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GRANITE FORMATION SERIES IN ULTRAMETAMORPHIC ZONES: PETROLOGICAL ASPECT

(8 Figs., 5 Tabs.)

Abstract: The rocks successively formed as a result of various ultrametamorphic processes during a single tectono-metamorphic cycle are united into granite formation series. This series is divided into three separate fragments dependent on the predominant processes of granite generation.

1. Volume replacement of the initial rocks under fluid flow without a melting stage takes place, this is regarded as metasomatic preparation of the rocks for melting. It is shown to be a necessity for the introduction and removal of different components. As a result of this process, the formation of granite-and charnockite--gneisses (nebulites) occurs.

2. Partial melting leads to the formation of successive generations of stromatic migmatites. The reasons for changes in leucosome compositions are discussed. In most cases these changes are due to a temperature decrease.

3. The third fragment of the series under consideration is connected with the transition of rocks to a mobile state, when the melt amount increases sufficiently or complete melting (diatexis) takes place.

Earlier, two types of evolution of ultrametamorphic zones were established. These types (or ways) resulted from two different sequences of ultrametamorphic processes changing in time and can be recognized based on the correlation of the rates of mass- and heat-transfer. According to evolutionary types of ultrametamorphism, one can establish two complete series of granite formation and four incomplete series.

Key words: ultrametamorphic zones, granite formation, volume replacement, partial melting.

Introduction

The granite formation processes and all their relationships, from the first stage to that of the generation of acidic and intermediate composition magmas, followed by their mobilization can be seen in deep zones of the Earth's crust under ganulite and amphibolite facies conditions. These zones are known as those of ultrametamorphism. Since these phenomena are accompanied by melt formation which replaces the country rocks, they can be considered to be the processes of magmatic replacement (Korzhinsky, 1952, 1977).

Under lower temperature conditions, where melting cannot yet take place, alkali metasomatism occurs. As a conseqence, quartz-bearing albitites, oligoclasites, microclinites and plagiogranite-gneisses can be formed (Sedova et al., 1980; Glebovitsky et al., 1981).

It is under conditions where partial melting accompanied by metasomatism and then rheomorphism becomes possible in utrametamorphic zones, that migmatites of different kinds (stromatic, network, agmatites), granite- and charnockite-gneisses (nebulites), granites and charnockites are generated.

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The rocks formed successively as a result of the ultrametamorphic processes during one tectonometamorphic cycle are related in granite formation series. It is obvious that a particular type of granite formation series is due to a combination of different factors, namely thermodynamic and fluid regime of a particular structure. Therefore the purpose of the present contribution is to establish the types of granite formation series and to show their relationship to the sequence of stages developed during the evolution of ultrametamorphic zones.

The present paper summarizes my multiyear studies, concerning migmatite typical of both Archean and Proterozoic terrains of the Aldan Shield and its fold margin, Baltic Shield, southwestern Pamirs, Ladoga Complex and Phanerozoic fold belts of the Central Pamirs and South Tien-Shan.

Fragments of the granite formation series

Let's consider some granite formation series, divided into separate fragments which, as shown, differ in the predominant granite formation processes. The complete series consists of three fragments. The essence of the first fragment is volume replacement of the initial rocks (Sedova – Glebovitsky, 1984). The final products are layer-parallel bodies and fields of plagiogranite- and granite-gneisses in amphibolite facies, enderbite- and charnockite-gneisses in granulite facies. The second fragment of a granite formation series is the suite of successively forming leucosomes of stromatic migmatites, completing the leucosome generation of network migmatites. The third fragment includes the transition of migmatites to a mobile state and generation of granite bodies. As shown below, these fragments occur in different age ranges, but the third fragment always follows the first and/or second fragment.

Volume replacement of the initial rocks. Let's discuss some examples. Hornblende-biotite and epidote-biotite plagiogneisses of tonalite composition, orthoamphibolites and metagabbros are developed in the Belomorian Complex of the eastern Baltic Shield. The biotite plagiogranite-gneisses, locally garnet-bearing, replace both these rock types. The morphology of this process is seen in Fig. 1. The processes of volume replacement are more difficult to establish in gneisses of tonalite composition than in schists. Sometimes the relict layers of the tonalite gneisses are preserved among newly formed plagiogranite-gneises. The latter are characterized by higher content of SiO_2 and lower content of CaO, MgO, FeO, unlike the former (Tab. 1). The generalization of these data in the form of histograms of the oxide distribution (Fig. 2) shows that the plagiogranite-gneiss, replacing plagiogneisses, unlike varieties after amphibolites, are characterized by higher SiO_2 and lower TiO_2, Fe_2O_3, MgO contents while the content of Na_2O, K_2O, FeO, CaO is similar. It should be pointed out that these compositional differences of the two granitoid groups are less essential than those of the initial rocks.

The successively forming stromatic veins of three generations of the leucocratic plagiogranites are arranged along the gneissosity of the initial rocks and parallel to the axial surfaces of the isoclinal, and then tight and open folds. The layer-parallel veins can amount to 30–40 vol.%. But they are included in the second fragment of granite formation series.

The volume replacement process can show a potassium trend, similar to the Yablonova series of the Vitim-Olekma Highlands. In basic schists of these series syenite-diorite- and granodiorite-like rock appear. They are characterized by special textures: plagioclase and hornblende are replaced by newly formed orthoclase. In places hornblende and biotite are

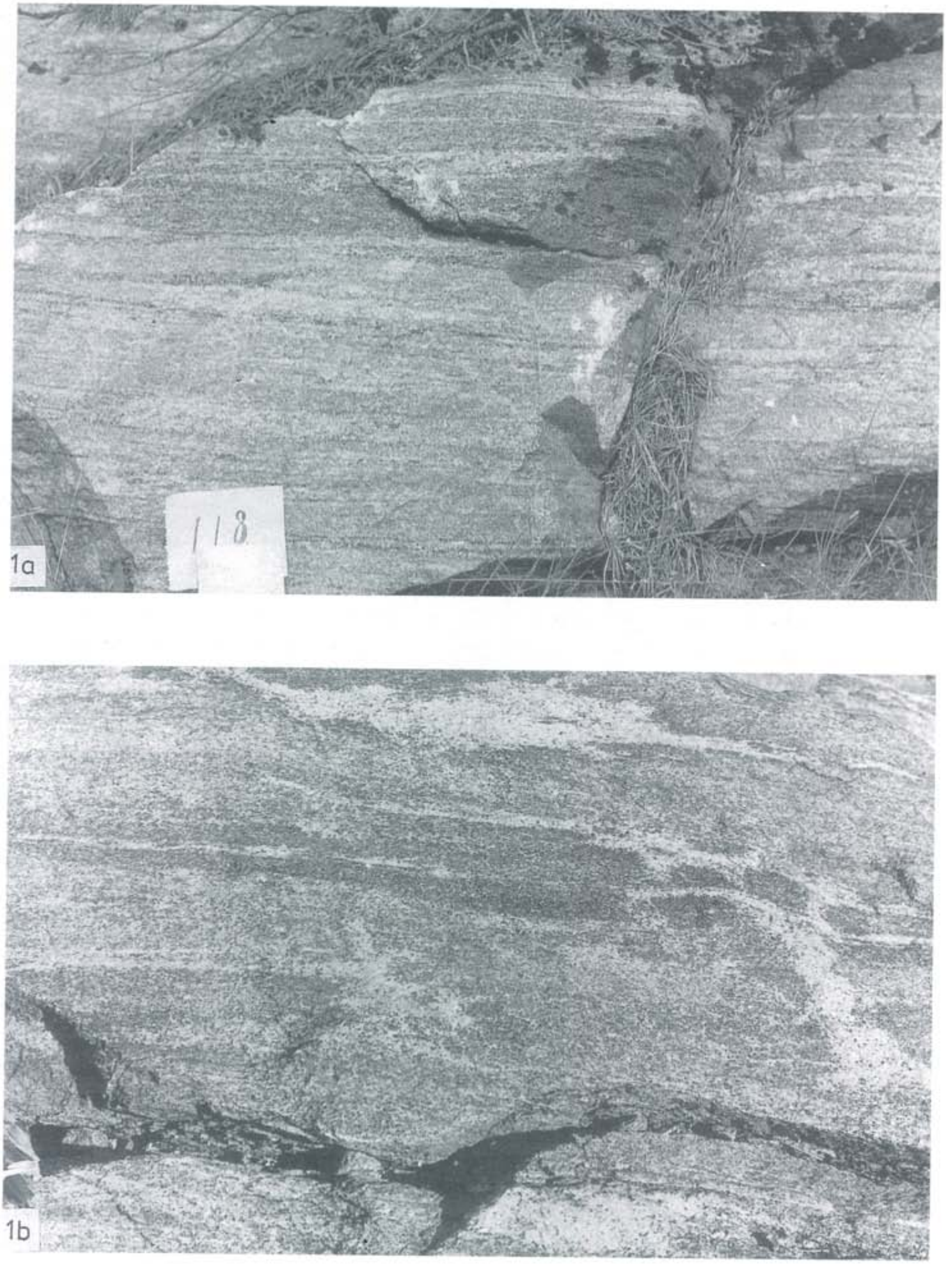

Fig. 1. Replacement of tonalitic gneisses (a) and basic composition rocks (b) by granite rocks (Belomorian Complex, Baltic Shield). Younger leucosomes are seen in these rocks.

