Composition of metamorphic rocks and some aspects of evolution of the Lapland Granulite Belt on the Kola Peninsula, USSR

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Combined geological and petrochemical data suggest that the Lapland Granulite Belt can be divided into a lower sedimentary-volcanic unit and an upper, predominantly sedimentary sequence. Metamorphic rocks from the lower parts of the section have given zircon ages of 2.7 - 2.8 Ga. The geochemical signatures of the metavolcanites and metasedimentary rocks suggest that the Lapland granulites are comparable to Phanerozoic island arc complexes. The composition of the pre-Lopian basement blocks is in agreement with this hypothesis. According to our proposed model, the development of the Belt was initiated by underthrusting of the Belomorian block beneath the Kola block. This led to widespread volcanic activity, which was eventually superseded by the sedimentary cycle. The complex was then taken down to depths sufficient for metamorphic transformations in granulite facies; this occurred at around 1.9 - 2.0 Ga.

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Introduction

Data obtained from various regions of the world indicate that a considerable proportion of granulite terrains occur in the most ancient formations of mobile belts. This explains why a study of these terrains is of great importance for the investigation of the early stages of evolution of the Earth's crust and its metallogenic properties. Examination of the primary nature and pre-metamorphic structure of strongly metamorphosed Archaean sequences presents difficulties since the shapes of geological bodies, and structures and textures of the rocks differ from those in the initial state, and it is also difficult to decide whether the primary form of rock layers has been preserved. Petrochemical study of supracrustal formations, however, provides an efficient means of reconstructing the conditions of sedimentation and volcanism.

The present work is the result of long-term investigations (1977 - 1990) carried out by the authors in the Lapland Granulite Belt in the territory of the USSR. It should be considered in conjunction with the investigations started by Mikkola (1941), Eskola (1952), Belyaev (1971) and Meriläinen (1976), and continued later by Vinogradov et al. (1980), Barbey et al. (1980, 1984, 1986), Hörmann et al. (1980), Krylova (1983), Marker (1985) and Raith & Raase (1986).

The results of our investigations are based on geological and geochemical data comprising over 600 complete silicate chemical analyses (more than a half of them are original) and about 400 quantitative determinations of minor element contents, conducted at the Geological Institute of the Kola Science Centre of the USSR Academy of Sciences, in Apatity. The limited length of the paper does not allow us to document the results in full; consequently, in some cases, we outline only the most significant conclusions and emphasize the results of the geochemical studies.

Regional setting

Integrated geological and geophysical investigations of the Granulite Belt enabled us earlier (Kozlov 1983, 1988a) to suggest that it consists of two parts: a lower sedimentary-volcanic unit and an upper, originally sedimentary sequence (Fig. 1). It should be noted that, like many geologists (Belyaev 1971, Krylova 1983), we believe that the Belt is composed of both the granulite rock complex and the rocks occurring in the south-southwest adjacent to the granulites and metamorphosed

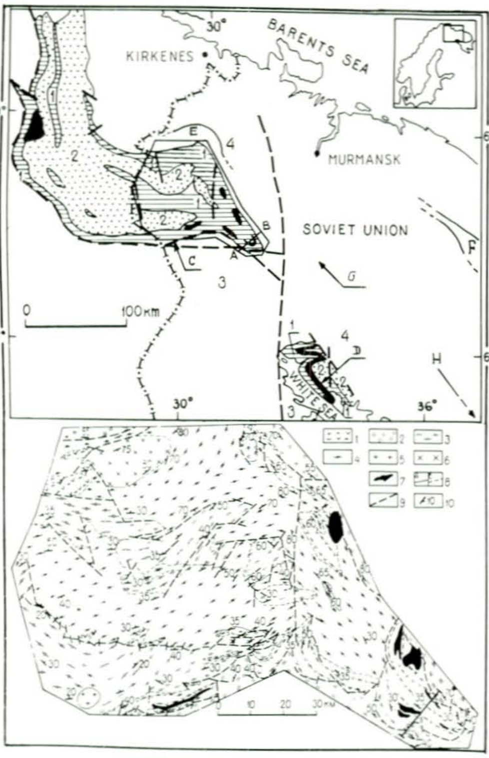

Fig. 1. Simplified geological map of the Lapland Granulite Belt; based on Barbey et al. (1980), Marker (1985) and Predovsky (1987). Arabic numerals indicate the location of metavolcanites from the lower (1) sequence of the belt and metasedimentary rocks from the upper (2) sequence. 3, 4 - Early Archaean metamorphic sequences of the Belomorian and Kola megablocks, respectively. AB - line of section, Salny tundra; C-H — terrains: C - Korva tundra; D - Kolvitsa tundra; E - Allarechensk; F - Kolmozero - Voronya; G - Imandra; H - Tersky block.
The detailed map (below) shows the geology of the northwestern part of the Lapland Granulite Belt (Kozlov et al. 1990). Legend: *Supracrustal and ultrametamorphic formations*: 1 - garnet amphibolites and meso-melanocratic pyroxene-plagioclase schists, commonly with garnet and locally with biotite and amphibole; 2 - gneisses and amphibolites of the peripheral areas; 3 - garnet-biotite gneisses, granitic gneisses, quartz-feldspar granulites with garnet and sillimanite-biotite-garnet-quartz-feldspar granulites; 4 - endebites. *Intrusions*: 5 - plagiomicrocline granites; 6 - diorites; 7 - metagabbro-anorthosites. *Other symbols*: 8 - geological boundaries (a - defined, b - hypothetical); 9 - tectonic boundaries and major fracture zones; 10 - foliation.

under amphibolite-facies conditions. The latter rock complex is distinguished by many investigators of the Norwegian and Finnish fragments of the Granulite Belt as the Tanaelv Belt (Barbey et al. 1984, 1986; Marker 1985).

Our opinions are presented in the monograph of Kozlov et al. (1990b), and here we list only the major grounds for this interpretation:

1. According to the available data there is no break in sedimentation in the sequences of the above-mentioned complexes. Laterally within the Belt the boundary of granulite metamorphism occupies different positions in the section relative to the primary varieties of metamorphosed volcanic rocks that subsequently replace each other in the Belt. This has been described, for example, from the Salny tundra area (Kozlov et al. 1988a); see Fig. 2.
2. Metamorphosed volcanic rocks of both complexes have similar geochemical properties. The same has been described by Barbey et al. (1984, 1986) for the rocks occurring in Finland. A special emphasis should be given to the fact that all rock types, irrespective of their metamorphic grade, have increased contents of strontium and, in some cases, barium. This we relate to a particular regime of formation of the sequences in the whole complex at the pre-metamorphic stage (Kozlov et al. 1989).

