GEOLOGICKÝ ZBORNÍK – GEOLOGICA CARPATHICA, 41, 6, BRATISLAVA, DECEMBER 1990,
Pp 693–708

O. M ROSEN – V. S. RACHKOV* – V. E. SONYUSHKIN*

METASOMATISM AND PARTIAL MELTING OF TECTONITES AND ORIGIN OF GRANITES IN SHEAR-BELTS OF THE ANABAR SHIELD (NORTH SIBERIA)

(7 Figs., 1 Tab.)

IUGS UNESCO 235 Project

The Archaean (2.7 Ga) Anabar Granulitic Complex in the Northern Siberian Shield was cut by the Proterozoic shear-belts at 1.96 Ga ago and the Lamuyka Complex was formed by transformation of previous granulites. The rock-forming processes appear to be as follows: areal retrograde metamorphism of amphibolitic facies with influx of H_2O (amphibole-biotite gneisses were formed after granulites); early tectonization (blasto-mylonites were formed), an assemblage of processes combined under the term of granitization (generation of metasomatic porphyroblastic rocks and anatectic migmatites and granitoids), later tectonization (mylonites of greenschist facies were formed). Geochemical data for the metasomatic and anatectic processes shows influx of K_2O, SiO_2 and lithophile elements, and depletion at the same time of MgO and Fe-group elements. The average contents in gneisses, migmatites and granites were calculated correspondingly as follows: K_2O-1.92, 4.35, 5.14 percent; Rb - 52, 120, 150 ppm; Ni - 33, 10, 4 ppm; Cr - 85, 27, 10. Another variations in the same rocks are correspondingly as follows: Ba – 830, 1540, 820 ppm; Sr – 306, 350, 110 ppm; Zr – 241, 380, 130 ppm; Nb - 7, 21, 11 ppm; Ta - 0.5, 1.4, 1.0 ppm. The migmatites suppose to be especially enriched with these elements as a some kind of restite after extracting of granite melt. Sr, Ba seem to be concentrated in plagioclases, Zr - in zircons; Nb, Ta - in femic minerals. The last tectonites after granites appear leaching of K_2O and enrichment with CaO.

Fluid inclusions in quartz of the Archean hypersthene plagio-gneisses composed mostly by high-density CO_2 and were generated under T = 860–890 °C, P = 8–9 kbar. The migmatites of the Lamuyka Complex contain mostly H_2O-inclusions. Their parameters varied from T = 780–810 °C, P = 6–6.5 kbar to T = 500 °C, P = 4–5 kbar. The last tectonites were formed at T = 200–300 °C, P = 0.7 kbar under H_2O-fluid influence. Melt inclusions were investigated by microprobe analysis. In the Lamuyka Complex they contain grains of quartz, K-feldspar, plagioclase, biotite (about 0.5–2 μm across), fine grained devitrified glass material and bubbles of H_2O and gas. This composition allows to suppose anatectic granite melt to form in migmatites.

A plate collision model was proposed for these processes including stages: 1 – tension the Archaean primary sialic crust, appearing of shear-belts, amphibole-biotite diaphtorites arised after granulitic rocks under H_2O-fluid influence; 2 – collision and overthrusting along these shear-belts of previously separated blocks of sialic crust, thickening of the crust, metasomatic potassium feldspar and migmatites were generated after tectonites under influx of H_2O, K_2O, SiO_2 and lithophile elements in fluid, granite partial melt was generated and extracted; 3 – tectonic movements faded, low temperature tectonites were formed under leaching of alkalies by post-granitization fluid, composed by H_2O.

Key words: metasomatism, granite origine, partial melting, Anabar Shield, North Siberia.

* Dr. O. M. Rosen, Dr. V. S. Rachkov, Dr. V. E. Sonyushkin, Institute of Lithosphere, U. S. S. R. Academy of Sciences, Staromonetny per. 22, 10980 Moscow.

Preliminary remarks

A process of granite formation is the most important one in the generation of the continental crust. It's average granodioritic composition (Taylor – McLennan, 1985) seems essentially to be the consequence of granite formation mainly realised as batholiths which produced from crustal rocks (Wyllie et al., 1976).

Two alternative mechanisms may be proposed to explain the general features of the "granitization" process (Marakushev, 1988a): 1 – debasification of the open rock system of the early crust under the influence of mantle fluid influx, including metasomatic processes and granite formation as a consequence of magmatic replacement (after D. S. Korzhinsky) which was outlined by Marakushev (1988b), and 2 – partial (incomplete) melting of the closed rock system after R. J. Holmquist which was later developed by Winkler (1968), Mehnert (1968), Wyllie et al., 1978; McRae – Nesbitt (1980) and others. The Anabar Shield represents an example the early, pre-batholitic stage of granite formation in Earth crust where the connection between crust permeability, fluid invasion along fault-belts, metasomatic generation of porphyroblastic blasto-tectonites and initial melting of granite material may be seen.

Analytical procedures

Major elements were analysed by XRF-method, trace elements Ni, Co, Cr, V, Sc, Zn, Pb, Cu, Zr, B, were investigated by quantitative spectrographic methods with a sensitivities to 1–5 ppm, Ba, Sr, F with sensitivity to 30 ppm at the analytic errors (relative standard deviation) ±30 percent. The flame photometry method was used for Li (0.5 ppm) and Rb (5 ppm). An extractive-fluorometric chemical methods were used for Nb (1 ppm), Ta (0.4 ppm), Ga (1 ppm), Ge (0.5 ppm), at the analytical errors as given above. To control the standard rock samples of the USSR, SGD-1A "gabbro-diorite", ST-1A "trapp", SNS-1 "nepheline syenite" and international standard samples of COMECON (Council for Mutual Economic Aid) countries: BM „basalt", GM "granite" have been used.

Fluid inclusions were studied by methods of thermometry and cryometry (Röedder, 1984; Tomilenko – Chupin, 1983). Temperature of heating was up to 1500 °C. Temperature of cooling varied from −180 °C to +20 °C (at speed up to 13 °C/min) and measurement accuracy in a static regime was ±0.3 °C. An electron microscope ISI-60 with energy-dispersive X-ray microanalyser Link-860 was used for detailed observations and phase analyses in inclusions.

Geological setting

The Anabar Shield is the Northern window of the crystalline basement of the Siberian platform. The main parts of the shield structure are the Archaean Anabar Complex, which includes granulite facies rocks and related anorthosites, and the Proterozoic Lamuyka Complex. The latter amphibolitic facies complex was generated through reworking of the Archaean complex along shear belts (Fig. 1).

