GEOLOGICKÝ ZBORNÍK – GEOLOGICA CARPATHICA, 41, 6, BRATISLAVA, DECEMBER 1990,
Pp. 653–670

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GRANITIZATION REGIME IN DIFFERENT METAMORPHIC FACIES SERIES; A NEW APPROACH TO CALCULATE P-T CONDITIONS OF PETROGENESIS

(6. Figs., 7 Tabs., App.)

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Abstract: Comparative analysis was performed with respect to structure, composition, geochemistry and conditions of migmatite and granite formation for zonal kyanite- and andalusite-sillimanite metamorphic series from the Baikal region. This analysis confirms the quasi-isochemical nature of the prograde metamorphism. A variable extent of metasomatism and anatexis, depending on the type of metarmophism and the important nature of the fluid regime, have been established. The lower the total and fluid pressure, and the higher the tectonic permeability of sequences, the greater is the significance of juvenile solutions and alkaline metasomatism in granitization. In high-P belts the permeability of sequences decreases, while the role of metamorphic fluids increases. Metamorphic differentiation and anatexis become the major mechanism of migmatization.
In order to find out the causes of replacement of the isochemical metamorphic stage, by the allochemical granitization stage, it is important to correctly define P-T conditions. A new method of geothermobarometry, based on solving the inverse problem of physico-chemical computer modelling by minimization of the isobar-isothermal multisystem potential, allows definition of P-T conditions of formation of typical parageneses of metamorphosed and granitized rocks in the Khamar-Daban complex (South Baikal region). This method considers a certain overall chemical composition for rocks and minerals in the association, its errors, as well as the uncertainty of input thermodynamic information, and include the coefficients of component activity. In addition, solution of the inverse physico-chemical problem makes it possible to estimate the probable fluid composition which equilibrated with the mineral parageneses studied.

Key words: granitization regime, metamorphic series, P-T conditions, North Baikal – Kutim block.

Introduction

The Precambrian metamorphic belts sufferred voluminous granite formation. This is the point to be considered in solving problems of granitoid origination. A common point of view as to its mechanism is still not available. Many investigators, including experimenters, believe that migmatites and granites were formed by anatexis during prograde metamorphism (King, 1967; Wyllie, 1977; Thompson, 1982; Mehnert – Büsch, 1982; Wickham, 1987; Shkodzinsky, 1987). The scientists of the Soviet metamorphic school concerned with regional studies, are prone to recognize the significant role of metasomatism in this phenomenon (Korzhinsky, 1952; Sudovikov, 1959; Perchuk, 1970; Makrigina, 1981; Petrova – Levitsky, 1984; Sedova, 1984; Olsen, 1984).

The cause for such differences in opinions is the diversity of migmatitic complexes in various metamorphic belts and of granitization under conditions close to those of melting at the

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granite eutectic. The migmatitic complex is understood as an aggregate of migmatites, granite-gneisses and granites formed within the metamorphic belt. This study was based on thoroughly investigated migmatitic complexes, and we make an effort to show that the conditions of their formation affect the relationship between metasomatism and anatexis as well as the metallogeny of associated pegmatitic belts.

Metamorphism

The materials from migmatite complexes in metamorphic belts of high pressure (the Mama synclinorium and Patom highland), moderate pressure (Khamar-Daban), and low pressure (Chuya series of the North Baikal highland and Kutim block) have been used to analyse the geochemical features of granitization. Metamorphism of these zonal complexes and its geochemical features are reported in Makrigina (1981), Manuilova et al. (1964), Petrov – Makrigina (1975), Shafeev (1970). Some major patterns of processes and the main differences between complexes of different pressures should be pointed out (Makrigina, 1981).

1. The high-P facies series of kyanite-sillimanite type are formed either in miogeosynclinal troughs filled with thick sequences of sand-carbonate-clay sediments, or in nappe packages, i.e. in compression structures. The low-P metamorphic complexes are confined to uplifts or rifting structures composed of dominantly effusive-sandy sequences. Extension periods prevailed in the development of these structures. The moderate-P facies series occupy the intermediate position according to composition of sequences and relationship of stress sign.

2. At a progressive stage of metamorphism rocks lose H_2O, CO_2, C and B. With respect to other elements, the rock composition practically does not change. The levels of trace element contents and proportions common for each rock variety, are retained.

3. Each type of metamorphism exhibits the particular dynamics of H_2O and CO_2 removal, and fluid regime. The higher fluid pressure characteristic of metamorphism of kyanite-sillimanite facies series results in widening the stability fields of muscovite and carbonates, in formation of highly dense CO_2 inclusions in minerals and in high H_2O contents in them. Both high P_{load} and the initial weak permeability of clay-carbonate rocks saturated in volatile components promote creation and long preservation of high fluid pressure. On the contrary, in low-P series there is widening of anorthite stability fields, the carbonate decomposition at lower temperature and narrowing the muscovite stability field that is the evidence of lower fluid pressure. This is the consequence of both lower P_{load} and higher permeability of effusive-sandy sequences under extension conditions.

Migmatitic complexes

The metamorphic zonation of kyanite-sillimanite type from sericite-chlorite to kyanite-muscovite-almandine zone of the Patom trough and Mama synclinorium was formed in a thick flyshoid sequence (Petrov – Makrigina, 1975; Fig. 1). In the kyanite zone of metapelites pegmatoid separations of quartz-plagioclase composition appear. In increasing their dimensions and amount they are combined into net-like bodies of non-zonal plagiomigmatites. According to morphology and composition such formations are plagiomigmatites. They are conformable with their host gneisses in orientation if micas and numerous gneiss skyaliths. Small lenses and nests possess biotite-rich rims which indicate redistribution of gneissic substance. When calculating the mass balance, sodium addition was observed even in small bodies (Petrov – Makrigina, 1975).

