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GRANITIZATION AS A MAJOR CRUST-FORMING PROCESS IN KARELIA, U.S.S.R.

(3 Figs., 5 Tabs.)

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Vast areas occupied by ultrametamorphic rocks, which surround the relict Late Archean greenstone belts of Karelia and are usually part of a grey gneiss complex, represent polychronous units that fall into two geological complexes : early granulitic and late migmatite-granitic. The former complex represents an old basement of presumably Early Archean age. Its most common rocks are hypersthene-biotite plagiogneisses, biotite tonalite gneisses and plagiogranite gneisses. Bipyroxene-amphibole crystalline schists and gneisses and aluminous gneisses are subordinate. The late migmatite – granite complex developed after Late Archean volcanic-sedimentary rocks and contains numerous relicts of them. The one kilometre thick arenite deposits preserved after replacement at the boundary of the White Sea geoblock are comparable in composition to Late Archean magmatite granites and suggest that Late Archean metasedimentary rocks transformed into granitoid rocks are much more thicker. This implies that greenstone belt volcanism was preceded by intense sedimentation.

Late Archean syntectonic regional metasomatism was superposed on both Late Archean volcanogenic rocks and basement rocks, thereby obscuring their structural unconformity and making their composition more similar. As a rule, the isotopic age of basement rocks indicates the time of superposed processes rather than primary age. The Earth's crust acquired the composition of a mature continental crust by enrichment in potassium and lithophilic minor elements. Thus it differs from a protocrust which acted as a basement for Late Archean greenstone belts.

Key words: ultrametamorphic rocks, granitization, crust forming process, Karelia.

Introduction

The block struckture of the Earth's crust in Karelia makes it possible to observe in the present erosion section some geological complexes which occur at different depths and form part of the different layers in the four-layered model of the Earth's crust (Kratz et al., 1978). The upper volcano-sedimentary layer I (density $\sigma = 2.62-2.87$ g/cm^3) is represented by a platform mantle complex and has a sharp geological and geophysical boundary with the underlying granite – ultrametamorphic layer II ($\sigma = 2.60-2.65$ g/cm^3). The lower boundary of the layer is indistinct. It shows elastic wave propagation rate Vr = 6.0–6.4 km/s. The lower part of the third "diorite", layer ($\sigma = 2.75-2.80$ g/cm^3) is confined to Conrad discontinuity (Vr = 6.6 km/s). It is underlain by a "basaltic" (granulite – basic) layer with an average density $\sigma = 2.95$ g/cm^3 which is restricted to Moho discontinuity (Vr = 8.1–8.2 km/s).

No rocks corresponding to this layer in terms of physical parameters were observed to crop out, and the nature of Conrad discontinuity is open to question.

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The geological complex of the "diorite" layer constitutes the Belomorian geoblock (Fig. 1) and a few other blocks (1–6) within the Karelian geoblock. The rocks of the complex show a density of 2.70–2.85 g/cm^3 in the present erosion section and up to 2.66 g/cm^3 in case of superimposed processes. The bulk of the Karelian geoblock is represented by granite-gneisses, variable in composition, with relict structures of volcano-sedimentary rocks which occur in Late Archean greenstone belts. The density of the granite-gneisses varies within a broad range, the predominant values corresponding to the density of the most common rocks (biotite plagio-gneiss, and granite-gneiss) that varies from 2.68 to 2.63 g/cm^3. This complex constitutes the granite-ultrametamorphic layer.

Tonalite-gneisses and plagiogranite gneisses make up the two geological complexes to be correlated. Their subdivision is, thus, difficult. Being invollved in folded deformation, both complexes are structurally conformable.

