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ANATEXIS AND GRANITIZATION: CRITERIA AND MODELS

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Abstract: The models of anatexis and granitization (very popular in the Soviet literature) are compared, based on experimental, mineralogical, geochemical, structural geological data. The melt inclusion and mineralogical data coupled with field geological observations are good evidence that the origin of most of migmatites, charnockites and gneiss-granites is the result of crystallization of acidic melt saturated by H_2O and CO_2 at the temperature 650–900 °C. Three possible variants of the process of formation of these acidic melts may be considered: a) pure anatexis; b) partial melting with some additional mantle-derived fluids; c) granitization as magmatic substitution with intensive fluid infiltration. The model of anatexis is the most likely as the simpliest one and it is based on geological, mineralogical and melt inclusion data (Bowen, Tuttle, Winkler, Brown, Fyfe, Sobolev, etc.). The evidence put forward for alternative models (Zharikov, 1987, etc.) may be explained in the framework of the anatectic model or are very ambiguous in reality.

The geological and petrological data on some typical areas (Baikal region, Aldan shield, Pamir block, the South India) were compared from these points of view. The CO_2-rich fluid flow typical of granulite complexes is possible from the "hot" mantle. The source of H_2O for melting in the lower crust may be the biotite of the rocks or filtrating and crystallization of specific mantle magma enriched in H_2O (Litvinovsky and Podladchikov, 1990).

Key words: anatexis, granitization, migmatites, granites, melt and fluid inclusion, mantle fluids.

Introduction

Granites are main features of continental crust, and contribute greatly to the overall composition and metallogeny of Earth's crust (Dobretsov, 1981). Naturally, in present attention is still paid to the problem of granite origin.

Three main models of granite origin are popular in the Soviet literature: 1) anatexis; 2) granitization as magmatic substitution; 3) syntexis, or secondary genesis of crust acidic melts under the influence of mantle basic magmas. The last model is not connected with the main aim of the symposium in 1988. It is useful only to outline that this model is more probable for gabbro-granite series in folded areas (Chappel and White, 1974; Isokh, 1978; Dobretsov, 1987).

The classic model of anatexis (Eskola, 1933; Tuttle and Bowen, 1958; Winkler, 1967; Huang and Wyllie, 1975 etc.) is the main dogma in Western geological literature and „has been so for years" (S. L. Harley, personal comm.). But the models of granitization (Sederholm, 1913) or metasomatic granites (Perrin and Roubault, 1949) were very popular up to 1960–1970 and remain so for many petrologists particularly in the Soviet Union after classical Korzhinsky's work (Korzhinsky, 1952; Zharikov, 1987). Some authors formulate the comlex anatectic model with H_2O undersaturated granitic liquids (Thomson, 1982; Shkodzinsky, 1976, 1985) or combine several models (Glebovitsky et al., 1985).

In this paper we will compare the models of anatexis and granitization using experimental, mineralogical, structural geological data, particularly in the light of detailed study of migmatites and granites in some typical regions.

Melt inclusions, mineral data and possible models

In our opinion the most direct and essential evidence of a melt origin for migmatites and all types of granites (including gneissic granites, called rheomorphic or paraautochthonous) is the presence of crystallized melt inclusions. The conditions of homogenization of such inclusions are similar to theoretical and experimental data in the system granite – H_2O-CO_2 (Wyllie and Tuttle, 1964; Sobolev et al., 1973; Tomilenko and Chupin, 1983; Kadik and Eggler, 1975; Mysen and Eggler et al., 1976).

For example, in the leucosomes of migmatites and in paraautochthonous granites of Aldan granulite facies the homogenization temperatures of crystallized acidic melt inclusions (mostly in quartz) are in the range 820–910 °C (average 860 °C). The H_2O/H_2O+CO_2 ratio in melt is about 80 %, whereas in fluid inclusions it is nearly 20 %. These values are consistent with data on the granite – H_2O-CO_2

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system at T = 860 °C and P = 7 kbar. Secondary salt-rich inclusions are highly concentrated fluids formed by crystallization of the last portion of anatectic melt at T = 600−650 °C and P = 6 kbar. These estimations are correlated in general with data of mineral thermometry and barometry (Tomilenko and Chupin, 1983; Dolgov et al., 1976; Dobretsov, 1981; Dook et al., 1986) in Aldan region.

A similar picture is evident in the Sharyzhalgai complex of SE Pribaikalye (see below Fig. 1). Based on compositional data for garnets, hypersthene and biotite, enderbites, charnockites and two-pyroxene crystalline schists were metamorphosed at 730−750 °C, whereas biotite-garnet migmatites and biotite gneiss-granites were crystallized at 620−700 °C (Shafeev, 1973). The investigation of minerals, melt and fluid inclusions (Kurdukov and Berdnikov, 1987) from this terrain yields temperature estimates of 700−800 °C for enderbite, charnockite and two-pyroxene schists and 650−750 °C for biotite gneiss granites (Tab. 1).

