suites (e.g., Prinz et al., 1975; Moore and Gurney, 1989; Wang, 1998) and to the problem posed by the very low REE content ($\sim 0.2 \times \text{MORB}$) of the eclogitic suite inclusions in diamond from No. 50 kimberlite in China (Wang, 1998). The physical crystallization conditions are not well constrained because of the lack of appropriate mineral assemblages. Some features like the potassium content in clinopyroxene and the excess Si content of garnet indicate crystallization of these phases under high pressure (Moore and Gurney, 1985; Harlow and Veblen, 1991). Above 50 kbar, the octahedral Si content of garnet continuously increases while its atomic Al + Cr content decreases with rising pressure, and on this basis we can make a rough estimation of the prevailing pressure (Irifune, 1987; Irifune et al., 1989; Moore et al., 1991). The garnet compositions indicate that the pressure was around 50–70 kbar during the formation of diamondites. Temperature can be estimated using the garnet-clinopyroxene thermometer of Ellis and Green (1979) for sample Dia 012 which gives a temperature around 1150 °C. However, this thermometer was calibrated for eclogitic or garnet-clinopyroxenitic assemblages and it is doubtful whether it can be applied for high-Cr assemblages. The thermometer based on the Ni content of garnets (Griffin et al., 1989) gives temperatures of about 1300–1400 °C. However, this thermometer is based on the distribution of Ni between olivine and garnet, but olivine is lacking in our assemblages but could, however, have buffered the fluid composition.

Thus, the diamondites crystallized under high temperature and not extraordinarily high pressure conditions, probably close to the diamond-graphite transition curve (the presence of diamond is – of course – a limiting factor). The garnet-clinopyroxene relationship in Dia 012 suggests changing conditions after clinopyroxene formation which led to exsolution of garnet from the pyroxene. This could be interpreted as indicating a pressure release. Consequently, the silicate-diamond assemblage probably was formed at greater depth than indicated by the mineral equilibria. In that case, the diamondites must have been transported to shallower depth before being sampled by the kimberlite.

Conclusion

Diamonds and silicates of diamondites very likely formed by precipitation from fluid(s) with the diamonds having been formed first and – in smaller amounts – contemporaneously with the silicates. Major upper mantle minerals like olivine, orthopyroxene and omphacite are missing, indicating that the minerals behaved as refractory phases and were not mobilized by these fluids. The chemical composition of “eclogitic” and “peridotitic” garnets differ only in the Cr and Ti contents but not in the Fe/Mg ratio, which is low and the same in both types, indicating a peridotitic source of the fluids. The compositional difference in minor and trace elements appears to be the result of different fluid processing rather than of a different source, i.e., peridotitic or eclogitic. Strong positive abundance anomalies of HFSEs in garnets indicate trace element partitioning between carbonates and silicates. Thus, carbonatitic fluids/melts seem to have been involved which is also indicated by trace element-rich fluid inclusions in the silicates.

Rocks consisting of diamond (diamondites) which contain minor amounts of silicates extend the compositional range of monomineralic (mostly fluid precipitate) rocks known from the Earth's upper mantle.

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