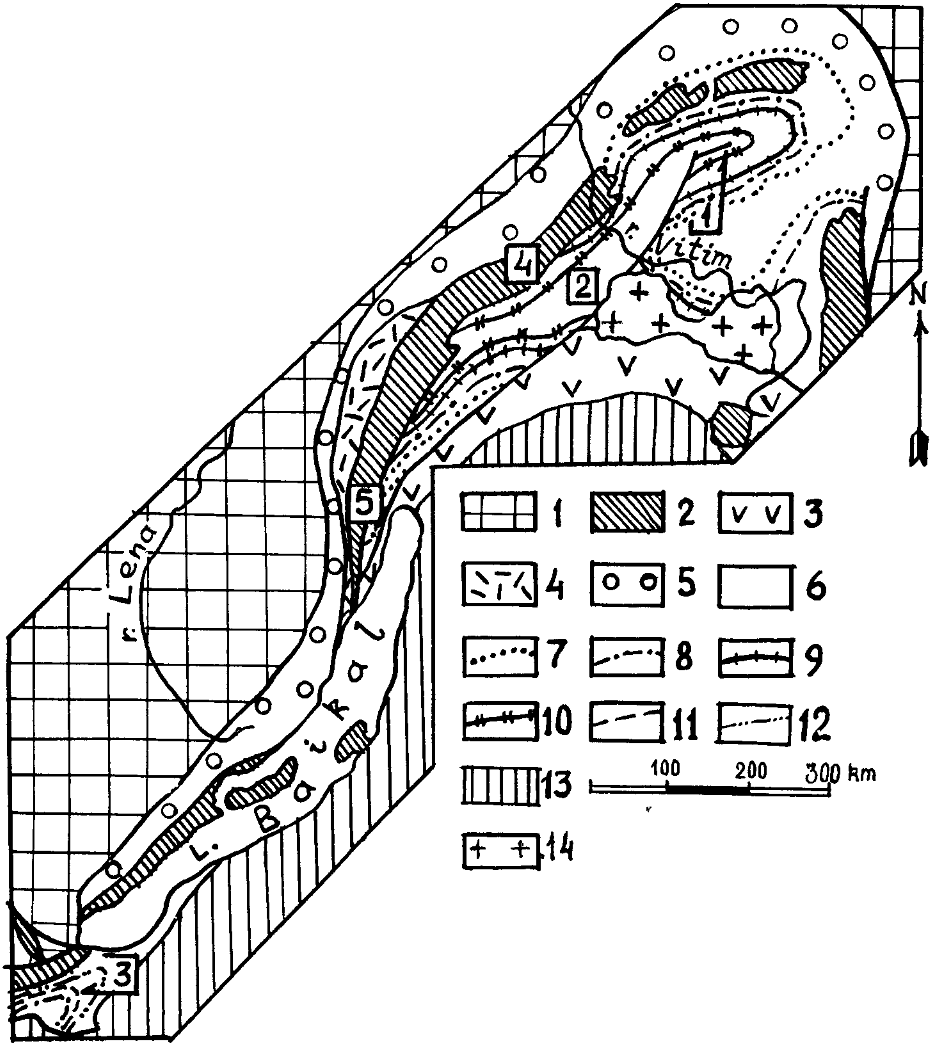

Fig. 1. Geological structure and metamorphic zonation of the Baikal region; position of districts under study (Petrov–Makrigina, 1975).

1 – Siberian platform; 2 – AR-PR_1 sequences, granulite-retrograde amphibolitic facies; 3 – Baikal--Muya ophiolite belt (PR), 4 – Baikal volcano-plutonic belt (PR_2), 5 – terrigenous sequences of the outer trough (R); 6 – zonal metamorphosed sequences of the internal trough (R). *Isograds:* 7 – biotite, 8 – garnet, 9 – staurolite, 10 – kyanite, 11 – andalusite, 12 – sillimanite, 13 – areas of younger consolidation, 14 – granites (PZ).

Numbers denote districts studied: 1 – Patom, 2 – Mama, 3 – Khamar-Daban, 4 – Chuya, 5 – Abchada.

K-feldspar zones appear in plagiomigmatites closer to the central axial uplift of the synclinorium. The chain of massifs of bi-feldspar pegmatoid granites run along the uplift. They produce granite-gneissic swells and domes which may be autochthonous or have evidence of displacement. The granites are accompanied by a series of magmatic pegmatites which overlap the fields of pegmatoid migmatites and have muscovite formation.

Particular features of the Mama series granitization are reflected in the pegmatitic structures of all migmatitic formations, and include a wide distribution of plagiomigmatites, with high contents of mica due to high fluid pressure at the prograde stage.

The Khamar-Daban zonal metamorphic complex of andalusite-sillimanite type occurs in the south-west Baikal region (Shafeev, 1970; Fig. 1). Migmatites are observed in the middle part of the muscovite-sillimanite subfacies. The front of granitization runs in accord with the isograds but like them crosses the strike of the rocks (Makrigina, 1981). As a result, a single layer of metapelites (and other rocks) is sampled in all metamorphic zones from greenschist facies to amphibolitic facies. The first 'migmatites' are rocks with dominantly lit-par-lit separations. They are found both in diopside-garnet-anorthite rocks where quartz veinlets are accompanied by the formation of epidote and apmhibole from diopside, and of zoisite from anorthite, i.e. water-bearing phases from water-absent ones. Consequently, this process is accompanied by the addition of H_2O and SiO_2 (the host schists contain no quartz). Then oligoclase is added to quartz, thus displaying transition to the zone of plagiomigmatites. The quartz+oligoclase neosome constitutes 15 to 20 % of plagiomigmatites in metapelites. The size of grains, in contrast to the Mama region migmatites, is close to that of the gneiss minerals.

In the Khamar-Daban complex the plagiomigmatite zone is several kilometers wide. It is replaced by a zone of K-feldspar migmatization, which coincides with the orthoclase-sillimanite zone, where mineral associations envolving muscovite are unstable and are replaced by paragenesses containing K-feldspar. Since no increase of potassium contents is observed in this zone, K-feldspar is probably formed by the decomposition of muscovite, and veinlets are segregated by metamorphic differentiation or partial melting of rocks.

In contrast to the Mama region migmatites, the process of migmatization in Khamar-Daban takes place isochemically with respect to alkalies but with Si increase and Al decrease. Finally, it results in the formation of autochthonous and little displaced granitic massifs. Non-displaced massifs contain mafic or infusible minerals of host rocks, e. g. sillimanite in metapelites, garnet or amphibole in amphibole schists. The front of granitization (rather than separate massifs) is rimmed by a zonal pegmatitic belt of rare metal – muscovite type (Shafeev, 1970; Makrigina, 1981).

The Chuya series in the North Baikal highland sufferred repeated metamorphism under conditions of the granulite facies and superimposed amphibolite facies. The front of granitization crosses the boundaries of metamorphic zones which are conformable with the strike of rocks (Petrov – Makrigina, 1975; Fig. 1). Compared to the Mama region and Khamar-Daban migmatitic complexes, which formed in the same tectono-magmatic cycle with metamorphic zonation at its inversion stage, the Chuya series granitization is considerably later in time (Petrov – Makrigina, 1975). It is typified by a significant change of the composition both along each layer and of the whole sequence, minor width of plagiomigmatization zone (100–300 m) with a strong K-feldspar development (up to 50–70 % of the whole rock amount) and a significant decrease of mafic and accessory minerals.

The granite-gneisses of the Chuya sequence contain spots of homogeneous granites and grano-syenites, which indicate remelting of some migmatites which attained compositions close to the granitic eutectic in the process of metasomatic transformation. They display a relation to the composition of the host migmatites, i.e. biotitic granites are formed in biotitic migmatites while amphibole grano-syenites and alaskites develop in amphibole migmatites.

In the south of the Chuya uplift (Minya-Abchada complex, Fig. 1) granitization was so strong that unaltered metamorphic rocks are not available. Fairly large skyaliths of biotite and garnet-sillimanite plagiogneisses and weakly altered bodies of ortho-amphibolites are available. Both in structure and composition the remaining plagiogneisses are plagiomigmatites because their mafic minerals are alkaline varieties characteristic of this type of granitization (Makrigina, 1981).

The next stage – K-feldspathization of the rocks – takes place in fault zones and layered rock planes. Its intensity increases towards the zone of the Abchada fault. The aegerine-diopside-K-feldspar paragenesis is formed in amphibolites. Gneisses contain microcline lenses and veinlets. The K-feldspar content in migmatites is as much as 70 %. Alkaline metasomatism is the true mechanism of granitization. A particular feature of the alkaline granitization of the Kutim block rocks, is not only preservation but a noticeable increase within the migmatites of accessory minerals amount (apatite, zircon, ortite, sphene, magnetite), set against a sharp decrease of mafic mineral abundances.