The Archaean Anabar Granulite Complex comprises two major formations or groups: the widespread hypersthene-plagiogneiss (enderbite) and two-pyroxene schist (metabasite) volcanogenic formation and the more localized metacarbonate-garnet gneiss of metasedimentary formation. These formations make up about 75 % of the total shield area

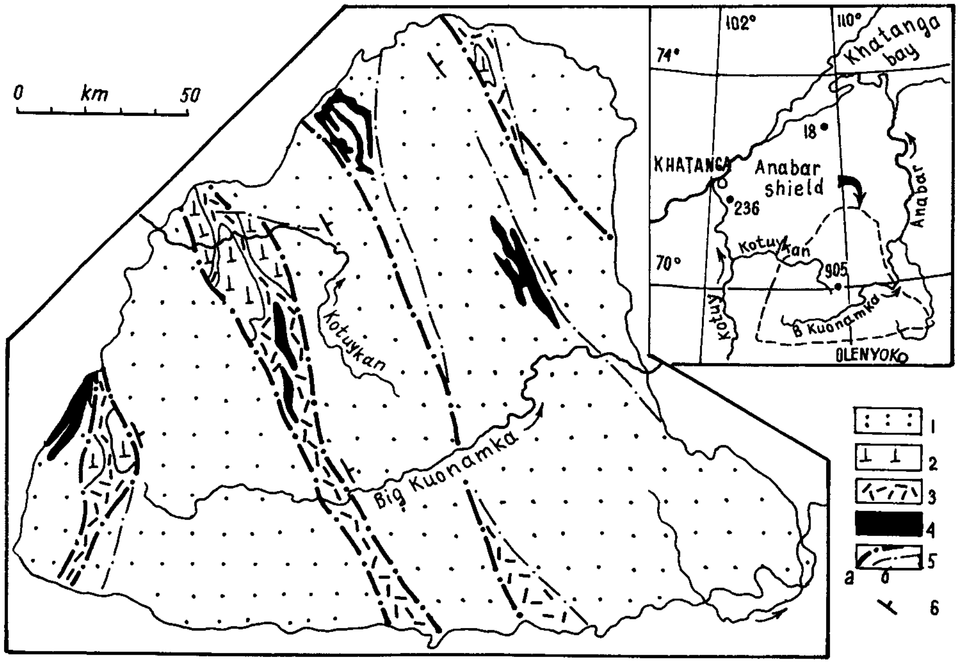


Fig. 1. Schematic geological map of the Anabar Shield.
1 – The Archean Anabar Complex of granulite grade metamorphism: hypersthene-plagioclase gneisses (enderbites), two pyroxene schists (metabasites), some garnet gneisses (metagraywackes) and metacarbonate rocks; 2 – anorthosites; 3 – the Proterozoic Lamuyka Complex: biotite-hornblende gneisses and amphibolites, tectonites, migmatites, and autochthonous granodiorites and granites; 4 – granites and granodiorites of parautochthonous setting; 5 – faults: a-large, b-small; 6 – direction of rock inclination.

which itself covers some 50.000 km^2 (Rosen, 1986). The age of protoliths measured by U-Pb zircon dating exceeds 3.3 Ga. Metamorphism of granulite facies occurred at 2.7 Ga (Bibikova et al., 1988).

The Proterozoic Lamuyka Complex was formed by reworking of the Anabar Complex along linear deep-seated shear-belts. This reworking is inferred to have occurred in the middle Proterozoic (1.9 Ga ago) based on the U-Pb discordia obtained from zircons and monazite (Stepanov, 1974). These shear-belts are each about 10–30 km in width and more than 200 km in length (see Fig. 1). Their strikes are near-parallel to the general orientation of the earlier Archaean structures and they dip steeply ENE. An analysis of general structure indicates reverse or thrust sense of moving in these zones, and blocks of the Archaean complex were thrusted to the WSW (Rosen, 1986). The earliest rocks in these zones are amphibolite facies schists and gneisses formed through the retrograde overprinting of the granulites. Typically hornblende-biotite gneisses and amphibolites contain relics of granulitic pyroxenes and pseudomorphic textures after high-grade assemblages of minerals. Large elongated tectonic blocks (rafts or inclusions) of only slightly retrograted granulitic rocks and rounded to equant bodies of anorthosite are also present. Size of these blocks is variable with some rafts up to 10–15 km in width.

The hornblende-biotite gneisses are strongly deformed over large areas, often leading to the production of blasto-mylonites. These contain porphyroblasts of potassium feldspar (0.5–1 cm) showing signs of rotation under growth and deformed fragments of amphibolitic layers. In some places these mylonites may show transitions to migmatites.

Biotite-potassium feldspar migmatites are common in the Lamuyka Complex. These were formed subsequent to the gneisses, amphibolites and tectonites. The layered structures in these migmatites is determined by the concentration of mafic minerals (mainly biotite, sometimes hornblende and garnet) in melanosomes and of feldspar and quartz in the leucosomes. Localised intensive disharmonic folding is typical in these migmatites, and is interpreted to be a consequence of reduction of viscosity when the temperature has been raised.

Many sheat-like bodies of porphyroblastic biotite-hornblende granodiorite and biotite--bearing leucocratic granite occur. Sometimes they have subalkaline chemical compositions. The thickness of these bodies varies from only meters up to 1–2 km. These granitoids show gradual transitions into the surrounding gneisses through migmatite zones but show discordant and intrusive relations with amphibolites where agmatitic structures may occur. Within the fault-belts the granitoids show a close spatial association with migmatites and tectonites, and hence are interpreted to be autochthonous. However numerous granite bodies occur in the Archaean complex outside the fault-belts (see Fig. 1). These are interpreted to be parautochthonous granitoids (i. e. removal somewhat from their source regions).

The low-temperature tectonites of the Lamuyka Complex are represented by epidote--chlorite-muscovite mylonites and cataclasites formed under conditions of the epidote-amphibolite and prehnite-pumpelliite facies. These rocks were generated at the last stage of tectonic activity in the shear-belts considered here. Tectonic movements in these shear-belts appear to have occurred throughout a part of the Proterozoic.

Geochemical peculiarities

The representative chemical analyses and average compositions of examined rocks are given in Tab. 1. Potassium feldspar was a new mineral phase generated in all of the main events confined to the Lamuyka Complex. This potassium feldspar is inferred to have formed as a consequence of metasomatism by K-rich fluids in porphyroblasts and as a consequence of melt crystallization in granite vein-type bodies. The potassium contents increase from primary rocks (gneisses and amphibolites) through migmatites to granitoids. The contents of silica also increase in the same order. Incompatible trace elements follow potassium and silica, but FeO, MgO, CaO and trace elements of the Fe-group display decrease of contents. General petrochemical tendencies are shown on Fig. 2 and are based on the average concentrations and the standard deviations given in Tab. 1.