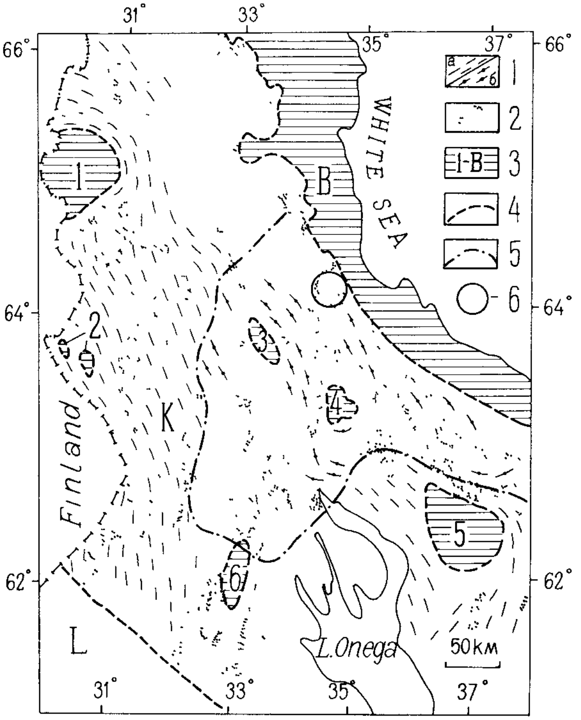

Fig. 1. Geological complexes of the "diorite" and granite-ultrametamorphic beds in Karelia. 1 – Late Archean migmatite-granite formation making up the granite-ultrametamorphic layer of the Earth's crust (plagiogranite gneisses, tonalite gneisses with relics of Late Archean supracrustal rocks); a – formed under moderate and high-alkali conditions; b – formed under low-alkali conditions; 2 – relict variably metamorphosed sedimentary-volcanogenic deposits of greenstone belts; 3 – oldest basement belonging to the "diorite" layer of the crust (diorite gneisses, tonalite gneisses, amphibolites with relicts of enderbites and bipyroxene-amphibole crystalline schists). Blocks: 1 – Voknavoloksky, 2 – Tulossky, 3 – Ondozersky, 4 – Vygozersky, 5 – Vodlozersky, 6 – Syamozersky, B – Belorian (White Sea), K – Karelian; L – Ladogian; 4 – boundaries of blocks; 5 – conventional boundary dividing Late Archean granitization areas differing in alkalinity type.

Conventional isotopic dating for their subdivision is equivocal. Thus, the age of Archean granulite metamorphism determined by the U-Pb method on zircon is 2645 ±45 Ma for western Karelia and 2650 ±45 Ma for southeastern Karelia (Lobach-Zhuchenko – Levchenkov, 1985). At the same time the dating of the earliest zircon generation from the same complex in western Karelia (Kozhevnikov et al., 1987) provided an age of 3.37–3.13 Ga. According to the above authors, this indicates that the rocks studied are not younger. The U-Pb method was employed to obtain an age of 3150 ±5 Ma for two varieties of zircon in the amphibolites and amphibole-biotite gneisses of the Vodlozero block which is regarded as part of the "diorite" bed (Levchenkov et al., 1978), but the authors assume that the age may be apparent, and results from the rejuvenation of the U-Pb system in the course of superimposed metamorphism. A similar isotope age (3.1 Ga) was obtained by the same method for zircons from gneissic granodiorites in Palaya Lamba, Central Karelia (Lobach-Zhuchenko – Levchenkov, 1985), which belong to the granite-ultrametamorphic layer, but the most common dates for the ultrametamorphic granitoids of the complex range from 2700 to 2800 Ma.

An additional criterion for the subdivision of these complex polychronous rocks can be provided by a difference in the metasomatic patterns of the geological complexes in both the "diorite" and granite-ultrametamorphic layers.

Geological complex of the "diorite" layer

The blocks of the "diorite" layer within the Karelian geoblock show low positive gravitational anomalies In the present erosion section they are composed of biotite-amphibole and biotitic diorite gneisses, tonalitic gneisses, and amphibolites with relics of medium and basic granulites (enderbites and bipyroxene-amphibole crystalline schists).