The Chuya uplift rocks display development of acid plagioclase and K-feldspar at both stages of granitization from cataclised metamorphites. This implies that plagioclase and K-feldspar migmatization produce both spacial zones and stages of granitization.

Geochemistry of migmatitic complexes

Comparison of the average composition of unaltered metapelites (gneissic part of sequences) with plagiomigmatites, K-feldspar migmatites and granites within each migmatitic complex shows that the chemistry of granitization is on the whole the same. This rock series undergoes an increase of Si and Na contents and then Si and K whilst the concentrations decrease of all other petrogenic components (Tab. 1). Calculation of the material balance during migmatization of various rocks of the Chuya series provides good evidence (Tab. 2).

A model of granite formation, in which metasomatism of the substrata (granitization proper) precedes melting, is supported by Mehnert (1971), Sedova – Glebovitsky (1984), Petrova–Levitsky (1984), Olsen (1984). Different intensities of changes and the inheritance of features of parent metamorphic rocks composition at all stages of granitization up to formation of granites, were revealed in comparing different migmatitic complexes. In low-P complexes migmatites and granites are more siliceous, less aluminiferous, contain more alkalies and have a considerably higher degree of ferrum oxidation (from 15–19 % in the Mama migmatites and granites to 63–67 % in migmatites of the Minya-Abchada complex, Tab. 1). An increase of calcium concentration (plagioclase abundance) is common for high-P migmatites and granites, whereas in moderate- and low-P complexes the Ca contents in migmatites decrease in the course of granitization development. In anatectic granites, K:Na ratio regularly changes from 0.9 in the Mama complex and 1.28 in Khamar-Daban to 1.5 in the Chuya complex and 1.67 in Minya-Abchada. At the same time such initial features of the gneisses of high-P series, as high alumina, water content and degree of Fe reduction are retained at all stages of their granitization.

While granitization proceeds, the ratio of volatiles is retained from prograde metamorphism. A general tendency for H_2O, CO_2 and B loss continued from the prograde metamorphic stage. However, in high-P series their level is highest. In low-P series initial gneisses and migmatites have lower H_2O, CO_2 and B abundances. Phosphorus and fluorine are more indifferent to the level of pressure (Tab. 1). Evidently, an increase of external pressure typical

Table 1

Average composition of gneisses (GN), plagiomigmatites (PM), K-feldspar-migmatites and granites (G) in different migmatites complexes

Oxides	Mama series				Khamar-Daban series				Chuya series							
	Mama–Patom				Khamar–Daban				Chuya				Abchada			
	GN[1]	PM	KM	G[2]	GN	PM	KM	G	GN	PM	KM	G	GG	PM	KM	G
SiO_2	65.95	67.11	67.24	72.88	61.21	66.33	68.10	72.23	67.10	70.09	73.78	75.35	75.31	64.70	74.24	73.76
TiO_2	0.74	0.68	0.64	0.20	1.15	1.16	1.02	0.14	0.34	0.37	0.16	0.15	0.08	0.90	0.38	0.28
Al_2O_3	17.75	18.02	17.66	15.32	16.52	15.75	15.11	15.48	15.71	14.30	13.47	12.95	12.61	14.87	12.39	12.36
Fe_2O_3	0.88	0.75	0.69	0.18	2.08	1.72	1.40	0.36	1.70	1.24	0.87	1.02	0.86	1.34	1.93	2.18
FeO	5.62	4.13	4.02	0.75	5.85	5.49	4.89	1.21	2.80	2.67	1.59	0.37	0.43	5.39	1.21	1.26
MnO	0.15	0.11	0.10	0.01	0.12	0.09	0.10	0.03	0.04	0.07	0.02	0.02	0.03	0.10	0.04	0.04
MgO	2.59	1.99	1.94	0.40	3.86	1.98	1.68	0.13	1.14	0.84	0.59	–	0.08	1.73	0.34	0.31
CaO	1.50	1.87	1.67	2.01	2.22	1.07	1.35	0.64	2.92	1.83	1.16	0.64	0.76	2.09	0.74	0.68
Na_2O	1.87	2.79	2.35	4.31	2.33	2.14	2.51	3.65	3.38	3.55	3.00	3.27	3.96	4.68	2.90	3.23
K_2O	2.96	2.29	3.25	3.88	2.76	2.89	2.63	4.68	3.64	3.75	4.73	4.89	4.73	2.54	5.36	5.40
H_2O	2.10	1.24	1.29	0.51	1.50	1.17	0.82	0.77	1.02	0.99	0.62	0.47	0.26	0.63	0.31	0.31
F	0.06	0.07	0.10	0.04	0.07	0.05	0.05	0.05	0.07	0.04	0.03	0.04	0.02	0.06	0.06	0.08
P_2O_5	0.14	0.12	0.11	0.08	0.16	0.10	0.13	0.31	0.09	0.08	0.04	–	–	0.18	0.03	0.02
B, ppm	46	n. d.	n. d.	n. d.	55	57	35	28	12	9	9	8	7	3	9	7
F_o	13.5	15.3	14.7	19.4	26.2	23.8	22.2	22.9	37.8	31.8	35.4	73.5	66.8	20.0	61.5	63.5
n	11			9	8	5	6	9	6	4	5	4	6	7	12	8

Notes: 1 – after (Shmakin – Makrigina, 1969); 2 – after (Makagon, 1977); compositions of PM and KM of Mama migmatite complex are calculated to be 70 % of gneisses (paleosome) and 30 % of plagioclase (PM) and bi-feldspar (KM) pegmatites (neosome); GG – granite-gneisses of earlier granitization in the Kutim block; $F_o = \frac{Fe_2O_3}{FeO + Fe_2O_3} \cdot 100\%$; dash – not discovered, n. d. – not determined, X-ray-fluorescent analyses, Vinogradov Geochemistry Institute. Analysts: T. N. Gunicheva, L. F. Piskunova, A. L. Finkelstein.

Table 2

The material influx-loss in granitization of gneisses (GN) Chuya series on the stage of plagiomigmatization (PM) and K-feldspar–migmatization (KM) (Petrov – Makrigina, 1975) along one layer. (Differences of cation numbers cn the basis of 1600 oxygen atoms, Barth method)

Oxides	metaarkose		biotite gneisses		garnet-hypersthene gneisses		amphibolite		epidote-biotite gneisses	
	GN-PM	PM-KM	GN-PM	PM-KM	GN-PM	PM-KM	GN-PN	PM-KM	GN-PM	PM-KM
SiO_2	−1	+4	+105	+4	+13	+29	+70	+100	+58	+63
Al_2O_3	+5	−6	−43	+21	+11	−20	−1	−17	−23	−2.9
Fe_2O_3	−2.1	+4.4	−9.2	−1.9	+1.1	−15.7	−11.7	−4.1	−13.4	−4.8
FeO	+1.5	+0.2	−5.8	−6.1	−8.3	−6.9	−9.8	−43.1	−22.4	−11
MgO	−3.7	+2.2	−12.2	−22.5	−11.4	−8.9	−70.8	−58.9	−11.7	−11
CaO	+2.9	−3.3	−12.2	−15.3	0	−12.2	−27.3	−60.2	−23	−21.4
Na_2O	+9.2	−3.5	+14.5	−1.7	+1	−9.8	+26.6	−20.2	+21.2	−20
K_2O	−2.5	+15.5	−11.6	+33.4	+3.1	+37.3	+11	+43.4	−4	+20
L.O.I.	−5.1	−6.8	−47.5	−2.7	−22.9	+5.7	−37.8	−18.6	−13	−4.2