Considering this approach to the interpretation of the overall structure, we believe that it includes the Korva tundra rocks located in the southwestern part of the Belt, in the USSR, where conglomerates with pebbles of plagioclase granite, similar to those described for the Kolvitsa tundra area, are known near the basal contact. The novelty of this interpretation is that one of the authors (A.A.I.) considers the main Korva tundra structure to be an anticline (Fig. 3). This assumption is supported by the data on the chemical composition of the rocks from the zone near to the contact (Table 1). The contact structure is analogous to that reported from the Salny and Kolvitsa tundras (Kozlov et al. 1990b). Accepting that our suggestions and interpretations are correct, the term 'granulite belt' becomes a conventional one and does not reflect the nature of the metamorphism in the structure as a whole; hereafter it is used only because of tradition.

Up to the present there are no reliable radiometric datings which allow one to speak about an Archaean age for the Belt. The age of 2.6 Ga for the granulites, obtained by Sukhanov et al. (1987) for metamorphosed volcanites of the Kolvitsa tundra by the Pb^{207} - Pb^{206} zircon method of thermionic emission, may be considered only as a preliminary date. As for the datings of Zykov et al. (1984) yielding 2.78 Ga (Pb-Pb whole-rock age for metamorphosed

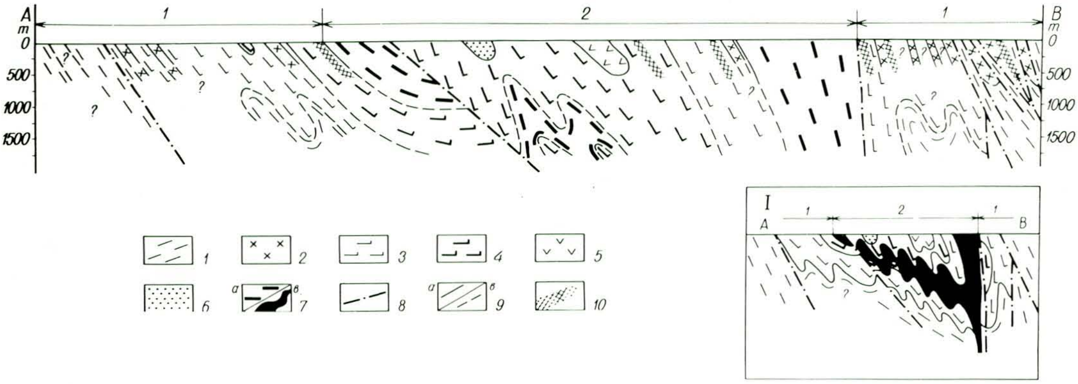

Fig. 2. Schematic cross-section of the granulite complex of the Salny tundra area (A-B in Fig. 1). Legend: 1 - the basement rocks (biotite gneisses); 2 - andesite-dacites and dacites (amphibole-biotite gneisses, locally with pyroxene); 3 - tholeiites (garnet amphibolites, pyroxene schists with or without garnet): 4 - aluminous basalts (garnet amiphibolites, pyroxene schists with garnet); 5 - aluminous andesitic basalts (pyroxene-plagioclase schists with garnet); 6 - greywackes and subgreywackes (alkaline granulites); 7 - anorthosites; 8 - faults (real and inferred); 9 - geological boundaries: a - real, b - inferred; 10 - mylonitization zones. I (inset profile) - tentative general interpretation of the section.

volcanites), they seem to be rather doubtful. The rocks metamorphosed in granulite facies (andesite tuffs) and, in our opinion, constituting the lower parts of the section, were dated to 2.7 Ga (U-Pb zircon method, Kolvitsa tundra; Bogdanova & Yefimov 1984). This figure is complemented by the datings of 2.7 - 2.8 Ga obtained by the lead thermionic emission method on zircons from metamorphosed andesites of the Kolvitsa tundras (Sukhanov et al. 1987), Korva tundra, and areas to the southeast, which are considered to belong to one and the same complex (Kozlov et al. 1990a). These age determinations need to be confirmed, and this is a subject of our future investigations.

Our suggestion for an Archaean age for the volcanic and sedimentary rocks of the Granulite Belt is based on the following:

1. The general nature and characteristic features of the belt — geological structure, aspects of the chemical composition, and primary features of the rocks — indicate that there is an essential similarity between these formations and the Lopian (Late Archaean) sections of the Kola and Karelian regions that have yielded reliable age determinations which are older than Proterozoic (Predovsky 1987).
2. The rocks of the granulite complex lie directly upon formations of the Belomorian (White Sea) megablock (as shown in Fig. 3) which are considered to be Early Archaean. The Belomorian formations, in contrast to the rocks of the Granulite Belt, have been affected by two additional stages of deformation (Balagansky et al. 1986). If the granulites were of Proterozoic age, then

Table 1. Chemical composition of the rocks from the contact zone of the Granulite Belt and the basement complex, Korva tundra area.

Sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
2493	66.28	1.29	14.03	5.45	3.25	0.03	0.82	0.95	2.78	3.11
2486	62.37	0.70	19.00	3.50	3.69	0.06	1.62	1.76	2.43	2.03
IA-101/1	49.94	2.84	13.29	6.27	10.00	0.23	4.99	8.86	1.36	0.37
2477	51.06	1.63	11.14	0.41	10.41	0.21	8.68	10.33	2.99	0.41
2479	71.75	0.37	12.82	1.33	1.88	0.02	2.11	1.18	4.49	2.80
IA-108	67.94	0.40	13.30	0.81	3.66	0.02	3.45	1.88	3.91	2.42
2474	71.80		14.42	0.00	2.68	0.02	1.00	0.55	7.90	0.38
2476	64.61	0.68	16.76	2.50	5.79	0.10	2.06	1.24	1.24	2.09
2484	81.23	0.17	11.15	1.09	0.36	0.00	40.27	0.00	0.46	3.25
2483	46.78	0.19	17.55	2.05	3.89	0.11	10.56	14.56	1.60	0.19
2498	52.67	0.25	22.08	2.18	1.07	0.14	2.36	12.73	4.10	0.39
2481	67.52	0.12	15.28	1.30	2.90	0.06	1.15	3.52	4.94	1.97
2495	65.14	0.48	14.98	2.00	2.49	0.03	3.34	2.40	5.25	2.16
IA-107	49.73	1.26	14.22	1.63	10.55	0.21	6.87	10.60	2.56	0.45

Note: Sample numbers correspond to those in Fig. 3.

