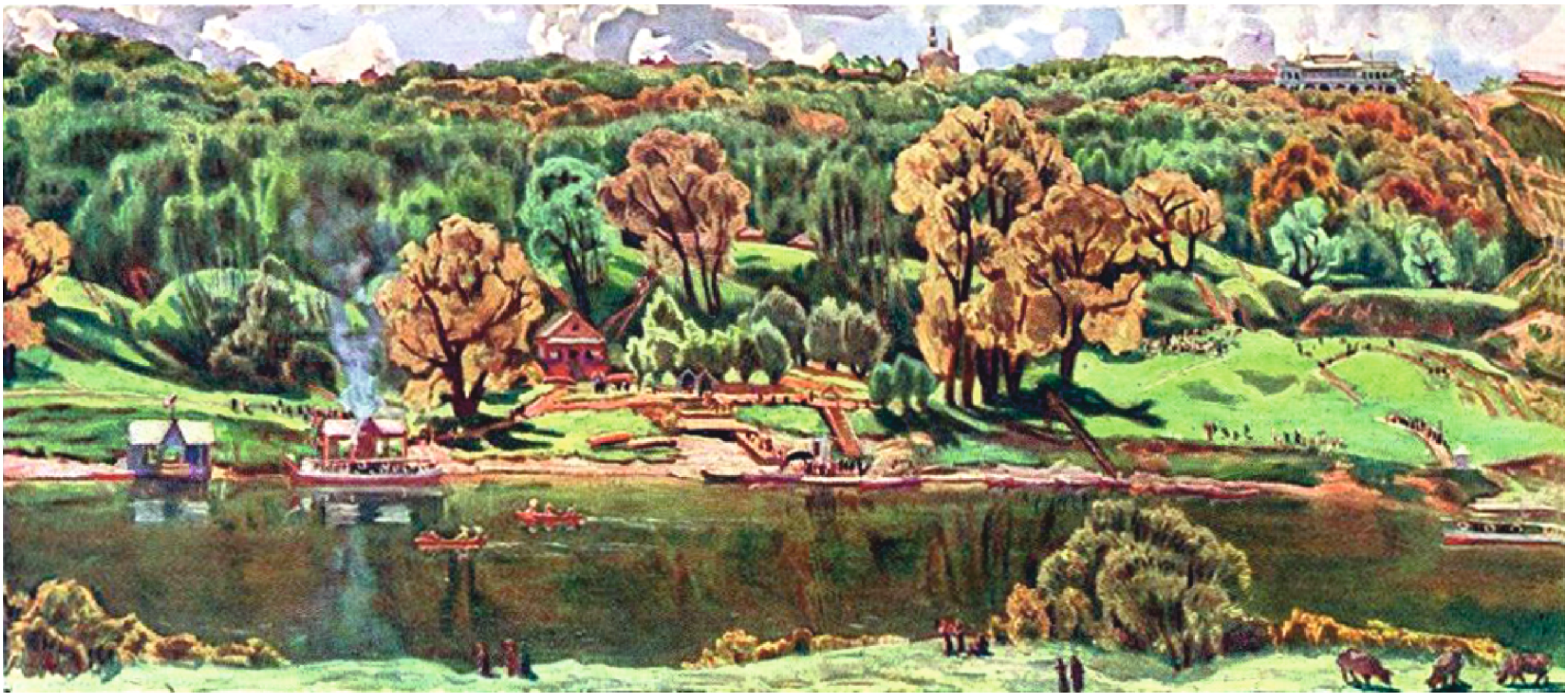
MAGMATISM OF THE EARTH AND RELATED STRATEGIC METAL DEPOSITS



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Magmatism of the Earth and related strategic metal deposits

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The mineral deposits of strategic metals are vulnerable to political and economic changes, and their availability is essential for high-technology, green energy, and other applications. The most of they are related to the deep – seated alkaline magmas.

This book offers a collection of papers presented at the 35th International Conference on Magmatism of the Earth and Related Strategic Metal Deposits held from September 3th to 7th 2018 in Moscow, Russia.

The conference articles are focused on the understanding of the geological processes that produce high concentrations of critical metals in geological systems such as the metal transport in the mantle (possibly from the core-mantle boundary) and crust and enrichment processes, hydrothermal and metasomatic processes leading to the formation of such significant deposits. Papers in this book give a representative overview including mineralogy, geochemistry and origin of strategic metals deposits.

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The cover pictures - Sparrow Hills, May. Konstantin Fedorovich Yuon, 1910.

P-T AND FLUID CONDITIONS OF INTERACTION BETWEEN MAFIC XENOLITHES AND PLAGIOGRANITES IN THE RIVER LOTTA AREA OF THE LAPLAND GRANULITE BELT

Butvina V.G., Safonov O.G.