Table 3
Numbers of hydroxyl-ions in minerals from different metamorphic facies series

Metamorphism type		kyanite- -sillimanite	andalusite- -sillimanite	
mineral	rock	Patom	Khamar- -Daban	Chuya
chlorite	metapelites marls orthoamphibolites	7.69–8.68 7.81–8.91 6.71–7.48	6.30–7.16 – –	6.42 – –
biotite	metapelites marls amphibolites	3.15–3.56 1.71–1.96 2.06–2.74	1.31–2.19 – 1.99–2.86	1.57–1.90 – 1.35–1.74
staurolite	metapelites	2.04–2.60	0.60–1.29	–
amphibole	paraamphibolites orthoamphibolites	1.78–2.48 2.09–2.71	0.95–1.65 –	– 1.62–1.86

Notes: The water is determined by kulonometric method. Analysts: L. G. Trufanova, V. A. Shiriaeva, Vinogradov Geochemistry Institute

for compressional structural situations in poorly permeable clay-carbonate sequences is accompanied by a sharp increase of fluid pressure, the main components of which are H_2O and CO_2. This is proved by widening of the stability fields of carbonates and water-bearing minerals. All stages of granitization take place in the stability field of muscovite. The changes of pressure lead to variable incorporation of water in hydroxyl-bearing minerals (Tab. 3) and, consequently to variations of bulk water content in rocks.

In granites from different migmatitic complexes there are also differences in water content similar to those for initial gneisses (Tab. 1). However, in the Mama pegmatoid granites the water content is at an intermediate level despite its high amount in the gneisses and migmatites of this complex. Initially, the granitic melts probably contained abundant water, but at late stages of crystallization of the massifs there was boiling of melts and separation of a large amount of water, which was the agent for the widely developed metasomatism in pegmatites. This process – hydrolysis of feldspars was responsible for a muscovite formation in pegmatites.

In low-P complexes where pressure of water is negligible in the fluid, other volatile components become more significant, e. g. boron and phosphorus in Khamar-Daban and fluorine in Chuya, that are reflected in the high amount of tourmaline and apatite in pegmatites of Khamar-Daban and CaF_2 in Abchada migmatites and pegmatites. The phosphorus and boron accumulation is due to evolution of anatectic melt which formed in a sequence rich in these components (Tab. 1). Since initial gneisses of the Chuya series do not show high fluorine contents it may be assumed that fluorine was added together with granitizing solutions.

The rare element compositon of metamorphic sequences is to a large degree inherited in the formation of migmatites and anatectic granites and affects the composition and mineralization of pegmatite belts associated with each complex. The differences in pressures

Table 4

Average contents of trace elements (ppm) in gneısses (GN), plagıomıgmatites (PM). K-feldspar-migmatites (KM) and granites (G) of different migmatites complexes.

Element	Mama				Khamar-Daban				Chuya				Abchada			
	GN	PM	KM	G	GN	PM	KM	G	GN	PM	KM	G	GN	PM	KM	G
Li	68	54	50	27	77	69	37	105	14	19	7	18	2.5	45	10	3.2
Rb	128	96	112	118	98	112	87	108	87	139	141	192	303	170	154	366
Cs	n.d.	n.d.	n.d.	n.d.	6.5	6	3.4	10	–	7	4	–	6.7	8.2	2.6	3.5
Ba	860	860	3420	5500	785	638	464	400	1665	910	1040	890	250	1062	754	390
Sr	551	558	767	820	212	150	216	60	440	246	170	165	26	94	61	31
Pb	12	12	12	24	11	28	30	18	11	9 9	17.5	18	58	27	24	40
Sn	n.d.	n.d.	n.d.	2	2 3	5.9	4.5	4.0	2 2	1.4	1 7	3	5.4	9.2	9	10
Be	1.6	1.7	1.3	1.3	1.7	1.3	1.2	4.0	2.4	1.1	1 2	2.4	6 5	5 3	5.7	5.3
La	28	15	13	3.2	36	45	41	10	20	45	40	37	9.2	62	140	147
Ce	94	45	30	32	104	110	78	30	75	76	100	94	28	135	198	202
Nd	29	16	11	9	38	38	37	10	20	34	40	30	11	58	111	94
Yb	5.5	2.2	n.d	n.d.	4 5	4.6	3.5	0.5	2.1	3 4	2.4	1.4	3 9	7 2	12.9	17.3
Y	29	25	18	3.4	31	33	38	4.5	13	21	23	9	26	64	101	115
Zr	188	n.d.	n d.	n.d.	222	195	212	65	127	135	181	53	126	1417	785	689
Hf	6	n.d.	n.d.	n.d	7.8	6	8	2.9	4 5	4.8	5.4	2.6	3.6	24.6	24.2	19.8
Nb	9.9	n.d.	n d.	n.d.	12.6	11	13.6	18.4	5 8	8.7	6.8	4.6	20.6	40.6	58.5	93
Ta	0.8	n.d.	n.d.	n.d.	1.4	1.8	1.2	2.0	–	–	1.1	–	1.5	1.6	1.8	3.5

Notes: see Table 1; analyses of Li, Rb, Cs are performed by flame photometric method (T. N. G a l k i n a, L. S T a u s o n); Ba, Sr - by quantıtative spectrographic method (E. S. K o s t y u k o v a); Pb, Sn, Be, REE – by quantitative spectrographıc methods (Pb, Sn – L. A. S o m i n a, Be – L. L. P e t r o v, REE – E. V. S m i r n o v a); Zr, Nb, Hf, Ta – by chemical-spectrographıc method with prelimınary enrichment (L. D. M a k a g o n, L. A. C h u v a s h o v a, S. N. A r b a t s k a y a).

Table 5

Average contents of major (mas. %) and trace (ppm) elements in fine and middle granular zones of pegmatites accompanying migmatites complexes

Elements	Mama		Khamar-Daban		Chuya	Abchada		
	M	RM	M	RM	FSB	B	A	RM-REE
SiO_2	70.17	74.32	75.48	73.63	73.70	73.73	76.15	76.94
TiO_2	0.08	0.18	0.04	0.02	0.01	0.12	0.18	0.04
Al_2O_3	17.75	14.44	13.99	15.34	15.22	13.41	11.77	12.62
Fe_2O_3	0.08	0.28	0.43	0.38	0.60	1.23	1.40	0.76
FeO	0.90	0.71	0.64	0.73	0.38	0.48	0.38	0.36
MnO	0.03	0.02	0.03	0.13	0.05	0.05	0.05	0.01
MgO	0.42	0.16	0.01	–	0.03	0.11	0.14	0.03
CaO	1.24	1.03	0.57	0.35	1.20	0.94	0.47	0.37
Na_2O	2.14	4.40	4.62	4.36	3.51	3.44	3.13	6.46
K_2O	6.40	3.31	3.08	2.17	6.50	5.79	5.45	1.14
F	450	600	250	410	–	1750	1150	300
B	n.d.	n.d	232	151	36	6	4	8
H_2O	1.34	0.99	0.71	1.26	0.20	0.32	0.41	0.53
Li	28	52	58	78	16	3	–	–
Rb	178	358	61	251	144	434	640	45
Cs	10	33	2	11	–	7	12	–
Ba	2850	175	215	71	45	283	45	36
Sr	425	85	40	97	90	29	12	10
La	18	30	–	–	–	16	–	18
Ce	58	20	–	–	–	35	–	33
Nd	20	3	–	–	–	13	–	17
Yb	n.d.	1.4	1.1	0.5	0.7	2.3	8	10
Y	8	13	4.0	1.7	3.0	48	20	90
F_o	8	30	40	34	62	72	79	68
n	6	5	11	21	2	6	1	3

