

MELT AND FLUID INCLUSIONS IN ANORTHOSITE XENOLITH FROM THE UDACHNAYA KIMBERLITE PIPE, YAKUTIA

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The origin of anorthosites, which always attracted the attention of scientists and was repeatedly discussed in literature, remains an unresolved issue (Simmons, Hanson, 1978; Bogatkov, 1979; Owens, Dymek, 2001). Of particular interest is the origin of Precambrian autonomous anorthosites, since they are considered characteristic rocks of the early stage of the Earth's evolution. Despite the long-term study of these rocks, their genesis remains controversial.

This paper presents first results of the microscopic, microthermal, cryometric, Raman-spectroscopic, and microprobe investigations of melt and fluid inclusions in the minerals of anorthosite xenolith from the Udachnaya kimberlite pipe, Yakutia.

According to the tectonic scheme of Rozen et al., 2001, this pipe is located within the Markhin granulite-greenstone terrane. Doubly polished plates (100-150 µm) were used for optical investigations of the melt and fluid inclusions under the transmitted light. Microthermometric investigations were performed in heating stage and freezing stage designed by Osorgin and Tomilenko (Osorgin, Tomilenko, 1990a, 1990b). Raman spectroscopy was performed on a RAMANOR U-1000 (Jobin Yvon) one-channel Raman-spectrometer using argon laser. The chemical composition of minerals and melt inclusions was measured on a Camebax-micro microprobe and on the ion microanalyzer IMS-4f in the standard regime.

The xenolith groundmass mainly consists of hypidiomorphic plagioclase grains (>85 vol %) with orthopyroxene, clinopyroxene, and amphibole in the interstices. Mafic minerals account for less than 15 vol %. Amphibole is observed as subordinate xenomorphic grains. Occasionally, orthopyroxene is partially replaced by secondary amphibole along the margins. In addition, plagioclase hosts individual crystals or groups of crystals of octahedral spinel. Microstructural relationships between minerals in the studied xenolith suggest the following sequence of crystallization: plagioclase-spinel-orthopyroxene-clinopyroxene-amphibole.

Based on XRF data the chemical composition of xenolith (Sample Ud 90/4) is as follows (wt %): SiO₂ 48.0; TiO₂ 0.22; Al₂O₃ 22.4; Fe₂O₃ 5.0; MnO 0.13; MgO 6.8; CaO 15.0; Na₂O 1.33; K₂O 0.2; L.O.I. 0.78; total 99.86. In terms of mineralogy and petrochemistry, the xenolith corresponds to anorthosite association. Specific features of the chemical composition of minerals in the xenolith are illustrated by microprobe data presented in the table.

Table. Chemical composition of minerals and melt inclusion in clinopyroxene from the anorthosite xenolith, wt %.

Component	Plagioclase		Orthopyroxene		Clinopyroxene		Amphibole		Spinel	Spinel *	Melt inclusion**
	core	rim	core	rim	core	rim	core	rim			
SiO ₂	47,4	47,2	52,5	52,8	49,6	50,1	40,6	40,9	0,06	0,07	58,1
TiO ₂	0,03	0,02	0,02	0,02	0,38	0,4	2,0	2,0	0,12	0,16	0,3
Al ₂ O ₃	33,3	33,4	4,6	4,9	6,7	6,4	16,5	15,9	58,4	58,2	19,0
FeO	0,08	0,08	16,3	15,3	7,2	7,0	10,8	10,5	23,5	23,3	3,05
MnO	0,0	0,0	0,33	0,28	0,12	0,19	0,1	0,09	0,14	0,15	0,08
Cr ₂ O ₃	0,0	0,0	0,08	0,09	0,18	0,19	0,19	0,15	2,25	1,77	0,0
MgO	0,06	0,05	25,1	25,6	13,3	13,3	13,8	13,6	14,5	15,4	2,54
CaO	16,1	16,4	0,52	0,81	20,9	21,4	10,7	11,0	0,19	0,36	6,7
Na ₂ O	2,19	2,24	0,04	0,07	0,69	0,66	2,96	2,77	0,1	0,03	3,02
K ₂ O	0,05	0,04	0,0	0,0	0,02	0,0	0,6	0,8	0,0	0,0	4,36
Total	99,21	99,43	99,49	99,87	99,09	99,64	98,25	97,71	99,26	99,44	97,15
Ca/Ca+Na+K	0,80	0,80									

Notes: * - lamellar spinel in clinopyroxene; ** - quenched glass of the homogenized (Thom = 1120°C) melt inclusion in clinopyroxene.

