

Partial Melting in Mantle Eclogite Xenoliths: Connections with Diamond Paragenesis

ZDISLAV V. SPETSIOUS

Institute of the Diamond Industry, Alrossa Diamond Company, Ltd. Mirny, Yakutia, 678170, Russia

AND LAWRENCE A. TAYLOR¹

Planetary Geosciences Institute, Department of Geological Sciences, University of Tennessee Knoxville, Tennessee 37996

Abstract

Worldwide, most eclogite xenoliths from kimberlites display evidence of partial melting, brought about by the introduction of K-Na-rich fluids. This is particularly well developed in eclogites from Udachnaya, Mir, and other Yakutian kimberlites in Russia. The crystallization products of these incomplete reactions, typically represented as a “spongy” texture around primary omphacite, include secondary clinopyroxene (with lesser Na₂O), spinel, feldspar, and glass. In intragranular partial-melt veins, orthopyroxene, plagioclase, amphibole, and phlogopite also can be present. With partial melting of kyanite eclogites, corundum and mullite are formed. In all cases, primary garnet shows evidence for partial melting, with the formation of orthopyroxene, spinel, olivine, and glass, with typical development of kelyphitic rims.

The chemistry of the systems involved indicates that melting was definitely not isochemical, but involved the introduction of metasomatic fluids rich in alkalis, mainly K, and probably volatiles. There are indications from the secondary assemblages that different reactions occurred as a function of the chemistry of the primary minerals and that of the metasomatic fluids. The source of the fluids that induced most of the partial melting of the eclogites was from the kimberlitic melt. The alteration of the primary eclogitic minerals by these fluids may have begun upon entrapment of the xenoliths by the kimberlite, but continued even during upward movement of the kimberlite to depths of less than ~30 km. Evidence for the various reactions observed is evaluated in detail, and scenarios are depicted that might account for the observed reaction products. In addition, spatial correlations exist between the presence of some diamonds and the partial-melt products, as well as zones of alteration. We postulate that the partial melting process was connected with the resorption of some diamonds and the formation of last-stage fibrous diamond coatings and possibly some microdiamonds.

Introduction

THE INFLUENCES OF kimberlite on xenolithic rocks and minerals of the crust and upper mantle have been addressed in numerous studies. The major alterations are dominated by low-temperature metamorphic processes, such as carbonatization, serpentinization, zeolitization, etc. (e.g., Berg, 1968). However, the effects of high-temperature modification of primary mantle rocks are widespread among mafic and ultramafic xenoliths in pipes of Yakutia and South Africa (e.g., Dawson, 1980; Spetsius and Serenko, 1990; Fadili and Demaiffe, 1999). Studies of such high-temperature processes have not been common, although some notable investigations have

been performed (e.g., Lappin, 1978; Menzies, 1990; Dawson, 1999).

Many of these secondary alterations have been initiated by infiltrating metasomatic fluids that have caused various degrees of partial melting of the primary mineralogy. Williams (1932) first noted evidence for such melting of mantle minerals in xenoliths from the mines at Jagersfontein and Roberts Victor. In a classic study, high-temperature alterations were described in kyanite eclogites from the Roberts Victor pipe (Switzer and Melson, 1969) and attributed to partial melting under the influence of rapidly rising kimberlite magma. Eclogites with evidence for extensive development of melting in the Mir and Udachnaya pipes of Yakutia have been more recently characterized (Ponomarenko, 1977; Sobolev, 1977; Spetsius, 1980; Spetsius and Ponomarenko, 1979), as well as altered xenoliths from

¹Corresponding author; email: lataylor@utk.edu

the pipes of South Africa (Chinner and Cornell, 1974; McCormick et al., 1994). Similar evidence for melting also has been observed in other kimberlites—i.e., incongruent, metasomatically induced melting of megacrysts of garnet in the kimberlite of Fayette County, Pennsylvania (Hunter and Taylor, 1982). More recently, the effects of metasomatism in Udachnaya eclogites have been studied as recorded in the chemistry of the secondary alteration products, as well as the source of the altering fluids (Sobolev et al., 1999).

The overall effects of metasomatism on mantle xenoliths and their trace-element fingerprints on the chemistry and mineralogy of eclogites were described by Ireland et al. (1994) and Snyder et al. (1997a). In addition, distinctive evidence has been presented concerning the possible relationship of diamond growth and overgrowths versus stages of mantle metasomatism (Spetsius, 1999; Taylor et al., 1996, 1998). In order to better understand the mantle environments associated with such metasomatism, particularly involving partial melting, it is essential to fully characterize the phases involved. To this end, we have undertaken an extensive examination of the eclogite xenoliths from diamondiferous kimberlite pipes of Yakutia.

Methodology

Polished thin sections of numerous eclogite xenoliths, mostly diamondiferous, were examined with standard petrographic microscopy. Detailed photography provided the basis for the electron microprobe analyses and backscattered electron (BSE) imaging using a Cameca SX-50 microprobe, equipped with an Oxford Instrument energy-dispersive spectrometer (EDS) and cathodoluminescence detector. Electron microprobe (EMP) analyses were obtained using a potential energy of 15 kV, 10–20 nA beam current, and 20 second counting times. FeatureScan software on the EDS was used to obtain detailed modal mineralogy of portions of the thin sections.

Evidence for Partial Melting

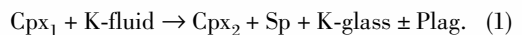
Detailed petrographic investigations of xenoliths from pipes in the Daldyn-Alakit and Malo-Botuobia regions of Yakutia demonstrate that partial melting has occurred in the majority of the xenoliths, especially in eclogites, but also garnet websterites and pyroxenites. Such evidence is pronounced in both

eclogites and kyanite eclogites, including diamondiferous varieties. Partially devitrified glass and other products of melting are clearly observed between garnet and clinopyroxene grains, sometimes in the form of veinlets that transect these minerals (Fig. 1A). The degree of partial melting varies between xenoliths, as well as the modal abundances of the melt products, as shown in Table 1.

Partial melting of clinopyroxene

The alteration of omphacitic clinopyroxene in most eclogite xenoliths from Yakutia was described as an alteration of omphacite by a “serpentine-like” substance (Williams, 1932; Bobrovich et al., 1959). The degree of alteration varied to almost complete replacement. Our studies have shown, however, that this secondary assemblage does not contain serpentine, but instead consists of fine-grained secondary clinopyroxene, spinel, and glass and/or plagioclase feldspar. Glass is almost always noted, and its presence is readily identified from its optical properties, as well as from its chemistry (McCormick et al., 1994). This alteration of primary omphacite is actually the evidence for its partial melting, with the glass resulting from the former presence of melt. Upon closer examination, intergrowths of secondary pyroxene with glass and/or feldspar are readily apparent (Misra et al., 2001).