Pegmatites: B – biotitic, M – muscovitic, RM – rare metal-muscovitic, FSP – feldspathic without mica, A – amasonitic, RM-REE – rare metal–rare earth ones.

contribute to accumulation and loss of different components during the process of migmatization. This particularly concerns alkaline and alkaline-earth elements. The initial depletion of the Chuya sequence in Li, B and Sr is enhanced in migmatization and granite formation (Tab. 4). This is displayed in the entire absence of these components in the composition of pegmatoid veins which accompany migmatitic complexes in the Chuya and Abchada (Tab. 5). On the other hand, primary enrichment of the Mama sequence in Ba and Sr under conditions of granitization at high pressure which favours incorporation of these elements in feldspars, is the cause of fairly high Ba and Sr concentrations in granites and pegmatites of the Mama complex (Makagon, 1977). In migmatitic complexes of moderate and low pressures granitization leads to a progressive depletion of Ba and Sr and increase of Rb contents.

We should focus on the behaviour in the process of granitization of different pressures of REE group and high-valence rare metals (Zr, Hf, Nb, Ta). Their contents in initial gneisses of the Mama (Patom), Khamar-Daban and Chuya series are close.

But REE distribution in minerals regularly changes from low-P series to high-P series. In gneisses of andalusite-sillimanite series REE are dispersed in rock-forming minerals making their structures loose (high molar volume), whilst in the kyanite-sillimanite series accessory minerals (which occupy little volume) are of major importance in the REE balance (Makrigina et al., 1982). The REE depletion is observed in granites and granite-gneisses of high- and moderate-P series because of a marked decrease of accessory minerals amount (Figs. 2 and 3).

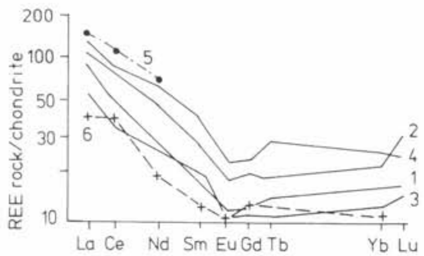

Fig. 2. REE distribution in metapelites of the Patom metamorphic complex, North Baikal region.
An average for zones: 1 – chlorite-sericite; 2 – chloritoid-garnet; 3 – staurolite-almandine; 4 – kyanite-almandine; 5-6 – Mama region migmatitic complex;, 5 – kyanite-almandine migmatites; 6 – granite.

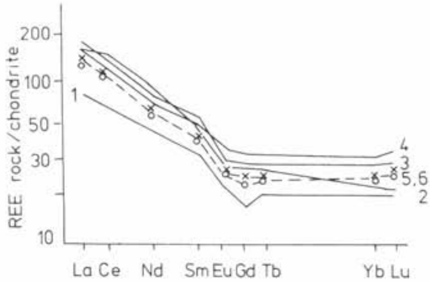

Fig. 3. REE distribution in metapelites of the Khamar-Daban metamorphic complex, South–West Baikal region.
An average for zones; 1 – chlorite-biotite; 2 – andalusite-garnet; 3 – staurolite-garnet; 4 – muscovite-sillimanite; 5 – plagiomigmatites, 6 – K-feldspar migmatites.

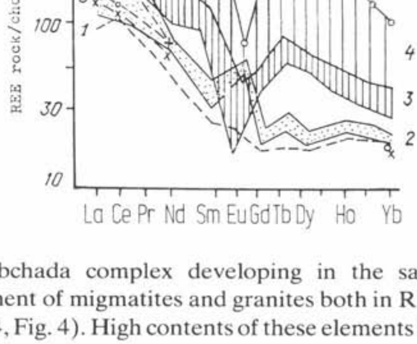

Fig. 4. REE distribution in rocks of the Minya-Abchada migmatitic complex, North Baikal region. 1 – amphibolite-biotite schist; 2, 3, 4 – plagiomigmatites, K-feldspar migmatites and granites (first granitization); 5, 6, 7 – plagiomigmatites, K-feldspar migmatites and granite-gneisses (second alkaline granitization).

The alkaline granitization in the Minya-Abchada complex developing in the same substratum (Chuya series) causes a wide enrichment of migmatites and granites both in REE (Y and Ce groups) and Zr, Hf, Nb and Ta (Tab. 4, Fig. 4). High contents of these elements are characteristic of only alkaline rocks and are not induced by the initial composition of gneisses.

This is evidence for alkaline metasomatism in the development of the rocks of the Chuya series (Kutim block) in contrast to earlier normal granitization in the same series here (Tab. 4, GG) and in the north of uplift. Formation of the alkaline migmatitic complex rich in Zr, Hf, Nb and REE is evidently related to deepening of faults bounding the Kutim block and addition of alkaline juvenile solutions.

Geothermometry and geobarometry of metamorphism and granitization

The temperature of metamorphism and granitization has been estimated from the distribution of components between coexisting minerals. In order to lessen the scatter of results of mineral geothermometry, the diagrams of phase equilibria and their analytical expressions from the same authors have been used. The temperature from garnet-biotite geothermometry was calculated from the formula:

$$10^3/T = 0.72567+0.2533 \ln K^{Ga-Bi} \text{ by Perchuk (1986).}$$

The diagrams by Perchuk – Ryabchikov (1976) have been employed for geothermometers based on distribution of Fe and Mg in pairs: Ga-St, Ga-Chl, Ga-Ctd, Ga-Amph as well as Ca and Na between Am and Pl, KFsp and Pl. Pressure was determined from Ga-Pl-Al_2SiO_5-Q geobarometer (Perchuk, 1986).

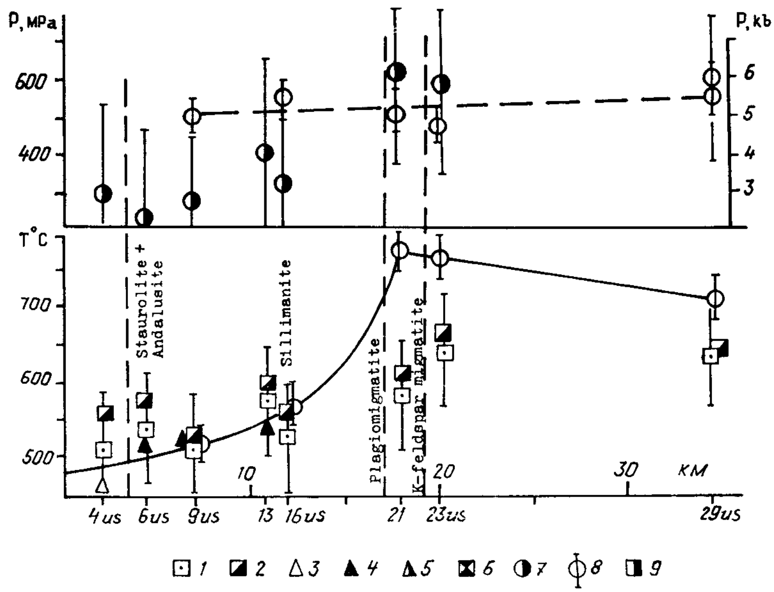

Fig. 5. P-T conditions of metamorphism and granitization of the Khamar-Daban belt, South–West Baikal region.