It should be noted that all studied grains of plagioclase, clinopyroxene, and amphibole are compositionally homogeneous. However, they significantly differ from minerals of Precambrian autonomous anorthosite massifs located in the northern part of the Kotuikan-Monkhoolin zone and the Magan zone of the Anabar Shield (Sukhanov, 1984). Plagioclase (An₈₀) is compositionally similar to the calcic end member of this mineral group from the Anabar anorthosite. However, orthopyroxene and clinopyroxene significantly differ, primarily in terms of the Al₂O₃ content, from those of the Anabar anorthosite (4.9 and 2.12 wt % in orthopyroxenes and 6.7 and 3.63 in clinopyroxenes, respectively). Amphibole is also enriched in Al₂O₃ relative to the Anabar anorthosite. In addition, some clinopyroxene grains contain spinel as by lamellar spinel an exsolution product. The octahedral spinel in plagioclase and lamellar spinel in clinopyroxene are compositionally similar (table). The lamellar spinel

typically restricted to the clinopyroxene core is occasionally developed over the entire grain. The higher Al₂O₃ content in the studied orthopyroxene relative to the Anabar anorthosite indicates its crystallization at a higher pressure (Longhi et al., 1993).

Partially and completely crystallized primary melt inclusions and associated fluid inclusions were found in clinopyroxene and studied during microscopic investigations of plates. In some cases, in addition to normal melt inclusions (i.e. formed through homogeneous entrapment), composite melt inclusions containing initially entrapped anomalously large fluid phase (heterogeneous entrapment) were also found. The associated fluid inclusions typically occur together with the composite melt inclusions. The melt inclusions in clinopyroxene consist of several crystalline phases, residual glass (in partially crystallized inclusions), and fluid phase, which often occurs in the interstices between crystalline phases. The clinopyroxene-hosted inclusions (up to 20 µm) make up azonal groups of 2-5 inclusions. They are homogenized at 1100-1120 °C. The fluid inclusions in clinopyroxene are no more than 15 µm in size. At room temperature, all fluid inclusions in clinopyroxene are monophase formations. Cryometric investigations showed that they consist of liquid CO₂. The heterogenization during their cooling in the freezing stage is accompanied by the formation of gas bubbles. The freezing temperature of liquid CO₂ is less than that of CO₂ triple point, whereas its melting temperature is always about -56.6 °C, indicating nearly pure CO₂ composition of the inclusions. Inclusions in clinopyroxene are homogenized into a liquid CO₂ at temperatures ranging from -16 to -9 °C and indicating CO₂ density (ρ) ranging from 1.01 to 0.98 g/cm³ (Vargaftik, 1972). The Raman spectroscopy of fluid inclusions and of fluid phase in melt inclusions in clinopyroxene also confirmed their nearly pure CO₂ composition. Fluid phase of melt inclusions lack rims of liquid water or water solution, suggesting the absence of significant water accumulation in the parental melt of anorthosites. Such high density values of liquid CO₂ indicate that clinopyroxene crystallized in the magmatic system under high fluid pressure. At temperatures of ~ 1100-1120 °C (homogenization temperature of melt inclusions in clinopyroxene), the fluid pressure is no less than 8.0 kbar (intersection of the corresponding isotherms and isochores in the CO₂ system). Analogous pressure estimates were obtained from experimental data on solubility of the Ca-Tschermak molecule component in clinopyroxene associated with anorthite, plagioclase, orthopyroxene, and spinel in the CaO-MgO-Al₂O₃-SiO₂ system.

The comparison the chemistry of anorthosite xenolith and quenched glasses from the homogenized melt inclusions in clinopyroxene from the same sample revealed a distinct enrichment of residual melt in SiO₂ (up to 58.1 wt %), Na₂O + K₂O (up to 7.38 wt %), and especially K₂O (up to 4.36 wt %) at the moment of clinopyroxene crystallization. Simultaneously, the melt is depleted in FeO, MgO, and CaO.

Plagioclase and orthopyroxene contain only monophase liquid CO₂ inclusions that are similar to those in clinopyroxene. They are up to 30 µm in size. Their homogenization temperatures ranges from -19 to -12 °C (ρ = 1.03-0.99 g/cm³) in plagioclase and from -16 to -9 °C (ρ = 1.01-0.98 g/cm³) in orthopyroxene. The largest fluid inclusions universally exhibit evidence of partial opening and partial leakage of the substance (This is suggested by the presence of halos of secondary tiny fluid inclusions). Therefore, the above density values of these inclusions are the lowest estimates. The melting temperature of solid CO₂ is also -56.6 °C. Based on Raman spectroscopy data, fluid inclusions in plagioclase and orthopyroxene, like those in clinopyroxene, contain pure CO₂.

Thus, the detection and study of melt inclusions showed that the anorthosites crystallized from a high-Ca and high-Al melt at temperature higher than 1100 °C and fluid pressure no less than 8 kbar. The obtained data support the magmatic origin of anorthosites. The pattern of distribution of trace elements in minerals from anorthosite, as well as in melt inclusions in clinopyroxene and high homogenization temperatures of melt inclusions indicate that the anorthosites could not be formed during the melting of crustal rocks under the granulite-facies metamorphism.

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