Commonly, the partial-melt alteration products rim the primary omphacite. This has been termed “spongy texture” (Taylor and Neal, 1989). The primary clinopyroxene in this case typically is optically continuous with the isolated grains of secondary clinopyroxene in the reaction rims, as shown in Figure 1B. This secondary clinopyroxene is commonly intergrown with interstitial spinel, plagioclase, and feldspar-composition glass. This type of secondary alteration of primary omphacite is extensively developed in all mantle eclogites. The secondary clinopyroxene is similar in composition to the primary omphacite, but it always contains less jadeite component (Table 2). The partial melting of the primary omphacite can be represented by the following reaction:



Partial melting of garnet

Garnet in kimberlites, present as megacrysts or in xenoliths, invariably shows the presence of a kelyphitic rim, developed to various degrees, generally thought to be a function of its interaction with

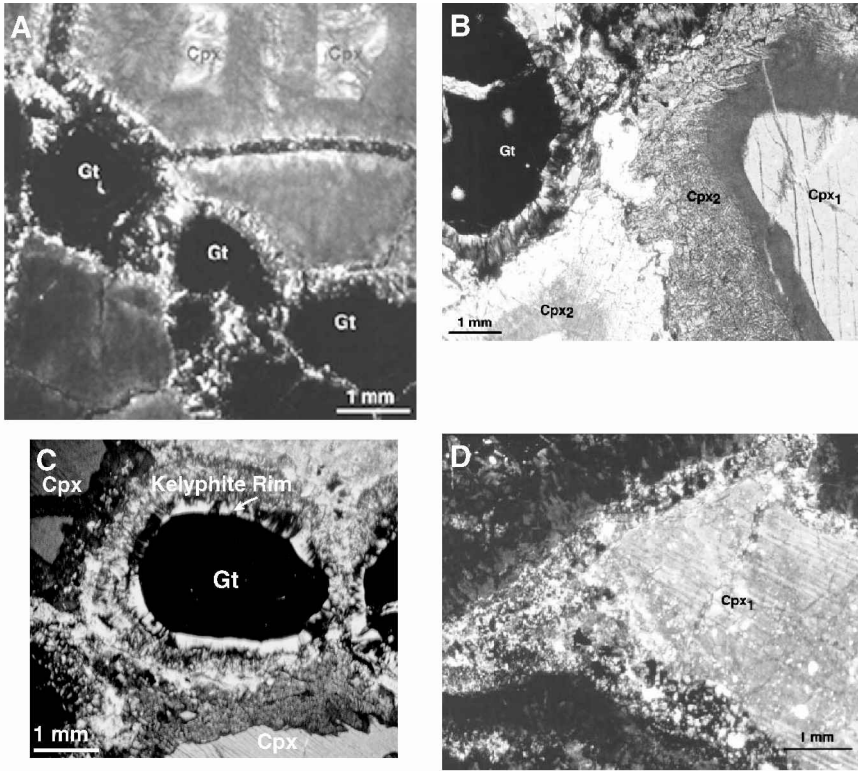
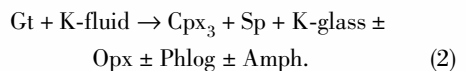


FIG. 1. Photomicrographs of partial-melt products in eclogite xenoliths from the Udachnaya kimberlite pipe; crossed polarized light. Abbreviations for this and subsequent photomicrographs: Gt = garnet; Cpx or Cpx₁ = primary omphacite; Cpx₂ = secondary clinopyroxene in spongy texture; Cpx₃ = secondary clinopyroxene in partial-melt veinlets; Sp = spinel; Plag = plagioclase; Phl = phlogopite; Q = quartz; D = diamond. A. Fine-grained partial-melt products with pronounced ophitic textures between grains of garnet and clinopyroxene. Note the intersecting veinlet of partial-melt products in the clinopyroxene. Relicts of primary omphacite and garnet are present. B. Spongy texture of secondary pyroxene (Cpx₂) with plagioclase and glass. Garnet with a kelyphitic rim is also present. C. Intergranular partial-melt products and a kelyphitic rim around garnet. A thickening of the kelyphitic rim occurs in contact with the partial-melt products. D. Partial-melt products between garnet and clinopyroxene. The greater alteration of garnet is obvious.

kimberlitic fluids. In many of these cases, the garnet has undergone a process of partial melting, similar to the omphacite described above. As detailed by Hunter and Taylor (1982), this reaction can be considered as a form of incongruent melting of the garnet composition, promoted by the metasomatic introduction of alkalis and volatiles from the kimberlite. These garnet-melt products consist of spinel, orthopyroxene, and sometimes amphibole. Interstitial pockets of glass are ubiquitously present between the secondary pyroxene, spinel, and the host garnet.

A correlation between the degree of development of kelyphite rims around garnet and the abundance of the intergranular melt is also apparent. In thin

section, there is typically a distinct thickening of kelyphite rims on grains in contact with the products of melting and widespread development of kelyphitization with evidence for increased partial melting (Fig. 1C). It should be emphasized that the formation of kelyphite rims on garnet is evidence for late-stage metasomatism. The following reaction depicts the partial melting of garnet:



The degree of alteration of garnet (and clinopyroxene) in mantle eclogites is governed by various fac-

TABLE 1. Modal Compositions of Eclogite Xenoliths and Partial-Melt Products

Sample	Total eclogite modes				Modal compositions of partial-melt products								
	Gt	Cpx	Ky	Prt/mlt product	Cpx	Plag.	Sp	Glass	Opx	Q+K-Fldsp	Cor + Mull	Amph + Phlog	
U-2045	59.5	26.7	—	13.8	83.8	1.8	12.8	1.6	—	—	—	—	
U-2110	67.6	8.7	—	22.8	—	19.7	25.3	—	54.2	—	—	—	
U-720	37.3	44.6	—	18.1	54.6	20.5	9.5	—	2.8	—	—	10.4	
U-26	32.8	49.4	0.9	16.9	66.9	21.9	11.2	+	—	—	—	—	
U-9	46.7	42.7	1.1	9.5	42.4	30.7	9.4	17.5	—	—	—	—	
U-1	28.0	30.9	8.4	32.7	43	+	8.4	13.1	—	12.2	12.9	2.5	
U-947	25.5	47.8	4.8	21.9	31.6	+	1.3	43.2	—	23.3	+	0.9	
U-820	34.6	30.1	1.3	34	35.9	+	5.1	12.8	—	25.6	15.4	5.2	
U-228	17.9	22.6	3.5	56	9.5	—	9.1	10.4	+	1.7	3.5	65.8	

tors affecting the kinetics of the situation, including availability of fluids and the permeability of the xenoliths. The degree of partial melting of garnet is usually less than that of clinopyroxene, possibly due to inherent differences in susceptibility to reaction of these two minerals. However, there are eclogites with large degrees of such alteration to the garnets (Fig. 1D).

Intergranular partial melting

An additional stage of partial melting has often occurred, as revealed by the presence of well-developed, secondary mineral assemblages of pyroxene + spinel ± plagioclase ± amphibole ± phlogopite ± glass ± calcite. This is usually later than the “normal” partial melting, and in some xenoliths, veinlets of partial-melt products also contain minute grains of sulfides, where alteration of primary pyrrhotite-pentlandite is represented by the replacement by djerfisherite. The fine-grained, intragranular products resemble an ophitic texture (Figs. 1A and 2A). Glass is present interstitially, locally forming a microlitic texture (Fig. 2B). The products of the partial melting are non-uniformly distributed throughout single specimen. Intersecting veinlets of partial-melt products in many cases can be traced over the entire xenolith. These “veins” are developed around selected grains of garnet and clinopyroxene, both along boundaries between the minerals and apparently independent of the surface of the

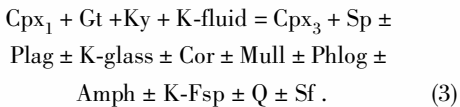
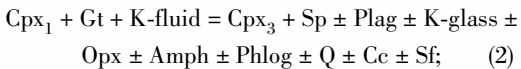
xenoliths (see Fig. 1A). However, the partial melting appears to have occurred along preexisting avenues of high permeability in the eclogite. Phlogopite typically present between these assemblages, suggesting the K-rich nature of the metasomatic fluids.

