Lithos 112S (2009) 934–941

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Polymict breccia xenoliths: Evidence for the complex character of kimberlite formation

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A R T I C L E I N F O

Article history:
Received 3 October 2008
Received in revised form 30 April 2009
Accepted 13 June 2009
Available online 1 July 2009

Keywords:
Upper mantle
Xenolith
Polymict breccia
Kimberlite formation

A B S T R A C T

Very rare xenoliths of polymict breccia provide important information for understanding the nature, mechanism and conditions of kimberlite-forming processes. The purposes of this study are: a) to detail the petrology and mineralogy of the first find of a polymict breccia xenolith from the Precambrian Premier Mine, South Africa, and the same type of xenolith from the Middle Paleozoic Sytykanskaya pipe, Yakutia; and b) to estimate the possible relationship between the polymict breccias and kimberlite formation. A comparative analysis of extreme disequilibrium between the mineral phases leads to the conclusion that upper mantle material from a depth interval from 120 to 220 km is present in the studied xenoliths. A combination of compositional and petrographic features shows that initially the most deep-seated material from the base of the lithospheric mantle was intensely deformed under conditions of significant deviatoric stress, and then the first stage of partial melting produced a liquid fraction which served as a lubricant that enabled movement of the mixture of dominantly solid phases plus minor liquid from the base of the lithosphere to a shallower level in the lithospheric mantle. The absence of material of crustal origin or from the upper levels of lithospheric mantle in the studied polymict breccias leads to the conclusion that, before the transportation to the Earth surface, this complex mixture halted for a very short time (but enough for its consolidation) at a depth near 120 km. So, most probably the formation of polymict breccias was directly related to the initial phases of kimberlite formation and polymict breccias are a type of "underdeveloped embryo" of ordinary kimberlite.

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1. Introduction

Xenogenic material of deep-seated origin in kimberlites carries unique information about the structure and composition of the ancient cratonic lithosphere. This material also carries information concerning the character and dynamics of the processes occurring in the zones of kimberlite generation in the cratonic lithosphere upper mantle as well as processes involved in cratonic mantle formation and evolution (e.g., Boyd, 1973; Sobolev, 1977; Dawson, 1980; Boyd and Gurney, 1986; Richardson, 1990; Pokhilenko et al., 1991, 1993, 1999, 2004; Boyd et al., 1993, 1997; Shimizu et al., 1994, 1997; Pearson et al., 1995; Griffin et al., 2004; Sobolev et al., 2008; Tychkov et al., 2008). Xenogenic material in kimberlites represents a vertical cross section through the lithosphere from the Earth's surface up to at least 300 km. This results from the rare finds of the ultra-deep rock xenoliths and garnet inclusions in diamonds containing significant contents of majorite component (Haggerty and Sautter, 1990; Moore and Gurney, 1985, 1989; Moore et al., 1991; Sobolev et al., 1997a,b) including majorite-bearing high-Cr subcalcic pyropes definitely belonging to the extremely depleted peridotites of harzburgite–dunite paragenesis of lithospheric mantle (Pokhilenko et al., 2001, 2004). Thus, the kimberlites provide perhaps the only opportunity for direct study of the structure, composition and evolution of the greater part of the ancient craton lithospheric mantle.

Of special interest is information related to the processes of kimberlite formation. The character of such a relationship can be both genetically directly related to the generation and evolution of kimberlite melts and indirectly related to the processes which occurred at the same time and related to the general activation of cratonic and subcratonic upper mantle. Direct and indirect indications of the processes of partial melting and possible reasons for that melting, as well as of processes associated with kimberlite formation can be gained from mantle samples. Such indications are: a) presence of sharp zoning within the mineral grains of upper mantle xenoliths of evidently highly deep-seated and high-temperature origin (e.g., Smith and Boyd, 1992; Sobolev et al., 1997a,b; Burgess and Harte, 1999; Pokhilenko et al., 1999); b) the presence of sheared peridotite suite xenoliths of very deep-seated and high-temperature origin having many signs of very intensive deformation (sometimes up to full mylonitisation of peridotites) and often clear features of disequilibrium between rock-forming mineral phases and the signs of intensive re-crystallization synchronous with rock deformation; and c) the presence of rare xenoliths of heterogeneous peridotites consisting of mineral grains with