Geothermometers: 1 – garnet-biotite; 2 – garnet-biotite (with Mn); 3 – chlorite-garnet; 4 – staurolite-garnet; 5 – chloritoid-garnet; 6 – amphibole-plagioclase; 7 – Ga-Pl-Al_2SiO_5-Q geobarometer; 8 – P-T estimates from solution of inverse physico-chemical problem. 4us – 29us – samples: 4us – Ga+Bi+Pl+Chl+Ms+Q; 6–9us – St+And+Ga+Bi+Chl+Ms+Pl+Q; 13us – St+And+Ga+Bi+Ms+Pl+Q; 16–21us – Sill+Ga+Bi+Ms+Q; 23–19us – Sill+Bi+Pl+Kfsp+Pl+Q;

In order to estimate mineral parageneses of the Khamar-Daban complex we used a new method of geothermobarometry involving solution of the reverse physico-chemical problem by considering the complete chemical composition of rocks and minerals (see Appendix, Baksheev – Karpov, 1984).

Fig. 5 represents the plots of distribution of temperature and pressure estimates in sequential zones of metamorphism and granitization of the Khamar-Daban complex defined from mineral geothermometers. The scatter of results of various thermometers from the same paragenesis achieves 100° (sample 4us). These data may be linearly approximated from point 4us to the front of granitization – point 23us. The results obtained via solution of the reverse physico-chemical problem approximately coincide with the averaged temperature in points 9 and 16us, but they are considerably higher in granitization zones (21–29us). From experimental data, the temperature of muscovite decomposition with formation of K-feldspar at $P_{H_2O}<0.5\ P_{load}$ is 700–750 °C which is close to the obtained estimates (Velde, 1966). The trend toward temperature lowering in the K-feldspar migmatite zone, as compared to plagiomigmatites, is likely to be related to the consumption of heat by partial melting.

The low temperature estimates in granitization zones, as indicated by Ga-Bi geothermometer, may reflect the temperature of cessation of the exchange reaction between garnet and biotite at a regressive stage (Avchenko, 1986). Under relatively "dry" conditions such an exchange is possible only at high temperature when the kinetic energy of atoms is high enough. These processes result in the presence of regressive rims in garnets from zones of granitization. The cores of granites from Ga-Bi geothermometer show tempparetures about 680–700 °C. In the zones of low-grade metamorphism the regressive processes are slowed down, garnets

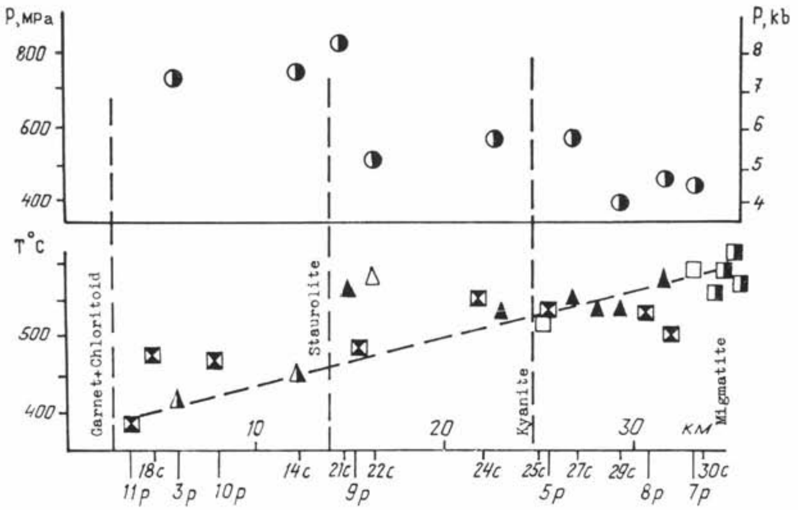

Fig. 6. P-T conditions of metamorphism and granites (1) of the Mama-Patom belt, North Baikal region. See explanation in Fig. 5. *Metapelites:* 18 c – Chl+Ms+Ga+Ab+Q, 14c – Ctd+Chl++Ms+Bi+Ga+Ab+Q, 21c-22c – St+Ctd+Ga+Bi+Ms+Pl+Q, 24c – St+Ga+Bi+Ms+Pl+Q. *Metaaleurolites:* 11p – Chl+Ep+Am+Bi+Ab+Q, 3p – Ga+Am+Ep+Pl+Q, 9p – Ga+Am+Bi+Pl+Q, 5p – Ga+Am+Pl+Q, 7–8p Ga+Am+Zo+Pl+Q. *Granites* – after Makagon (1977).

Table 6

The temperatures of gneisses and migmatites formation in the Minya-Abchada migmatitic complex from the bimineral geothermometers (Perchuk-Ryabchikov, 1976)

NN samples	Rocks	Paragenesis	X_{Mg}^{Am}	X_{Mg}^{Bi}	T, °C
	A Biotite-amphibole geothermometer				
AB-101	biotite-amphibole plagiogneiss	Bi + Am + Pl + Q + Mt	0.269	0.247	570
AB-233a	K-feldspar-migmatite	Bi + Am + Pl + KFsp + Q + Mt	0.192	0.248	525
AB-194	granite-gneiss	Bi + Am + Pl + KFsp + Q + Mt	0.090	0.216	400
AB-233	granodiorite	Bi + Am + Pl + KFsp + Q + Mt	0.250	0.300	530
	B. Garnet-biotite geothermometer		X_{Mg}^{Ga}	X_{Mg}^{Bi}	
AB-284	garnet-sillimanite gneiss	Ga + Bi + Sil + Pl + Q + Mt	0.115	0.429	580
AB-237	garnet migmatite	Ga + Bi + Pl + KFsp + Q + Mt	0.114	0.400	602
	C Bi-feldspar geothermometer		X_{Na}^{KFsp}	X_{Na}^{Pl}	
AB-131	granite-gneiss (early granitization)	Bi + Pl + KFsp + Q + Mt	0 102	0.750	420
AB-136	granite-gneiss (early granitization)	Bi + Pl + KFsp + Q + Mt	0.174	0 72	580
AB-421	migmatite (alkaline granitization)	Bi + Pl + KFsp + Q + Mt	0.171	0.72	550
AB-561	augen-gneiss migmatite	Am + Bi + Pl + KFsp + Q + Mt	0.119	0.75	480
AB-7	granite-gneiss	Am + Bi + Pl + KFsp + Q + Mt	0 077	0 79	390
AB-562	granite-porphyre (granophyre)	Bi + Pl + KFsp + Q	0.219	0.72	680
AB-603	ovoid granite	Am + Pl + KFsp + Q + Mt	0.180	0.70	640

retain progressive zonation, and the temperature estimates lie close to the peak of progressive metamorphism (Fig. 5).