Table 1

Average composition ($\bar{X}$) and standard deviation (σ) of the initial rocks and autochthonous plagiogranite-gneisses (Belomorian Complex)

	n		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Loss
sch	10	$\bar{X}$	55.21	0.82	14.73	2.84	7.30	0.18	5.00	8.06	2.89	1.31	0.17	1.56
		σ	3.45	0.15	1.93	1.26	1.77	0.05	1.78	1.62	0.96	0.25	0.08	0.55
pl γ gn^{sch}	13	$\bar{X}$	68.86	0.45	14.95	1.14	2.32	0.05	1.37	4.10	4.20	1.19	0.12	0.72
		σ	3.96	0.22	1.18	0.62	0.95	0.03	0.71	1.13	0.46	0.34	0.04	0.35
plgn	18	$\bar{X}$	66.93	0.49	15.91	0.99	2.85	0.08	1.40	4.58	4.11	1.36	0.22	0.80
		σ	3.67	0.13	1.26	0.50	0.77	0.04	0.55	0.87	0.23	0.36	0.05	0.24
pl γ gn^{plgn}	14	$\bar{X}$	71.76	0.30	14.69	0.50	2.04	0.05	0.81	3.49	4.23	1.43	0.07	0.64
		σ	1.41	0.11	0.86	0.32	0.55	0.02	0.20	0.70	0.44	0.88	0.04	0.22

n – number of analyses, sch – biotite-hornblende-plagioclase schists; pl γ gn^{sch} – plagiogranite-gneisses after schists; plgn – plagiogneisses (epidot-biotite, hornblende-epidote); pl γ gn^{plgn} – plagiogranite-gneisses after plagiogneisses and tonalites

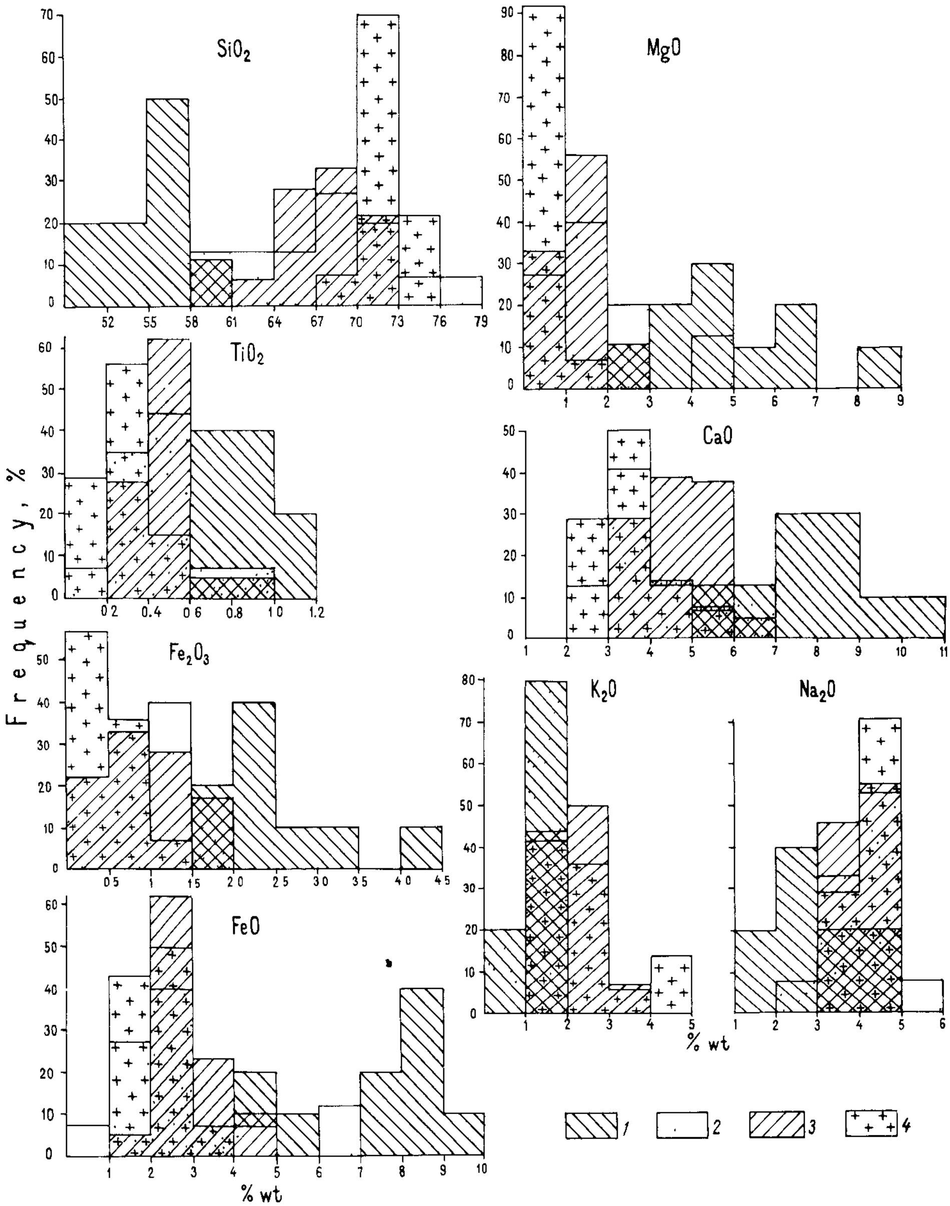

Fig. 2. Histograms of oxide distribution ın the Belomorian Complex rocks.
1 – basic schists; 2 – plagiogranite-gneisses, replacing the basic schists; 3 – plagiogneisses of tonalite composition (Bt, Bt + Hb, Bt + Ep); 4 – plagiogranite-gneisses after tonalitic gneisses.

recrystallized and increase in grain size, but farther they disappear. Granite and granosyenite--gneisses are generated. They are distinguished by having a foliation and a granoblastic texture. Sometimes drop-like portions with a massive structure and fine-grained aplite-like or micropegmatite textures can be found within these rocks. In my opinion, these parts can be considered as a result of rock melting (Krilova et al., 1971). One can demonstrate how similar parts gather together to form larger bodies, mainly veins, which show transition to second fragment of granite formation series. The succession of mineral assemblage generation corresponding to stages of volume replacement processes is $Pl_{35}-_{45}$ + Hb + Bt → KFsp + $Pl_{25}-_{35}$ + Hb + Bt → $Pl_{20}-_{30}$ + KFsp + Qtz + Bt → Qtz + $Pl_{15}-_{20}$ + FKsp. The compositional change in such series of granite formation is seen in Fig. 3.

The events of similar type occur in the granulite facies of the Aldan Shield. The succession of rock formation at replacement of the basic composition rocks: basic rocks → intermediate rocks → enderbite → charnockite → granite gneisses, corresponds to the following consequence of mineral assemblage change OPx + CPx + Pl ± Bt → OPx + Pl ± Hb ± Bt → OPx + Pl + Qtz + Bt → OPx + Pl + KFsp + Qtz ± Bt → Pl + Qz + KFsp ± Bt ± Mgt.