The relative contents of potassium (K_2O/ (K_2O + Na_2O) increase throughout the metasomatic and partial melting processes but contents of MgO decrease. Relative contents of iron [tFeO/ (tFeO + MgO)] show an uniform increase. The main chemical process was the influx of SiO_2, K_2O and extraction MgO, tFeO, and CaO. Mafic minerals undergoing recrystallization process of their reconstruction appear to delay the loss in total FeO. Chemical data also show an increase in average H_2O contents from 0.1–0.5 percent in the granulites up to 1.0–1.5 percent in hornblende-biotite gneisses formed after hypersthene plagioneisses (enderbites) and amphibolites formed after two-pyroxene schists. Being concentrated in mafic minerals, H_2O-component appears to deplete in leucocratic granitoids.

Table 1

The representative chemical analyses and average compositions of widespread rocks of the Proterozoic Lamuyka Complex of the Anabar Shield

	gneiss and amphibolite		migmatite				granitoid		late tectonite		
	GN	AMPH	MG-H	MG-A	MB-H	MB-A	GD	G	T-GN	T-AMPH	T-G
	1	2	3	4	5	6	7	8	9	10	11
percent											
SiO_2	61 51/4.19	47 59/2.14	67.30/3.37	67.09/3.28	58.16/3 59	57.41/3 05	66 52/0.91	73 88/1 87	68.12/2 45	58.76/13 25	71.99/0 47
TiO_2	0.62/0.22	1.12/0.30	0 67/0.27	0 59/0 23	0 96/0.35	1 00/0 44	0.74/0 20	0 21/0.15	0 53/0 18	082/0 42	021/0 09
Al_2O_3	16.16/0.47	14.85/2.09	13.99/1.49	14.81/0 76	15 22/0.74	15 54/2 14	14.98/0 24	13.22/1.31	14.25/0.7	15 44/1 43	14 20/0 65
Fe_2O_3	2.20/0.58	2.21/0.75	1 24/0 50	1 41/0 62	2 57/0.51	3.61/1 33	1.67/0 62	0 75/0.21	0 80/0.46	1.27/0 89	0.75/0.39
FeO	3 42/1.59	9.64/2.21	3.87/1 41	3 45/1 28	5 40/1.07	5.54/1 96	3.72/0.62	1.52/0.57	3.02/1.08	4.68/2 47	1 89/0 59
MnO	0.08/0.02	0.18/0.04	0.08/0.06	0 07/0 04	0.12/0.05	0 11/0.06	0.06/0 01	0 03/0.03	0 06/0.02	0.09/0 05	0.04/0 01
MgO	3 10/1.66	7.96/2.05	1.55/0.55	1 37/0.66	3 39/1 30	3 94/1.74	1.22/0.30	0.35/0.28	1 53/0 77	2 83/1 05	0.63/0 14
CaO	5.01/0.79	10 81/1 38	2 50/0 95	2.38/1.35	5.48/1 71	5 28/1.53	2.09/0.79	0.99/0 40	3.07/1 22	8 07/3.51	1 50/1.32
Na_2O	4 05/0.51	2.57/0.77	3 49/0.53	3.44/0.75	3.32/0 56	3 31/0.81	3 51/0 22	3.12/0 73	3.31/0 32	3 59/0.62	3.87/0 71
K_2O	1 96/0.59	0 96/0.33	4.11/1 09	4.50/0.93	3 42/1 26	2.99/1.23	4.21/1 20	5.14/1 22	3.40/0 91	2.74/0.98	4.34/2.01
P_2O_5	0.22/0.13	0 12/0 08	0 20/0.13	0.17/0.11	0.32/0 16	0 31/0.14	0 26/0 04	0.06/0 06	0.18/0.05	0.36/0 23	0 06/0.0
nnn	0.71/0 46	1.03/0.58	0 42/0 3	0.30/0.33	0.54/0 45	1 11/1.14	0 49/0 01	0.09/0.19	0.73/0 11	1 06/0.55	0 37/0.21
H_2O *)	–	1.00/0 21	0 92/–	0.60/0.20	–	0.74/0.11	0.63/0 51	0.43/0 20	0.97/0 32	0 89/0 10	–
CO_2 *)	0.26/0.02	0 30/–	0.54/–	0 20/0 13	–	–	0.52/0.21	–	0.18/0 03	1.02/0 85	0 12/–
Total	99.04	99.04	99.42	99 58	98.90	100.15	89.47	99 36	99 00	99 69	99 35
n **)	7/6	8/6	9	11/9	8/6	8/6	4	11	8	9	3

Letters: GN – amphibole-biotite gneisses, AMPH – amphibolite and mafic schist; MG-H, MG-A, MB-H, MB-A – migmatite after hypersthene-bearing gneiss and amphibole-biotite gneiss, and after pyroxene-bearing metabasite and amphibolite, correspondingly; GD-granodiorite; G-granite; T-GN, T-AMPH, T-G – greenschist facies late tectonites (mainly mylonites) after amphibole-biotite gneiss, amphibolite and granite, correspondingly. Intervals of SiO_2 – contents for gneisses as 53–73 wt . %, for amphibolites and mafic schists as 46–53 wt. % are used for calculation of averages.