As mentioned above, clinopyroxene is more reactive to partial melting than garnet. The garnet participation in the melting process is corroborated by the chemical comparison of melting products and primary phases. Even with a considerable introduction of alkali components (Ponomarenko, 1977), formation of glass and crystallized phases, typically observed in the intergranular melt, is not due to the reaction of the omphacite or garnet alone. For example, high-Mg spinel, orthopyroxene, and rutile are present interstitially between phases of the partial-melt assemblage. In partially melted kyanite eclogites, quartz and feldspar are also present between the crystallized phases (Fig. 2C). Also, kyanite can be involved in this alteration process, as represented by its replacement by needles of corundum and rims of mullite.

It should be stressed that the degrees of melting and modifications to the primary eclogites varies from one sample to another. Although evidence exists for a general scheme to the partial melting reactions, there are undoubtedly additional reactions that have occurred, with distinctive modes and chemistry to the melt products (Table 1). Some generalized reactions are given below:

TABLE 2. Compositions of Primary Omphacite and Secondary Clinopyroxenes in Partial-Melt Products in Eclogite Xenolith Ud-24

Description	Primary (Cpx ₁)	Secondary (Cpx ₂)	Secondary (Cpx ₃)	Secondary (Cpx ₄)	Secondary (Cpx ₄)
SiO ₂	56.6	53.2	54.5	54.4	53.6
TiO ₂	0.44	0.39	0.31	0.5	1.26
Al ₂ O ₃	11.1	4.07	4.82	0.25	0.18
Cr ₂ O ₃	<0.03	<0.03	<0.03	<0.03	<0.03
FeO	5.13	6.88	5.88	18.9	21.5
MnO	<0.03	<0.03	<0.03	<0.03	<0.03
MgO	8.58	14.7	14.3	6.55	4.56
CaO	12.2	20.0	18.3	10.6	6.64
Na ₂ O	6.62	1.72	2.55	7.95	10.7
Total	100.67	100.96	100.66	99.15	98.44
Oxygen basis	6	6	6	6	6
Si	1.996	1.923	1.963	2.017	2.003
Ti	0.012	0.011	0.008	0.014	0.035
Al ^{IV}	0.004	0.077	0.037	0.000	0.000
Al ^{VI}	0.458	0.097	0.168	0.011	0.008
Cr	0.000	0.000	0.000	0.000	0.000
Fe	0.151	0.209	0.177	0.613	0.711
Mn	0.000	0.000	0.000	0.000	0.000
Mg	0.451	0.791	0.765	0.362	0.254
Ca	0.462	0.773	0.704	0.422	0.266
Na	0.453	0.121	0.178	0.572	0.771
Cation total	3.988	4.027	4.011	4.169	4.245



Evidence supporting different stages of metasomatic-induced partial melting are recognized based on detailed petrography: (1) alteration of primary omphacite to clinopyroxene with less jadeite content, and with the presence of glass and plagioclase feldspar (in a few samples, garnet is involved in a similar type of melting, but in both cases, the meta-

somatic fluid that initiated these was enriched in K₂O; (2) larger degrees of partial melting involving *both* primary omphacite and garnet, with fluids enriched in K₂O and water; and (3) extensive melting involving fluids containing appreciable K₂O and Na₂O, in addition to H₂O and CO₂. In a single xenolith, it is possible to recognize at least three stages of melting and subsequent crystallization. This is demonstrated by the presence of four different compositions and temporal associations of clinopyroxenes (Table 2). These compositions reflect fluctuations in the composition of the metasomatic fluids in Na₂O and FeO contents, as well as possible changes in oxygen activity. It is unclear how these different stages of metasomatism and partial melting relate to

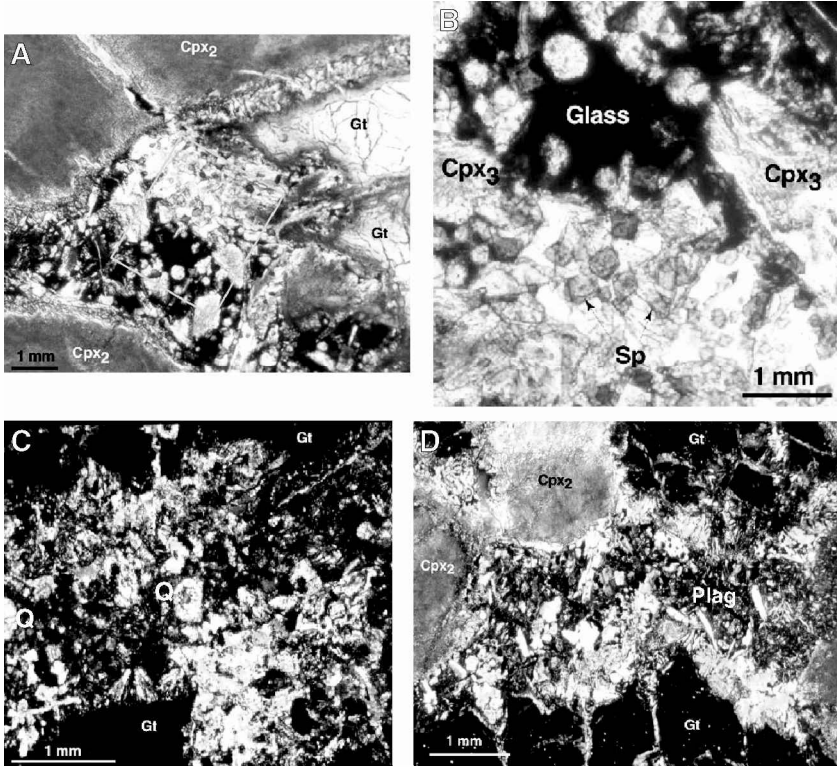


FIG. 2. Examples of intergranular partial melting in eclogite xenoliths from the Udachnaya kimberlite pipe. A. An intergranular vein of partial-melt products between grains of garnet and clinopyroxene; plane-polarized light. B. Part of intergranular vein shown in Figure 2A, at higher magnification. Notice the secondary Cpx_2 and Sp in the glass; plane-polarized light. C. Crystallized partial-melt products in veinlets, including feldspar and quartz; crossed polarizers. D. Vein of partial-melt products, displaying different degrees of crystallization; crossed polarizers.

one another in time, but it is believed that they are closely connected in origin.

We observed a non-uniform degree of crystallization of the interstitial melts even within a single thin section (Fig. 2D). In one veinlet, it is possible to have glass, partly crystallized glass, and completely devitrified glass, consisting of microlites of plagioclase, pyroxene, and spinel. In addition, large variations in grain sizes and overall texture exist; a scenario of different melt episodes is obvious. Similarly, the abundance of partial-melt products is also non-uniform, comprising up to 30–50 vol% of an initial xenolith, but more commonly 5–20 vol% (Spetsius, 1980).

The nature of the metasomatic influences upon eclogite xenoliths has been quantified by Sobolev et al. (1999), who demonstrated a central theme to alteration of eclogites, despite large variations.

Above, we have established the mobility that involves K_2O and Na_2O , as well as other elements. As shown in Figure 3, a comparison of potassium and sodium contents in eclogites with different degrees of partial melting shows that during this melting, there is a considerable increase in the K/Na ratio. This explains the characteristic property of eclogites from kimberlite pipes distinguished by high K_2O contents. A sharp increase of K_2O content occurs in diamondiferous kyanite eclogites that have developed more extensive melting (Spetsius, 1980).

Mineralogy of Partial-Melt Products

The modal abundances of the partial-melt products are highly variable (see Table 1). The intergranular melt typically consists of newly formed

clinopyroxene, plagioclase/glass, and spinel, and more rarely, orthopyroxene and amphibole, with possible phlogopite and/or amphibole. The accessory minerals are represented by calcite and sulfides. K-feldspar, with minor quartz, is present among the products in kyanite eclogites. Generally, a glass is present, and secondary corundum and mullite are developed about kyanite. In rare cases, Na-, K-, and Cl-bearing phases are present as sodalite and djerfisherite (Sobolev et al., 1999). Primary omphacite is replaced by a mixture of glass, plagioclase, clinopyroxene, and veinlets of glass. The primary garnets and clinopyroxenes of these eclogites are well known; therefore, we will characterize mainly the minerals formed by crystallization of the melts. Selected representative, major-element analyses of the products of the partial-melt assemblage are presented in Table 3.