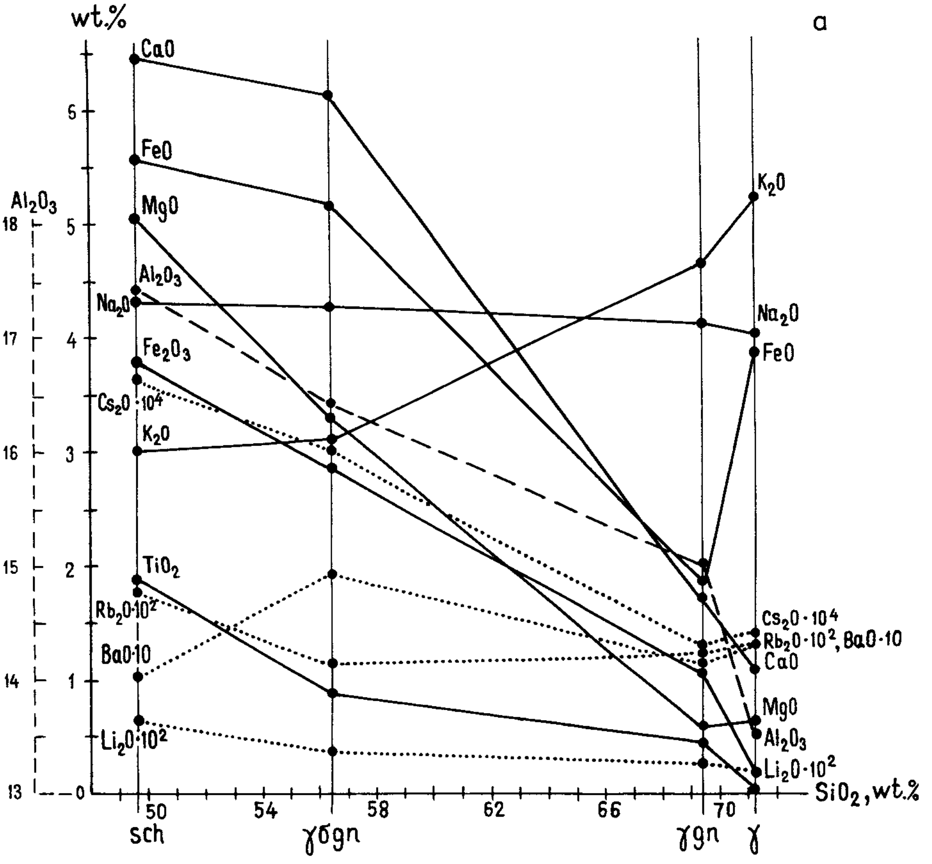

Fig. 3a — macroelements.

Fig. 3. Diagram of compositional change during granitization in basic schists of Yablonian unit of the Vitim-Olekma highlands.

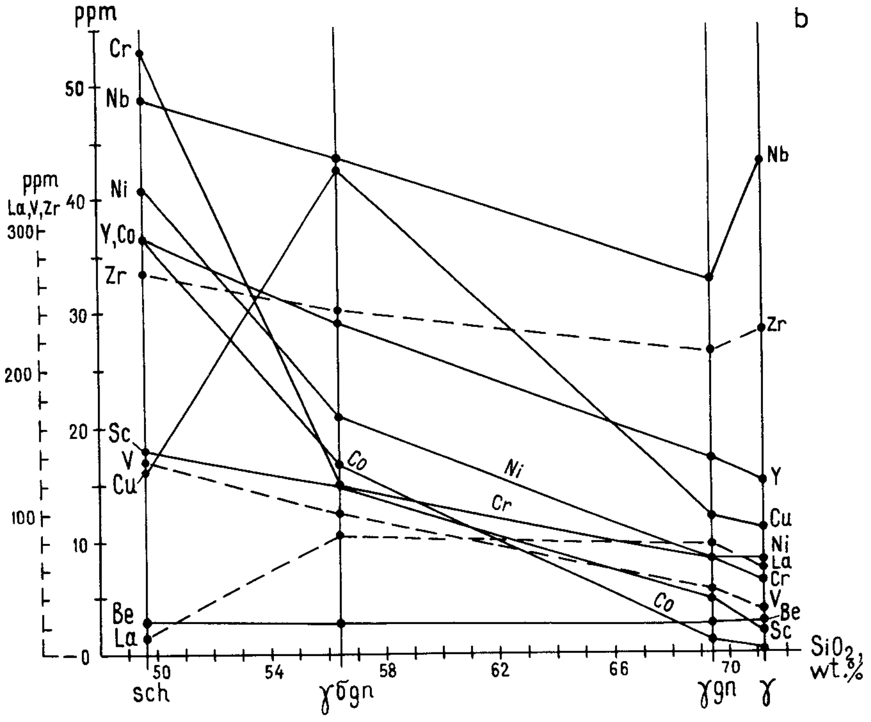

Fig. 3b – microelements

Explanations: sch – biotite-hornblende-plagioclase schists, γδgn – intermediate composition rocks (biotite-hornblende-syenite-diorite-and granodiorite-like rocks), γgn – granite-gneiss, γ – granite.

Thus the volume replacement processes are characterized by following features: gradual change of the initial rocks and in connection with this the rock formation of the intermediate composition, restite lack, replacement of mafic minerals and plagioclase by felsic plagioclase, quartz, K-feldspar, generation of mafic minerals veins in the granite- and charnockite-gneisse field.

Successively forming leucosomes of migmatites. The second fragment of a granite formation series is a suite of successively forming leucosomes (up to 3–4 generations) of stromatic and then network migmatites (Fig. 4). The former are usually coplanar with the axial surfaces of the isoclinal folds of successive generations, although they can be arranged along all the earlier planar directional fabric, such as banding or schistosity. The latter are used by the earlier leucosomes. Sometimes mafic selveges are present in contact of these veins. The leucosome volume increases from the first generation to the second or the third, and then decreases with successive generations. From earlier generations to later, the leucosome thicknesses increase, they become more coarse-grained, and gneissosity decreases. The texture of later varieties is hypidiomorphic, unlike the granoblastic earlier granites. According to their structural position, it is obvious that their crystallization could take place during folding. As a result, leucosome veins have been folded at the same time as gneissosity. If their crystallization was

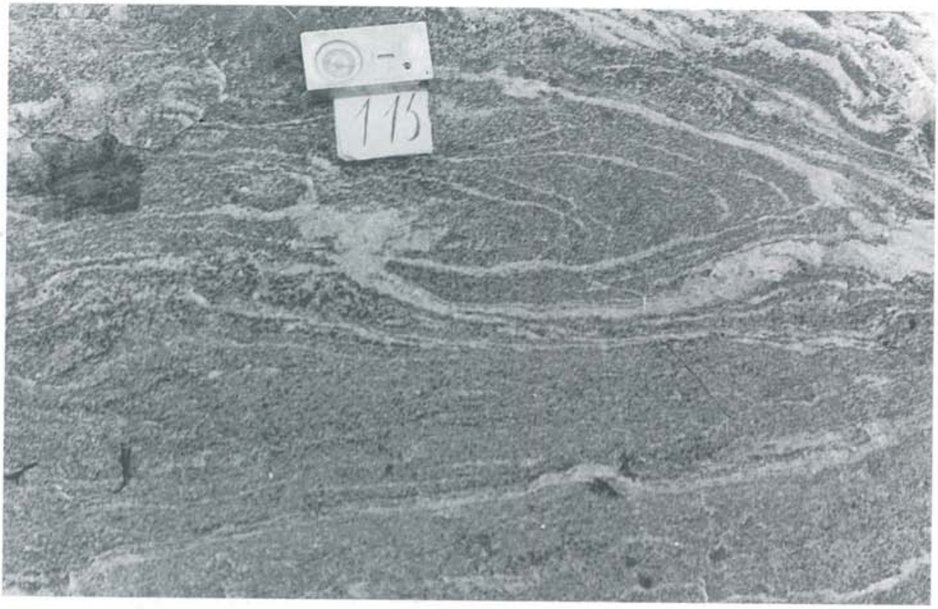

Fig. 4. Successively forming leucosomes of migmatites in the Belomorian Complex.

terminated after deformation, the structure of these veins is massive. Sometimes segregations or veins of mafic minerals, crossing leucosome vein contacts, occur in the migmatite fields. It seems most likely that the transfer of the leucosome substance was not significant during this stage for rock complexes under consideration. It is confirmed by some dependence of leucosome composition on that of mesosome, modal similarity of the leucosomes and the country rocks in respect to mafic minerals. For example, leucosomes in the garnet- and cordierite-bearing gneisses contain garnet and cordierite, leucosomes in hornblende and hypersthene schists include hornblende and hypersthene. Even vein network segregation completing stromatic migmatite generation, do not cross the lithological boundaries of the different layers.