continuation of Tab. 1

	1	2	3	4	5	6	7	8	9	10	11
ppm											
Ni	28/16	98/46	10/6	9/6	20/20	28/21	8/1	4/2	15/4	16/8	10/8
Co	18/7	48/9	7/4	7/2	15/12	19/5	8/2	2/1	8/6	13/7	4/1
Cr	69/53	140/100	29/34	22/22	69/66	43/31	14/4	10/5	36/12	50/28	43/50
V	104/9	260/100	51/51	34/22	105/100	125/80	59/15	9/9	53/45	91/51	14/7
Sc	16/8	32/16	5/4	6/4	8/4	15/8	10/5	7/5	7/5	11/9	4/3
Ba	730/480	150/100	1170/1400	1350/400	1150/250	830/805	1065/305	824/705	1530/242	1200/819	770/213
Sr	310/170	130/90	340/280	350/340	260/115	450/270	240/90	108/60	300/28	500/140	400/165
Pb	16/3	8/2	27/9	34/12	20/4	23/11	27/7	29/14	22/3	18/3	30/11
Zn	54/22	90/40	93/108	37/25	67/36	92/82	48/17	23/14	43/7	60/32	30/9
Cu	19/13	65/35	19/13	14/9	19/20	35/28	27/14	9/8	37/17	34/32	40/52
Zr	252/99	100/45	420/250	350/215	260/80	200/280	395/300	133/161	260/10	170/81	150/47
Ga	31/5	28/6	25/6	32/9	25/5	25/10	33/13	29/4	27/4	25/7	30/2
Ge	1.1/0.2	1.2/0.5	1.1/0.4	1.0/0.4	1.4/0.3	1.0/0.3	3.4/3.6	1.0/0.5	0.8/0.0	1.1/0.2	1.0/0.5
Nb	7/4	9/7	22/19	21/21	13/6	9/3	38/35	11/10	14/–	12/9	14/–
Ta	0.6/0.5	0.5/0.5	1.4/0.8	1.4/1.3	1.0/0.4	0.8/0.6	2.4/2.4	1.0/1.2	0.7/–	0.8/0.6	1.0/0.3
Li	13.7/4	11.2/3.1	13.3/7.8	11.5/5.4	21/14	26/27	12/4	9/7	11/3	9/2	27/26
Rb	46/13	13/10	103/44	134/53	85/26	78/83	116/23	146/67	88/22	60/18	78/95
B	8/2	16/14	12/3	17/8	–	11/8	15/7	15/6	10/4	10/2	18/2
F	863/568	1720/2500	510/720	650/740	1370/2070	970/400	1290/1430	210/136	530/91	530/231	175/18

Comments: "–" no data. Numerator is average concentration, denominator – standard deviation.
*) Results of single analyses, excluded from the total.
**) Number of analyses of main elements (numerator) and of trace elements (denominator), if the numbers are the same, only one figure is given.
The explanatory notes are the same for the both tables.

Some incompatible elements appear to be concentrated mainly in the intermediate rocks such as migmatites (Fig. 3). This geochemical feature is consistent with the process of partial melting in migmatites. Some elements (Ba, Sr, Zr, Nb, Ta) appear to be retained in migmatites. If the granites are a result of the partial melting processes beginning in the migmatites, the migmatites themselves may be somewhat restitic. Hence, Zr is retained in the zircons of migmatites, Nb, Ta – in femic minerals, Ba, Sr – in plagioclases.

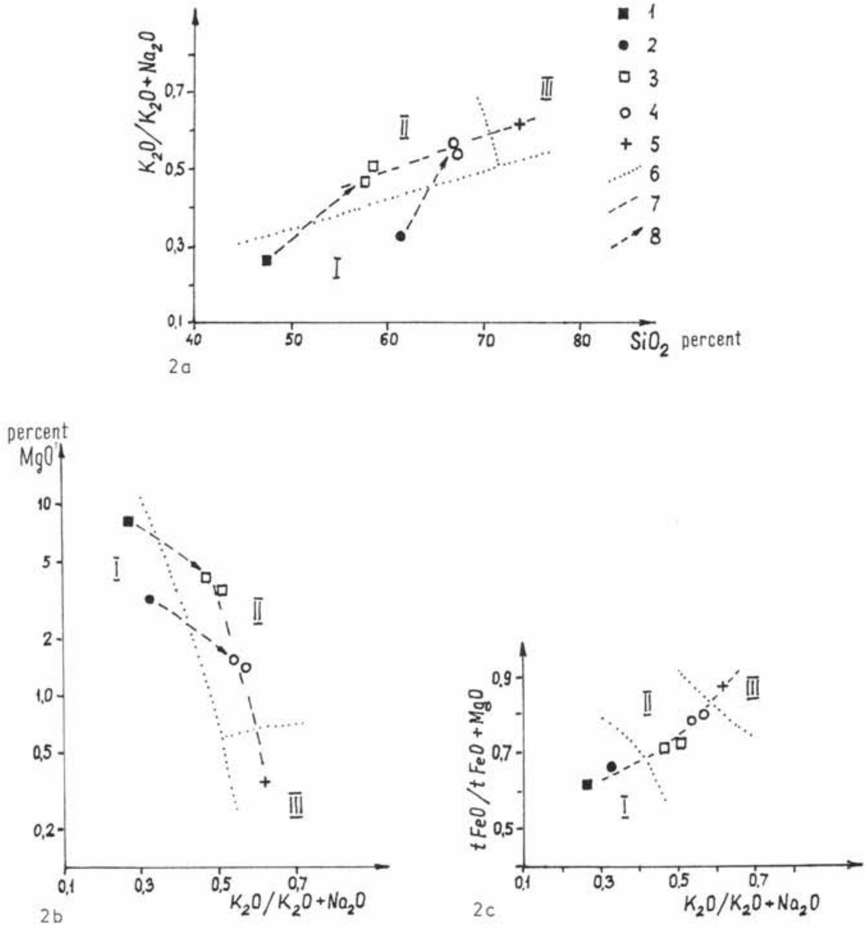


Fig. 2. Petrochemical tendencies of the metasomatic and anatectic processes (average values). *Diagrams:* 2a – SiO_2 – K_2O/K_2O + Na_2O; 2b – K_2O/K_2O – Na_2O – MgO; 2c – K_2O/K_2O + Na_2O – tFeO/tFeO + MgO. 1 – amphibolites, average of 9 analyses; 2 – hornblende-biotite gneisses, average of 8; 3–4 – migmatites (two points present migmatites containing relics of granulitic minerals and migmatites without these relics): after amphibolites, av. of 17, 4 – after gneisses av. of 20; 5 – granites, av. of 11; 6 – boundaries between fields: I – primary rocks, gneisses and amphibolites; II – migmatites; III – granites. 7–8 – trends: 7 – general, 8 – of migmatization. Averages and standard deviations are mostly given in Tab. 1.

The low temperature schists generated in the last stages of tectonic activity appear to be a result of retrograde metamorphism of all rock types considered above. They show reverse geochemical trends (Fig. 4). K_2O and Rb is evidently leached from and CaO influxed in the gneisses, amphibolites, migmatites and granitoids. These geochemical changes seem to be a consequence of a change in the fluid regime at the last low temperature (see below) stage and may be considered as a result of postmagmatic fluid process.