Korzhinskii Institute of Experimental Mineralogy (IEM) RAS, Chernogolovka, butvina@iem.ac.ru

Garnet and orthopyroxene plagiogranites within the Lapland Granulite Belt (LGB) are confined to the northeastern part of the complex, building large areas in the Lotta river and Lovnaozero lake regions and extending westward to northern Norway (Mitrofanov et al., 1974; Kozlov and Kozlova, 1998). They are usually associated with peraluminous granulites (khondalites), showing intrusive contacts with these country rocks. Based on chemical and mineral composition of plagiogranites, which are typical for the S-type granites, the plagiogranites are usually considered as products of anataxis of khondalites at the peak of D3/M3 metamorphism during ~1.91 Ga at temperatures 800-850°C within a wide pressure interval 6.8-9.5 kbar (Mitrofanov et al., 1974; Kozlov, Kozlova, 1998; Mints et al., 2007, 2015; Kaulina et al., 2014). Magmatic origin of the plagiogranites is confirmed by a presence of xenoliths of various lithologies, which are products of earlier metamorphic stages at 1.97-1.96 Ga (e.g. Kaulina et al., 2014). Among the xenolith rocks, mafic rocks are abundant, but are not investigated in detail. Therefore, the object of this study are mafic (amphibolized two pyroxene-plagioclase-quartz rocks) xenoliths in plagiogranites of the river Lotta Area of the Central Zone of the LGB. These xenoliths reflect interaction of mafic rocks with fluids issued by granitic magmas during their crystallization.

Mafic xenoliths are equally grained granoblastic rocks consisting of low-aluminous clinopyroxene (10-15 %, X_{Mg} = 0.56 - 0.58, 2 - 2.5 wt. % Al_2O_3), orthopyroxene (25 - 30 %, X_{Mg} = 0.43 - 0.44, 1-1.3 wt. % Al_2O_3), plagioclase (30-40 %; An_{47-54}), and quartz (5-10 %). Clinopyroxene cores contains thin lamellae of orthopyroxene. Accessory magnetite, ilmenite and pyrrhotite form both separate grains and complex grains. In addition, the rocks contain fluor-apatite and zircon. Ti-bearing (up to 2 wt. % TiO_2) pargasite-edenite amphibole forms elongated grains, rims and coarse-grained symplectites with quartz at the contacts of pyroxenes, magnetite, ilmenite and pyrrhotite with plagioclase. It is mostly developed after orthopyroxene, which is preserved, in this case, as resorbed relics. In contacts with clinopyroxene with plagioclase, amphibole is either absent or forms just thin rims. Thus, the process of amphibolization can be represented by the following schematic reaction Opx + Ilm + Mt + Pl + H_2O = Amph ± Qtz, where clinopyroxene participates just indirectly. Amphibole formation is locally accompanied by the biotite, as well as the formation of magnetite ± pyrite along cracks in orthopyroxene suggesting addition of alkali-bearing oxidizing fluids.

Using the TWQ 2.32 software (Berman, 2007), a pressure of 6.0-6.4 kbar was estimated for equilibrium clinopyroxene + orthopyroxene + plagioclase + quartz in non-amphibolized domains of xenoliths (***Table 1***). The temperatures corresponding to this association are 800-860 °C and are within the crystallization temperature range of plagiogranites (Kaulina et al., 2014), as well as peak temperatures of the tectono-thermal stage M2 in the Lapland granulite belt (Mints et al., 2007). The amphibole-plagioclase equilibrium (Blundy, Holland, 1990) recorded the temperatures of the process of amphibolization of xenoliths 740-780 °C at a pressure of 5.0-5.5 kbar (***Table 2***). Based on certain thermodynamic conditions for the formation of the main xenoliths in the Lotta region of LGB, we can confidently confirm the assumption that the formation of plagiogranite magmas probably occurred at depths of the order of 25-30 km. As they uplifted, they captured a variety of xenoliths (Kozlov, Kozlova, 1998). The results of new thermobarometric studies, data on fluid inclusions and isotope data for carbon in these rocks confirmed these conclusions (Safonov et al., 2017).

Conclusions. Using the TWQ 2.32 software package (Berman, 2007), a pressure of 6.0-6.4 kbar was estimated for clinopyroxene + orthopyroxene + plagioclase + quartz equilibrium in non-amphibolized sections of xenoliths.

Table 1. P-T conditions for the equilibrium clinopyroxene + orthopyroxene + plagioclase + quartz in non-amphibolized domains of xenoliths estimated using the TWQ 2.32 software (Berman, 2007).

Pl,№№	Opx,№№	Cpx,№№	T,C	P, kb
40*	16	9	804	6,2
41	18	9	804	6,4
43	20	17	862	6,0
43	21	17	839	6,0
38	29	6	802	6,2
39	29	6	800	6,2

Table 2. Thermodynamic conditions of granulite amphibolization process determined by means of amphibole-plagioclase equilibrium (Blundy, Holland, 1990).

