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Metasomatism in lithospheric mantle roots: Constraints from whole-rock and mineral chemical composition of deformed peridotite xenoliths from kimberlite pipe Udachnaya

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ABSTRACT

We report new data on the geochemical evolution, metasomatic and deformation processes in the lower layers of cratonic lithospheric mantle based on a detailed study of extraordinarily fresh and large deformed peridotite xenoliths from the Udachnaya kimberlite pipe, Siberia. Based on our T–P estimates, the deformed peridotites are localized in a depth range of 170 to 220 km near the base of cratonic mantle. The degree of deformation is not correlated with the depth and equilibration temperatures of the xenoliths.

The deformed peridotites are depleted in magmaphile major elements indicating their residual nature, but are enriched in incompatible trace elements, Fe and K. The deformed peridotites experienced a complex evolution, i.e., they were formed initially as high-degree melt extraction residues and later were subjected to three main stages of metasomatic modification. (1) An old, mostly cryptic metasomatism by melt/fluid of carbonatitic composition, which formed garnets with sinusoidal REE patterns ($Sm_n/Er_n > 1$). (2) Silicate metasomatism, which led to the most significant changes in mineralogical and chemical composition of the deformed peridotites. (3) Fe and Ti metasomatism just before the entrainment of the deformed rocks into kimberlite magma. Enrichment of the peridotites in large-ion lithophile elements (K, Rb, Ba) is related to the formation of kelyphitic rims around garnet.

The nature of the metasomatic agent of silicate metasomatism was evaluated from mass-balance of measured and calculated whole-rock compositions, ratios of highly incompatible elements ($D < 0.1$) and fractional crystallization modeling. All this evidence indicates that the agent of silicate metasomatism had a composition intermediate between that of kimberlites and HIMU OIB.

The metasomatic processes responsible for the formation of deformed peridotites and precipitation of megacryst suites cannot be widespread at the base of the cratonic mantle. Rather, they are local features only existing in the cratonic mantle below kimberlite fields and localized along the metasomatic vein system.

1. Introduction

Lithospheric mantle under Archean continental blocks (cratons) is a lithospheric domain depleted in magmaphile elements, and less dense than surrounding younger mantle, which extends approximately to the depth of 220–250 km (Eaton et al., 2009; Rudnick and Nyblade, 1999) and is isolated from convection. It is composed predominantly of peridotites and less common eclogites and pyroxenites. These rocks are available for study only as xenoliths brought up by deeply formed magmas such as kimberlites and some continental basalts. Peridotites of cratonic mantle are represented by two texturally distinct types: coarse (granular) and deformed (sheared). In contrast to the granular type, deformed peridotites display a bimodal grain size with large porphyroclasts set in a fine-grained neoblastic matrix. Pressure and temperature (P–T) estimates of mineral equilibration of peridotites define a conductive type of geotherm, however deformed peridotites usually yield higher P–T estimates and define a high-temperature thermal disturbance of the geotherm.

The geotherm inflection was first reported by Boyd and Nixon (1975) as a result of a study of deformed peridotites from Lesoto kimberlites, which led these authors to conclude that these peridotites could represent convecting asthenosphere. Deformed peridotites have recently been considered as refertilized parts of Archean cratonic mantle (O'Reilly and Griffin, 2010) which make up the lower layer of the cratonic mantle. While the origin of deformed peridotites remains controversial, interaction with convecting asthenosphere is generally considered as the main explanation of their textures and composition. The models proposed include deformation by rising mantle diapirs (Green and Gueguen, 1974), deformation driven by

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Table 1
Summary of petrographic features, modal composition and P–T estimates for Udachnaya deformed peridotite xenoliths. Samples are ordered by pressure.

	Sample	Rock type	Texture[a]	Degree of deformation	Ol	Modal mineralogy			T (°C)	P (kbar)
						Opx	Cpx	Gar		
1	Uv208/02	Grt Hzb	M-P, F	High	79	12	2	7	1300	56
2	Uv285/02	Grt Hzb	M-P, F, L	High	80	10	4	6	1275	57
3	Uv32/04	Grt Hzb	M-P	Medium-high	79	13	3	5	1319	59
4	Uv03/02	Grt Lhz	P	Medium-low	59	12	14	15	1255	60
5	Uv33/04	Grt Hzb	M-P	Medium	77	13	4	6	1318	60
6	Uv18/04	Grt Hzb	M-P, F	Medium	85	7	3	5	1330	60
7	Uv213/02	Grt Hzb	M-P, F	Medium-high	75	18	2	5	1330	60
8	Uv-153/02	Grt Lhz	M-P	Medium	78	10	6	6	1340	61
9	Uv268/02	Grt Lhz	M-P	Medium	63	14	11	12	1320	62
10	Uv257/02	Grt Lhz	M-P, F, L	High	75	5	11	9	1327	62
11	Uv 3/05	Grt Lhz	P	Medium-low	65	13	14	8	1340	64
12	Uv205/02	Grt Hzb	P	Medium-low	80	11	3	6	1289	64
13	Uv1/04	Grt Lhz	M-P, F, L	High	66	15	7	12	1260	65
14	Uv38/02	Grt Lhz	M-P, F	Medium-high	77	11	6	6	1281	65
15	Uv30/04	Grt Lhz	M-P	Medium	74	11	6	9	1310	65
16	Uv3/01	Grt Lhz	M-P, F, D	High	81	6	6	7	1403	66
17	Uv97/02	Grt Lhz	M-P	Medium	67	14	9	10	1321	68
18	Uv252/02	Grt Lhz	P	Low	67	18	6	9	1340	69
19	Uv27/01	Grt Lhz	M-P	Medium	60	17	12	11	1400	69
20	Uv24/05	Grt Lhz	P	Low	79	6	8	7	1370	70