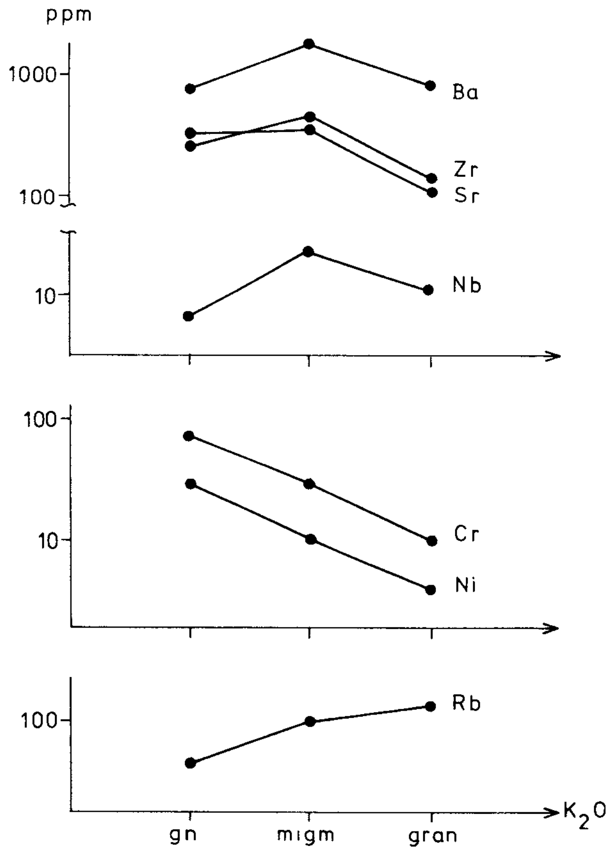


Fig. 3. Geochemical tendecies of the metasomatic and (anatectic processes) (average values of the Lamuyka Complex).
„gn“ – hornblende-biotite gneisses, average of 8 analyses; „migm“ – migmaites after gneisses, av. of 20; „gran“ – granites, av. of 11.

Fluid inclusions and the processes of retrogression, metasomatism and melting

The study of fluid inclusions involves some uncertaintes (Röedder, 1984), however comparisons of fluid inclusions in the Archaean granulites and in the Proterozoic rocks allows examination of the whole range of P-T-X parameters and the incorporation of petrological data.

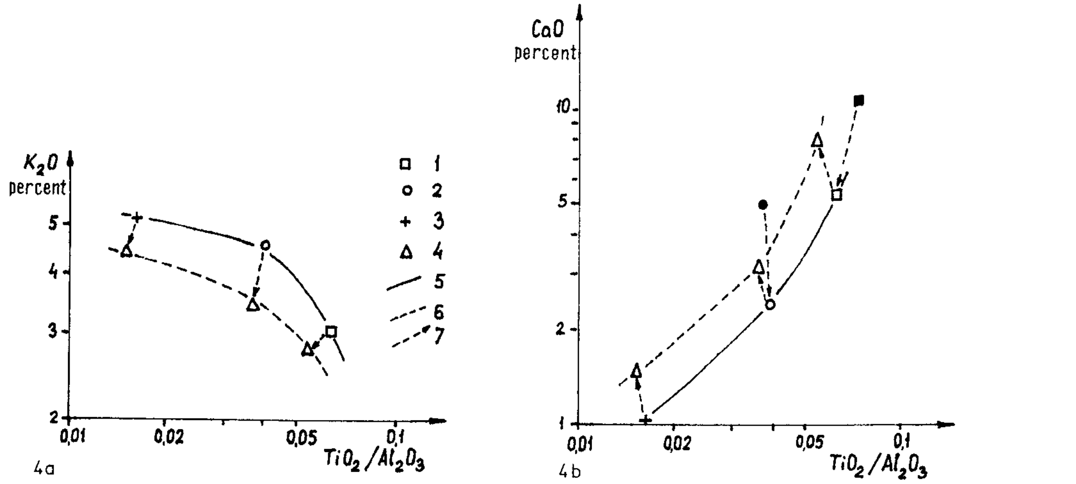


Fig. 4. Petrochemical tendencies of the post-granitization processes in the late tectonites (average values). *Diagrams:* 4a – TiO_2/Al_2O_3 – K_2O; 4b – TiO_2/Al_2O_3 – CaO. 1–2 – migmatites: 1 – after amphibolites, 2 – after gneisses; 3 – granites; 4 – greenschist facies mylonites (epidote-chlorite-muscovite schists) after amphibolites, average of 9 analyses, after gneisses av. of 8 and after granites av. of 3; 5–6 – variation-lines: 5 – of amphibolitic facies rocks, 6 – of greenschist facies mylonites; 7 – trends of greenschist metasomatic processes.

Fluid inclusion composition and fluid evolution

The specific volumes of liquid CO_2 in metamorphogenic inclusions in quartz of some rocks of the Anabar Shield are given in Tab. 1. In the Archaean hypersthene plagiogneisses fluid inclusions usually have a shape of negative (empty form) crystal about 5 μm in size. They are mostly composed by CO_2 of high density. An admixture of water and salts in some inclusions is established by lower temperatures of freezing and formation of daughter crystals under cooling. These crystals are discovered in freezed inclusions after dissection and thawing under electronic microscope.

Fluid inclusions in rocks of the Lamuyka complex have size of 5–20 μm and more. They contain H_2O and CO_2 in amphibolitic facies rocks but in rocks of epidote-amphibolitic facies H_2O essentially prevails. In vein-type and druse-type quartz of late tectonites both primary and secondary inclusions are filled by H_2O, CO_2-containing inclusions are rare.

Some examples of quartz were studied to examine differences between primary and secondary inclusions, CO_2-inclusions were divided to: 1 – clustered group of inclusions in the cores of grains, apparently of primary type; 2 – inclusion trails associated with cracks in the inner parts of single grains (primary-secondary type); 3 – inclusions distributed along cracks cutting several grains (secondary type). It is clear (Fig. 5) that CO_2 inclusions form two quite different groups: the first group of inclusions, occurring in hypersthene-plagiogneiss (enderbite), have homogenization temperatures of −40 to −15 °C; and group which occur in biotite-amphibole migmatite, show homogenization temperatures of −15 to +5 °C. The distribution of inclusions of different T_{hom}°C show that the cracks developed in all rock-types formed and healed at the last stage of a single metamorphic event.