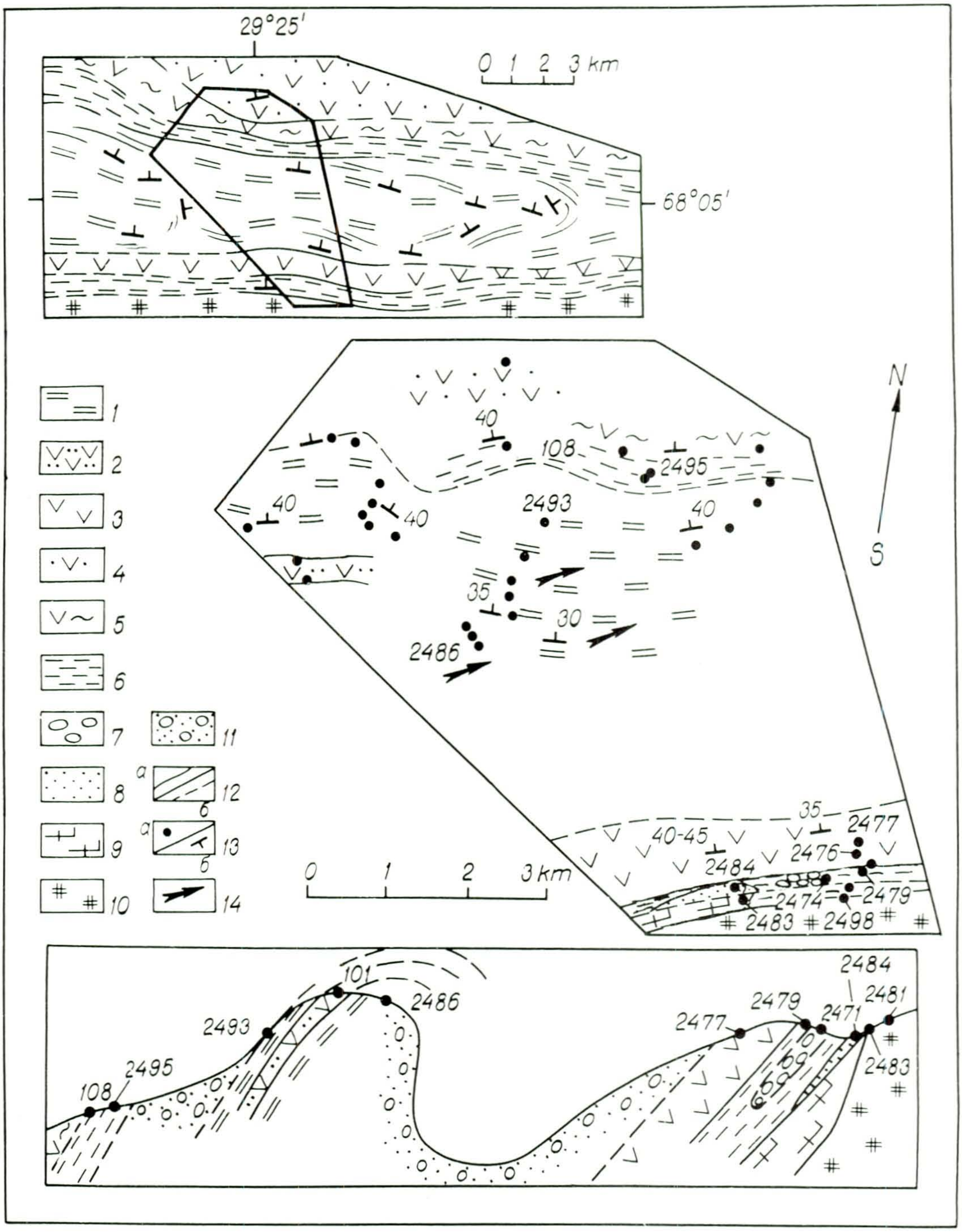

Fig. 3. (a) Schematic geological map of the contact zone between the granulite-gneisses and granulite complexes in the area of the M. Korva-tundra. (b) Enlargement of the area framed in (a). (c) - schematic section of the contact zone in the area of the river Pados, not to scale. Legend: Belomorian complex: 1 - biotite gneisses; 2 - amphibolites with garnet. Lopian complex: 3 - plagioclase amphibolites; 4 - garnet amphibolites; 5 - amphibolite gneisses; 6 - biotite- amphibole gneisses; 7 - metamorphosed conglomerates; 8 - muscovite-quartz gneiss-schists; 9 - gabbroanorthosites; 10 - palingenetic granitoids; 11 - Quaternary deposits; 12 - real (a) and inferred (b) geological boundaries; 13 - (a) observation points and (b) - strike and dip of foliation; 14 - plunge of fold axes.

we must infer that there were only two stages of deformation during the late Archaean.

The opinion favouring a probable Archaean (Lopian) age for the Lapland Granulite Belt is fairly popular among soviet geologists (Krylova 1983, Rundkvist & Mitrofanov 1988). Providing that this conception is true, the younger ages reported by Bernard-Griffiths et al. (1984) probably reflect the subsequent metamorphic transformations of the complex at around 2.0 Ga. These transformations were, in our opinion, accompanied by processes of enderbitization, charnockitization and partial melting. Nevertheless, some of the primary geochemical properties of the various formations survived these changes (Kozlov et al. 1990c).

Geochemical features of metamorphosed volcanic and sedimentary rocks

Specific features of the primary composition of the supracrustal formations reconstructed by the petrochemical method (Predovsky 1970) have been discussed by Kozlov (1983, 1988a). The most typical rock-types within the belt as a whole have a fairly homogeneous chemical composition (Table 2). The probable primary rock-types of the diverse metamorphic assemblages are indicated in Table 3.

Metamorphic rocks of a tentatively primary volcanogenic origin constitute the lower part of the section, which begins with tholeiites (group 1 in Table 2) composing about 43-45% of the total volume of volcanites. Andesites, dacites and andesite tuffs, reaching up to 15-18% by volume, are intercalated with the above rocks. Upwards, the tholeiites are replaced by aluminous basalts (group 4, Table 2), which make up 33-35 % of the volume of the volcanites. Aluminous andesitic basalts and andesites, at the top of the metavolcanite section, do not occur everywhere; their volume varies considerably from 0 to 15 %. The alternation of basalts, andesites and andesitic tuffs in the lower part of the section can be explained by the occurrence of faults located

Table 2. Chemical composition of the main rock types in the Kolvitsa tundras (K), northwestern part of the Granulite Belt (C) and Lake Inari region (I).