Amph,№№	24c	25r	27c	28r	35r	42c	43r
SiO2	42,49	42,16	42,99	42,38	43,44	43,26	42,86
TiO2	1,71	1,32	1,88	1,71	0,80	1,34	1,57
Al_2O_3	11,65	11,67	11,94	11,97	11,82	11,14	11,52
FeO	20,59	20,34	20,37	20,98	19,67	19,90	20,81
MgO	8,39	8,50	8,26	8,34	9,31	8,91	8,40
MnO	0,38	0,28	0,35	0,13	0,33	0,31	0,29
CaO	12,24	12,19	11,09	12,23	12,14	12,46	12,11
Na_2O	1,47	1,35	1,44	1,14	1,16	1,56	1,21
K_2O	1,25	1,32	1,29	0,95	0,99	1,24	1,10
F	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cl	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Sum	100,17	99,13	99,61	99,83	99,66	100,12	99,87
Pl							
xAb	0,53	0,53	0,53	0,53	0,53	0,53	0,53
xAn	0,47	0,47	0,47	0,47	0,47	0,47	0,47
T,°C	**766**	**756**	**780**	**763**	**746**	**740**	**760**
P, kbar	**5,0**	**5,3**	**4,9**	**5,3**	**5,5**	**5,2**	**5,0**

Temperatures corresponding to the association, make 800-860°C and are within the crystallization temperature range plagiogranites (Kaulina et al., 2014), as well as peak temperatures of the tectono-metamorphic stage D2/M2 in the Lapland granulite belt (Mints et al., 2007). Amphibole-plagioclase equilibrium (Blundy, Holland, 1990) recorded the temperatures of the process of amphibolization of xenoliths 740-780 °C at a pressure of 5.0-5.5 kbar. Variations in the composition of the amphibole are in the direction of lowering the temperature. It was probably connected with the interaction of a substantially aqueous fluid from the cooling plagiogranite magma with xenoliths as they were captured and uplifted. Indeed, the xenoliths are intersected by veins of plagiogranite composition. The abundance of water-salt (12-20 % NaCl eq.) inclusions and a subordinate amount of carbonic inclusions in minerals of plagiogranites (Safonov et al., 2017) confirm this assumption.

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IN SITU EXPERIMENTAL STUDY OF BASALT – COH SYSTEM AT THE UPPER MANTLE CONDITIONS

***Chertkova N.V.*, Ohfuji H., Irifune T.**

Ehime University, Geodynamics Research Center, Matsuyama, Japan, chertkova.nadezda.sj@ehime-u.ac.jp

Experimental investigation of the complex systems involving silicate and C-O-H components at simultaneous high temperatures and high pressures is a challenging task, since volatile components can easily change aggregate state and escape upon quenching and opening of the sample chamber. Recent technological advances provide an opportunity to observe and analyze such systems *in situ*, directly at the pressure and temperature conditions of interest (e.g., Chertkova and Yamashita, 2015; Thompson et al., 2016; Masotta and Keppler, 2017; Mysen, 2018).

In the present work, we applied a lever-type diamond anvil cell with an external heater to study interaction between basaltic (MORB) and C-O-H components at the conditions of cold subduction zones. The starting material was first compressed in the diamond anvil cell, which was placed under the microscope, connected to a highly confocal Photon Design Raman system, and then heated to temperatures exceeding 900°C. Visual observations of the sample and Raman measurements were performed *in situ* during heating (Fig. 1).

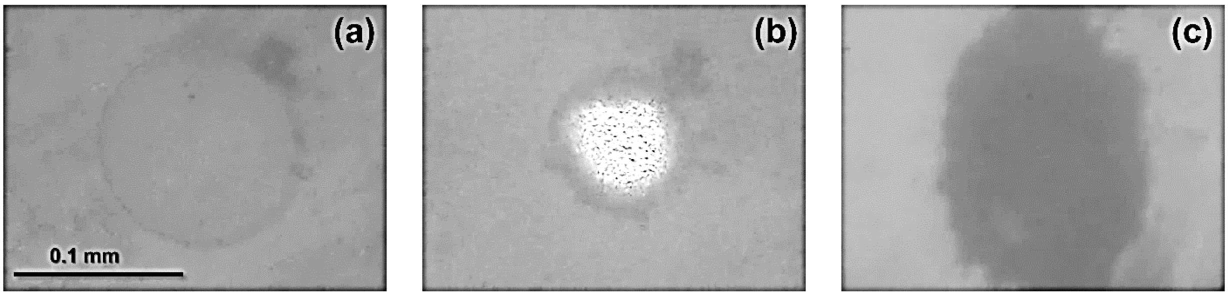

Fig. 1. Microphotographs of the sample (80 wt.% basalt + 20 wt.% $C_2H_2O_4$), taken during experiment in the diamond anvil cell: (a) compressed mixture at 25 °C and 0.8 GPa; (b) decomposition of oxalic acid, 395 °C and 4.0 GPa; (c) coexistence of opaque polymeric phase and silicate phases at 900 °C and 4.7 GPa.

In the chosen basalt – $C_2H_2O_4$ system, an appearance of polymeric phase with the dominant *G* bond-stretching mode and *D* breathing mode in the Raman spectra, common for carbon materials (Ferrari and Robertson, 2000), was detected at temperatures above 600 °C and pressures above 4 GPa along with the silicate minerals (Fig. 1c). This observation indicates that $C_2H_2O_4$ compound is not suitable as a fluid source at the mentioned experimental conditions. In the future work, water-rich compounds with lower carbon content will be used for experiments, modeling fluid and rock interaction in the geological settings of subduction zones.