The modal compositions of the main rock types of the "diorite" layer are given in Tab. 1. The layer is characterized by the absence of primary potassium feldspar. Hypersthene-biotite plagiogneisses (enderbites) and products of their alteration (biotite tonalite-gneisses) are the most common rocks of the complex. They are notable for the brownish-grey colour of plagioclase and show nematogranoblastic equigranular texture. The biotite is pleochroic in brown. The plagioclase of enderbites is calcic oligoclase-andesine (27–42 % An) and is antiperthitic.

Bipyroxene-amphibole crystalline schists and gneisses are dark-green, distinctly schistose rocks. Banding is also caused by alternation of leucocratic and melanocratic beds. The texture of the rocks is mainly nematogranoblastic. Clinopyroxene is the most common dark mineral. Chemically, it is at the salite–augite field boundary (Sviridenko, 1974). The hypersthene is similar to that of enderbites. Hornblende is greenish-brown, and plagioclase is represented by andesine (30–49 % An). Bytownite (71–78 % An) and labradorite (50–69 % An) are occasionally present in quartz-free associations.

Tonalite gneisses show a banded structure. The rocks have an inequigranular texture. Microcline is commonly present. It usually builds up as individual porphyroblasts or interstitial fillings between the grains of the major rock-forming minerals. Plagioclase is normally present in several generations, the earliest one being andesine (27–33 % An). Antiperthite is fairly common. Biotite is usually a brown-greenish variety characteristic of diaphthorites.

As a whole, the complex can be correlated with the Varpasjärvi granulite complex north of Kuopio, Central Finland (Paavola, 1984), formed at a temperature of 700 ±50 °C and a pressure of 8 ±1kbar.

Table 1

Average modal compositions of the major rock varieties of the "diorite" layer

Minerals	bipyroxene-amphibole crystalline schists (N = 41)	enderbites (N = 45)	tonalite-gneisses (N = 14)
quartz	6 98	30 44	28.91
plagioclase	61 89	60 56	52.97
biotite	4 06	4 42	3.03
amphibole	14 76	–	–
orthopyroxene	3 47	1.96	–
clinopyroxene	8.22	–	–
microcline	–	–	3.58

The metamorphic rocks of the "diorite" layer in Karelia show fairly uniform chemical composition (Tab. 2) which can be compared with that of magmatic rocks by assuming isochemical granulite metamorphism. In this case the average chemical composition of bipyroxene-amphibole crystalline schists and gneisses corresponds to basalt with possible variations to andesitic basalt, that of enderbites to andesite-dacite and that of plagiogranite gneisses to rhyolite-dacite. All the rocks of the granulite complex are rich in barium and strontium and poor in potassium and lithophile minor elements.

Table 2

Average major (weight oxide) and minor element (ppm) composition of the major rock varieties of the "diorite" layer

Oxides	bipyroxene-amphibole crystalline schists and gneisses, Lake Tulos (N = 11)	enderbites Lake Tulos (N = 14)	tonalite-gneisses Lake Vyg (N = 10)
SiO_2	52 95	64.99	67.38
TiO_2	1 03	0.54	0 36
Al_2O_3	16.15	16 35	14.95
Fe_2O_3	3 19	1.42	1 63
FeO	7 17	3.86	1.73
MgO	5 11	1 86	1.39
MnO	0.16	0.10	0.05
CaO	9.89	4 56	4.80
Na_2O	3.14	3.89	5 21
K_2O	0.87	1.68	1 46
Rb	20.0	40 0	76.6
Cs	2.5	2.3	4.9
Ba	465.0	460.0	464.2
Sr	456 0	440 0	452.5
Cr	206	212	179
V	121	49	30
Ni	16	32	16
Co	41	16	5
Zn	134	70	31
Pb	8	15	12
Sn	4	4	3

Geological complex of the granite-ultrametamorphic layer

The Karelian geoblock is marked by a great negative anomaly which agrees with the density of the most common rocks such as biotite migmatite-granites (biotite plagiogneisses, granodiorite gneisses and granite-gneisses).