Pressure was determined by the Ga-Al_2SiO_5-Pl-Q geobarometer. The temperature necessary for calculation was taken from the temperature plot (Fig. 5). From these data the pressure increased from 3.0 to 6.2 kb from the low- to high-T zones. Such a gradient of pressure in a single layer is unreal. The results obtained from solution of the reverse physico-chemical problem provide evidence of an isobaric trend of metamorphism and granitization of the Khamar-Daban complex (within the calculation error, see Fig. 5).

The temperature of regional metamorphism of the Patom highland was also measured from all possible mineral geothermometers to show the range from 380 to 575 °C. It seems that the temperatures are somewhat underestimated in the kyanite-almandine subfacies. The maximum temperature with regard to geological data and data on mineral stabilities must be 650–750 °C.

Pressure was also defined from Ga-Pl-Al_2SiO_5-Q geothermometer and ranges from 7.5–8.5 kb to 4.5 kb in high-T zones (Fig. 6).

The temperature was taken from the line which actually was the highest temperature gradient to lessen the impact of points scatter. The obtained trend of pressure lowering to the high-T part of zonation is obviously related to underestimation of readings of mineralogical thermometers from temperature. It is probable that total pressure through the entire zonation was 7.5–8.5 kb since in the high-T part there is kyanite, and P_{CO_2}, in inclusions of carbon dioxide acid in this mineral is 8.0 kb (Dolgov et al., 1967). The temperature estimates in granitization zones (pegmatization) of the Mama series from Ga-Bi geothermometer also provide low estimates both in gneisses (490–610°) and in pegmatoid granites (650–700 °C).

The temperatures of migmatite and granite-gneiss formation in the north of the Chuya uplift (standard granitization) and south (Kutim block, late alkaline granitization) are approximately 540 to 580 °C and 400 to 580 °C (Tab. 6). The granites which underwent melting show higher values, e.g. 640–680°C. The low values of temperatures for migmatites in the orthoclase-sillimanite zone are not true. It seems that in metasomatic migmatites reverse exchange reactions took place at a retrograde stage, while chilled magmatic granites retained a more high-T distribution of components. Low estimates of temperatures in high-grade metamorphic zone, large discrepancies in estimates from different mineral geothermometers and the formulae for calculation from different authors lower the efficiency of utilization of these methods.

Determination of mineral equilibria parameters via solution of the reverse physico-chemical problem is used for a more perfect substitution of bi-mineral geothermometers. This method considers an equilibrium distribution of all components of the system between all phases of the paragenesis as well as the uncertainty of the input information in order to ensure reliability of determinations. In addition to P and T, this method may be used to calculate partial pressures of volatile components of the gaseous phase which could be in equilibrium with the mineral paragenesis studied.

Table 7

Computed mole fractions (m_i^f) of major gas components in fluid phase of Khamar-Daban complex metamorphic rocks

$-\lg m_i^f$ / No. samples	H_2	O_2	H_2O	CO	CO_2	CH_4	m_i^f
9 us	3.1724	28.3443	0.8413	4.4533	2.0499	2 0499	0.1586
16 us	2 7227	26 4548	0 4353	4 0315	1 7119	1 7666	0 4055
23 us	2 0174	21.9056	0.8537	2.8814	1 8404	1.5407	0.1798

As an example, we provide calculation results of partial pressures of the gaseous phase components for three samples from staurolite-garnet (9us), sillimanite-muscovite (16us) and orthoclase-sillimanite (23us) zones of the Khamar-Daban complex (Tab. 7). The calculation is made with allowance for the errors of thermodynamic features of the mineral paragenesis and the bulk composition of the samples. The sum of mole gas fractions amounts to 0.16–0.41, the rest being for non-considered phases, for example nitrogen, the inclusions of which are present in rocks of the complex. A common feature is the low pressure of water and carbon dioxide, which is verified by the decomposition of muscovite and carbonates by comparison with the Patom kyanite-sillimanite series.

Conclusions

Examination of data shows that migmatitic complexes formed in metamorphic belts of different pressures are different in a number of respect: 1. *structures* with dominant pegmatoid migmatites in kyanite-sillimanite series; 2. *relation of amounts of plagio-and K-feldspar migmatites* with an increasing amount of the latter as pressure decreases; 3. *composition* with increasing K:Na, Si:Al and Fe:Mg ratios in migmatites and granites of the andalusite-sillimanite series; 4 – *geochemistry* where migmatites inherit all features of the substratum in high-P series whilst there is an influence of juvenile solution compositions on trace element characteristics in migmatites of low-P series increases; 5. *mechanism of formation* with an increasing role of metasomatism relative to anatexis in low-P complexes; 6. *mineral abundances in pegmatitic belts* which accompany migmatitic complexes – from muscovitic pegmatites in kyanite-sillimanite series to the rare metal-muscovite and rare metal complexes in andalusite-sillimanite series.

However, calculation of temperatures and pressures of migmatite formation of different complexes provides a narrow and uniform range of values: 700–780 °C and 5.0–5.5 kb from thermodynamic calculations and 550–640 °C and 4.5–6.2 kb from mineral geothermometers. They do not account for the differences of migmatites and granites leading to a considerably different metallogeny of complexes.

After examination of stability of carbonates, water-bearing minerals, plagioclase, geochemical distinctions of H_2O, CO_2, B, and F it was concluded that fluid regime has an important control on particular features of migmatitic complexes. This is verified by calculation of the composition and partial pressures of the gaseous phase in the Khamar-Daban complex. Reduction of H_2O and CO_2 proportion in fluids from high-P and low-P series makes minor fluid components (B, F, P) active that leads to a change of muscovite specialization of pegmatites by rare metal-muscovite and rare-metal ones and is the cause for all the above-described differences in morphology, extent of development, composition of migmatites and granites and metasomatic-anatectic relationships.

A new method of geothermobarometry of mineral equilibria via solution of the inverse physico-chemical problem is promising for solving problems of the analysis of fluid regime and providing reliable evaluation of P-T parameters of petrogenesis.

MATHEMATICAL APPENDIX

The chemical equilibrium problem for a multisystem at constant temperature, pressure and specific bulk composition is a direct physico-chemical modelling sum. In this case, determination of temperature and pressure of the chemical equilibrium is inverse physico-chemical problem. The geothermobarometry problem may be presented as a nonlinear programming sum:

$$(t,p) = Argmin\ \{F(T,P),\ T \in T^{\circ},\ P \in P^{\circ}\},$$

where (t,p) is temperature and pressure of the chemical equilibrium; F(T,P) is nonlinear function of temperature (T) and pressure (P) of determination field; T° and P° – continuum of points of T and P determination field. Then F(T,P) is replaced by:

$$F(T,P) = \sum_{\alpha=1}^{f} \sum_{j=1}^{l_\alpha} m_j^r (g_j/RT + ln\, m_j^r + ln\, \gamma_j - \sum_{i=1}^{n} a_{ij} u_i),$$

Here $m_j = x_j^r / X_\alpha^r =$ really observed mole fraction of *j* dependent component (minal) in the phase of the mineral paragenesis under study; x_j^r = total number of moles of the dependent component j present in the given chemical equilibrium, then $X_\alpha^r = \sum_{j=1}^{l_\alpha} x_j^r$ = number of moles of paragenesis α phase; γ_j = activity coefficient of the dependent j component; f = total number of phases of mineral paragenesis; 1_α = number of dependent components (minals) in α phase; g_j = free energy of j component at temperature T and pressure P; R = gas constant; a_{ij} = stoichiometric coefficients, which indicate the number of moles of independent i component in the dependent j component (minal); n = number of independent components of the chemical system; u_i = Lagrangian multiplier or chemical potentials of independent components determined from solution of the direct problem of physico-chemical modelling via the method of Gibbs free energy minimization.