No.	Region	Number of samples	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	F	A	K
1	K	18	50.50	1.02	14.46	2.48	9.96	0.18	6.84	9.91	2.57	0.72	0.39	-73	-38
	C	11	49.55	1.09	14.63	2.49	10.27	0.22	6.74	9.99	2.57	0.64	0.45	-88	-39
	I	2	51.52	1.30	14.00	2.89	9.29	0.23	6.45	10.12	2.36	0.51	0.36	-88	-33
2	K	4	67.79	0.54	14.88	1.68	5.19	0.07	2.13	4.95	3.91	1.16	0.13	-11	-51
	C	2	64.19	0.67	13.86	1.29	4.27	0.08	3.18	4.62	3.24	1.76	0.14	-36	-60
	I	1	61.08	0.51	15.10	3.71	4.36	0.14	2.69	7.29	2.69	0.68	0.15	-33	-37
3	K	16	67.84	0.52	12.57	1.45	4.06	0.08	2.01	3.71	3.71	1.70	0.10	-17	-38
	C	6	68.32	0.51	13.15	1.76	3.74	0.06	1.72	4.52	2.99	2.01	0.09	-15	-33
	I	1	67.37	0.74	13.37	1.31	2.85	0.08	1.95	6.78	4.03	0.30	0.09	-56	-62
4	K	10	51.52	0.67	16.86	1.89	6.75	0.15	7.59	9.73	2.81	0.47	0.35	-59	-40
	C	10	50.96	0.56	18.64	1.56	6.04	0.12	8.46	9.96	2.47	0.32	0.36	-34	-27
5	K	4	52.78	0.69	19.59	2.19	4.82	0.11	4.97	9.68	3.56	0.47	0.24	-50	-53
	C	5	55.05	0.64	17.29	1.59	6.36	0.10	5.55	7.29	3.28	0.66	0.26	-37	-43
	I	1	52.56	0.60	19.46	1.56	6.80	0.22	5.81	8.10	2.96	0.61	0.29	- 7	-42
6	K	3	60.53	0.47	18.41	1.45	3.71	0.07	2.54	6.01	4.59	1.16	0.12	-18	-63
	I	1	56.97	1.33	18.11	2.06	5.01	0.10	1.98	7.36	4.48	1.14	0.14	-39	-61
7	K	7	78.62	0.38	10.27	0.52	3.30	0.06	1.17	1.75	2.51	1.33	0.07	+17	-26
	I	8	76.75	0.31	11.87	0.76	2.38	0.05	0.92	1.51	2.05	2.56	0.06	+30	- 6
8	K	17	66.03	0.58	14.77	1.31	5.08	0.08	2.81	2.66	2.79	3.32	0.14	+30	-17
	C	4	67.22	0.60	14.10	1.74	5.61	0.08	2.90	1.60	1.73	2.92	0.16	+53	+ 3
	I	7	65.13	0.69	10.75	1.25	4.34	0.07	2.77	3.36	2.46	2.08	0.13	+42	-17
9	K	5	58.57	0.72	18.52	2.10	7.05	0.11	3.47	1.25	1.76	4.24	0.20	+93	+17
	C	7	63.11	0.67	17.22	1.27	6.59	0.08	2.88	1.18	1.62	2.63	0.16	+94	+ 2
	I	2	65.89	0.54	17.30	1.36	4.75	0.08	2.98	1.52	1.70	2.78	0.14	+85	+ 3

1 - tholeiites; 2,3 - andesites and dacites interlayered with basalts; 4 - aluminous basalts; 5 - andesitic basalts with higher aluminium content; 6 - andesites with higher aluminium content; 7 - subgreywackes interlayered with greywackes and pelites; 8 - greywackes; 9 - pelites. The numbers 1- 9 indicate the position of the rocks in the total section.

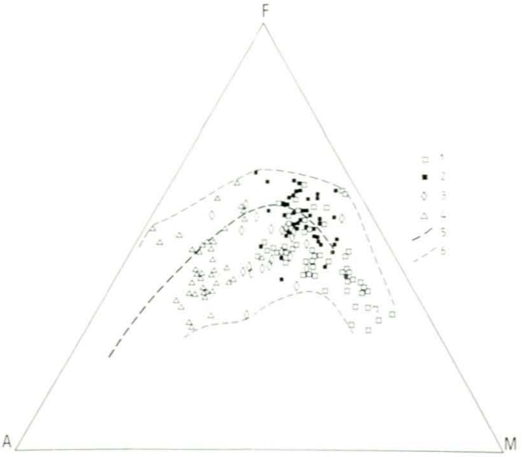

Fig. 4. AFM diagram for the metavolcanites of the Lapland Granulite Belt. Legend: 1 - tholeiites; 2 - aluminous basalts; 3 - andesitic basalt; 4 - andesites and dacites; 5 - boundary between tholeiitic and calc-alkaline series (Irvine & Baragar 1971); 6 - boundary limits showing the general trend of evolution of the metavolcanites.

close to each other at various depths, and formed in a period of increased tectonic activity (Bogdanova & Yefimov 1978). The presence of a tuffogenic cement in conglomerates in the Kolvitsa tundra section (Predovsky 1987) also signifies volcanic activity.

In an AFM diagram (Fig. 4) the trend of chemical compositional change of the metavolcanites from the Granulite Belt is located close to the boundary between the fields of the tholeiitic and the calc-alkaline series, though closer to the latter. On the petrochemical diagram proposed by Piskunov (1987) for separating the volcanites of oceanic and folded zones, the average composition of all typical varieties of the granulite belt metavolcanites (see Table 2) is found within the field of the 'folded zone', i.e. island arc plus continental margin. Of the various magmatic products of this zone the granulitic formations, which were primarily volcanogenic, fall within the field of island arc volcanic associations (Fig. 5).

The diagrams of Lutz (1980) show that the basalts of the belt are close to both island arc associations and volcanites of oceanic origin (Fig. 6). Such an intermediate composition can probably be explained by their ocean-marginal location in the proto-island arc system, which is characterised by Al-rich basalts (Ivanov & Kozlov 1987, Kozlov 1988b). The obtained evidence is in good agreement with the data of Barbey et al. (1984) who suggested the presence of two series, tholeiitic and calc-alkaline, in volcanic rocks of both the Tanaelv and the Granulite Belts.

The complete set of analytical data, showing

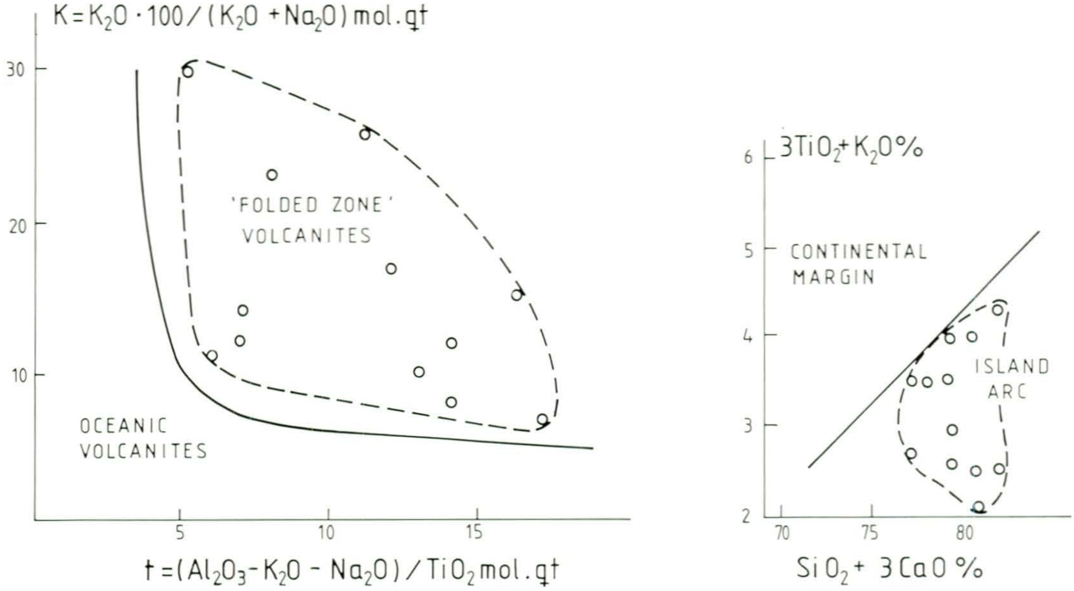

Fig. 5. (a) K-t and (b) $3TiO_2$+K_2O-SiO_2+3CaO diagrams of Piskunov (1987) for metavolcanites of the Lapland Granulite Belt.