The granite-ultrametamorphic layer of the Karelian geoblock was formed during the Late Archean Reboly folding which terminated the Late Archean tectono-magmatic cycle (Sviridenko, 1980) at the 2700–2800 Ma boundary. As a result, both metasedimentary and metavolcanogenic rocks, similar in composition to granite, were transformed into granitoid on a regional scale. Late Archean greenstone belts are mapped as relict structures in

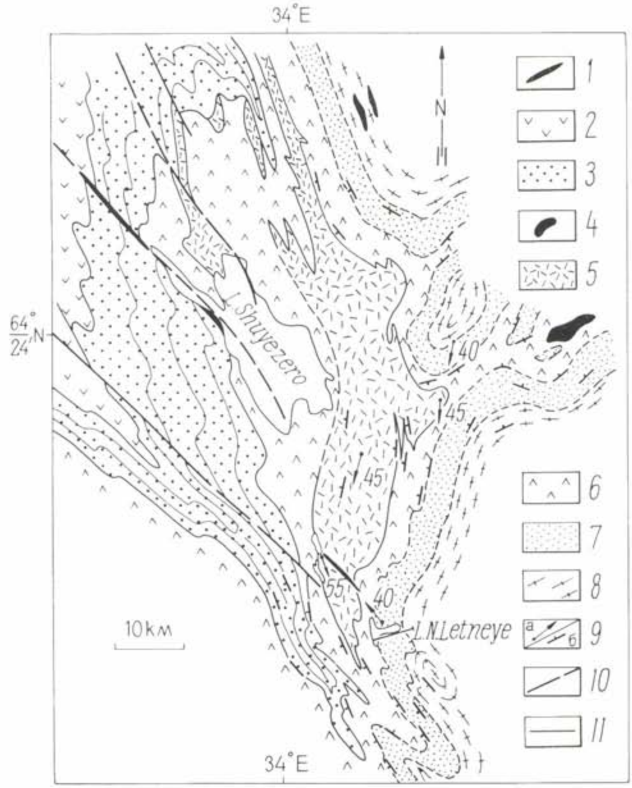

FIG. 2

Fig. 2. Schematic geological map of the Lake Nizhneye Letneye-Pushnoye settlement area, Central Karelia (after mapping by A. P. Svetov, L. P. Sviridenko, A. I. Golubev, V. I. Ivashchenko, G. M. Pavlov, S. R. Kotov, N. I. Kondrashova and A. S. Ein).

Jatulian (Early Proterozoic): 1 – basic dykes; 2 – basalts; 3 – quartzites, sandstones and conglomerates. *Lopian* (Late Archean): 4 – ultrabasic intrusions; 5 – volcano-plutonic plagiorhyodacite-rhyolitic association; 6 – andesitic basalts; 7 – metasedimentary rocks of the terrigenous deposit; 8 – plagiogneisses and plagiogranite gneisses with relict fine-grained sandstone beds; 9 – bed position (a – lineation, b – bedding); 10 – fault zones; 11 – section line (Fig. 3).

migmatite-granite terraines. It has been found that biotitic varieties of autochthonous granitoids were formed solely by replacement of biotite gneisses and schists.