The direct problem of physico-chemical modelling may be written as:

$$\text{minimize } G(x) = \sum_{\alpha=1}^{f} \sum_{j=1}^{l_\alpha} \mu_j x_j$$

$$\text{on condition } \sum_{\alpha=1}^{f} \sum_{j=1}^{l_\alpha} a_{ij} x_j = b_i, \quad i = 1,n.$$

Here μ_j = chemical potential of the dependent j component in α phase equal to

$$\mu_j = g_j/RT + ln(x_j/X_\alpha) + ln\ \gamma_j,$$

f = number of phases in multisystem; b_I = number of moles of i independent component in the multisystem; n = number of independent components; l_α = number of dependent components in α phase.

The minimization problem $G(x)$ with constraints is replaced by the problem of absolute Langrangian maximization L:

$$L(x, u) = G(x) + \sum_{i=1}^{n} u_i(b_i - \sum_{\alpha=1}^{f} \sum_{j=1}^{l_\alpha} a_{ij} x_j),$$

where u_i = Langrangian multipliers. In the optimum point for all phases $x_\alpha \geqq \varepsilon$, $x_j \geqq \varepsilon$, where ε = given minor positive number, partial derivatives $L(x,u)/\delta x=0$, i.e.

$$g_j(RT + ln(x_j/X_\alpha) + ln\ \gamma_i = \sum_{i=1}^{n} a_{ij} u_i.$$

This expression may be used to define partial fugacities of gas components which are or could be in equilibrium with mineral paragenesis under study.

In order to obtain the error of calculated temperature t and pressure p, statistical testing was made through multiple solution of thermobarometry problem at interval of initial data uncertainty (g_j, m_p^r, γ_j, b_i).

A number of programs which employ this approach for defining temperature and pressure of mineral equilibria is based on computer PL/1 language and involves the procedure of initial information compilation to solve the problem in the dialog regime.

REFERENCES

AVCHENKO, O. V., 1986: Interpretation problems of temperature and pressure estimations based on mineralogical geothermobarometers. *Izv. Akad. Nauk SSSR, Ser. geol.* (Moscow), 10, pp. 19–25.

BAKSHEEV, S. A. – KARPOV, I. K., 1984. P-T parameters metamorphism calculated by method of Gibbs energy minimization. *Dokl. Akad. Nauk SSSR* (Moscow), 277, 4, pp. 936–938 (in Russian).

DOLGOV, Yu. a. – MAKAGON, V. M. – SOBOLEV, V. S., 1967: The liquid inclusions in kyanite from metamorphic rocks and pegmatites of the Mama region. *Dokl. Akad. Nauk SSSR* (Moscow), 175, 2, pp. 444–447 (in Russian).

KING, B. K., 1967: Nature and origin of migmatites. In: Nature of metamorphism. *Mir,* Moscow, pp. 227–242 (in Russian).

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

MAKAGON, V. M., 1977: The pegmatoid granites of regional metamorphism zones of high pressure. *Nauka,* Novosibirsk, 205 pp. (in Russian).

MAKRIGINA, V. A., 1981: The geochemistry of regional metamorphism and ultrametamorphism at moderate and low pressures. *Nauka,* Novosibirsk, 199 pp. (in Russian).

MAKRIGINA, V. A. – SMIRNOVA, E. V., 1984: REE in minerals of Minya-Abchada migmatitic complex. *Geokhimia* (Moscow), 9, pp. 1293–1307 (in Russian).

MANUILOVA, M. M. – VASKOVSKY, D. P. – GURULEV, S. A., 1964: The Precambrian geology of the North Baikal region. *Nauka,* Moscow-Leningrad, 225 pp. (in Russian).

MEHNERT, K. R., 1971: Migmatite and granite origin. *Mir,* Moscow, 327 pp. (in Russian).

MEHNERT, K. R. – BÜSCH, W., 1982: The initial stage of migmatite formation. *Neu. Jb. Mineral.* (Stuttgart), 145, 3, pp. 211–238.

OLSEN, S. N., 1984: Mass-balnce and mass-transfer in migmatites from the Colorado Front Range. *Contr. Mineral. Petrology* (Berlin–New York), 85, 1, pp. 30–44.

PERCHUK, L. L., 1970: Thermodynamic conditions of metapelitic sequences granitization. In: Physico-chemical property essays – 2. *Nauka,* Moscow, pp. 188–213 (in Russian).

PERCHUK, L. L., 1986: Evolution of metamorphism. In: Experiment in actual geological problem solution. *Nauka,* Moscow, pp. 151–174 (in Russian).

PERCHUK, L. L. – RYABCHIKOV, I. D., 1976: Phase conformity in mineral systems. *Nedra,* Moscow, 287 pp. (in Russian).

PETROV, B. V. – MAKRIGINA, V. A., 1975: The geochemistry of regional metamorphism and ultrametamorphism. *Nauka,* Novosibirsk, 342 pp. (in Russian).

PETROVA, Z. I. – LEVITSKY, V. I., 1984: The petrology and geochemistry of granulitic complexes, Baikal region. *Nauka,* Novosibirsk, 201 pp. (in Russian).

PLATTEN von G., 1967: The experimental investigation of anatexis and migmatite genesis. In: The nature of metamorphism. *Mir,* Moscow, pp. 211–226 (in Russian).

SEDOVA, I. S. – GLEBOVITSKY, V. A., 1984: Ultrametamorphism development in amphibolitic facies conditions. *Izv. Akad. Nauk SSSR,* 2, (Moscow), pp. 46–60 (in Russian).

SUDOVIKOV, N. G., 1959: Ultrametamorphism and granite formation. *Vest. LGU,* 1, 6, pp. 51–62 (in Russian).

SHAFEEV, A. A., 1970: The Precambrian of the South-West Baikal and Khamar-Daban regions. *Nauka,* Moscow, 170 pp.

SHKODZINSKY, V. S., 1987: The analysis of physico-chemical migmatite formation conditions and the role of anatexis and rheomorphism in granite magma formation. Ph. D. Thesis, 19 pp. (in Russian).

THOMPSON, A. B., 1982: Dehydration melting of pelitic rocks and the generation of H_2O undersaturated granitic liquids. *Amer. J. Sci.* (New Haven), 282, 10, pp. 1567–1595.

VELDE, B., 1966: Upper stability of muscovite. *Amer. Mineralogist* (Washington), 51, 5–6, pp. 924–929.

WILLEY, P. J., 1977: Crustal anatexis: an experimental review. *Tectonophysics* (Amsterdam), 43, 1–2, pp. 41–71.

Reviewed manuscript received February 28, 1989.