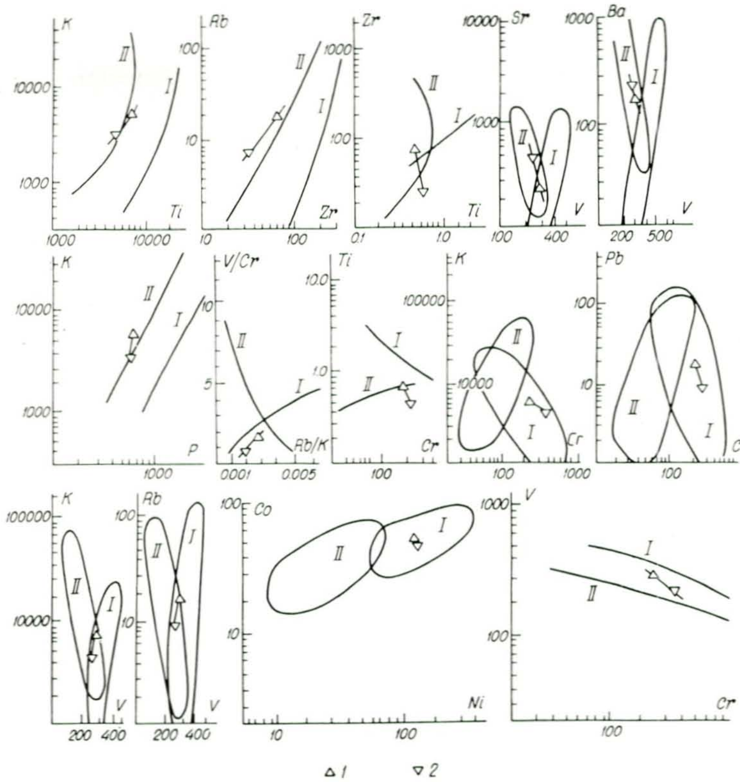

Fig. 6. Tholeiites (1) and aluminous basalts (2) of the Granulite Belt plotted on diagrams by Lutz (1980). The roman numerals indicate the fields and trends of oceanic (I) and island arc (II) basalts.

the initial tholeiitic volcanism, the occurrence of dacites in association with tholeiites in the very early stages, and the replacement of this bimodal association by Al-rich volcanites which are close to calc-alkaline in composition, accord with the pattern of evolution of island arcs (Bogatikov & Tsvetkov 1988, using A. Ringwood's materials). The absence of alkaline volcanites in the section indicates the similarity of this association to that of juvenile arc complexes, which is confirmed by the presence of abundant alumina-rich basalt with subordinate andesite basalts, andesites and dacites.

Metavolcanites in the southwest adjacent to the Granulite Belt are represented by a wide range of rock-types from tholeiites to dacites. In composition they can be compared to metavolcanites from the lower part of the sedimentary-volcanic sequence, but at the same time they differ from the lower metavolcanites in an almost complete absence of Al-rich units and the presence of metamagmatites with a low content of alkalies. The latter fact, taking into account the increasing alkalinity of volcanites in island arc systems from the ocean towards the continent, corresponds well with the scheme of petrochemical zonation of the Lopian formations (Kozlov 1988b).

We should probably not look for a direct similiarity between the pre-Lopian basement blocks and those of oceanic or continental types; nor should we accept the supposition concerning the similarity of the northwestern Kola region complex to that of an island arc as entirely corresponding to the mode of formation of Phanerozoic island arcs. If we assume that the granulite complex was formed in an environment similar to that of an island arc, then we should find comparable features with corresponding crustal types for the pre-Lopian formations. To define such features we have compared the rocks from the basement of the Lopian assumed island arc system with those in adjacent blocks or microplates. As a basis for tectonic zonation of the region we have adopted the scheme devised by geologists from the Institute of Precambrian Geology and Geochronology (Earth's crust ... 1978).

In the present paper we have used some data from the southwestern area, outside the granulite complex, together with published material and information kindly provided by

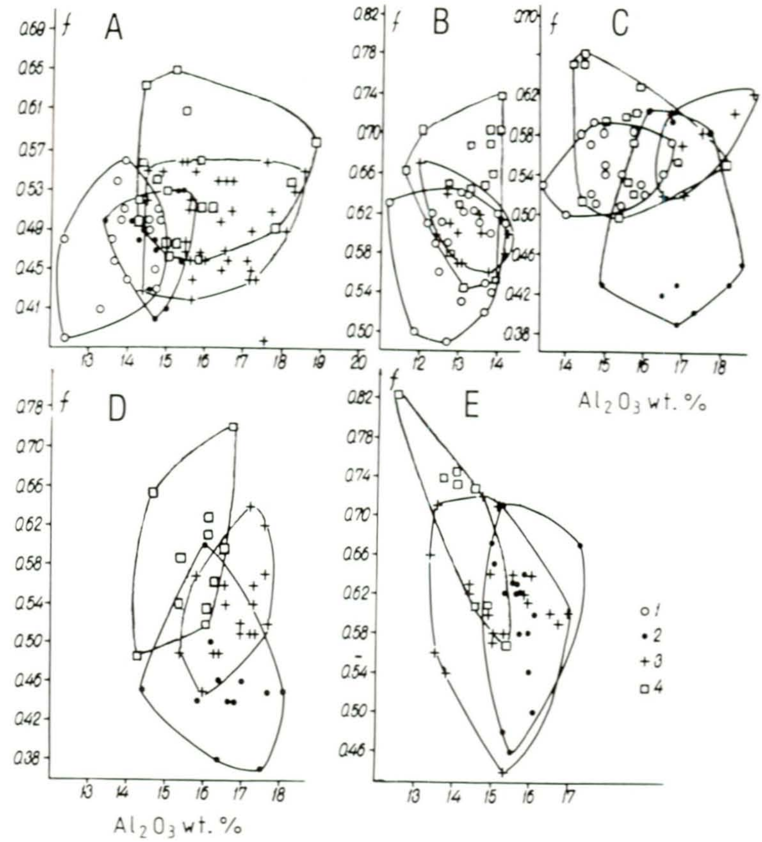

Fig. 7. Al_2O_3-f diagrams for Early Archaean metavolcanites of the Kola Peninsula and northwestern Belomorie. Legend: 1. Allarechensk region, 2. Imandra region, 3. Tersky block, 4. Northwestern Belomorie and southwestern part of the Kola Peninsula. A - tholeiites, B - ferruginous basalts, C - andesitic basalts, D - dacites-rhyolites.

our colleagues V.V. Balagansky, V.I. Bolotov, M.M. Yefimov and V.I. Pozhilenko.