Clinopyroxene is the most abundant melt product, characteristically forming xenomorphic grains ~0.01–0.4 mm in size, in some cases appearing “sieve-like” due to spinel inclusions. Secondary clinopyroxenes (Table 3) are lower in Na₂O (to <3 wt%) and Al₂O₃ (to <1 wt%) and contain minor jadeite component. Relative to the primary clinopyroxenes, they usually contain more MgO (12 to 16 wt% versus 8–11 wt%) and have variable Mg# from 70 to 87. CaO contents are similar to those in the primary omphacites (Table 2). Clinopyroxenes are sometimes enriched in TiO₂ (up to 1.2 wt%).

In some eclogites, secondary pyroxene is present as prismatic elongated crystals up to 0.2 mm in size, and with a green-yellow pleochroism; this phase typically has a high Na₂O content (≈10 wt%, Table 2), but with low Al₂O₃ (<1 wt%). This phase has distinctly higher FeO contents (>20 wt%), and corresponds to a large amount of aegirine component (NaFe³⁺Si₂O₆). This drastic increase in Fe³⁺ indicates a large increase in oxygen activity in the late-stage metasomatizing fluids. Such aegirine-bearing clinopyroxene is also present in diamondiferous xenoliths (Spetsius and Griffin, 1998).

Spinel, as a phase that crystallized from the partial melt, is represented by grains 0.01–0.02 mm in size (Table 1). The color is usually green, although greyish brown and black spinel are detected in transmitted light. Dark opaque spinel is characteristic of ferruginous eclogites. Chemical zonation is abundant and is most pronounced in the outer rim zones of the grains (Fig. 4A), a possible product of fractional crystallization. Electron microprobe analyses show that the general compositions of this

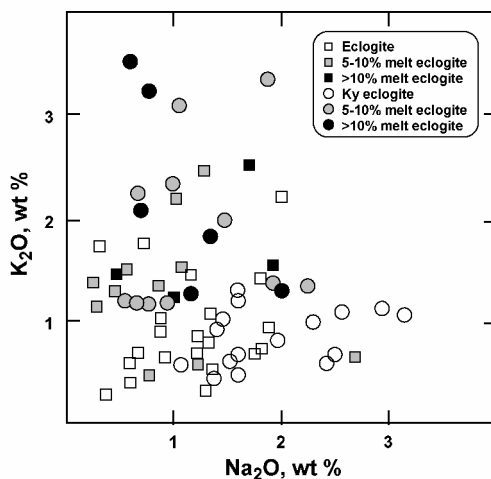


FIG. 3. A comparison of K and Na ratios in eclogites as a function of degrees of partial melting.

spinel vary in composition between two end members: spinel, MgAl₂O₄ and hercynite, FeAl₂O₄ (Table 3). Usually TiO₂ and Cr₂O₃ contents are less than 0.5 wt%, but in some samples spinel contains up to 3.5 wt% Cr₂O₃.

Plagioclase is present as elongated needles with a dominant size of 0.04–0.5 mm, rarely as lamellar crystals 0.02–1.0 mm in size. Usually it is polysynthetically twinned (albite law) with chemical zonations in the range An 30–50. Plagioclase of An30 is developed about the primary omphacite, in a few cases forming graphic intergrowths. However, the plagioclase is usually present as irregular segregations about 0.01–0.03 mm in size. Among the products of partial melting in some kyanite eclogites, bundles of albite also are present. It is the presence of this plagioclase that indicates the crystallization of the partial melt at pressures <10 kbar.

Phlogopite is typically developed in more altered specimens, predominantly in kyanite eclogites, where the grain sizes vary from 0.1 to 1.0 mm. As revealed in thin section, this phlogopite formed late (Fig. 4B). Microprobe data yield variations in K₂O (8–13 wt%) and TiO₂ (0.70–3.20 wt%), but TiO₂ can range up to 9.50 wt% (Table 3). In most analyzed samples, the Ba content is below detectable limits (e.g., <0.04%), but in one xenolith the phlogopite contained 0.65 wt% BaO.

Amphibole is characterized by prismatic or irregular grains 0.1–0.2 mm in size. It displays pleochroism in green-brown tones, whereas a red-brown

TABLE 3. Representative Compositions of Mineral Assemblage of Partial-Melt Products in Eclogite Xenoliths

Sample:	1	2	3	4	5	6	7	8
	A-952	U-5/91	U-35/1	HRV-17	SBB-13	SBB-20	SBB-21	SBB-67
Secondary pyroxenes of partial-melt products								
SiO ₂	50.3	54.2	52.4	50.5	53.3	51.8	53.3	53.8
TiO ₂	0.19	0.3	0.72	0.76	0.2	0.13	0.21	0.35
Al ₂ O ₃	5.02	3.36	4.64	11.1	9.67	3.61	11.6	1.96
Cr ₂ O ₃	0.18	0.09	0.09	0.05	0.05	0.08	<0.03	0.79
FeO	7.79	4.88	6.54	5.16	2.65	4.95	3.32	4.11
MnO	0.12	0.07	0.18	0.12	0	0.11	0.09	0.11
MgO	13.8	15.4	15.3	11.9	11.7	15.1	10.4	16.8
CaO	20.0	21.2	18.5	15.9	18.9	21.8	17.2	19.8
Na ₂ O	0.83	1.27	1.66	3.63	2.98	1.67	3.64	1.38
K ₂ O	0.06	0.03	0.08	<0.03	<0.03	<0.03	<0.03	0.09
Total	98.29	100.80	100.11	99.12	99.45	99.25	99.76	99.19

Sources: 1 = this study; 2–3 = Sobolev et al., 1999; 4–8 = McCormick et al., 1994.

Sample:	1	2	3	4	5	6	7	8
	HRV-17	SBB-13	SBB-20	SBB-22	SBB-46	SBB-50	SBB-50	SBB-67
Secondary spinels of partial-melt products								
SiO ₂	0.06	0.04	0.06	0.08	0.21	0.11	0.11	0.5
TiO ₂	0.14	<0.03	0.08	0.36	0.44	0.45	0.25	0.25
Al ₂ O ₃	60.7	60.8	56.8	64.8	59.0	49.6	56.5	55.7
Cr ₂ O ₃	0.04	0.13	0.16	0.13	3.32	0.34	0.57	3.49
FeO	23.8	23.2	27.4	15.5	18.2	37.8	28.0	24.2
MnO	0.28	0.3	0.27	0.21	0.22	0.88	0.86	0.38
MgO	15.4	14.3	15.1	19.6	17.1	11.0	14.6	16.3
CaO	0.05	0.05	0.07	<0.03	0.09	0.03	0.03	0.07
Total	100.47	98.82	99.94	100.68	98.58	100.21	100.92	100.99

Sources: 1–8 = data from McCormick et al., 1994.