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doi:10.1016/j.lithos.2009.06.019

homogeneous intra-grain composition but very variable inter-grain compositions (Pokhilenko and Sobolev, 1978; Lazko et al., 1983; Sobolev et al., 1984; Pokhilenko et al., 1993; Zhang et al., 2003). There can be little doubt that the processes of formation of rocks having these features are closely related not only in time but they evidently have a common general origin during a certain stage of dynamic magmatic activation of cratonic lithosphere roots and subcratonic upper mantle related with the processes of more deep-seated origin such as influence of plumes.

The term "polymict peridotites" was coined by P. Lawless (Lawless et al., 1979), and very rare xenoliths of this type of rock are described from the Siberian kimberlites of Middle Paleozoic age (Pokhilenko and Sobolev, 1978) and the South African pipes with Mesozoic emplacement ages (Lawless et al., 1979; Zhang et al., 2003; Höfer et al., this issue). They belong to the most interesting and important upper mantle rocks, as they provide valuable information for understanding the nature, mechanism and conditions of kimberlite-forming processes. These xenoliths are composed of a complex mixture of small fragments of various types of upper mantle peridotites, mineral phases representing disintegration products of these peridotites, and minerals of the megacryst suite. In some samples fragments of eclogites are also present, and all this material is cemented by minor amounts (15–25 vol.%) of fine-grained groundmass composed of variable amounts of serpentine, serpophyte, phlogopite, magnesian ilmenite, sulfides, carbonates and rutile.

The aims of this study are: a) a detailed petrological and mineralogical characterization of a unique xenolith of polymict breccia from the Premier Mine — the first find of this type of rock in the kimberlites of Precambrian age, and a xenolith of similar rock type from the Siberian Sytykanskaya pipe of Middle Paleozoic age; and b) investigation of a possible relationship between the formation processes of polymict breccias and kimberlites.

2. Sample description and methods

A unique xenolith of polymict breccia from the Premier Mine, South Africa, and a xenolith of polymict peridotite from the Sytykanskaya Pipe, Siberia, are described in this paper.

Sample FRB 1318 is the first find of such a xenolith from a kimberlite pipe emplaced during the Precambrian. The xenolith of polymict breccia ($14\times8.7\times4.1$ cm) is slightly lighter than the dark grey host kimberlite. Around 80 vol.% of the xenolith is composed by megacrysts and macrocrysts of ilmenite, garnet, pyroxenes, olivine, and rare fragments of peridotite rocks cemented by greenish-dark grey matrix approximating 20 vol.%. The matrix is very heterogeneous in composition. Its components are: dark grey serpophyte, sometimes with a greenish tint, which developed after very fine-grained quenched products of partial melting of metasomatized material in the primary groundmass; irregularly distributed phlogopite as single flake crystals up to 0.8 mm in size (5–15 vol.% of cementing mass); fine-grained ilmenite (0.05–0.4 mm); rare small grains of rutile and carbonate; and very rare fresh fine grains of opx and cpx are presented in the groundmass of sample FRB 1318 as well (for composition features of groundmass pyroxenes, see Table 1 and 3). Unlike the xenoliths of polymict peridotite from the Mesozoic kimberlites of the Kimberly Field (Lawless et al., 1979) the matrix does not contain sulfides. There are four relatively large fragments (up to 2 cm) of peridotites on the xenolith's surface. Coexisting olivine and enstatite were found in three of them and olivine+enstatite+Cr-pyrope were identified in the other peridotite fragment. Smaller (less than 1 cm) fragments of peridotites composed of intensely serpentinized olivine (sometimes re-crystallized) are also present in the xenolith.