What is the change of the composition of the newly forming stromatic leucosomes? As a rule the SiO_2 content and sometimes K_2O rises, that of CaO, MgO, FeO decreases from early generations to late ones, among which garnet-bearing granite occurs often. This tendency is traced for a leucosome sequence of the SW Pamirs and the NW White Sea region (Tab. 2) and is reverse to that of known for synmetamorphic leucosomes in prograde zonal complexes.

Let's discuss an example. It was established that early leucosome generations of the stromatic and network migmatites of the Ladogian Complex arose simultaneously with the metamorphic zonation during the Early Proterozoic at temperatures ranging from 680 to 780 °C at a pressure = 4.5 kbar (Glebovitsky et al., 1985). This was determined by the change of critical mineral assemblages and confirmed by thermobarometry data. The leucosomes belong to the three metamorphic zones corresponding to the muscovite-garnet--biotite-sillimanite subfacies (I) and garnet-biotite-cordierite-orthoclase subfacies (IIa) of the amphibolite facies and that of granulite facies (IIb). Homogenization temperatures of the crystallized melt inclusions increase from zone I to zone IIb in the order: 680 → 710 → 770 °C for γ_{1+2} and for γ_3 from 730 to 745 °C.

Table 2

Average composition of the succesive leucosomes generation of the stromatic and network migmatites

	n		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Loss
			Belomorian Complex, the Baltic Shield, Lopian cycle (Late Archean)											
γ_2	22	$\bar{X}$	73.02	0.19	14.68	0.39	1.23	0.04	0.57	3.28	4.15	1.55	0.04	0.64
		σ	2.32	0.13	0.92	0.24	0.66	0.02	0.24	0.93	0.70	1.77	0.03	0.24
γ_3	31	$\bar{X}$	72.53	0.21	14.46	0.41	1.14	0.09	0.49	3.40	4.52	1.78	0.05	0.63
		σ	3.13	0.18	1.34	0.62	0.39	0.03	0.31	0.92	0.30	2.10	0.03	0.24
γ_4	17	$\bar{X}$	74.10	0.13	14.31	0.15	1.02	0.05	0.44	2.59	4.18	2.12	0.04	0.51
		σ	3.34	0.11	1.83	0.11	0.41	0.07	0.31	1.20	1.00	2.22	0.02	0.25
			Vakhan Complex, SW Pamirs, the second cycle (Late Archean)											
γ_1	7	$\bar{X}$	67.11	0.35	18.08	0.48	1.46	0.02	0.73	2.12	4.21	4.28	–	0.81
		σ	3.47	0.25	2.06	0.19	0.59	0.01	0.54	0.37	1.13	1.26	–	0.25
γ_{2+3}	7	$\bar{X}$	70.05	0.30	15.87	0.59	1.84	0.03	0.73	1.69	3.37	3.77	–	1.31
		σ	2.48	0.12	1.34	0.34	1.04	0.02	0.52	0.40	0.72	1.31	–	0.42
γ_4	8	$\bar{X}$	70.18	0.27	15.89	0.41	1.22	0.02	0.55	1.55	3.00	5.47	–	1.02
		σ	2.68	0.30	1.35	0.38	0.90	0.01	0.49	0.64	0.50	1.54	–	0.31
			Elgacan Complex, the river Nuikzha, the margin of the Aldan Shield (Late Archean)											
γ_2	13	$\bar{X}$	73.00	0.18	14.88	0.54	1.13	0.04	0.50	1.69	4.05	2.31	0.05	0.60
		σ	2.15	0.11	1.06	0.36	0.40	0.02	0.27	0.52	0.82	1.79	0.03	0.22
γ_3	8	$\bar{X}$	69.02	0.33	15.39	1.54	1.94	0.06	1.21	3.19	4.11	2.27	0.09	0.66
		σ	4.02	0.13	2.40	1.03	0.67	0.02	0.76	1.51	0.82	1.46	0.09	0.20
γ_4	10	$\bar{X}$	70.57	0.24	15.16	1.28	1.80	0.07	0.61	2.21	4.09	2.64	0.05	0.58
		σ	4.30	0.11	1.06	1.80	1.66	0.09	0.38	1.30	0.81	1.64	0.03	0.28

γ_1, γ_2, γ_3 and so on – generation of migmatite leucosomes in migmatite sequence of every region

It was also found that the increase in metamorphism grade leads to an increase in the anorthite content of the plagioclase for γ_{1+2} and γ_3 (Fig. 5). The composition of the leucosomes becoming more basic with increasing metamorphic grade (Tab. 3).

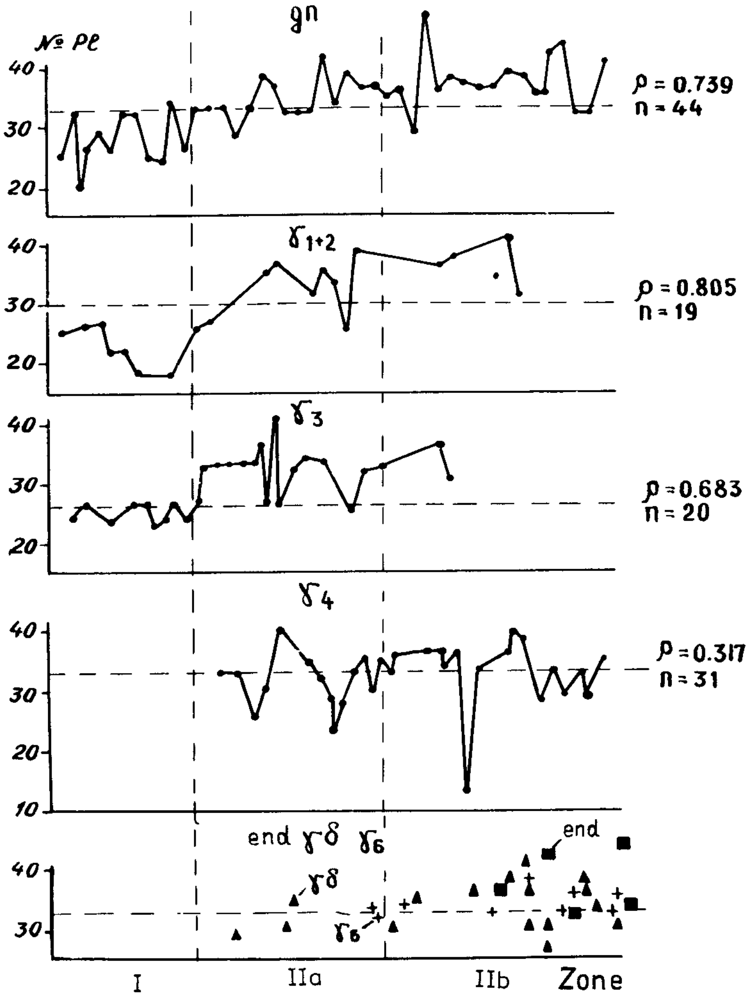

Fig. 5. The trend of plagioclase composition change of the Ladogian Complex metapelites and different generation leucosomes under prograde metamorphism (left to right).

The metamorphic zones: I – biotite-garnet-sillimanite-muscovite subfacies and IIa – biotite-garnet-orthoclase-cordierite one of the amphibolite facies, IIb – same subfacies, but in granulite facies.

In granite formation series of the Ladogian Complex: $\gamma_0 \rightarrow \gamma_1 \rightarrow \gamma_2 \rightarrow$ [β, end, δ] $\rightarrow \gamma_3 \rightarrow \gamma\delta \rightarrow \gamma_4 \rightarrow \gamma_5 \rightarrow$ [β, γδ] $\rightarrow \gamma_6 \rightarrow [\gamma_7]$ leucosomes γ_0, γ_1, γ_2 and γ_3 arose simultaneously with the metamorphic zonation. Leucosomes γ_4, γ_5 and γ_6 are formed after metamorphic zonation. Intrusion complexes are shown in brackets.

gn – metapelitic gneisses, j – granite, end – enderbite, γδ – granodiorite, δ diorite, β – gabbro, ϱ – correlation coefficient of Spirman, n – number of analyses.