Volumes of typical rock-types in the northeastern (Predovsky 1987) and southwestern areas peripheral to the granulite complex are, respectively; rhyolites — 6 % and 4 %; dacites — 7 % and 11 %; andesites — 11 % and 11 %; andesitic basalts — 7 % and 7 %; basalts — 25 % and 42 % from 56 % and 75 %, the percentage of metavolcanites in the total volume of supracrustal rocks. Differences between the metamorphic rocks of the southwestern and northeastern marginal areas are evident on comparing them in Al_2O_3 - f diagrams (Fig. 7). A more detailed comparison of the most typical metavolcanites (except basalts, which are more widespread in the area to the southwest of the Granulite Belt) shows that within the groups of similar mafic index they are characterised by a somewhat higher iron content. The differences revealed in the compositions of rocks forming the pre-Lopian basement complexes in these northeastern and southwestern areas outside the Granulite Belt are thus in agreement with our hypothesis for the probable evolution of the Earth's crust in this region in pre-Lopian time.

Rocks of a tentatively primary sedimentary origin within the belt constitute the bulk of the upper sequence and occur as interlayers in the lower, sedimentary-volcanogenic unit. Within the upper metasedimentary sequence, greywackes predominate and are confined to the lower part of the section. Pelites prevail in the upper part of the section. Approximate percentages of the different rock-types in the section are as follows: greywackes 50% (group 8 in Table 2), subgreywackes 14% (group 7), arkoses 1-2%, pelites 24% (9), tuffites 20% (only in Kolvtsa; Kozlov 1983).

Additional information on the primary character of the rocks has been obtained from the distribution of C_{org} (Sidorenko & Sidorenko 1975, Petersilje et al. 1979). These data are supplemented by the results of a detailed study of the most typical varieties of rocks shown in Table 3 (58 determinations). The rocks interpreted herein as metasedimentary formations

Table 3. Metamorphic rocks of the Granulite Belt and surrounding areas and their suggested primary character.

Metamorphic rock names	Primary nature of the rocks
Schistose anchimonomineralic tremolite amphibolites.	Picrites
Garnet amphibolites, meso-melanocratic garnet-clinopyroxene plagioclase schists, meso-melanocratic garnet-bipyroxene-plagioclase schists, mesocratic bipyroxene-plagioclase schists.	Tholeiitic basalts
Garnet amphibolites, meso-melanocratic garnet-clinopyroxene plagioclase schists, meso-melanocratic garnet-bipyroxene plagioschists, mesocratic bipyroxene-plagioclase schists.	Tholeiitic basalts
Leucocratic garnet-clinopyroxene-plagioclase schists, mesocratic bipyroxene-plagioclase schists, meso-melanocratic garnet-amphibole gneisses and gneiss-schists.	Andesitic basalts
Leucogratic and mesocratic biotite, amphibolebiotite, biotite amphibole and amphibole gneisses and gneiss-schists, rare leucocratic garnet-orthopyroxene-plagioclase schists.	Andesites and dacites
Biotite and biotite-amphibole gneisses, gneiss-schists and granitegneisses.	Rhyodacites and rhyolites
Felsic granulites, garnet-biotite gneisses, garnet-biotite granite gneisses, garnet-biotite plagiogranites. Pyroxene-garnet-biotite plagioclase schists (?) Micaceous and amphibole-micaceous gneiss schists.	Greywackes
Felsic granulites. Garnet-micaceous, micaceous and amphibole micaceous gneiss-schists.	Subgreywackes
Felsic granulites.	Arkoses
Felsic granulites, garnet-biotite, garnet-bimicaceous gneisses and gneiss-schists with kyanite, staurolite and sillimanite. Micaceous and amphibole-micaceous gneissschists.	Pelites
Biotite-pyroxene gneisses	Tuffites of intermediate composition
Muscovite quartzites	Quartzitic sandstones

have a less homogeneous C_{org} content than the metavolcanites and, in general, are enriched in this element. The C_{org} content in the pelites, for example, reaches 2.4 %, according to the data of T.A. Fedkova (Petersilje et al. 1979).

To estimate the quantitative characteristics of weathering and sedimentation we calculated the intensity (W_1) and extensiveness (W_2) of weathering and the degree of sedimentary differentiation (d) (Predovsky 1970). These parameters (Table 5) allow us to refer the metasedimentary formations of the Granulite Belt to the zones of strong or maximum-activised downwarping. This is in good agreement with the conclusion regarding the active tectonic regime during the time of formation of the metavolcanogenic sequences. This conclusion is supported by plots of metamorphosed clastic rock samples in Bhatia's (1983) diagrams; although somewhat scattered, they tend to fall in island arc fields (Fig. 8).

Another specific feature of the metaclastic rocks is their higher content of strontium (Kozlov et al. 1989) as compared with the typical strontium content for similar Phanerozoic and Precambrian formations. This can readily be explained by inherited features of the metavolcanites, while simultaneous volcanic activity and its influence on sedimentation testifies to the active tectonic regime.

Table 4. Content of C_{org} in various rocks groups from the Granulite Belt (in gr/t).

	n	x	Variations
Andesites and dacites	10	100	40-200
Quartzites and arkoses	8	175	30-500
Subgreywackes	10	110	40-200
Greywackes	29	140	40-600
Clastoliths	47	140	30-600
Pelites	9	300	50-1400

Data by T.A. Fedkova (Petersilje et al. 1979)

