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Thermobarometric and Petrological Study of Mafic Xenolithes in Plagiogranites of the River Lotta Area of the Central Zone of the Lapland Granulite Belt

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Abstract

Thermobarometric data, fluid inclusions data and carbon isotope data confirm the conclusion that leucocratic garnet-bearing plagiogranites of the Lapland Granulite Belt (LGB) are associated with the anatexis of country khondalites during peak of metamorphism. The formation of these magmas occurred at depths of 25-30 km. During ascent, granitic magmas trapped mafic (two pyroxene-plagioclase) xenoliths at pressures 6.0-6.4 kbar. The interaction of predominantly aqueous-salt fluids issued by the magmas with the xenoliths during cooling at depths less than 20 km (5.0-5.5 kbar) led to their widespread amphibolization at temperatures of 740-780°C.

Keywords: Lapland Granulite Belt; The River Lotta Area; Granulite; Amphibolization; Thermobarometric data

Abbreviations: Ab: albite; Amph: amphibole; An: anorthite; Cherm: chermakite; Cpx: clinopyroxene; Ed: edenite; Opx: orthopyroxene, Pl: plagioclase; Parg: pargasite; Qtz: quartz; Tre: tremolite

Introduction

When studying the Lapland Granulite Belt (LGB), plagiogranites attract special attention, since they are formed at high P-T parameters and often carry information about the "peak" conditions of metamorphic mineral formation. Garnet and orthopyroxene plagiogranites within the LGB are confined to its northeastern part, forming large areas in the area of the Lotta and Lovnaozera rivers and extending westward to the Ivalo and further northern Norway [1]. With such a wide distribution of these rocks, the question of the origin of their protoliths has been little studied and, is, to the end, not elucidated. Here are a few points of view about the genesis of plagiogranites. Taking into account the similarity of the chemical and mineral composition of garnet plagiogranites and acid granulites, a number of authors considered them to be coarse-grained varieties of granulites.

In the future, the origin of synmetamorphic garnet-bearing plagiogranites (1.917-1.909 Ga) of the River Lotta Area of the Central Zone of the Lapland Granulite Belt is associated with the anatexis processes of high-alumina metapelites (khondalites) of the complex at the peak of granulite metamorphism [1-4]. It should be noted, according to geological observations, the crystallization of plagiogranites from the melt is beyond doubt. This is indicated by finds within the granulite belt of the River

Lotta Area of the LGB of magmatic breccias, in plagiogranite cement of which fragments composed of the main rocks occur, among which plagiogranites are of particular interest, with the xenoliths of apogabbro-norite of granulite composition included. These mafic rocks against the background of a good study of the LGB are practically not investigated, but they play an important role in the genesis and synmetamorphic transformations of plagiogranites and can be a source of information about the origin of the melt and the nature of the interaction of rocks as the melt is raised. In connection with the above, the purpose of this work is to reveal the genesis of plagiogranites, based on a detailed petrologic-mineralogical and thermobarometric study of the main xenoliths of plagiogranites in the River Lotta Area of the Central Zone of the LGB.

Petrological and Mineralogical Study of Mafic Xenolithes

Analytical Methods

The main methods for studying natural samples are: a) mineralogical and petrographic study using an Eclipse polarization microscope from Nikon LV100 POL; and b) electron microscopy and polarization analysis of samples on an electron microscope CamScan MV2300 (VEGA TS 5130MM) equipped with a Link INCA Energy 450 energy dispersive microanalyzer and an Oxford INCA Wave 700 wave dispersion spectrometer at the IEM RAS, in lithosphere laboratory and physical research laboratory.

Amphibolized Two-Pyroxene-Plagioclase Granulite

Xenoliths are uniformly grained rocks with a massive texture and granoblastic structure. Mineral composition: orthopyroxene (20%) + clinopyroxene (10%) + plagioclase (40%) + amphibole (15%) ± quartz (5-10%) + magnetite + ilmenite + pyrrhotite (5-8%) + biotite + chlorite (less than 2%).