Table 3
Average composition of migmatite leucosomes in the different metamorphic zones of Ladogian Complex

	I γ_{1+2}		IIa γ_{1+2}		IIb γ_{1+2}		I γ_3		II γ_3	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
SiO_2	73.47	4 38	71 95	3.49	70.36	6.12	72.97	2 02	70.25	2 87
TiO_2	0.36	0.18	0.35	0.20	0 35	0 20	0 35	0.10	0.57	0.20
Al_2O_3	13 29	2 35	14.41	1.76	14.18	2.32	13.61	0.97	14.53	1 70
Fe_2O_3	0.61	0.34	0.58	0.48	1.01	0.61	0.47	0.20	0.49	0.31
FeO	2 08	1 05	2.00	0.97	2.93	1.50	2.16	0.55	2.62	1 15
MnO	0.07	0.06	0.04	0.02	0.09	0.05	0.05	0.01	0.04	0.02
MgO	1.30	0.71	1.00	0.54	1.49	1.05	1.19	0.33	1.55	0.84
CaO	2.12	0.79	2.33	0.64	2.70	1.34	1.97	0.43	1.97	0.88
Na_2O	2 95	1.16	3.34	0.58	2.78	0 53	3.24	0.68	2.90	0.44
K_2O	2.05	0.99	2 94	1 33	2.43	2.24	2.25	0.95	4.07	2.99
P_2O_5	0.20	0.14	0.07	0.04	0.12	0.10	0.18	0.14	0.09	0.06
n	13		10		10		13		8	

γ^{I}_{1+2} – leucosomes of stromatic migmatites mainly of the second generation in muscovite-garnet-biotite -sillimanite subfacies (I); γ^{IIa}_{1+2} – those in garnet-biotite-cordierite-orthoclase subfacies of amphibolite facies (IIa); γ^{IIb}_{1+2} – but in the granulite facies (IIb); γ^{I}_{3} – leucosomes of network migmatites of the third generation in the subfacies I, γ^{II}_{3} – those of subfacies IIa and IIb, $\bar{x}$ – average content of the oxides, σ – standard deviation

Under lower temperature where melting cannot yet take place, quartz-bearing veins with various amount of plagioclase occur in the metapelitic rocks. Plagioclase contents increases with prograde metamorphism. The above-mentioned trend of change of chemical composition of the different generations of leucosomes from basic to acid occurs not always. Sometimes in the middle of a sequence their basicity rises. A similar instance concerns migmatites of the middle Nykzha (W. Siberia), on the southern margin of the Aldan Shield. From γ_2 to γ_3 basically increases and decreases to γ_4 (Tab. 2). Leucosome γ_3 forms stromatic and network migmatites, γ_2 and γ_4 are leucosomes of stromatic migmatites only.

Generation of mobile granitoid bodies. The third fragment of granite formation series involves the transition of different rocks (migmatites, granite and charnockite-gneisses) to a mobile state. One can see in many outcrops that migmatite loses its banding and becomes homogeneous, that is mixing of leucosome and paleosome takes place and melanosome dissolves (Fig. 7.). It can be observed displacement of the migmatite fragments and replacement of migmatite xenoliths by granitoid melt (Fig. 8). Moreover, early leucosome can be preserved as more stable bands in xenoliths (Fig. 8). Scales of the above phenomena vary greatly from a series of zones, the separate parts to the large sources which may represent autochthonous and paraautochthonous bodies up to several kilometers in diameter.

The compositions of granitoids, formed during this process are similar to those of migmatites according to analysis of the rock from the same outcrop. However, on the whole there may not be total and absolute coincidence of composition between migmatites and reomorphic granitoids. Sometimes the acidity and alkalinity of the latter rise. In some cases the basicity of the new formed granitoids increases (Tab. 4) because of restite assimilation.

The formation of third generation leucosome (γ_3) and then granodiorite bodies in the Ladogian Complex and the Karategin series in the S. Tien Shan given an idea of the processes under consideration. The mobilization phenomena in the small scales can be distinguished in every ultrametamorphic complex. It is well known that the mobilization of the granite- and charnockite-gneiss complexes of the Aldan Shield, led to the generation of granite and charnockite bodies. A similar mode of granite formation for Muskol Metamorphic Complex in the Alpine fold belt has been established (Central Pamirs).

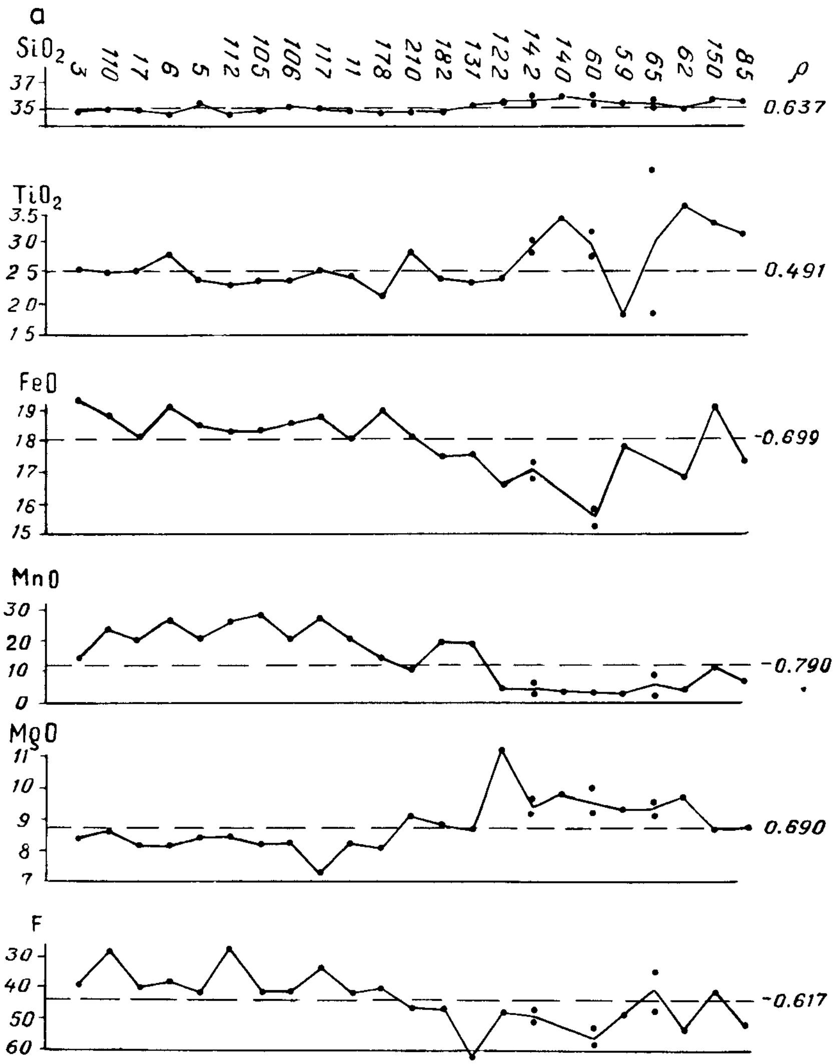

Fig. 6. The trend of biotite composition in melanosome (a) and leucosome (b) under prograde metamorphism (left to right).

1 = $\gamma_1 + {}_2$; 2 = γ_3; 3 = γ_4; 4 = $\gamma\delta$. Figures mean numbers of outcrops. Only those elements are shown whose amouts change statistically significantly. ρ – correlation coefficient of Spirman.