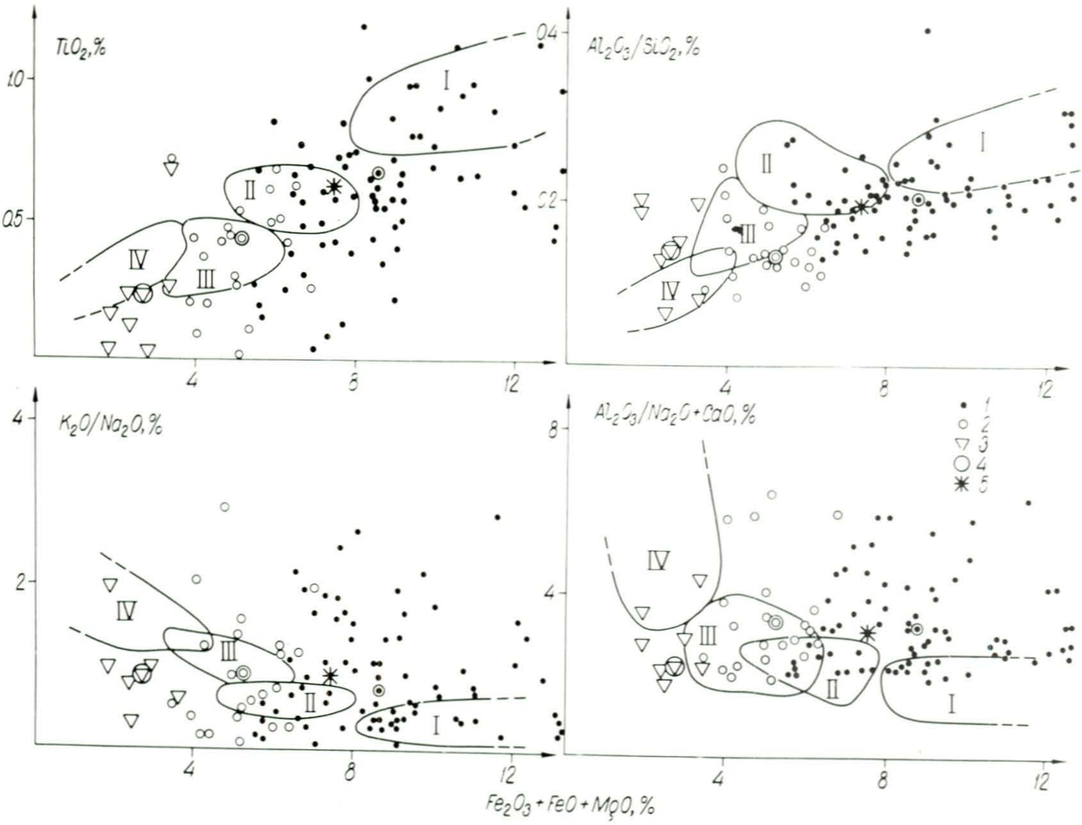

Fig. 9. Diagrammatic SW-NE profiles showing the suggested geodynamic evolution of the Lapland Granulite Belt (not drawn to scale). Legend: 1 - tholeiites; 2 - andesite-dacites; 3 - aluminous andesitic basalts and basalts; 4 - sedimentary rocks; 5 - intrusive complex; 6 - sedimentation; 7 - dominant crustal motions. II and I indicate the areas of the Granulite Belt and its southwestern Lopian periphery, respectively.

Based on a comparative increase in the general intensity and character of the paleotectonic regime, the Lopian formations of central and northwestern Kola can be separated into three regions: (1) Granulite Belt; (2) Allarechka region; (3) Kolmozero-Voronya (Predovsky 1987). This constitutes a kind of tectonic zonation similar to that reported earlier for aluminous basalts (Kozlov 1988b). This zonation can be traced when comparing the approximate volumes of metavolcanic and metasedimentary rocks of the above complexes (Table 6).

A more local zonation is identified by comparing metasedimentary formations from the central and south-southwestern parts of the Granulite Belt. In general, the rocks are similar in major element contents, but differ considerably in a number of minor elements. This is clearly seen in the metapelites, which in the south-southwest are noticeably enriched in copper, nickel, cobalt, chromium and boron (Table 7), testifying to the considerable effect on their formation of simultaneous volcanism. The above difference becomes clear on examining the complete set of data. Thus, Al-rich metabasalts, which form considerable volumes in the upper part of the section of the volcanogenic formations in the centre of the belt, are absent beneath the metasedimentary sequences of the southwestern part of the belt. This indicates that, here, sedimentation began earlier, while within the central parts of the belt the intensive simultaneous volcanic processes continued.

Discussion

The complete geological and petrochemical data allow us to trace the sequence of processes involved in the formation of the Lapland Granulite Belt (Fig. 9).

Probably in Lopian time, during a phase of compression of the Earth's crust, the Belomorian megablock underthrusted the Kola megablock formations along the Belomorian deep fault. Deformations and metamorphism dated to 2.87 - 2.66 Ga in the Lopian basement (Petrov et al. 1986) probably reflect this stage of compression, though this age might be somewhat younger. Differences in composition of the rocks of the pre-Lopian basement blocks led to the initiation of subduction which defined the character of the volcanic activity. At the initial stage, under conditions of higher tectonic activity which controlled the uprise of magmatic sources at various depths, effusion of tholeiitic and andesite-dacite lavas occurred accompanied by outbursts of dacitic and andesitic tuffs. Volcanite sequences were formed, evidently in a submarine environment. This is supported by the presence of conglomerates with a tuffaceous cement, partially weathered and containing admixtures of sedimentary material in the lower section. During a subsequent volcanic cycle the lava composition changed due to an increase in the aluminium content, and as a result thick units of aluminous basalt were accumulated; in the final stage they were replaced by andesitic basalts and andesites with even higher contents of Al_2O_3.

With downwarping of the Lopian basin and displacement of the boundary of volcanism to the northeast of the underthrusting plate (Fig. 9), simultaneously with volcanic activity in the outer part of the belt, the sedimentation continued at the same time as volcanism decreased both within and to the southwest of the belt. The sedimentation resulted in the formation of clastolithic sequences, greywackes, subgreywackes and, after the complete cessation of volcanic activity, of pelites.

After the formation of the volcano-sedimentary Lopian complex had been completed, the next stage of tectono-magmatic activation

Table 5. Quantitative characteristics of the degree of weathering of the parent rocks and of the degree of differentiation for sediments from the Granulite Belt.

Regions	W_1	W_2	d_{av}	d_{max}
Kolvitsa	39	1.1	1.0	10.3
Northwestern part of the Belt (USSR)	39	1.3	1.1	8.7
Inari	42	1.2	1.6	12.2
Belt (total)	39	1.3	1.2	17.2

Note: Calculations were made in molecular percentages.

W_1 (intensity of weathering) = $A_{av} + K_{av}$, where A_{av} and K_{av} are average A and K values for psammite and pelite;

W_2 (extensiveness of weathering) is calculated as a ratio of the maximum range of points for the sedimentary rocks (their basicity, parameter F) to the F axis division value in the FAK diagram (Predovsky 1970);

d_{av} (degree of sedimentary differentiation) = $\frac{\text{A for pelites}}{\text{F for psammites}} \cdot 1000$

where A and F are mean values;

d_{max} (degree of maximum sedimentary differentiation) = $\frac{\text{A for pelite}_{max}}{\text{F for psammite}_{min}} \cdot 1000$

A = $Al_2O_3 - (CaO^* + Na_2O + K_2O)$, where $CaO^* = CaO - CO_2$;

K = $K_2O - Na_2O$;

F = $\frac{SiO_2}{Fe_2O_3 + FeO + MgO}$

Table 6. Approximate volume proportions of the most typical rock groups of the Granulite Belt (1), Allorechensk (2) and Kolmozero-Voroninsk regions of Kola Peninsula.