The main minerals. The mafic xenoliths consist of low-zonal plagioclase (30-40%; An_{47-54}), low-aluminous clinopyroxene (10-15%, X_{Mg} = 0.56-0.58, 2-2.5% by weight Al_2O_3) and orthopyroxene (25-30% X_{Mg} = 0.43 - 0.44, 1-1.3 wt% Al_2O_3) (Tables 1a,1b,1c). As a secondary mineral, amphibole is present. Accessory minerals. In the mafic xenoliths, 5-10% quartz, accessory apatite, zircon as well as coexisting magnetite, ilmenite and pyrite and also pyrrhotite (sometimes sphalerite) occur.

Plagioclase, subidiomorphic tabular grains, up to 1 mm in size, extinction angles of 20-28, which corresponds to the composition of the plagioclase andesine-labrador, which is confirmed by analytical methods, not zonal or weakly zonal.

Orthopyroxene (hypersthene), subidiomorphic grains from 0.1 to 1 mm, hypersthene pleochroism. It is replaced by a secondary amphibole with the formation of an ore mineral (Figures 1a & 1b). Often fissuring of the orthopyroxene occurs, as well as the formation of the ore rim.

In the studied xenoliths, amphibolization processes are widespread in the form of wide rims of potassium-containing pargasite-edenite amphibole Figure 2 and its coarse-grained symplectites with quartz in the contacts of pyroxenes, magnetite, ilmenite and pyrrhotite with plagioclase. The more basic composition of the plagioclase and the lesser magnesia of the pyroxenes in the amphibolized sections of the xenoliths correspond to the amphibole formation: Opx + Cpx + Ab (in plagioclase) + H2O = Amph ± Qtz.

№№	16	20	26	29	33	18	21	25
Com-nt	center	center	center	center	center	center	rim	rim
SiO2	49,68	50,55	49,37	49,88	49,50	49,33	50,11	49,96
TiO2	0,17	0,14	0,07	0,00	0,31	0,00	0,00	0,14
Al2O3	1,26	1,33	1,31	1,37	0,98	1,29	1,28	1,24
FeO	32,93	31,77	32,66	32,29	32,18	32,50	32,26	32,26
MnO	0,83	0,92	1,19	0,98	1,26	1,14	1,14	1,23
MgO	14,56	14,58	14,56	14,41	14,66	14,36	14,59	14,20
CaO	0,57	0,70	0,76	0,69	0,91	0,60	0,53	0,88
Na2O	0,00	0,00	0,00	0,22	0,15	0,49	0,00	0,08
Total	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
Formula units								
Si	1,96	1,98	1,95	1,96	1,95	1,95	1,97	1,97

Ti	0,01	0,00	0,02	0,00	0,01	0,00	0,00	0,00
Al	0,06	0,06	0,06	0,05	0,06	0,06	0,06	0,06
Fe	1,08	1,04	1,08	1,06	1,08	1,07	1,06	1,06
Mn	0,03	0,03	0,04	0,03	0,04	0,04	0,04	0,04
Mg	0,85	0,85	0,86	0,84	0,86	0,84	0,85	0,83
Ca	0,02	0,03	0,03	0,03	0,04	0,03	0,02	0,04
Na	0,00	0,00	0,00	0,02	0,01	0,04	0,00	0,01

Table 1a: Electron microprobe analyses of orthopyroxenes from amphibolized two-pyroxene-plagioclase granulite of the River Lotta Area of the LGB.
***Note:** Electron microprobe analyzes of minerals were performed in the IEM RAS on the Camscan microanalyzer.