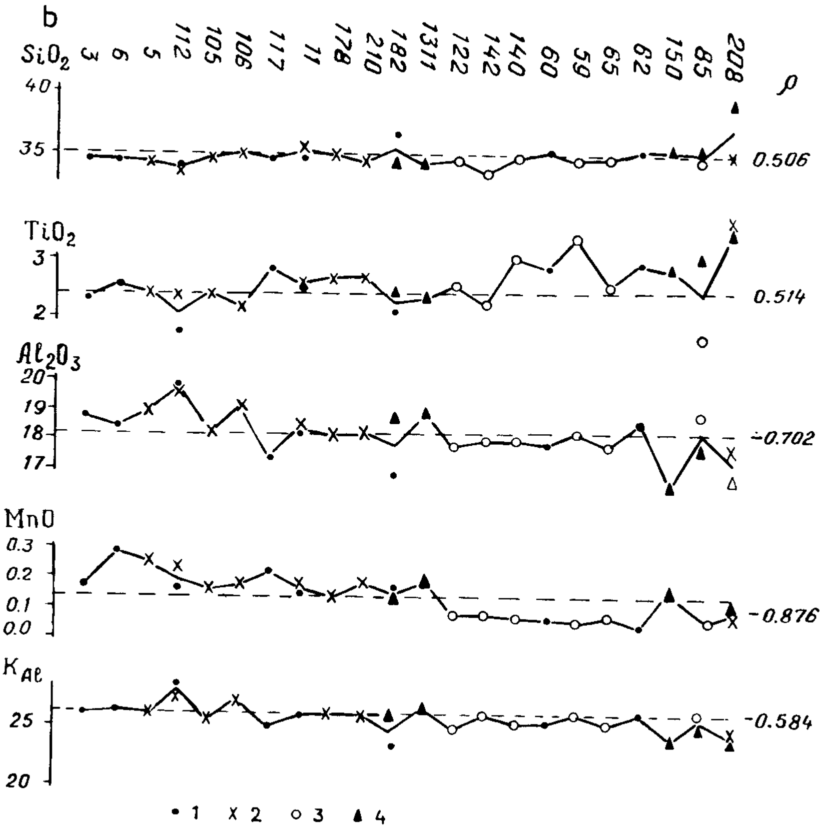

Fig. 6b.

Discussion

Principal processes generating the granite formation series. One can conclude that the morphology of volume replacement of the different compositional units by granite-like rocks without their mobilization at the first stage, the gradual transitions from initial rocks to granite- and charnockite-gneisses through intermediate composition rocks, the replacement of mafic minerals and plagioclase by more felsic plagioclase, quartz and K-feldspar, segregations of latter allow one to consider this process as a metasomatic precursor of rocks prior to melting. The onset of the melting leads to the formation of the drop-like portions and the development of granitic leucosomes and the formation of stromatic migmatites. If metasomatic processes continue with melting, they affect the composition of the resulting melt. This phenomenon, discovered by Korzhinsky (1973), is referred to as „metasomat-

Fig. 7. Formation of mobile granites.

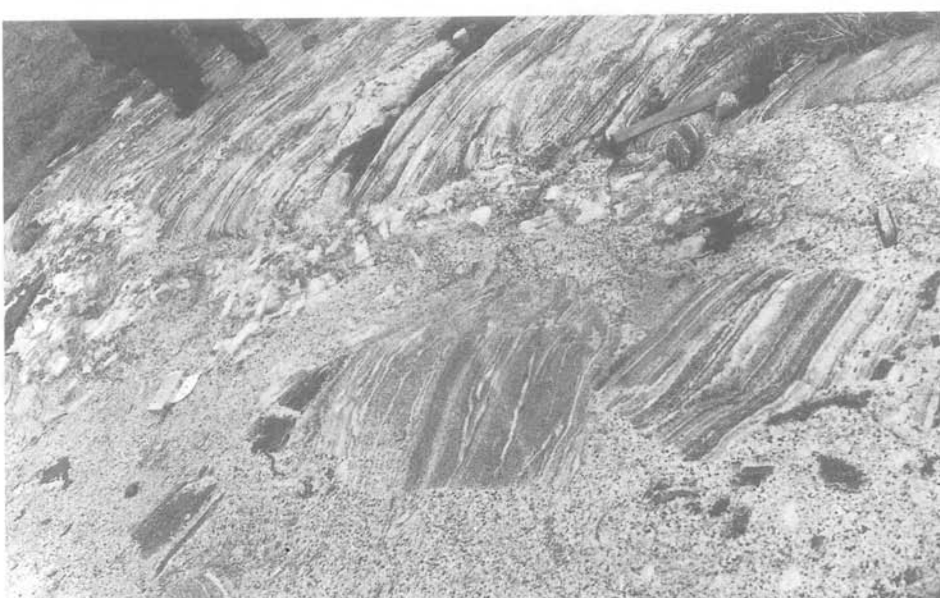

Fig. 8. Magmatic replacement of migmatite.

Table 4
Average compositions of granites, formed during rheomorphism of various rocks

		n		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Loss
The Aldan Shield, upper reaches of the Aldan River, Early Archean															
chgn (γ_1)	i. r. au.	48	$\bar{X}$	70.15	0.41	14.47		2.61*	0.05	0.85	1.57	3.44	4.81	0.09	0.26
			σ	3.22	0.24	1.58		1.55	0.03	0.52	0.72	1.18	1.18	0.08	0.21
ch (γ_3)	par. all.	21	$\bar{X}$	71.80	0.36	14.66		1.82*	0.03	0.57	1.57	3.39	4.81	0.07	0.37
			σ	3.13	0.23	2.25		0.61	0.02	0.31	0.74	0.52	1.60	0.06	0.21
γgn (γ_1^{II})	i. r. au.	35	$\bar{X}$	72.70	0.38	13.16		2.44*	0.04	0.57	1.22	3.51	4.54	0.07	0.26
			σ	3.34	0.21	1.28		1.40	0.03	0.40	0.62	0.87	0.98	0.07	0.17
γ_3^{II}	par. all.	21	$\bar{X}$	73.71	0.27	13.09		2.25*	0.02	0.43	0.96	3.72	4.88	0.05	0.34
			σ	2.31	0.18	1.48		1.22	0.01	0.18	0.52	1.08	1.19	0.05	0.17
The Vitim-Olekma highland, S margin of the Aldan Shield, Late Archean															
γgn (γ_1)	i. r. au.	8	$\bar{X}$	69.37	0.47	14.93	1.09	1.82	0.02	0.52	1.74	4.15	4.69	–	0.65
γ	par.	2	$\bar{X}$	71.20	0.05	13.53	0.29	3.90	tr.	0.59	1.13	3.98	5.25	–	0.60
The middle course of Nuikzha, S margin of the Aldan Shield, Late Archean															
γgn (γ_1)	i. r. au.	24	$\bar{X}$	69.80	0.36	15.19	1.18	2.04	0.06	1.13	3.02	4.11	2.12	0.08	0.76
			σ	3.54	0.18	0.88	0.60	0.87	0.03	0.57	1.28	0.50	1.15	0.07	0.35
γ_5	par.	14	$\bar{X}$	71.85	0.29	15.54	0.45	0.96	0.03	0.45	1.33	4.22	3.72	0.06	0.51
			σ	1.58	0.20	0.77	0.42	0.38	0.01	0.23	0.59	0.81	0.96	0.03	0.19
The middle course of Nuikzha, Early Proterozoic															
mig	i. r. au.	9	$\bar{X}$	65.24	0.49	15.80	2.25	2.75	0.09	2.07	4.14	4.24	1.98	0.16	0.95
			σ	2.48	0.08	0.49	0.81	0.80	0.03	0.84	0.50	0.37	0.30	0.08	0.21
γ_6^{all}	au.	19	$\bar{X}$	67.53	0.41	15.74	1.57	1.97	0.06	1.45	3.41	3.83	2.97	0.12	0.82
			σ	3.74	0.17	0.95	0.74	0.69	0.03	0.78	1.19	0.45	1.57	0.08	0.29
γ_6^{all}	par.	16	$\bar{X}$	70.41	0.33	15.29	1.05	1.50	0.04	0.69	2.30	3.75	3.63	0.09	0.72
			σ	1.76	0.14	0.78	0.59	0.61	0.02	0.26	0.96	0.37	1.41	0.04	0.24
The Stanovoy Range, S margin of the Aldan Shield, Late Archean															
γgn	i. r. au.	9	$\bar{X}$	70.76	0.21	15.96	0.81	0.92	0.03	0.51	1.89	4.14	4.17	–	0.37
			σ	2.77	0.11	1.26	0.47	0.73	0.02	0.48	0.61	0.70	0.68	–	0.15