Sample:	1	2	3	4	5	6	7	8
	U-41/3	U-51/3	U-73/3	SBB-21	SBB-22	SBB-42	SBB-67	SBB-50
Secondary phlogopites of partial-melt products								
SiO ₂	38.2	41.1	37.7	37.4	39.3	42.7	40.4	37.6
TiO ₂	3.44	0.66	2.63	1.05	3.22	3.05	2.21	1.18
Al ₂ O ₃	15.2	9.83	16.2	20.7	17.1	12.5	13.6	17.1
Cr ₂ O ₃	0.16	0.03	0.19	<0.03	<0.03	0.07	0.79	0.19
FeO	7.29	11.9	8.88	7.98	4.52	9.11	5.93	11.4
MnO	0.06	0.27	0.04	0.07	0.06	0.05	0.04	0.22
MgO	20.1	19.3	19.2	17.3	19.8	20.6	20.5	18.6
CaO	0.06	0.45	0.03	<0.03	<0.03	0.03	<0.03	<0.03
Na ₂ O	0.47	0.04	0.49	0.56	0.25	0.39	0.19	0.49
K ₂ O	10.0	9.47	8.79	9.18	9.77	7.33	9.29	8.64
BaO	0.03	0.19	0.11	n.d.	n.d.	0.12	n.d.	0.63
H ₂ O	3.98	3.68	4.03					
Total	98.99	96.82	98.79	94.24	94.02	95.95	92.95	96.05

Sources: 1–3 = Sobolev et al., 1999; 4–8 = McCormick et al., 1994.

Table continues

TABLE 3. *Continued*

Sample:	1 U-51/3	2 U-41/3	3 HRV-17	4 SBB-20	5 SBB-21	6 SBB-42	7 SBB-46	8 SBB-50
Secondary amphiboles of partial-melt products								
SiO ₂	42.1	39.5	39.7	39.5	40.6	40.4	38.0	41.1
TiO ₂	1.24	1.21	0.75	0.13	0.71	0.44	5.22	0.65
Al ₂ O ₃	15.5	15.2	19.1	17.8	20.9	16.4	17.5	15.3
Cr ₂ O ₃	0.03	0.07	<0.03	0.05	<0.03	0.13	0.46	0.05
FeO	8.43	12.9	9.99	12.6	11.0	13.2	9.45	11.1
MnO	0.18	0.27	0.17	0.38	0.22	0.70	0.24	0.84
MgO	16.7	13.4	12.7	13.1	12.1	13.4	11.7	15.6
CaO	8.47	11.2	9.78	8.94	10.6	9.63	10.5	9.41
Na ₂ O	3.60	1.95	3.27	3.91	1.86	3.51	3.25	2.61
K ₂ O	0.56	1.90	1.76	1.06	0.80	0.97	1.34	1.05
BaO	n.d.	n.d.	<0.03	0.04	n.d.	0.09	0.22	0.03
Total	96.81	97.60	97.22	97.51	98.79	98.87	97.88	97.74

Sources: 1–2 = Sobolev et al., 1999; 3–8 = McCormick et al., 1994.

Sample:	1 U-170	2 U-5/91	3 U-51/3	4 4B-3	5 4B-2	6 4B-3	7 4D-2	8 6D-2
Glass of partial-melt products								
SiO ₂	48.4	61.1	58.4	52.3	52.1	52.3	55.3	57.5
TiO ₂	0.03	0.04	0.31	0.89	0.92	0.89	0.48	0.37
Al ₂ O ₃	31.5	21.8	24.4	21.2	21.4	21.2	21.8	22.0
Cr ₂ O ₃	0.03	<0.03	<0.03	<0.03	0.07	<0.03	0.13	0.23
FeO	0.41	0.44	1.37	4.96	4.23	4.96	2.35	1.78
MnO	<0.03	0.03	<0.03	0.21	0.12	0.21	0.25	0.06
MgO	0.13	0.98	0.49	1.40	1.86	1.40	1.46	2.48
CaO	14.8	5.12	6.34	4.65	5.98	5.98	4.65	4.44
Na ₂ O	2.89	7.14	7.47	5.99	5.97	5.97	5.99	6.33
K ₂ O	0.38	3.46	0.18	3.16	3.22	3.22	3.16	2.29
Total	98.57	100.11	98.96	94.76	95.87	96.13	95.57	97.48

Sources: 1 = this study; 2–4 = Sobolev et al., 1999; 5–8 = Hunter and Taylor, 1982.

hornblende is commonly present in regular eclogites. Amphiboles are FeO-rich and variable in Na₂O and K₂O contents (Table 3). They contain low to detectable amounts of BaO and vary in TiO₂ contents from 0.13 to 5.20 wt%. According to Sobolev et al. (1999), they exhibit compositional variations in CaO, MgO, FeO, and Al₂O₃.

Orthopyroxene occurs as grains 0.1 to 0.3 mm in size. Microprobe analyses indicate this orthopyroxene to be hypersthene, containing 26 to 29 wt% MgO, 1.20 to 1.60 wt% CaO, and ~0.30 wt% TiO₂.

Potash feldspar is present in certain kyanite eclogites, where it is present as spongy-textured rims on clinopyroxene. This mineral was found in metasomatized lherzolite xenoliths from China (Sny-

der et al., 1997b) and noted in eclogites of Roberts Victor (Switzer and Melson, 1969). Sobolev et al. (1999) reported alkali feldspar containing ~2 wt% CaO, but rich in K₂O (8–13 wt%) and poor in Na₂O (1–5 wt%).

Glass is present in almost all eclogite xenolith samples as the quench product of the melt remaining from partial melting. It is intergranular in nature, commonly in the interstices of plagioclase and augite, and also as thin veinlets intersecting clinopyroxene. It also commonly is found in the kelyphitic rims around garnet. Partially devitrified glass, with microlites of plagioclase and clinopyroxene, is present in many kyanite eclogites (see Fig. 2B). In regular, bimineralec eclogites, the glass is

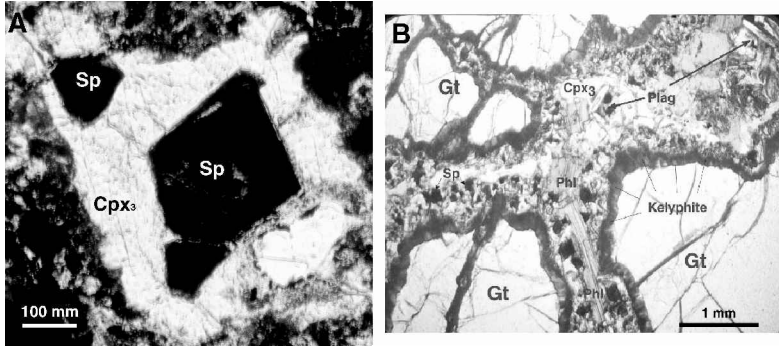


FIG. 4. Secondary spinel and phlogopite in partial-melt products. A. Zoned spinel in secondary clinopyroxene, plane-polarized light. B. Elongated needle of phlogopite encountered with secondary pyroxene, spinel, and plagioclase, plane-polarized light.

largely devitrified, and contains small euhedral plagioclase laths replaced by sericite and other alteration products. The color of the glass varies from dark grey and brown to light brown. It is an alkali-rich glass containing 50–55% SiO_2 (Table 3), and approaches plagioclase in composition. The high-silica composition of some glasses is also manifested by the presence of quartz and silica spherulites as crystallization products (Spetsius and Ponomarenko, 1979). Glasses are rich in sodium content, usually with ~6 wt% Na_2O , and can be divided into two groups with high and low K_2O contents—e.g., 2.3–3.5 and <0.2 wt%. Also, the glasses vary broadly in Mg and Ti contents (see Table 3). The SiO_2 component ranges as high as 61 wt%, higher than that of the primary clinopyroxene. This suggests possible addition of silica by metasomatizing fluids.

Corundum is observed in the form of small needles 0.01–0.2 mm long. Usually corundum replaces kyanite, and more rarely forms separate lamellar crystals up to 2 mm in kyanite eclogites, which have undergone a high degree of partial melting. It has a dark blue color and is referred to as sapphire.