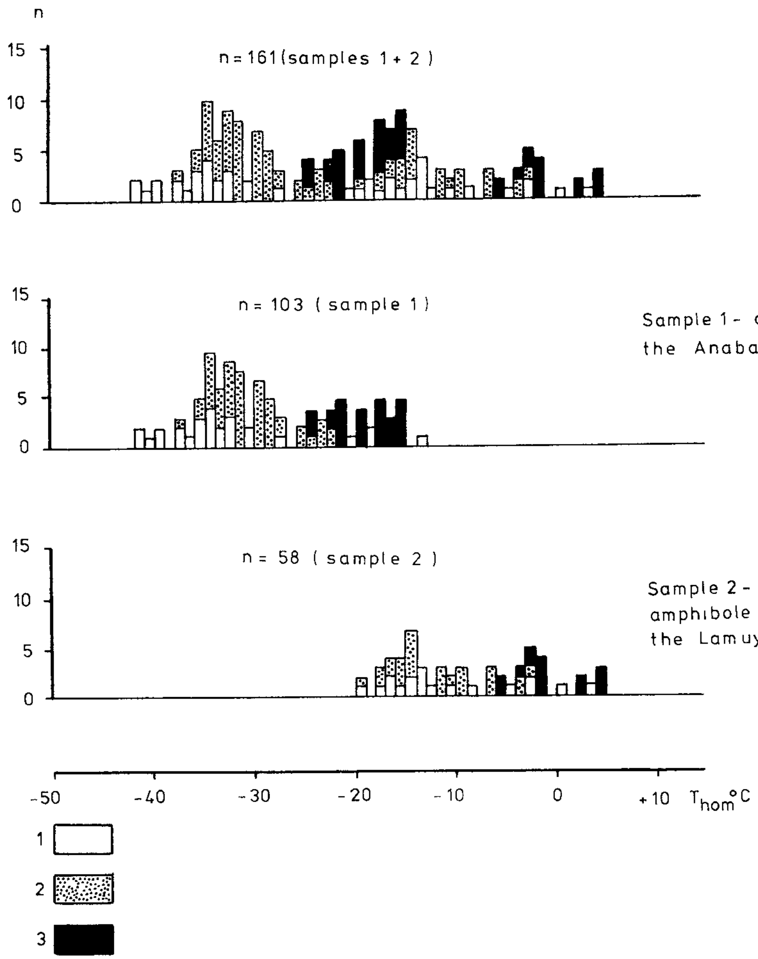


Fig. 5. Temperatures of homogenization in CO_2 – inclusions of different morphology in quartz. *Legend:* 1 – clusters of inclusions (primary); 2 – inclusions along cracks in quartz grains (primary-secondary); 3 – inclusions along cracks cutting boundaries of grains (secondary).

P-T conditions of fluid entrapment

Inclusions of crystallized magmatic melt are observed in quartz from anatectic biotite-bearing garnet gneisses of the granulitic facies in the Archaean Anabar Complex and in migmatites and pegmatites of the Middle Proterozoic Lamuyka Complex. Their sizes are usually less than 10 μm. These inclusions are rare and their distribution is irregular. Under heating they do not show visible changes until 700 °C, where the beginning of melting of the solid phases occurs. At about 800 °C extensive melting takes place and the fluid phase isolates. After that complete-homogenization occurs, and melting of inclusion walls is not observed. In addition to these unusual inclusions, the melt-brine inclusions were observed in pegmatites of the

Lamuyka Complex. These contain chlorides of Na, K, Ca and have lower temperature of homogenization (Tab. 1).

Entrapment pressures of the metamorphic fluids have been calculated using PTV diagrams for CO_2 (Bottinga et al., 1981; Shmulovitsch, 1988; Tomilenko – Chupin, 1983), by comparison of temperatures of homogenization of melt-inclusions and specific volumes of CO_2 in those inclusions composed by carbon dioxide (see Tab. 1). Pressures of granulite metamorphism in the Anabar Complex are in the range 8. 5–9.5 kbar at T = 850–900 °C. These values are in a good agreement with petrological data: P = 10 kbar, T = 850–950 °C (maximum calculated for eclogite-like and sapphirine-bearing mineral assemblages; Luts,

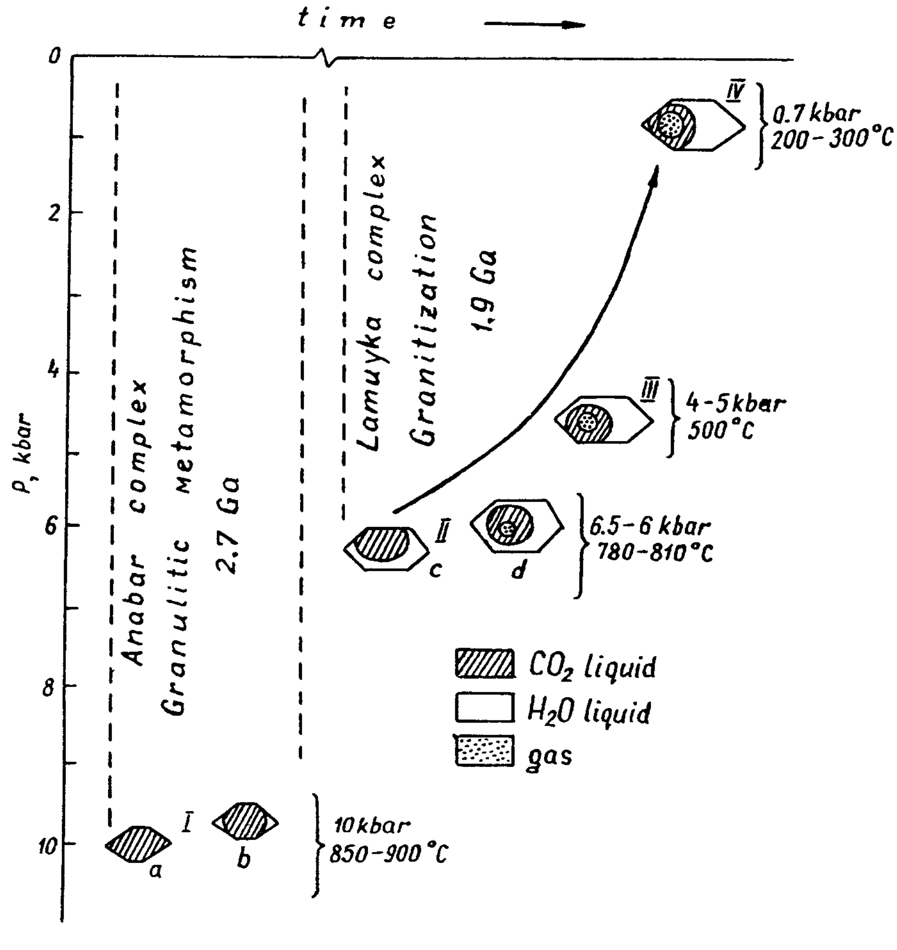
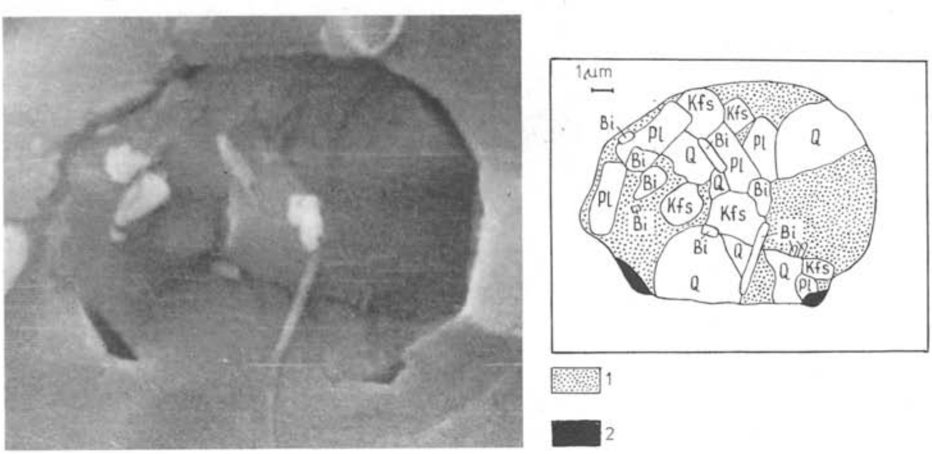