№№	**17**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SiO2	49,98	50,55	49,81	50,49	49,99	50,71	50,18	50,68	50,33
TiO2	0,25	0,31	0,38	0,36	0,44	0,36	0,31	0,36	0,24
Al2O3	2,23	2,28	2,12	2,21	2,13	2,41	2,22	2,09	2,26
FeO	14,69	14,03	14,23	14,08	13,84	14,52	13,27	13,65	14,05
MnO	0,54	0,86	0,64	0,69	0,39	0,50	0,45	0,33	0,47
MgO	10,25	10,24	10,75	10,73	10,87	10,51	10,42	11,00	10,77
CaO	21,20	21,43	21,50	21,04	21,58	20,64	22,24	21,40	21,11
Na2O	0,81	0,26	0,57	0,33	0,58	0,27	0,70	0,48	0,53
Total	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
Si	1,92	1,94	1,92	1,93	1,92	1,94	1,92	1,94	1,93
Ti	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Al	0,10	0,10	0,10	0,10	0,10	0,11	0,10	0,09	0,10
Fe	0,47	0,45	0,46	0,45	0,44	0,46	0,43	0,44	0,45
Mn	0,02	0,02	0,02	0,02	0,01	0,02	0,01	0,01	0,02
Mg	0,59	0,59	0,62	0,61	0,62	0,60	0,60	0,63	0,62
Ca	0,87	0,88	0,89	0,86	0,89	0,84	0,91	0,88	0,87
Na	0,06	0,02	0,04	0,02	0,04	0,02	0,05	0,04	0,04

Table 1b: Electron microprobe analyses of clinopyroxenes from amphibolized two-pyroxene-plagioclase granulite of the River Lotta Area of the LGB.
***Note:** Electron microprobe analyzes of minerals were performed in the IEM RAS on the Camscan microanalyzer

№№	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**
Com-nt	center	rim	rim	center	center	center	center	center	center
SiO2	55,82	55,67	55,57	56,58	56,06	55,71	57,41	56,50	56,26
TiO2	0,00	0,04	0,14	0,08	0,09	0,00	0,21	0,06	0,00
Al2O3	27,54	27,52	27,75	27,62	27,56	27,95	26,34	27,64	26,76
FeO	0,24	0,17	0,20	0,00	0,04	0,06	0,26	0,32	0,46
MnO	0,20	0,00	0,07	0,09	0,00	0,00	0,00	0,00	0,00
MgO	0,14	0,05	0,20	0,01	0,14	0,20	0,11	0,09	0,29
CaO	10,77	10,09	10,65	10,31	10,59	10,04	9,47	9,46	9,93
Na2O	5,10	6,12	5,25	5,12	5,29	5,83	5,84	5,66	6,15
Total	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
Si	2,51	2,50	2,50	2,54	2,52	2,50	2,51	2,53	2,53
Ti	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
Al	1,46	1,46	1,47	1,46	1,46	1,48	1,39	1,46	1,42
Fe	0,01	0,01	0,01	0,00	0,00	0,00	0,01	0,01	0,02

Mn	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Mg	0,01	0,00	0,01	0,00	0,01	0,01	0,01	0,01	0,02
Ca	0,52	0,49	0,51	0,49	0,51	0,48	0,45	0,45	0,48
Na	0,44	0,53	0,46	0,44	0,46	0,51	0,51	0,49	0,54

Table 1c: Electron microprobe analyses of plagioclases from amphibolized two-pyroxene-plagioclase granulite of the River Lotta Area of the LGB.