The polymict peridotite sample S-2 from Sytykanskaya pipe, Yakutia ($6.3\times4.1\times3.3$ cm) of greyish-green color is intensely weathered and composed mainly of serpentine with visible pseudomorphs after olivine (including deformed and re-crystallized varieties) and pyroxenes. Fresh phases are garnet grains of different color (from orange-red to purple) and size (0.2–7.3 mm), and ilmenite (0.1–9 mm). This sample does not contain any grains of fresh olivine and pyroxenes.

The mineral compositions were analyzed with a CAMECA "Camebax-Micro", JEOL JXA-8100 electron microprobes at the V.S. Sobolev Institute of Geology and Mineralogy, Novosibirsk, Russia, and JEOL JXA-8900L microprobe at the Geophysical Laboratory of Carnegie Institution, Washington, DC, USA.

3. Mineralogy

Olivine occurs in FRB 1318 in fragments of partially serpentinized peridotites with different textures: coarse, deformed and sheared, and as xenocrysts up to 4 mm in size. Representative analyses of the olivines are given in Table 1. Both fragments of peridotites and xenocrysts of olivine are intensely serpentinized. Olivine grains are practically colorless, sometimes they have a faint greyish or greenish hue. There are no visible grains of olivine of greyish-brown hue typical of olivine of the megacryst suite. The total amount of olivine in the studied sample is significantly less than in xenoliths described by Lawless et al. (1979). There are clear signs of interaction between olivine and partially melted cement in the form of thin (0.1–0.3 mm) grey opaque rims between olivine grains and semitransparent matrix. All the olivines in the xenolith are of forsteritic composition. The range of Mg# variations is 90.0–92.6% which is considerably less than that established for xenoliths of the same nature from the Bultfontein and DeBeers Mines

Table 1
Representative microprobe analyses of olivines and orthopyroxenes from polymict breccia xenolith FRB 1318, Premier Mine.

Mineral	Olivines				Orthopyroxenes						Fine orthopyroxene grains of cementing mass	
Grain #	6	5	3	1	7	11/1	6	8	3	4	10*	2*
SiO_2	41.5	40.6	41.2	41.0	56.1	56.0	56.5	56.9	57.0	56.9	53.6	54.0
TiO_2	0.01	0.01	0.02	0.00	0.26	0.32	0.26	0.23	0.10	0.09	0.52	0.67
Al_2O_3	0.02	0.05	0.02	0.02	0.96	1.00	1.07	1.02	0.85	0.84	4.12	4.16
Cr_2O_3	0.06	0.05	0.07	0.09	0.02	0.02	0.20	0.40	0.32	0.33	1.41	0.18
FeO	9.77	8.59	8.05	7.35	9.55	8.95	6.38	5.40	4.73	4.60	7.61	8.39
MnO	0.09	0.13	0.13	0.09	0.16	0.15	0.17	0.13	0.13	0.11	0.14	0.12
MgO	49.1	50.3	51.3	51.4	31.9	32.5	33.7	34.0	35.2	35.2	32.1	31.6
CaO	0.07	0.11	0.10	0.07	1.07	1.20	1.21	1.36	1.16	1.20	1.05	1.33
Na_2O	n.d.	n.d.	n.d.	n.d.	0.29	0.27	0.34	0.47	0.22	0.20	0.14	0.22
K_2O	n.d.	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	0.08	0.03
NiO	0.38	0.39	0.35	0.40	0.06	0.08	0.11	0.15	0.14	0.11	n.d.	n.d.
Total	101.0	100.2	101.2	100.4	100.4	100.5	99.9	100.1	99.9	99.5	100.8	100.7
Mg/(Mg+Fe),%	90.0	91.3	91.9	92.6	85.6	86.6	90.5	91.9	93.0	93.2	88.1	87.0

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