Rock groups	Regions 1	2*	3*
Volcanites	50	56	75
Rhyodacites	4	4	10
Andesites and andesitic basalts	8	6	3
Tholeiites	22	24	35
Aluminous basalts	16	10	5
Ferruginous basalts	-	3	2
Komatiitic basalts, picrites and hyperbasites	-	9	20
Sedimentary rocks	50	44	25
Greywackes	25	20	17
Subgreywackes	7	7	3
Arkoses	1	1	2
Pelites	12	2	1
Tuffites	5	-	-
Quartzites, sulphide-carbonaceous rocks, conglomerate and pyritic rocks	-	14	2

* — According to the data from Predovsky (1987).

Table 7. Composition of pelites from the central (IA-66 - IA-73) and south-southwestern parts (2622-2446) of the Granulite Belt.

Sample no	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cu	Ni	Co	Cr	B
IA-66	66.29	0.98	14.96	0.11	9.63	0.08	2.61	1.03	1.34	2.28	49	34	19	140	2
IA-65	69.49	0.40	15.39	1.15	5.78	0.06	2.30	1.21	1.47	2.57	36	17	10	130	2
IA-118	58.75	0.79	19.96	6.90	3.96	0.09	3.20	0.96	1.19	2.87	30	53	19	130	3
IA-73	62.26	0.97	16.65	0.00	11.15	0.10	2.94	1.00	0.58	1.66	62	83	20	140	13
$\bar{x}$	64.19	0.78	16.73	2.03	7.63	0.08	2.96	1.04	1.14	2.34	44	47	17	135	5
2622	62.09	0.69	17.21	0.47	8.13	0.15	4.19	1.33	1.54	1.75	130	330	47	830	16
2470	59.20	0.84	18.87	3.50	6.10	0.10	2.00	1.88	2.04	1.98	120	130	29	700	8
2476	64.61	0.68	16.76	2.50	5.79	0.10	2.06	1.24	1.24	2.09	55	100	24	700	8
2720	58.06	0.98	18.63	1.67	8.31	0.14	5.11	1.77	1.32	1.23	160	370	51	470	49
2446	60.86	0.69	18.10	4.70	3.06	0.05	2.39	0.48	1.72	4.35	10	90	20	380	31
$\bar{x}$	60.96	0.78	17.91	2.57	6.27	0.11	3.15	1.34	1.57	2.28	95	204	34	616	22

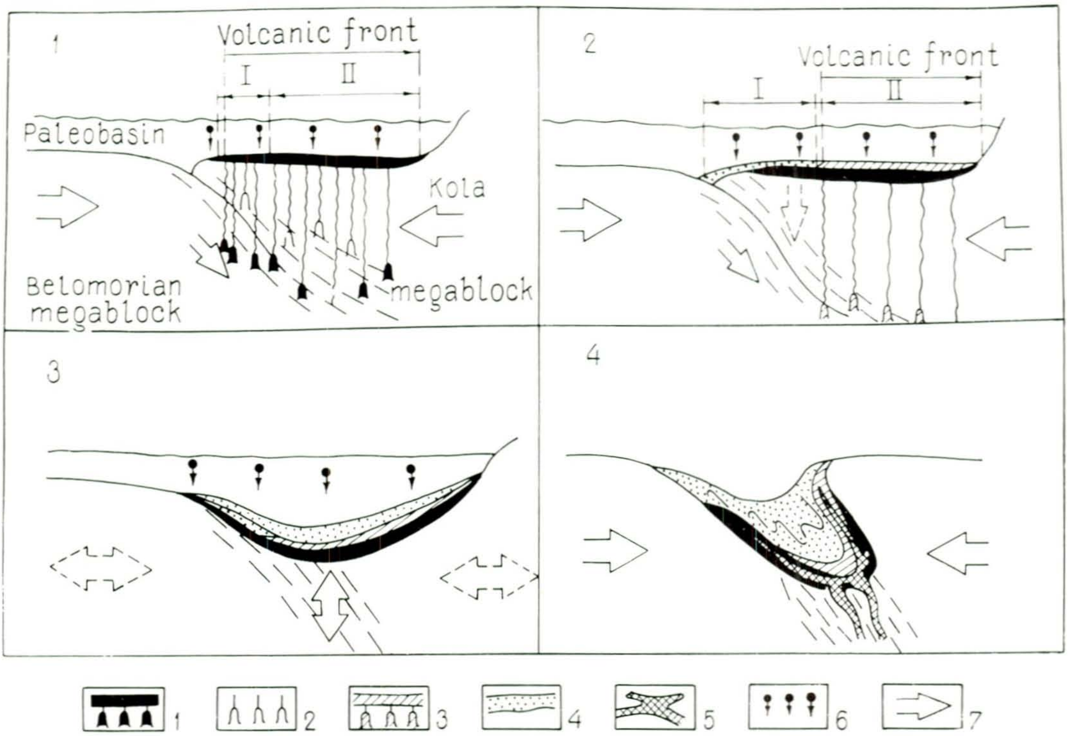

Fig. 8. Ratio diagrams of TiO_2, Al_2O_3/SiO_2, K_2O/Na_2O and $Al_2O_3/(CaO-Na_2O)$ to Fe_2O_3+FeO,MgO (Bhatia 1983). The lined areas show the fields corresponding to: I - oceanic island arcs; II - continental island arc; III - active continental margin; IV - passive continental margin. Legend: 1 - greywackes; 2 - subgreywackes; 3 - arkoses of granulite belts; 4 - average values for groups 1-3 (encircled symbols corresponding to these groups); 5 - average value for metaclastites of the entire belt.

began at 2.5 - 2.3 Ga (or maybe earlier) with intrusions of komatiitic, gabbro-labradorite and iron-rich mafic composition (Kozlov 1986, Sukhanov et al.1987, Kozlov et al. 1988b).

The model presented here describes only a part of the proto-arc system composing the granulite complex. Elaboration of the detailed development of the crust in this extensive region requires additional studies in other territories, which fall outside the scope of the present paper. For such work it will be necessary to take into account the described zonal structure of the Lopian formations.

The model does not show the further evolution of the complex. One can assume that resumption of the downward movement of the Belomorian megablock relative to the Kola block along the Lapland deep suture zone resulted in an eventual burial of the complex down to depths where the combination of pressure and temperature conditions facilitated metamorphic transformations in granulitic facies and partial palingenesis of supracrustal rocks. In subsequent stages the complex was uplifted, exposed and eroded. Presumably such stages of development were repeated.

Based on the interpretation of the primary origin of the rocks and the geodynamic development of the belt, the proposed model (see also Kozlov 1984) is most similar to that of Hörmann et al. (1980). It is also similar to the interpretation simultaneously and independently proposed by other scientists studying the Lapland Granulite Belt (e.g. Barbey et al. 1984), although it differs greatly from the latter in terms of structure and age correlation and therefore in relationships with other structures of the region.

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