continuation of Tab. 4

		n		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Loss
$\gamma^{p\,St}$	par.	14	$\bar{X}$	68.83	0.32	16.35	1.16	1.21	0.01	0.81	2.30	5.10	3.40	–	0.44
			σ	4.02	0.20	1.40	0.80	0.50	0.01	0.40	0.94	0.85	1.02	–	0.25
Central Pamirs, the Muskol Complex, Shatput thermal anticline, KZ															
γ_1^{sh}(gn)	i. r. au.	17	$\bar{X}$	75.24	0.26	12.55	0.82	1.29	0.03	0.85	0.96	4.39	2.92	0.08	0.53
			σ	2.66	0.20	1.12	0.79	0.73	0.02	0.62	0.51	1.40	1.64	0.05	0.27
γ_2^{sh}	par. all.	24	$\bar{X}$	72.07	0.30	14.71	0.62	1.20	0.02	0.45	1.83	4.07	4.25	0.07	0.49
			σ	2.08	0.31	0.97	0.43	0.61	0.02	0.76	0.35	0.80	0.98	0.04	0.32
γ_3^{sh}	all	10	$\bar{X}$	71.20	0.13	14.65	0.10	1.04	0.04	0.70	2.13	3.68	5.61	0.45	0.55
			σ	4.13	0.04	0.59	0.68	0.57	0.04	0.77	2.18	1.94	2.78	0.25	0.34
The Ladogan Complex, Early Proterozoic															
mig. IIa	i. r. au.		X^*	64.14	0.77	15.69	2.02	4.51	0.06	2.76	2.30	2.61	3.10	0.15	
γδ IIa	par.	15	$\bar{X}$	65.11	0.92	15.68	0.95	4.10	0.10	1.92	2.77	3.54	2.89	0.38	
			σ	4.44	0.26	1.30	0.46	1.20	0.14	0.62	0.64	0.45	0.77	0.29	
mig IIb	i. r. au.		X^{**}	65.40	0.64	15.86	1.00	3.77	0.08	2.20	3.09	3.23	2.95	0.19	
γδ IIb	par.	14	$\bar{X}$	61.67	0.72	17.30	1.51	3.57	0.08	2.02	4.10	3.70	3.01	0.57	
			σ	5.41	0.27	1.73	0.76	1.32	0.04	0.84	1.72	0.66	1.27	0.55	
S Tian chan, the Karategin Complex, Pz															
mig	i. r. au	19	$\bar{X}$	66.99	0.73	14.24	1.59	4.52	0.10	2.32	2.00	2.38	2.93	0.18	
			σ	4.06	0.16	2.47	1.18	0.89	0.03	0.61	0.98	0.60	0.74	0.07	
γδ	par.	43	$\bar{X}$	65.86	0.58	15.97	1.19	3.39	0.07	1.68	2.50	3.05	3.27	0.21	
			σ	2.72	0.14	1.17	1.08	1.19	0.03	0.85	1.04	0.54	0.65	0.09	

γ – granite; γδ – granodiorite; mig – migmatite; ch – charnockite; chgn – charnockite-gneiss; γgn – granite-gneiss, i. r. – initial rocks; au-autochthonous rocks; par – paraautochthonous granites; par. all. – more considerably moved granites, all – allochthonous granites. Ch and chgn occur in granulite facies, γgn (γ_1^d) and γ_β^d in amphibolite facies for Aldan Shield; mig. IIa (Ladogian Complex) – migmatites of the garnet-biotite-cordierite-orthoclase subfacies of amphibolite facies; mig. IIb – the same but of the granulite facies. X* – all the Fe as FeO. ** – calculated composition of the rocks according their proportion in outcrops.

ism". A similar interpretation of the above processes is given by Zharikov – Gavrikova (1987). In their opinion, the melting begins in the rear zone of a complete metasomatic column that is after the formation of the monomineral zone, consisting of plagioclase or K-feldspar.

The reliable estimation of the mass balance by volume replacement of the amphibolite and gneisses cannot be carried because of deformation processes and because of the presence of leucosomes belonging to several different stages, though some attempts to calculate this have been made (Olsen, 1982, 1984). However, the composition comparison of the protolith and the newly formed rocks generating core of dome-like structures and the scale of the development of similar processes show the obvious necessity of Si addition and sometimes alkalies and removal of Ca, Mg, Fe (Tab. 1, Figs. 1, 2, 3).

At upper level, where the melting conditions were not reached, quartz, albite, quartz-albite and microcline leucosomes are developed, at the zone of staurolite subfacies quartz-oligoclase rocks, sometimes with microcline, occur. They arise by metasomatic way, possibly partly by stress-induced mass transfer process (Sawyer – Barnes, 1988) and are analogous to products of the ultrametamorphic processes at deep level (Sedova et al., 1980; Glebovitsky et al., 1981).

The leucosome location along the axial surfaces of the folds and all the earlier plane structure elements, the presence of hypidiomorphic textures and of crystallized melt inclusions in quartz and other minerals of these rocks (Tomilenko – Chupin, 1983), composition of the rocks, often corresponding to cotectic composition in system Ab-Or-Qtz--An (H_2O) show that the stromatic migmatites can be considered as a result of partial rock melting and injection to the short distance.

On the basis of investigations in the last decade, it becomes clear that the model for the stromatic migmatite formation as an anatexis, as considered earlier (Winkler, 1979; Mehnert, 1968) is not always satisfactory (Ashworth, 1985; Atherton – Gribble, 1983). Processes of metamorphic differentiation both without fluid and water-saturated melting are considered as phenomena leading to migmatite formation. On the other hand, the absence of any difference in plagioclase composition between neosome and paleosome as discussed recently in literature (Ashworth, 1985), the gradual decrease in Fe-Mg mineral contents in paleosome with increasing leucosome amount and the absence of features of incongruent melting allow one to conclude that melting took place in a thermodynamic open system (Sedova – Glebovitsky, 1984).

What is the cause of the compositional change of the newly formed leucosomes, in particular, the increasing of their acidity? Because of the impossibility of estimating exactly, as mentioned above, the crystallization temperatures of leucosome generations, there is uncertainty in the interpretation of the change of their composition, especially in connection with new experimental and theoretical investigations (Ashworth, 1985). It was established that in some cases the fluid pressure does not change in a leucosome sequence from the first generation to the later (Vapnik's data). Pressure decreases to the moment of formation of a great mass of rheomorphic granites (Vapnik – Sedova, 1986). Therefore T, P, P_{H_2O} and fluid-magmatic interaction can be seen as the main factors, governing the evolution of rock composition. It should be pointed out that the basicity of the syn-metamorphic leucosomes in the prograde metamorphic sequence increases with temperature increasing, K_2O content increases or remains constant.

These data allow us to explain the above change of rock composition in the following way: partial melting and then formation of the granite melt take place at the peak of regional metamorphism. This melt is distributed in fracture zones and gives rise to leucosome generations – early high temperature ones corresponded to more basic composition, the later ones have a more acid composition, that is they are formed at lower temperature and therefore evolved over a longer period. This idea was first stated by Sudovikov (1964).

It is possible that the acidity rise of the late differentiates, if they are eutectic, is due to the influence of alkaline fluids. The latter extended the field of alkaline feldspar crystallization and displaced the eutectic composition to the acid field (Kusnetsov – Epelbaum, 1985).

Crystallization models on the base of the trace-element distribution in leucosome generations indicate that variations of leucosome compositions can be derived by fractionation of initial melts and depend upon their segregation and crystallization history (Sawyer, 1986; Sawyer – Barnes, 1988) which, in my opinion, is connected with the evolution of the P-T regime. If the melt basicity rises in the middle of a cycle and then again decreases, probably a temperature rise (or pressure decrease) or P_{H_2O} increase take place. It is possible that the series is of importance as an example of a new burst of melting, which was concentrated along separate zones and can be transitional to the third fragment of the granite-formation series.

This fragment involves the transition of different rocks (migmatites, granite-and charnockite-gneisses and so on) to a mobile state, when the volume of the melts increases sufficiently or complete melting (diatexis) takes place and a zone melt (or a magmatic source) arises. The granite autochthonous bodies in the deep zones can be seen as magmatic source. The composition of the mafic minerals, the structure state of feldspar, very high temperature of the melt inclusion homogenization can witness a prograde melting. Increasing of T in connection with an additional heating of the ultrametamorphic zones by influence of basic rock intrusions promotes this process. Duration of diatectic processes appears to be longer than the formation of one leucosome generation. Rather homogeneous bodies prove to be formed as a result of rheomorphism. Differentiation of melts is possible, the later variations becoming more leucocratic and coarse-grained unlike the earlier.

Thus, predominant process for the first fragment is metasomatism, for the second fragment is partial melting, as a rule, in thermodynamic open system, for the third fragments is diatexis and rheomorphism. This does not exclude the possibility to develop these processes simultaneously.