Mullite, non-stoichiometric Al_2SiO_5 , is developed only as a replacement of kyanite. In several samples it forms intergrowths with corundum along kyanite rims. Usually mullite forms elongate bunches of crystals, and in some cases, it replaces kyanite grains completely. It is characterized by a sharply elongated needle form, parallel extinction, and high relief. Its presence is supported by X-ray studies. Mullite is more typical among the xenoliths

with cataclastic textures. In the diamondiferous varieties of kyanite eclogites and grospsydites, it readily resorbs the kyanite grains. It is a possible indicator of the presence of diamonds. However, the inferred association of mullite and diamond requires further study.

A schematic diagram of the system (Mg, Fe)O-CaO- Al_2O_3 for the secondary, partial-melt products in eclogites is shown in Figure 5. The garnet disappears completely and water-bearing minerals appear—e.g., hornblende and phlogopite. Several assemblages are prominent on the compositional diagram of the partial-melt products, as depicted by the tie lines. As partial melting continues, the role of water-bearing minerals in the crystallization products increases (Cpx-Amph-Phlog trend), probably motivated by the changing composition of the penetrating fluids, as well as by possible decrease in temperature and pressure.

Nature of Partial Melting

There are two major sources of the metasomatism that caused the partial melting of the clinopyroxene and garnet in the mantle eclogites—mantle metasomatic fluids before entrapment of the xenoliths by the kimberlite; and fluids from the kimberlite that had captured the xenoliths. The later explanation involving melting of xenoliths under the influence of fluids from kimberlite magma is the simplest explanation, especially because the alteration leading to kelyphitic rims on garnets is generally thought to be caused mainly by the kimberlite. However, the

petrography of the numerous eclogite xenoliths that have been examined can be alternatively interpreted as indicating an earlier metasomatism, before incorporation of the xenoliths by the kimberlite magma. The major difference between these two theories lies in the *timing of the metasomatism*. In reality, there is evidence for each. Inasmuch as the two authors of this paper have different opinions on the timing of this metasomatism, we will attempt to present below an assessment of the pros and cons for each theory, allowing the reader to draw his/her conclusions accordingly.

Pre-kimberlite metasomatism

Virtually all mantle xenoliths have undergone some form of metasomatism while resident in the mantle, mostly long before their entrainment in the kimberlite. However, it is to the cause of the partial melting of clinopyroxene and garnet that resulted from the kimberlitic influence that this discussion is directed—the event that culminated with the formation of plagioclase and glass. Several observations are applicable here: (1) in some xenoliths, there does not appear to be a spatial connection between the intensity of melting and the surface of the xenoliths; (2) an inhomogeneous distribution of the degree of partial melting occurs within a given sample; (3) intersecting veinlets of partial-melt products exist, as well as evidence for two or more types of melting events, perhaps closely related in time; (4) on the exterior of some eclogites, a rim commonly exists, which is the direct result of interaction with the kimberlite, in contrast to the partial melting that has occurred throughout the xenolith; (5) differences exist in the intensity of partial melting of similar xenoliths in the same pipe; and (6) the degree of partial melting in eclogites varies from pipe to pipe within a given kimberlite field. Based on the above factors, a possible scenario would have the first stage of the overall partial melting process begin as

mantle metasomatism under the influence of fluids that originated in the mantle, possibly associated with a reduction in pressure. This process could have taken place just prior to kimberlite eruption. In reality, there is no unambiguous evidence for any pre-kimberlitic metasomatism.

Kimberlitic metasomatism

The most likely cause for the partial melting of the clinopyroxene and garnet involves fluids emanating from the kimberlitic magma. It is generally

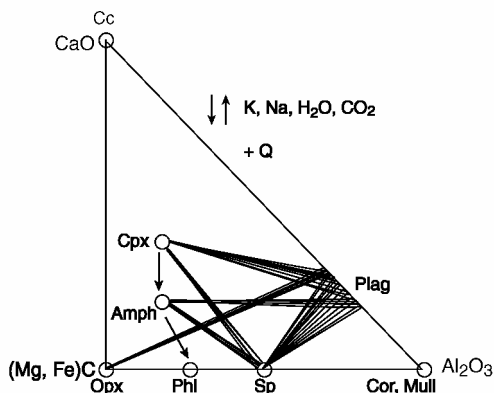


FIG. 5. Schematic diagram with compositions of mineral phases from the partial-melt products of clinopyroxenes and garnet.

accepted that the alteration rims (kelyphite) on garnets in peridotite and eclogite xenoliths are the direct result of interaction with kimberlitic fluids. Indeed, Hunter and Taylor (1982) pointed out that the presence of glass in the kelyphitic rims around garnets is evidence of metasomatic partial melting resulting from the influence of the kimberlite, with the glass being the product of rapid cooling (quenching) of the melt. This glass product is similar to that discussed above from the Yakutian eclogite partial melting.

The presence of glass and/or plagioclase indicates that the melt was still present in the eclogites at pressures below 10–15 kbar. This indicates that the partial melting reaction is rather recent relative to the eruption of the kimberlite. However, in the “pre-kimberlite, partial-melt scenario,” this melt would have been sitting in the eclogites since before the entrainment of the xenolith by the kimberlite, possibly even before the kimberlite formation.

The kimberlite metasomatism hypothesis involves a scenario where the cause of the partial melting of the clinopyroxene and garnet involves fluids emanating from the kimberlitic magma, as it intrudes its way into the upper mantle and lower crust. Particularly with the reduction of pressure that accompanies intrusion, the fluid and volatile components of the kimberlitic magma will become more mobile. The xenoliths, which have been entrained, are subjected to infiltration of these fluids, which may thoroughly penetrate the eclogites, particularly along pre-existing avenues of permeability formed by earlier mantle metasomatism. The

fluid discussed here is not to be confused with the far more viscous silicate kimberlitic magma that only affects the outer portions of the xenoliths. This K-rich fluid causes the instability of the clinopyroxene and garnet, resulting in incomplete reaction of these minerals with the resultant crystallization of various products, as discussed above. Depending upon the nature of the kimberlitic fluids migrating into the xenoliths and the compositions of the eclogitic minerals, omphacite or garnet may be attached preferentially. Given sufficient time and fluid abundance, it is possible that the clinopyroxene and garnet would completely react out of the xenolith, leaving only the melt products as evidence for this entire process.

P-T conditions for melting/crystallization

It is not possible to apply geothermometers or barometers to the products of the partial melting because of the disequilibrium nature of the assemblage and the lack of garnet in the product assemblage. However, the final crystallization products from the melting, particularly plagioclase, represent a low-pressure situation. Even if the partial melting in the eclogites may have started at temperatures of 900–1300°C and pressures in excess of 30 kbar, crystallization of the partial melt was only completed at pressures below 10–15 kbar.

The composition and abundance of the K-rich fluids, as well as kinetics, determine the development of the partial melting process. It would appear that fluids causing later melting possess high oxygen activities (fugacities), as indicated by the aegirine contents of some secondary, late-stage clinopyroxenes. A transition from a reducing environment with the initial eclogites to progressively more oxidizing conditions may have taken place during introduction of the metasomatic fluids involved in the partial melting episodes.

Association of Diamonds with Partial Melting Products

It is apparent from the tomography of diamondiferous eclogites (Keller et al., 1999; Taylor et al., 2000, 2001; Anand et al., 2003) that there is a general correlation of diamonds with the major zones of alteration within xenoliths. These studies concluded that this association was the result of the metasomatic formation of diamonds along avenues of greatest permeability in the eclogites. These zones of

alteration are also the ones with the largest degrees of partial melting of clinopyroxene. Therefore, there appears to be a spatial association of the regions of partial melting with the occurrence of diamonds. It should be emphasized that this association is only spatial, not temporal. Most, if not all, of the diamonds formed long before the latest metasomatism associated with the kimberlitic melt. It is possible that certain fibrous diamonds, such as commonly found on coated diamonds, present in some eclogites from the Udachnaya pipe are related in both time and space to the late-stage partial melting event.