Both autochthonous plagiogranites and the relics of gneisses present in them consist of plagioclase (23–29 % An), quartz, and biotite in varying amounts. Microcline is sometimes found (less than 10 %). Texturally, the autochthonous gneissoid plagiogranites are characterized by the porphyroblastic shape of feldspars and by their idiomorphism relative to dark minerals. The predominance of the biotitc types of autochthonous plagiogranites suggests, therefore, that the Late Archean volcano-sedimentary sequence consisted largely of some biotitic rock varieties similar in composition to granite. This assumption is supported by the relict metaterrigenous deposit at the base of the Lopian sequence of the East Karelian zone (Fig. 2). Lopian granitized rocks such as plagiogranite gneisses, granite gneisses and gneissoid granites are exposed in the present erosion section in the cores of domes. The degree of their transformation decreases markedly towards the domal flanks with a gradual transition to quartz-feldspar gneisses and, finally, meta-arkoses, metasiltstones with intraformational conglomerate horizons. The interdomal troughs are composed of overlying sedimentary volcanogenic rocks. The total thickness of the lower terrigenous portion of the sequence reaches 1 km (Fig. 3). The rocks are weakly metamorphosed, with preserved relics of blastopsammitic textures.

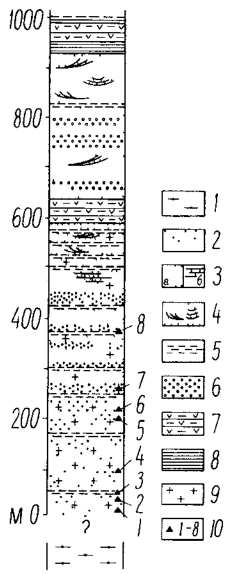

Fig. 3. Section through the relict terrigenous sequence at the base of the Lopian (Lake Nizhneye Letneye).

1 – tonalite gneiss (basement); 2 – coarse-grained arkose (meta-arenite); 3a – fine-grained arkose, 3b – calcified fine-grained arkose; 4 – cross-bedded arkose; 5 – siltstone; 6 – conglomerate; 7 – schistose andesite and andesitic basalt; 8 – tuffaceous schist; 9 – superimposed granitization; 10 – location of chemical samples (Tab. 3): 1, 2, 5, 6, 7, – metasandstone; 3, 8 – metasiltstone; 4 – gneissoid granite.

Graded bedding is characteristic of the lower (investigated) part of the terrigenous sequence. Rhythmicity is seen as a regular upward alternation of arkose gravel, medium- to fine-grained sandstone and siltstone. Cross-bedding and traces of reworking of beds are scarce. Individual calcitized metasandstone horizons are present. Relics of blastopsammitic structures were also reported from the remnant biotite schist member among migmatite granites on the northern shore of Lake Nyuk, Western Karelia (Sviridenko, 1974).

Table 3
Chemical composition
of the rocks of the terrigenous sequence, Lake Nizhneye Letneye

Oxides	1	2	3	4	5	6	7	8
SiO_2	69 99	69.22	62 98	72 14	65.86	67.90	70.84	61.22
TiO_2	0.25	0 41	0 55	0 21	0.37	0.55	0 21	0.66
Al_2O_3	15 45	15.45	16 22	14 67	16.22	15.61	15.70	16.74
Fe_2O_3	0.31	0.26	1.51	0.35	0.97	0.85	0.98	1.06
FeO	0.93	1.01	3.95	0.86	3 45	2.66	1.36	4.63
MnO	0.027	0.026	0.084	0.023	0.075	0 047	0.031	0.086
MgO	0.50	0 40	2 97	0.40	2 02	1 06	1.05	3.33
CaO	2.03	1.89	2.38	1.47	2 94	1.89	1 05	2 45
Na_2O	3.67	4.89	3.16	4.08	3.40	3.49	4 35	3.73
K_2O	3.73	3.96	3 82	4 12	2.86	3.86	2.88	3.70
P_2O_5	0.06	0.06	0.06	0.04	0.07	0 25	0 11	0.11
Rb	182	149	225	189	214	250	159	263
Ba	712	1068	979	623	623	712	801	623
Cs	15	16	34	16	29	22	16	37
Zn	88	48	128	40	96	80	64	152

Note. 1, 2, 5, 6, 7 – metasandstone, 3, 8 – metasiltstone, 4 – gneissoid granite.

The great thickness of the sediments in the composite sequence of Late Archean sedimentary volcanogenic rocks transformed into biotite migmatite granites is thus indirectly indicative of a sialic basement whose composition corresponds to that of the "diorite" layer.