Fig. 6. Evolution of fluid inclusions in quartz of metamorphic rocks in the Anabar Shield.
I – monophase inclusions of liquid CO_2 (a) and containing bubble of H_2O (b) in granulitic rocks; II – complex inclusions of liquid CO_2 and H_2O (c) and containing the same phases with gaseous bubble (d) in amphibolitic facies rocks; III – inclusions of the same composition as above in epidote-amphibolitic facies rocks; IV – essentially H_2O – inclusions in late quartz of veins in tectonites of greenschist facies.

1974), but mostly T = 780–850 °C, P = 7–8.5 kbar (Vishnevsky, 1978). Inclusions in migmatites of the Lamuyka Complex yielded P = 6.0–6.5 kbar at T = 780–820 °C whereas petrological values are determined as: P = 6–7 kbar, T = 650–750 °C for almandine--hornblende assemblages (Vishnevsky, 1978). In rocks of the late stages of Lamuyka Complex evolution temperatures were calculated using H_2O-inclusions (without CO_2) and pressures were estimated using complex (CO_2 + H_2O) inclusions according to the joint P-T diagram of H_2O and CO_2 (Röedder, 1984). Such inclusions gave P = 4–5 kbar T = 500 °C in schists of epidote-amphibolitic facies which are in a good correspondence with petrological data P = 4–5 kbar, T = 480–650 °C given for the cummingtonite-amphibolite subfacies and epidote-amphibolite facies (Vishnevsky, 1978). The final stage of final ingress occurred at P = 0.7 kbar and T = 200–300 °C, based on compositional data for inclusions in quartz veins. These parameters correspond to prehnite-pumpelliite facies. All these data are shown on Fig. 6.

Melt inclusion composition and melting processes

The melt inclusions usually contain grains of quartz, plagioclase and somewhere potassium feldspar. Some of the melt inclusions from migmatites of the Lamuyka Complex were investigated by area-scan microprobe analysis. An example of such an inclusion is given in Fig. 7. These inclusions appear to contain grains of quartz, potassium feldspar, plagioclase, biotite of 0.5–2 μm in size. Fine grained alumino-silicate material also occurs making up 30 % of the volume. This material is interpreted as devitrified glass. Usually one or two bubbles of gas are also present. This mineral composition of the melt inclusions implies that partial melting took place when the migmatites and granites were formed.



b

Fig. 7. The inclusion of crystallized melt in quartz of migmatite of the Lamuyka Complex (microprobe data).

Fig. 7 a – photo under electronic microscope,

Fig. 7b – microprobe data for the photo given as (a) on Si, Al, Mg, K interpreted as minerals symbolized.

Legend: 1 – fine-grained crystalline aggregate (crystallized melt); 2 – cavities (relics of gaseous bubbles).

In some crystal-fluid inclusions in migmatites of this type a crystalline aggregate of potassium feldspar were observed. This indicates directly that the fluid was saturated by potassium-silica material, being in equilibrium with granite melt.

As a whole the Proterozoic evolution of the Anabar Shield in case-study appears to be an interrelation between fluids and rocks of the Archaean sialic crust under heating and differential tectonic movements continued. Several stages are seen in this evolution. The early stage was caused by permeability of the early crust for H_2O-fluid and documented by areal retrogression of granulites to amphibolite facies rocks. The next one was marked by influx of K_2O, SiO_2 and other lithophile elements when metasomatic potassium feldspar was generated in rotating porphyroblasts which marked the beginning of differential tectonic movements. After that amphibolite facies migmatites were generated under the continued invasion of the fluid components outlined above. Partial melting of these migmatites resulted to autochthonous granite formation. Later, lower – T fluids brought silica into quartz veins and leached some alkalies from previous rocks, within the progressively deforming shear zones.

Conclusion

If metasomatism-driven anatexis can be considered as a part of a process of upper crust generation related to the formation and intrusion of granites, two stages of this process seem to be evident. The first stage is the generation of scattered migmatites and small granite bodies, while the second stage involves the generation of vast and complex granite batholiths. The first, pre-batholithic stage is described in this report. Granite material formed small vein-type bodies in the Proterozoic shear belts dissecting the earlier Archaean granulite basement (the Anabar Complex). Influx of water fluids containing alkalies, silica and other lithophile elements through permeable tectonites was the cause of metasomatic growth of potassium feldspar porphyroblasts. The later formation of migmatites involved partial melting and lead to the local segregation of granite bodies. Penetration of H_2O-rich fluid before these processes of metasomatism and anatexis caused the retrograde amphibolitic metamorphism over large areas of the Archaean granulites. Postgranitization H_2O-fluid leached some alkalies from consolidated rocks along mylonitic zones under low temperature conditions.

At present there is no diagnostic data on the source of the proposed fluids, however they cannost be derived from the granulite basement itself which has a very low water content whereas these granulites seem to compose all thickness of the Earth crust of the Anabar Shield (Dukhovsky et al., 1986; Rosen, 1986).

In the Anabar Shield the initial influx of water could have occurred in an early tensional tectonic regime (Rosen – Milanovsky, 1988) which resulted in a high permeability in local zones of the primary granulitic crust. At that time the process of the early retrograde amphibolitic metamorphism was realized by water influx. Subsequent compression and overthrusting seem to thickened the crust and led to an increase in temperatures. The fluid influx and hence the metasomatism were localized along thrust surfaces preserved now as the shear belts of the Lamuyka Complex. Geological and heat-flow analyses (Molnar et al., 1983) have shown that increase in temperatures is enough for granites to have been formed as a result of partial melting of the continental crust in the upper part of large overthrust zones, when the Earth crust has been doubled. The probable timescale of formation of complex granite bodies (5–60 Ma Dobretsov – Popov, 1974) is in a good accordance with calculated time parameters for the thermal evolution of such thickened zones (Molnar et al., 1983). In the Anabar Shield such events are consistent with tectonic activity in the neighbouring regions of Siberian platform where greenschist volcanic troughs opened and closed in the Middle Proterozoic (Bucharov, 1983; Gusev et al., 1983).