Such a relationship between the partial melting process and growth of fibrous diamond is conceivable. There have been several studies that have demonstrated that diamonds undergo multistage and interrupted growth, caused by changes of the chemical and P-T environment (e.g., Spetsius, 1995; Taylor et al., 1998; Bulanova et al., 1999). In particular, fibrous diamonds have grown rapidly and approximately during the time of kimberlite emplacement. These coats contain fluids that are highly enriched in K, Na, and other incompatible elements (Schrauder and Navon, 1994; Navon, 1999). Such components would seem to be the same ones involved with the metasomatic fluids responsible for the partial melting of eclogitic minerals. It is entirely possible that the rims of some of the diamonds in the partial-melt regions may have grown as a result of this metasomatically induced melting process. Certain microdiamonds may be formed at this same time, as well. Such spatial relations of diamonds have been found in eclogite xenoliths from Udachnaya, Sytykansky, and other Yakutian pipes, as displayed in Figure 6. As discussed above, limited interactions between diamonds and the late-stage partial melt are possible, both with the stable and metastable growth of coatings, as well as resorption of the diamonds, as shown in Figure 7.

Conclusions

1. Evidence for partial melting of omphacite and garnet occurs in almost all mantle eclogite xenoliths, including those that are diamondiferous, from the Yakutian kimberlite pipes.
2. This melting is induced by the infiltration of metasomatic fluids along zones of weakness and previous alteration in the eclogites.

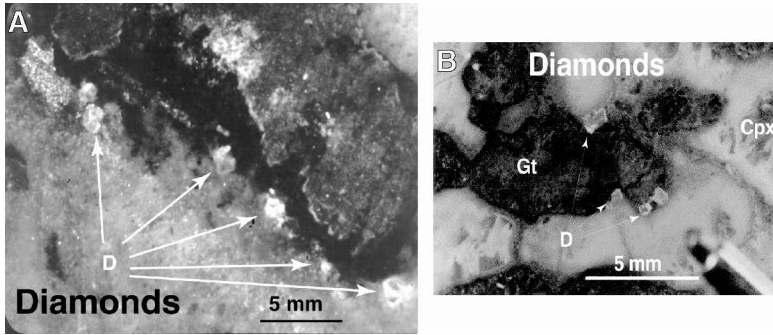


FIG. 6. Diamonds in partial-melt products of eclogites. A. Cubic crystals around garnet (Sample U-388). B. Microdiamonds associated with partial-melt products and a garnet kelyphitic rim (sample Ud-28).

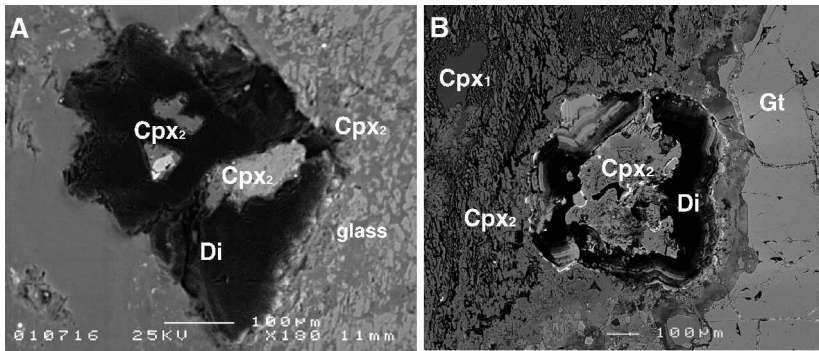


FIG. 7. Diamonds associated with partial-melt products. A. Slightly zoned diamond with the inclusion of secondary clinopyroxenes, situated between partially melted clinopyroxene with a “spongy” texture and garnet (sample Ud-24 in BSE + CL). B. Zoned crystal of hopper diamond with evidence for resorption by the partial melt (sample U-759 in BSE + CL).

3. Several stages of partial melting are recognized in eclogites, as the result of changes in compositions of the penetrating fluid.

4. Final crystallization of clinopyroxene- and garnet-associated melts in eclogites took place at low pressures, <10–15 kbar, in the crust during kimberlite transport and eruption.

5. Resorption and growth of fibrous-diamond coatings are associated in space with the products of this metasomatic melting, and may be its direct results.

Acknowledgments

We would like to express our appreciation to the Almazay Rossii-Sakha Company of Russia for their support of this study. The major support for the

senior author to travel to Tennessee and to write this paper came from the Planetary Geosciences Institute at the University of Tennessee. In addition, a portion of this research was supported by NSF Grants EAR 99-04057 to LAT, for which we are grateful. Interesting and educational exchanges with several colleagues, including Kula Misra, Mahesh Anand, Thomas Stachel, Ben Harte, Galina Bulanova, Jeff Harris, Nick Sobolev, and Kim Argunov have been instructive in our growing knowledge of the geologic significance of diamond inclusions. We are indebted to Brendon Griffin for his support with the diamond investigation. We thank Dr. Dong-Hwa Taylor for her invaluable assistance with preparation of the photographs, figures, and the electronic version of this manuscript.