Compositionally, metasandstones act as a link between the gneisses of the "diorite" layer and the autochthonous ultrametamorphic granitoids of the granite-ultrametamorphic layer. Plagioclase is their major rock-forming mineral. The quartz and biotite contents are highly variable. The granite gneisses and gneissoid granites in the central part of the domal structures are mainly formed by recrystallization of coarse-grained metasandstones and microcline porphyroblastesis, whereas dense fine-grained metasandstones are preserved as relicts. The chemical composition of metasandstones and metasiltstones (Tab. 3) is similar to that of the

Table 4
Average modal composition of the biotite granitization
series of the Late Archean migmatite-granite formation

Mineral	biotite gneisses and schists		biotite migmatite-granites (blastites)		veined facies of migmatites	
	Central Karelia (N = 10)	Western Karelia (N = 81)	Central Karelia (N = 43)	Western Karelia (N = 59)	Central Karelia (N = 44)	Western Karelia (N = 29)
quartz	26.23	23 48	32.59	28.65	30 32	27 55
plagioclase	46.15	54.29	39 13	47 31	45.63	39.77
biotite	18.72	13.36	4.71	11.14	2.02	2.45
microcline	–	6.71	15.65	10.80	19.27	27 61
muscovite	–	–	3 56	–	–	–
epidote	8.01	–	3.81	–	1.97	–

enderbites and tonalite gneisses of the basement, but differs in the higher content of potassium and lithophilic minor elements concentrated in biotite. It is this difference that makes them similar to biotite gneisses and schists observed as relict layers among autochthonous ultrametamorphic granitoids (Tabs. 4 and 5).

Other indirect evidence that the granulites of the blocks distinguished (Fig. 1) differ in age from the surrounding migmatite granites is the comparability of external conditions under which overpointing of granulites and progressive regional metamorphism of Late Archean volcano-sedimentary rocks took place in Western Karelia (Sviridenko, 1974). This is due to the fact that alteration occurs in the "diorite" layer (or in the basement of Late Archean volcano-sedimentary rocks) when the granulite block is raised into the overlying zone of ultrametamorphism and is, therefore, isofacial to the zone. The rocks of the granulite complex suffer intense reworking, recrystallization and potassium metasomatism only along linear shear zones. However, no uniform transformation throughout the entire rock sequence has been reported. These differences in the volume effect of granitization are responsible for the demarcation of the geological complexes of both the granite-ultrametamorphic and "diorite", layers in the geophysical pattern of the Karelian geoblock. It follows from the foregoing discussion that the boundary between the granulite complex and the granitized Lopian metasediments is also a geophysical one.

Lateral geochemical heterogeneity of metasomatic granitization

The primary compositional features of the basement rocks have not been completely destroyed but they are markedly distorted because a considerable amount of potassium and some lithophilic minor elements such as Ba, Rb, Li and Cs were supplied to the crust as a result of Late Archean regional metasomatic granitization. The scope of this phenomenon can be assessed if the composition of the basement granitoid rocks from pebbles of Late Archean pre-migmatite conglomerates is compared with the same rocks in the present erosion section and the composition of the pebbles from Late Archean pre-migmatite magmatic rocks is compared with that of corresponding rocks in the present section (Batyeva–Belkov, 1985; Vinogradov–Sviridenko, 1979).

As a result of syntectonic regional granitization, structural complexes of different ages become similar in composition. This gives the impression of a gradual transition. In this case the suture zones of different aged blocks, regarded as increased permeability zones are, as a rule, most intensely granitized.

The lateral geochemical heterogeneity of Late Archean ultrametamorphic granite formation, which correlates with the pattern of Karelia's regional magnetic field, has been established. The highly magnetic Late Archean autochthonous granitoids found in western Karelia developed at higher fluid alkalinity than the coeval nonmagnetic autochthonous granitoids from Central Karelia (Sviridenko, 1980).