In terms of collision and post-collision granites (Pearce et al., 1984) the early migmatites and associated vein like dispersed granite bodies assumed typical of the pre-batholithic stage of the granite generation process, may be classified as a collision type. Vast granite-granodiorite batholithes in the Precambrian crystalline complexes appear to concern to the post-collision type which present the main problem of tectonic classification. The collision model given above may be applicable to many Precambrian high-metamorphic areas where the early, pre-batholithic stage (metasomatism and anatexis) of the process of granite formation, is observed.

Acknowledgements: The geological and geochemical data used in this paper are the results of collective work of the Anabar expedition of the Institute of Lithosphere of the Academy of Sciences of the U. S. S. R. Chemical analyses haven been done in All Union Institute of Mineral Deposits (petrogenic elements) and in Institute of Mineralogy and Geochemistry of Rare Elements (trace elements).

The authors would like to express their thanks to B. G. Luts, A. A. Marakushev and L. L. Perchuk for useful scientific discussions on the granitization problem and to V. L. Zlobin for effective cooperative field work.

REFERENCES

BIBIKOVA, E. V. – BELOV, A. N. – ROSEN, O. M., 1988. Isotopic age of the Anabar Complex and peculiarities of dating of the oldest geological events. In: The Archaean of the Anabar Shield and the problems of early evolution of the Earth. *Nauka*, Moscow, pp. 115–133 (in Russian).

BOTTINGA, Y. – RICHET, P., 1981: High pressure and temperature equation of state and calculation of the thermodynamic properties of gaseous carbon dioxide. *Amer. J. Sci.* (New Haven), 281, pp. 615–660.

BUKHAROV, A. A., 1983: Stages and factors of the continental crust formation in Siberia. *Tektonika Sibiri*, 11, pp. 123–126 (in Russian).

DOBRETSOV, H. L. – POPOV, N. V., 1974: On duration of granite plutons formation. *Geol. Geofiz.*, 1, pp. 50–59 (in Russian).

DUKHOVSKY, A. A. – BELYAEV, G. M. – MUKHIN, V. N. – YASCHIN, B. A., 1986: Geological nature of gravimetric and magnetic anomalies of the Anabar Shield. *VIEMS, Ser. obshchaya i regionalnaya geol.*, 46 pp. (in Russian).

GUSEV, G. S. – GRINBERG, G. A. – KOVALSKY, V. V., 1983: Tectonics and stages of Earth crust formation in Yakutia territory. *Tektonika Sibiri*, 11, pp. 86–93 (in Russian).

LUTS, B. G., 1985: Petrology of deep seated zones of the continental crust and the upper mantle. *Nauka*, Moscow, 216 pp. (in Russian).

MARAKUSHEV, A. A., 1988a: Editors preface to Russian translation. In: Ashworth, J. R. (ed.) – *Migmatites.* Glasgow London, Blackie and Son, 1985. *Mir*, Moscow, pp. 5–10.

MARAKUSHEV, A. A., 1988: Petrogenesis. *Nedra*, Moscow, 292 pp. (in Russian).

McRAE, N. D. – NESBITT, H. W., 1980: Partial melting of common metasedimentary rocks: a mass balance approach. *Contr. Mineral. Petrology* (Berlin-New York), 75, 1, pp. 21–26.

MEHNERT, K. R., 1968: Migmatites and origin of granitic rocks. *Elsevier*, Amsterdam, 393 pp.

MOLNAR, P. – CHEN, W. P. – PADOVANI, E., 1983: Calculated temperatures in overthrust terraines and possible responsible for the Tertiary granites in the Greater Himalaya. *J. Geophys. Res. (Richmond, Va.)*, 88, 8-B, pp. 6415–6429.

PEARCE, J. A. – HARRIS, B. W. – TINDLE, A. G., 1984: Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrology* (Oxford), 25, 4, pp. 956–983,

RÖEDDER, E., 1984: Fluid inclusions. *Rev. Mineral., Mineral Soc. Amer.* 12, 644 pp.

ROSEN, O. M., 1986. Anabarides and the oldest plagiogneisses: some problems of the early Earth's crust generation. In: The Earth's crust structure of the Anabar Shield. *Nauka*, Moscow, pp. 155–187 (in Russian, English).

ROSEN, O. M. – MILANOVSKY, S. Yu., 1988: Geothermal gradient, heat flow and thickness of the primary Earth crust. In: The Archean of the Anabar Shield and the problems of early evolution of the Earth. *Nauka,* Moscow, pp. 231–252 (in Russian).

SHMULOVITSCH, K. I., 1988: Carbon dioxide in high temperature processes of mineral formation. *Nauka,* Moscow, 182 pp. (in Russian).

SONYUSHKIN, V. E., 1981: Electronic microscope investigations of fluid inclusions in quartz. *Izv. Akad. Nauk SSSR, Ser. geol.* (Moscow), pp. 85–95 (in Russian).

STEPANOV, L. L., 1974. Radiogenic age of the polymetamorphic rocks of the Anabar Shield. In: The Early Precambrian rocks of the Central part of the Arctic and ore deposits connected. *Nauka,* Leningrad, pp. 77–84 (in Russian).

TAYLOR, S. R. – McLENNAN, S., 1985: The continental crust: its composition and evolution (an examination of the geochemical record presented in sedimentary rocks). *Blackwell Sci. Publ.,* Oxford, 312 pp.

TOMILENKO, A. A. – CHUPIN, V. P., 1983 Thermo-baro-geochemistry of metamorphic rocks. *Nauka,* Novosibirsk, 200 pp. (in Russian).

VISHNEVSKY, A. N., 1978: The metamorphic complexes of the Anabar crystalline Shield. *Trans. Arctic geol. Inst.,* 184, 214 pp. (in Russian).

WINKLER, H. G. F., 1967: Petrogenesis of metamorphic rocks. *Springer,* Berlin, 273 pp.

WYLLIE, P. J.–HUANG, W.–L. STERN, C. R.–MALLÖE, S., 1976. Granitic magmas: posible and impossible source, water contents and crystallization sequences. *Canad. J. Earth Sci.* (Ottawa), 13, 8, pp. 1007–1019.

Reviewed manuscript received February 28, 1989.