***Note:** Electron microprobe analyzes of minerals were performed in the IEM RAS on the Camscan microanalyzer.

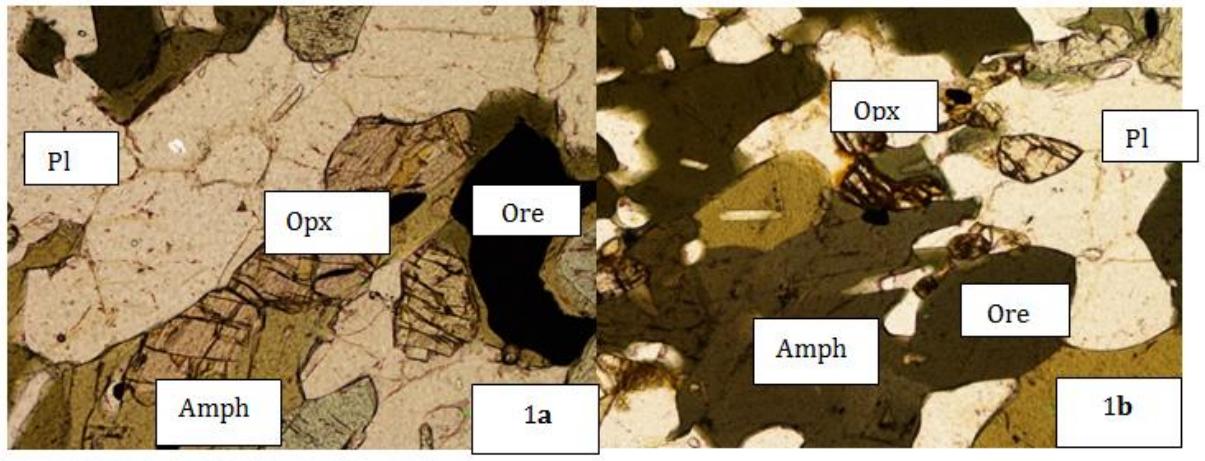

Figure 1a & 1b: Photomicrographs of granulite samples and their reaction textures. All figures are 5 mm wide.

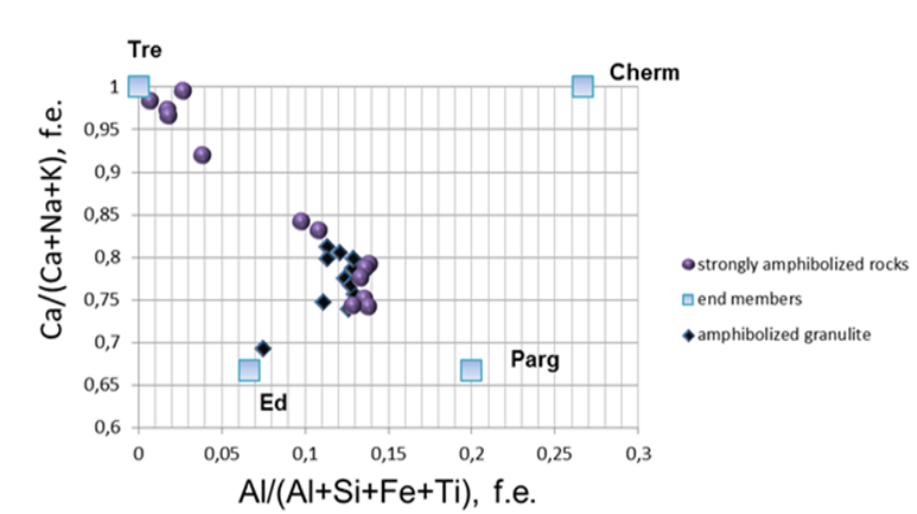

Figure 2: Compositions of amphiboles of mafic xenolithes in plagiogranites of the River Lotta Area of the Central Zone of LGB.

Amphibolization Figure 1b is sometimes accompanied by the formation of biotite and ferruginization of the orthopyroxene along cleavage cracks and the formation of an ore mineral (magnetite ± ilmenite ± rutile), indicating

the addition of additional components to the xenoliths. Amphibole forms elongated (up to 2.5 mm in length) crystals with a ratio of width to length of 1: 3 and forms reaction zones with orthopyroxene (Figure 1a), forms rims around the ore minera, (according to microanalysis is represented by two types of amphibole (Figure 2). Accessory minerals: zircon, apatite, magnetite, ilmenite and pyrite and also pyrrhotite (sometimes sphalerite).

Thermobarometric Study of Mafic Xenolithes and the Discussion of the Results

Using the TWQ 2.32 software package, a pressure of 6.0-6.4 kbar was estimated for equilibrium clinopyroxene + orthopyroxene + plagioclase + quartz in non-amphibolized sections of xenoliths (Table 2) [5]. The temperatures corresponding to this association are 800-860 °C and are within the crystallization temperature range of plagiogranites, as well as peak temperatures of the tectono-thermal stage M2 in the Lapland granulite belt [3,4]. The amphibole-plagioclase equilibrium recorded the temperatures of the process of amphibolization of xenoliths 740-780 °C at a pressure of 5.0-5.5 kbar 9 (Table 3) [6].