[a] Note: P — porphyroclastic, M-P — mosaic-porphyroclastic, F — fluidal, L — laminated, D — disrupted.

mantle metasomatism and associated with the introduction of asthenospheric melts (Ehrenberg, 1979) and, finally, heating by shear at the lithosphere–asthenosphere boundary (LAB) (Kennedy et al., 2002). Others consider the formation of deformed peridotites to be linked to crystallization of megacryst suites (Burgess and Harte, 2004; Harte and Hawkesworth, 1989; Solov'eva et al., 2008) and kimberlite melt formation (Agashev et al., 2010; Grégoire et al., 2006) within a single thermal event at the cratonic mantle base.

Because of the sizes which are not enough for whole-rock analyses and serpentinization (partial or complete) of xenoliths much of previous work only concerned the composition of rock-forming minerals in the xenoliths. Analytical data on bulk composition of these rocks at present are scarce and have been obtained on partially serpentinized xenoliths (Boyd et al., 1997; Grégoire et al., 2003; Kopylova and Caro, 2004).

In recent years, unique fresh mantle xenoliths have became available from kimberlite pipe Udachnaya located in the Siberian platform within the Daldyn kimberlite field. Preliminary geochemical data on these fresh xenoliths were reported by Agashev et al. (2008a,b, 2010), a more detailed study and a general description of major

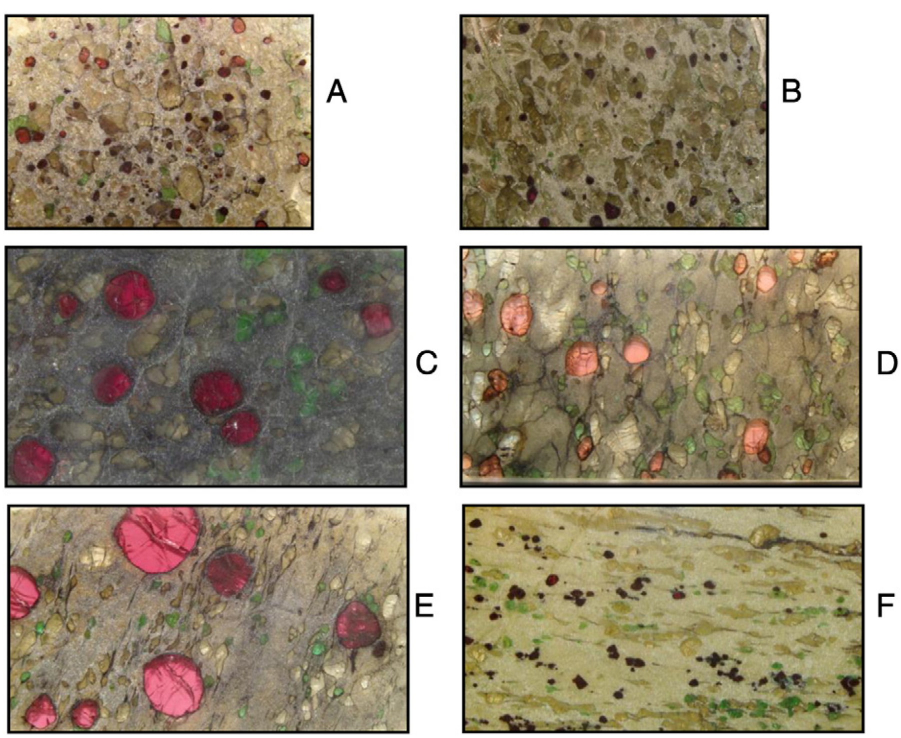

Fig. 1. Textural variations in deformed peridotite xenoliths from kimberlite pipe Udachnaya. A) and B) Samples Uv-252/02 and Uv-205/02 respectively, with low deformation degrees and porphyroclastic textures. C) and D) Medium-deformed samples Uv 30/04 and Uv 268/02 with mosaic-porphyroclastic textures. E) High degree of deformation in sample Uv-1/04 containing very coarse garnet porphyroclasts. F) Sample Uv 3/01 displays the highest degree of deformation and has fluidal-disrupted subtype of mosaic-porphyroclastic texture. View field is 3 cm along the long axis for a) and b) and 4 cm for all other samples.