Granite formation series. Earlier, two end-paths to the development of ultrametamorphic zone have been recognized, these are a function of the relative dominance of anatexis or metasomatism due to the differences in the rates of heat- and mass-transfer (Sedova – Glebovitsky, 1984). The first path, which is realized more often in the areas of the kyanite-sillimanite regime, corresponds to the conditions when the rate of mass-transfer is higher than that of heat-transfer. In such cases the sequence of processes is as follows: metasomatism → metasomatism + anatexis → diatexis and rheomorphism + metasomatism. The second part corresponds to reverse conditions of a heat-transfer rate greater than the mass-transfer rate and the ultrametamorphic succession is: anatexis → diatexis and rheomorphism (+ metasomatism) → anatexis + metasomatism.

In accordance with these two paths we recognize two complete series of granite-formation. The first begins with the suite of plagiogranite or granite-gneisses, enderbite- or charnockite-gneisses (at amphibolite and granulite facies, respectively), then it is followed by the stage of migmatite formation when several generations of leucosomes of migmatites appear and it is terminated by the generation of diatectic magma sources. The examples are granite series from the Aldan Shield during the second cycle of development, from the Stanovoy zone (Late Archean) and from the Vitim-Olekma Highland etc. (Tab. 5).

The second series begins with the formation of polymigmatites, firstly only in acid rocks, then possibly under the influence of basic magma heating, the generation of diatectic magmas and their rheomorphism takes place, followed by anatexis under conditions of fluid flow to

Table 5
Types of the granite formation series

I	metasomatism granite – gneisses plagiogranite – gneisses enderbito – gneisses charnockito – gneisses	→	anatexis ± metasomatism stromatic migmatites of several generations	→	diatexis, rheomorphism network migmatites small → large bodies of the granites
II	anatexis stromatic migmatites of several generation	→	diatexis + rheomorphism network migmatites small → large granodiorite bodies	→	anatexis + metasomatism (magmatic replacement) stromatic migmatites of several generations nebulites, KFsp – porphyroblasts
Ia	metasomatism	→	rheomorphism ± metasomatism		
Ib	metasomatism	→	anatexis ± metasomatism ± rheomorphism		
IIa	anatexis	→	anatexis ± metasomatism		
IIb	anatexis ± metasomatism	→	rheomorphism + metasomatism		

form migmatites, nebulitic granite-gneisses, and potassium metasomatism also occurs (porphyroblastic development of K-feldspar). The examples are a series of migmatite formation from the Northern Ladoga region and Karategin, S. Tien Shan (Tab. 5).

Besides these series, there are reduced series when a particular stage of the process is absent or weakly manifested; sometimes various processes occurred so close in time that their separation is impossible, this is characteristic of superimposed tectono-metamorphic cycles.

Conclusion

The rock, successively formed as a result of various ultrametamorphic processes during single tectonometamorphic cycle are united into granite formation series. This series is divided into three fragments depending on the predominant processes of granite generation. These are metasomatic volume replacement of the initial rocks, partial melting, leading to the formation of successive generation of stromatic and network migmatites, diatexis and rheomorphism, forming granite bodies. These processes (or fragments of the series) occur in different time relation.

Earlier on the base of the correlation of the rates of mass- and heat-transfer two types of evolution of ultrametamorphic zones were recognized. According to these evolutionary types of ultrametamorphism zones one can recognize two complete series of granite formation and four incomplete series. The latter are characterized either by the absence of migmatite formation or by the genetically distinct processes occurring contemporaneously that are not separated by any event. This is characteristic of the superimposed cycles usually related to tectonic zones where rates of heat- and mass-transfer were similar, and genetically different processes were associated.

REFERENCES

ASHWORTH, J. R. (ed.), 1985: Migmatites. *Blackie, Son. Ltd.*, 360 pp.

ATHERTON, M. P. – GRIBBLE, C. D. (eds.), 1983: Migmatites, melting and metamorphism. *Shiva*, Nantwich, 380 pp.

GLEBOVITSKY, V. A. – SEDOVA, I. S. – DUFUR, M. S. – MILLER, Yu. V. – DRUGOVA, G. M. – KRAVTSOVA, E. Y., 1981: Evolution in metamorphic belt of the Alpine type. 304 pp. (in Russian).

GLEBOVITSKY, V. A. – ZINGER, T. F. – KOZAKOV, J.K. – KOTOV, A. V. – KRILOV, D. P. – MANUILOVA, M. M. – MITROPHANOV, F. P. – ORLOVSKAYA, K. V. – SAMORUKOVA, L. M. – SEDOVA, Y. S., 1985: Migmatization and granite formation in various thermodynamic regimes. 310 pp. (in Russian).

KITSUL, V. I. – DOOK, V. L., 1986: The endogenic regimes of formation and stages of evolution of the Early Precambrian lithosphere of the Vitim-Aldan Shield. The endogenic regimes of crust formation and ore deposition in the Early Precambrian. *Nauka*, pp. 217–234 (in Russian).

KORZHINSKY, D. S., 1952: Granitization as magmatic replacement. *Izv. Akad. Nauk. SSSR, Ser. geol.* (Moscow), 2, pp. 56–69 (in Russian).

KORZHINSKY, D. S., 1973: Metamagmatic processes. *Izv. Akad. Nauk SSSR, Ser. geol.* (Moscow), 12 pp. 3–6 (in Russian).

KRILOVA, M. D. – SEDOVA, I. S. – KRILOV, I. N. – GLEBOVSKY, S. S. – GALIBIN, V. A., 1972: Evolution of substance under metamorphism. 180 pp. (in Russian).

KUZNETSOV, A. D. – EPELBAUM, M. B., 1985: Eutectic correlation in opened systems with perfectly mobile components. 109 pp. (in Russian).

MEHNERT, K. R., 1968: Migmatites and the origin of granitic rocks. 393 pp.

OLSEN, S. N., 1982: Open- and closed-system migmatites in the Front range, Colorado. *Amer. J. Sci.* (New Haven), 282, pp. 1596–1622.

OLSEN, S. N., 1985: Mass-balance and mass-transfer in migmatites from the Colorado Front Range. *Contr. Mineral. Petrology* (Berlin-New York), 85, pp. 30–44.

SAWYER, E. W., 1987: The role of partial melting and fractional crystallization in determining discordant migmatite leucosome compositions. *J. Petrology* (Oxford), 28, 3, pp. 445–473.

SAWYER, E. W. – BARNES, S. J., 1988: Temporal and compositional differences between subsolidus and anatectic migmatite leucosomes from the Quetico metasedimentary belt, Canada. *J. Metamorph. Geol.,* 6, pp. 437–450.

SEDOVA, I. S. – GLEBOVITSKY, V. A., 1984: Development of ultrametamorphism in the amphibolite facies conditions. *Izv. Akad. Nauk SSSR, Ser. geol.* (Moscow), 2, pp. 46–59 (in Russian).

SEDOVA, I. S. – GLEBOVITSKY, V. A., 1984: Granite formation under amphibolite facies conditions in the Stanovoy complex zone. The Aldan Massif and its marggin. *Nauka,* pp. 92–121 (in Russian).

SEDOVA, I. S. – GLEBOVITSKY, V. A. – DUFUR, M. S., 1980. Fluid regime and geochemistry of the ultrametamorphic processes (for an example of some regions of the Central Pamirs). Metamorphism of the Early Precambrian. *Nauka,* pp. 120–130 (in Russian).

SUDOVIKOV N. G., 1964: Regional metamorphism and some problems of the petrology. 550 pp. (in Russian).

TOMILENKO, A. A. – CHUPIN, V. P., 1983: Termobarogeochemistry of the metamorphic complexes. 201 pp. (in Russian).

VAPNIK, E. A. – SEDOVA, I. S., 1986: Pressure conditions and fluid compositions during ultrametamorphism in the Aldan megablock. *Int. Geol. Rev.,* 28, 11, pp. 1293–1305.

WINKLER, H. G. F., 1979: Petrogenesis of metamorphic rocks.

ZHARIKOV, V. A. – GAVRIKOVA, S. N., 1987: Granite formation in reactivated margin of the Aldan-Stanovoy Shield. *Zap. Vsesoyuz. mineral. Obshch.* (Moscow), 116, 4, pp. 377–399 (in Russian).

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