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 went up, they captured a variety of Xenoliths [1]. The results of new thermobarometric studies, data on fluid inclusions and isotope data for carbon in these rocks confirmed these conclusions [7,8].

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 equilibrium clinopyroxene + orthopyroxene + plagioclase + quartz in non-amphibolized sections of xenoliths, was estimated using the TWQ 2.32 software package [5].

*№ analysis, the compositions see Tables 1a,1b,1c

Conclusions

Using the TWQ 2.32 software package, a pressure of 6.0-6.4 kbar was estimated for clinopyroxene + orthopyroxene + plagioclase + quartz equilibrium in non-amphibolized sections of xenoliths [5].

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
Al2O3	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
Na2O	1,47	1,35	1,44	1,14	1,16	1,56	1,21
K2O	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	**766,3**	**756,0**	**779,9**	**762,9**	**745,6**	**739,9**	**760,4**
P,kb	**5,00**	**5,33**	**4,86**	**5,29**	**5,51**	**5,19**	**5,03**

Table 3: Thermodynamic conditions of granulite amphibolization process determined by means of amphibole-plagioclase equilibrium [6].

Temperatures corresponding to the association, make 800-860 °C and are within the crystallization temperature range plagiogranites, as well as peak temperatures tectonomagmatic thermal stage M2 Lapland's granulite belt [3,4].

Clinopyroxene, xenomorphic grains from 0.1 to 1 mm, occurs in paragenesis with plagioclase and orthopyroxene (Figure 3a).

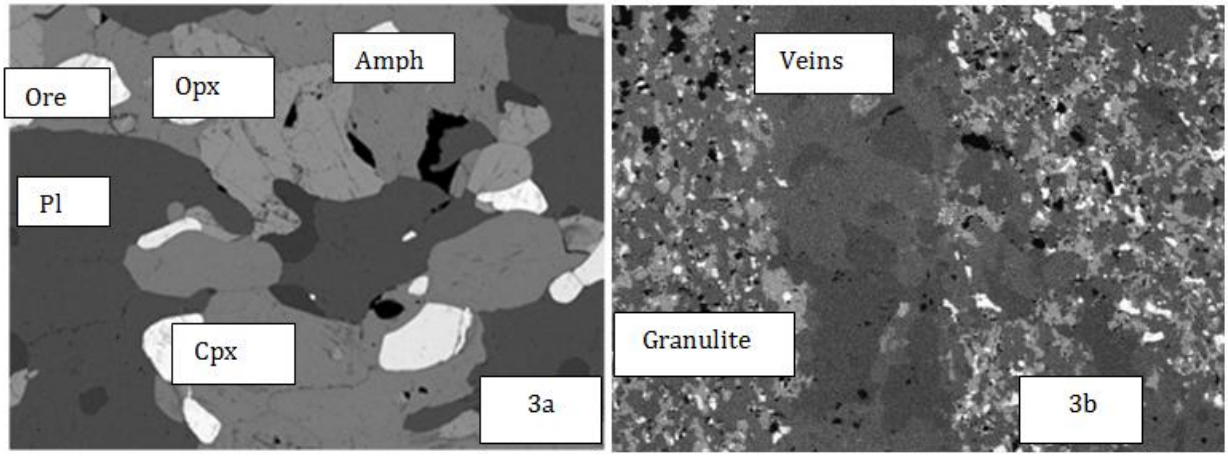

Figure 3a & 3b: Electron microprobe photos of mineral paragenesis of granulite (3a) and veins of plagiogranite composition in it (Figure 3b).

Amphibole-plagioclase equilibrium recorded the temperatures of the process of amphibolization of xenoliths 740-780 °C at a pressure of 5.0-5.5 kbar [6]. 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 lifted. Indeed, the xenoliths are intersected by veins of plagiogranite composition (Figure 3b). The abundance of water-salt (12-20% by weight NaCl equivalent) inclusions and a subordinate amount of carbonaceous inclusions in minerals of plagiogranites confirms this assumption [7,8].

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