REFERENCES

- Anand, M., Taylor, L. A., Carlson, R., Taylor, D.-H., and Sobolev, N. V., 2003, Diamond genesis revealed by x-ray tomography of diamondiferous eclogites, in Proceedings of 8th Annual Kimberlite Conference, in press.
- Berg, G. W., 1968, Secondary alterations in eclogites from kimberlite pipes: *American Mineralogist*, v. 53, p. 1336–1346.
- Bobrievich, A. P., Bondarenko, M. N., Gnevushev, M. A., Krasov, A. M., Smirnov, G. I. and Yurkevich, R. K., 1959, The diamond deposits of Yakutia: Moscow, Russia, Gosgeoltekhizdat, 527 p. (in Russian).
- Bulanova, G. P., Shelkov, D., Milledge, H. J., Haury, E. H., and Smith, S. B., 1999, Nature of eclogitic diamonds from Yakutian kimberlites: Evidence from isotopic composition and chemistry of inclusions, in Gurney, J. J., Gurney, J. L., Pascoe, M. D., and Richardson, S. H., eds., Proceedings of 7th International Kimberlite Conference, v. 1, Cape Town, South Africa, Red Roof Press, p. 57–65.
- Byrnes, A. P., and Wyllie, P. J., 1981, Subsolidus and melting reactions for join $\text{CaCO}_3\text{-MgCO}_3$ at 10 kbars: *Geochimica et Cosmochimica Acta*, v. 45, p. 321–328.
- Chinner, J. A., and Cornell, D. H., 1974, Evidence of kimberlite-grospyditic reaction: *Contributions to Mineralogy and Petrology*, v. 45, p. 153–160.
- Dawson, J. B., 1980, Kimberlites and their xenoliths: Berlin, Germany, Springer-Verlag, 252 p.
- _____, 1999, Metasomatism and melting in Spinel Peridotite xenoliths from Labait, Tanzania, in Gurney, J. J., Gurney, J. L., Pascoe, M. D., and Richardson, S. H., eds. Proceedings of 7th International Kimberlite Conference, v. 1, Cape Town, South Africa, Red Roof Press, p. 164–173.
- Fadili, S. E., and Demaiffe, D., 1999, Petrology of eclogite and granulite nodules from the Mbuji Mayi Kimberlites (Kasai, Congo): Significance of kyanite-omphacite intergrowths, in Gurney, J. J., Gurney, J. L., Pascoe, M. D., and Richardson, S. H., eds., Proceedings of 7th International Kimberlite Conference, v. 1, Cape Town, South Africa, Red Roof Press, p. 205–213.
- Hunter, R. H., and Taylor, L. A., 1982, Instability of garnet from the mantle: Glass as evidence of metasomatic melting: *Geology*, v. 10, p. 617–620.
- Ireland, T. R., Rudnick, R. L., and Spetsius, Z. V., 1994, Trace elements in diamond inclusions from eclogites reveal link to Archean granites: *Earth and Planetary Science Letters*, v. 128, p. 199–213.
- Keller, R. A., Taylor, L. A., Snyder, G. A., Sobolev, V. N., Carlson, W. D., Bezborodov, S. M., and Sobolev, N. V., 1999, Detailed pull-apart of a diamondiferous eclogite xenoliths: Implications for mantle processes during diamond genesis, in Gurney, J. J., Gurney, J. L., Pascoe, M. D., and Richardson, S. H., eds., Proceedings of 7th International Kimberlite Conference, v. 1, Cape Town, South Africa, Red Roof Press, p. 397–402.
- Lappin, M. A., 1978, The evolution of a grospyditic from Roberts Victor Mine, South Africa: *Contributions to Mineralogy and Petrology*, v. 66, p. 229–241.
- McCormick, T. C., J. R. Smyth, and F. A. Caporuscio, 1994, Chemical systematics of secondary phases in mantle eclogites, in Meyer, H. O. A., and Leonardos, O. H., eds., Kimberlites, related rocks, and mantle xenoliths: Rio de Janeiro, Brazil, Companhia de Pesquisa de Recursos Minerais, Special Publication, p. 405–419.
- Menzies, M. M., 1990, Petrology and geochemistry of the continental mantle: An historical perspective, in Menzies, M. M., ed., *Continental mantle*: New York, NY, Oxford University Press, p. 31–54.
- Misra, K., Anand, M., Taylor, L. A., and Sobolev, N. V., 2001, Paragenesis of diamonds in eclogite xenoliths from kimberlite pipes, Yakutia: A view from the host eclogite [abs.]: EOS (Transactions of the American Geophysical Union), v. 82, no. 47 (fall meeting supplement, abstract V12C-1002).
- Navon, O., 1999, Diamond formation in the Earth's mantle, in Gurney, J. J., Gurney, J. L., Pascoe, M. D., and Richardson, S. H., eds., Proceedings of 7th International Kimberlite Conference, v. 2, Cape Town, South Africa, Red Roof Press, p. 584–604.
- Ponomarenko, A. I., 1977, Partial melting of eclogites (natural processes): *Doklady Akademii Nauk SSSR*, v. 235, p. 1416–1418 (in Russian).
- Schrauder, M., and Navon, O., 1994, Hydrous and carbonatic mantle fluids in fibrous diamonds from Jwaneng, Botswana: *Geochimica et Cosmochimica Acta*, v. 58, p. 761–771.
- Snyder, G. A., Taylor, L. A., Crozaz, G., Halliday, A. N., Beard, B. L., Sobolev, V. N., and Sobolev, N. V., 1997a, The origin of Yakutian eclogite xenoliths: *Journal of Petrology*, v. 38, p. 85–113.
- Snyder, G. A., Taylor, L. A., Jin, Y., and Taylor, D. H., 1997b, Mantle-lherzolite xenoliths from eastern China: Petrogenesis and development of secondary textures: *International Geology Review*, v. 39, p. 681–687.
- Sobolev, N. V., 1977, Deep-seated inclusions in kimberlites and the problem of upper mantle composition: Novosibirsk, Russia, Nauka Press, 263 p. (in Russian) [English translation by Brown, D. A.; Boyd, F. R., ed., 279 pp., Amer. Geophys. Union, Washington, D.C., 1977].
- Sobolev, V. N., Taylor, L. A., Snyder, G. A., Jerde, E. A., Neal, C. R., and Sobolev, N. V., 1999, Quantifying the effects of metasomatism in mantle xenoliths: Constraints from secondary chemistry and mineralogy in Udachnaya eclogites, Yakutia: *International Geology Review*, v. 41, p. 391–416.
- Spetsius, Z. V., 1980, The form, nature and conditions of partial melting of eclogites from the kimberlite pipes:

- Vestnik Moskovskogo Gosudarstvennogo Universiteta, seriya geologicheskaya, no. 4, p. 101–105 (in Russian).
- _____, 1995, Diamondiferous eclogites from Yakutia: Evidence for a late and multistage formation of diamonds [ext. abs.], in *Extended abstracts of 6th International Kimberlite Conference*, Novosibirsk, Russia, p. 572–574.
- _____, 1999, Two generations of diamonds in the eclogite xenoliths, in Gurney, J. J., Gurney, J. L., Pascoe, M. D., and Richardson, S. H., eds., *Proceedings of 7th International Kimberlite Conference*, v. 2: Cape Town, South Africa, Red Roof Press, p. 823–828.
- Spetsius, Z. V., and Griffin, B. J., 1998, Secondary phases associated with diamonds in eclogites from the Udachnaya kimberlite pipe: Implications for diamond genesis [ext. abs.], in *Extended abstracts of 7th International Kimberlite Conference*, Cape Town, South Africa, p. 850–852.
- Spetsius, Z. V., and Ponomarenko, A.I., 1979, The amorphized eclogites—representatives of asthenosphere of the Earth: *Doklady Akademii Nauk SSSR*, vol. 235, p. 1415–1419 (in Russian).
- Spetsius, Z. V. and Serenko, V. P., 1990, Composition of continental upper mantle and lower crust beneath the Siberian platform: Moscow, Russia, Nauka Press, 272 p. (in Russian).
- Switzer, G., and Melson, W. G., 1969, Partially melted kyanite eclogite from the Roberts Victor mine, South Africa: *Smithsonian Contributions to Earth Sciences*, v. 1, p. 1–9.
- Taylor, L. A., Bulanova, G. P., Milledge, H. J., Snyder, G. A., and Keller, R.A., 1998, Metasomatic eclogitic diamond growth: Evidence from multiple inclusions: *International Geology Review*, v. 40, p. 663–676.
- Taylor, L. A., Carlson, W. D., Anand, M., and Misra, K., 2001, High-resolution X-ray computed tomography (HRXCT) of diamondiferous eclogites and the origin of diamond: EOS (Transactions of the American Geophysical Union), v. 82, no. 47 (fall meeting supplement, abstract V12C-1001).
- Taylor, L. A., Keller, R. A., Snyder, G. A., Wang, W., Carlson, W. D., Hauri, E. H., McCandless, T., Kim, K-R., Sobolev, N. V., and Bezborodov, S. M., 2000, Diamonds and their mineral inclusions, and what they tell us: A detailed “pull-apart” of a diamondiferous eclogite: *International Geology Review*, v. 42, p. 959–983.
- Taylor, L. A., and Neal, C. R., 1989, Eclogites with oceanic crustal and mantle signatures from the Bellsbank Kimberlite, South Africa, Part I: Mineralogy, petrography, and whole-rock chemistry: *Journal of Geology*, v. 97, p. 551–567.
- Taylor, L.A., Snyder, G. A., Crozaz, G., Sobolev, V. N., Yefimova, E. S., and Sobolev, N. V., 1996, Eclogitic inclusions in diamonds: Evidence of complex mantle processes over time: *Earth and Planetary Sciences Letters*, v. 142, p. 535–551.
- Williams, A.F., 1932, *The genesis of diamond*: London, Benn Ltd., 636 p.