A decline in biotite content and the appearance of microcline are related to the formation of autochthonous granitoids under the low-alkali conditions of metasomatic granitization (Karelia). The veined facies of migmatites has a comparable composition. (Tab. 5). Under moderate and high-alkali conditions of metasomatic granitization (Eastern Karelia) the mineral composition of autochthonous granitoids is quantitatively comparable with that of relict substrate, but the microcline present in small amounts in the latter is of metasomatic origin. The veined facies of migmatite differs from the autochthonous granitoids in microcline and biotite content, biotite being the lowest and microcline the highest. Under high-alkali conditions the composition of rock-forming minerals remains practically unchanged, whereas

Table 5
Average chemical composition of the biotite granitization series of the Late Archean migmatite-granite formation

Oxides	biotite gneisses and schists		biotite migmatite-granites (blastites)		veined facies of magmatites	
	Central Karelia (N = 20)	Western Karelia (N = 15)	Central Karelia (N = 25)	Western Karelia (N = 17)	Central Karelia (N = 13)	Western Karelia (N = 16)
SiO_2	63.25	64.45	73.00	68.06	75.16	71.96
TiO_2	0.56	0.67	0.22	0.39	0.12	0.19
Al_2O_3	15.59	16.48	14.40	15.91	13.67	14.92
Fe_2O_3	1.27	1.24	0.66	1.17	0.51	0.87
FeO	4.12	3.50	1.35	2.31	1.11	1.00
MnO	0.08	0.06	0.05	0.05	0.03	0.02
MgO	3.38	2.08	0.47	1.33	0.40	0.22
CaO	4.35	3.22	1.69	3.15	1.71	1.33
Na_2O	3.80	3.79	4.08	4.12	4.53	3.34
K_2O	1.93	3.39	3.56	2.81	2.19	5.49
Rb	137.4	154.1	174.4	135.7	246.1	121.6
Ba	415.0	1684.4	538.1	1223.6	686.6	2296.9
Sr	261.6	471.1	196.0	612.7	100	516.3
Cs	11.8	3.5	6.1	3.5	5.5	2.5

under low-alkali conditions plagioclase is diminished and the iron content of biotite increases (Sviridenko, 1980). Thus, the composition of the initial substrate is changed more appreciably under low-alkali conditions of granitization.

Change in the chemical composition of rocks granitized under low-alkali conditions is seen as decreased MgO, CaO and FeO and increased SiO_2 and K_2O (Tab. 5). The veined facies of migmatites has a comparable composition. Under high-alkali conditions potassium influx is observed at all stages of granitization, and the relict substrate has not preserved its initial composition. The veined facies of migmatites corresponds in composition to subalkaline granite. Oxyphile minor elements (Ba, Sr) accumulated under highly alkaline conditions of granitization and oxyphobic minor elements (Rb) under low alkaline conditions.

It can be inferred from this study that the "diorite" layer, i. e. basement of Late Archean volcano-sedimentary deposits differs from the Late Archean autochthonous granitoids of the granite-ultrametamorphic layer in the low content of potassium and lithophilic minor elements, and is more basic. In other words, the Earth's crust of the Karelian geoblock formed at the end of the Late Archean corresponds in both structure and composition to the continental type of a mature crust in contrast to the protocrust of the „diorite" layer which serves as a basement for Late Archean greenstone belts.

In the Ladoga geoblock the granite-ultrametamorphic layer formed in the Early Proterozoic along the same petrological and geochemical trends (Sviridenko, 1980), but melting processes played an important role here in granite formation owing to a higher geothermal gradient. The granite-forming processes responsible for the average density of the granite-ultrametamorphic layer are of the same type. The latter differs in age in adjacent geoblocks. The sequence of the geophysical layers in the vertical section of the crust is identical. All this indicates a relationship between mantle and crustal processes in the Earth's evolution.

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