According to density data on CO_2- inclusions the pressure conditions are estimated at 5.0−7.4 kbar for enderbite and charnockites and 2.0−5.5 kbar for biotite gneiss-granites. Similar pressure estimates are obtained for gneisses from India, Pamir and other granulite and transitional areas (see below).

Such inclusions and mineral data coupled with field geological observations are good evidence that origin of most migmatites, charnockites and gneiss-granites in high-temperature metamorphic rocks is the result of crytallization of acidic melt saturated by H_2O and CO_2 in the temperature interval 650−800 °C.

Three variants of the general process of formation of these acidic melts may be considered:

a) pure anatexis as the isochemical partial melting with possible redistribution of melts into zones of lower pressure (anticline parts of folds, fracture zones, etc.);

b) partial melting with some additional mantle-derived fluid (mainly H_2O, CO_2, K_2O and SiO_2) fully dissolved in original melts (Litvinovsky and Podladchikov, 1988);

c) granitization as magmatic substitution when intensive fluid infiltration and regional metasomatism involving the addition of H_2O, K_2O, SiO_2 and removed of MgO, FeO, CaO is recognised or inferred. This metasomatism may be followed by fusion of altered rocks, with the consequent substitution of altered rocks by magma (Korzhinsky, 1952; Zharikov, 1987).

Among these models the model of anatexis is the most probable

a) it is the simplest model in which intensive mantle fluid flow (with the removal of MgO, FeO, CaO, etc.) is not necessary;

b) in general, geological, geochemical and melt inclusion data are completely consistent with an anatectic model with partially redistributed melts (Tuttle and Bowen, 1958; Winkler, 1967; Brown and Fyfe, 1970, etc.);

c) the usual evidence put forward for alternative models (the substitution of basic and intermediate rocks by granites; petro- and geochemical comparison; unsatisfactory „restites"; the regressive character of „granitization", see for instance, Zharikov, 1987) may be explained in the framework of the anatectic model or are very ambiguous in reality.

The often-quoted retrogressive character of „granitization" is not correct especially for granulite facies because the charnockites and migmatites are isofacial with surrounding granulites. The biotite gneiss-granites and migmatites usually replace granulites during retrogression under amphibolite facies, or originate in transitional between the two facies conditions. We can observe the transitional alteration of enderbites into plagiogranites and charnockites into two-feldspar gneissic-granites with relics of granulitic minerals (see below some typical examples).

The problem of the compositon of primary continental crust (before „granitization") cannot be deduced from the composition of skialites or restites among granites and migmatites. It is possible only by the average estimation of crustal sections, including granites, migmatites and „restites". Such average compositions tend to andesite or even slightly more mafic compositions (Taylor, 1960; McLennan and Taylor, 1984). So, „granitization" in the general case may be the internal differentiation fo primary andesitic crust into a less-dense upper crust of granite-granodiorite composition and the denser andesitic-basaltic component (including enderbites and basic schists) which is predominant in the lower part of the crust. We can average estimations of the composition of these parts of the crust find in many works (for instance in the Soviet literature, Ronov, 1980; Lutz, 1980).

It is also possible that the primary magmatic stratification of oldest andesitic crust was formed from H_2O-rich mantle andesitic magma: the cumulates (anorthosites and some gabbro) were predominant at the base and tonalite, andesite, dacite with lenses of basalts and chemical sediments were predominant in the upper part of the crust. Such idea was formulated by author (Dobretsov, 1980, 1981) following the model of primary andesitic crust (Kushiro, 1972; Taylor, 1968) and some analogy of origin and stratification of modern oceanic and ancient andesitic crusts. The composition of primary magmas differed of course and the Archean terranes had long polygenetic history and greater thickness. But the close association of anorthosites, basic rocks, tonalite gneisses and andesitic enderbites in many areas support such idea. In any case the difference of composition of low and middle-upper parts of the Earth crust may reflect the relics of primary magmatic stratification, rather then only the redistribution of anatectic melt.

Some typical examples

From these points of view we can compare the geological and petrological data from Sharyzhalgai (SW Prebaikal region), Aldan shield, the Pamir and the South India.

The Sharyzhalgai complex is the South-West block of the Siberian platform basement and occurs in a NW trending belt extending some 300 km from the southern edge of Lake Baikal (Fig. 1). The complex consists of highly metamorphosed rocks and associated granitoids (charnockites, enderbites, biotite and amphibole-biotite plagiogranites and normal granite-gneisses) which form structurally and genetically united ultrametamorphic complex. In this geological history one can distinguish two stages: earlier granulite metamorphism (2.6−2.4 Ma) and later (2.0−1.8 Ma) retrograde metamorphism overprinting under amphibolite facies conditions (Krilov and Shafeev, 1969; Bibikova et al., 1986). The granitoids alter from charnockites into biotite granite-gneisses in areas of intense amphibolite facies overprinting.

The freshest granulite rocks facies are presserved in the south-west zone I (Fig. 1), particularly at Baikal. The typical

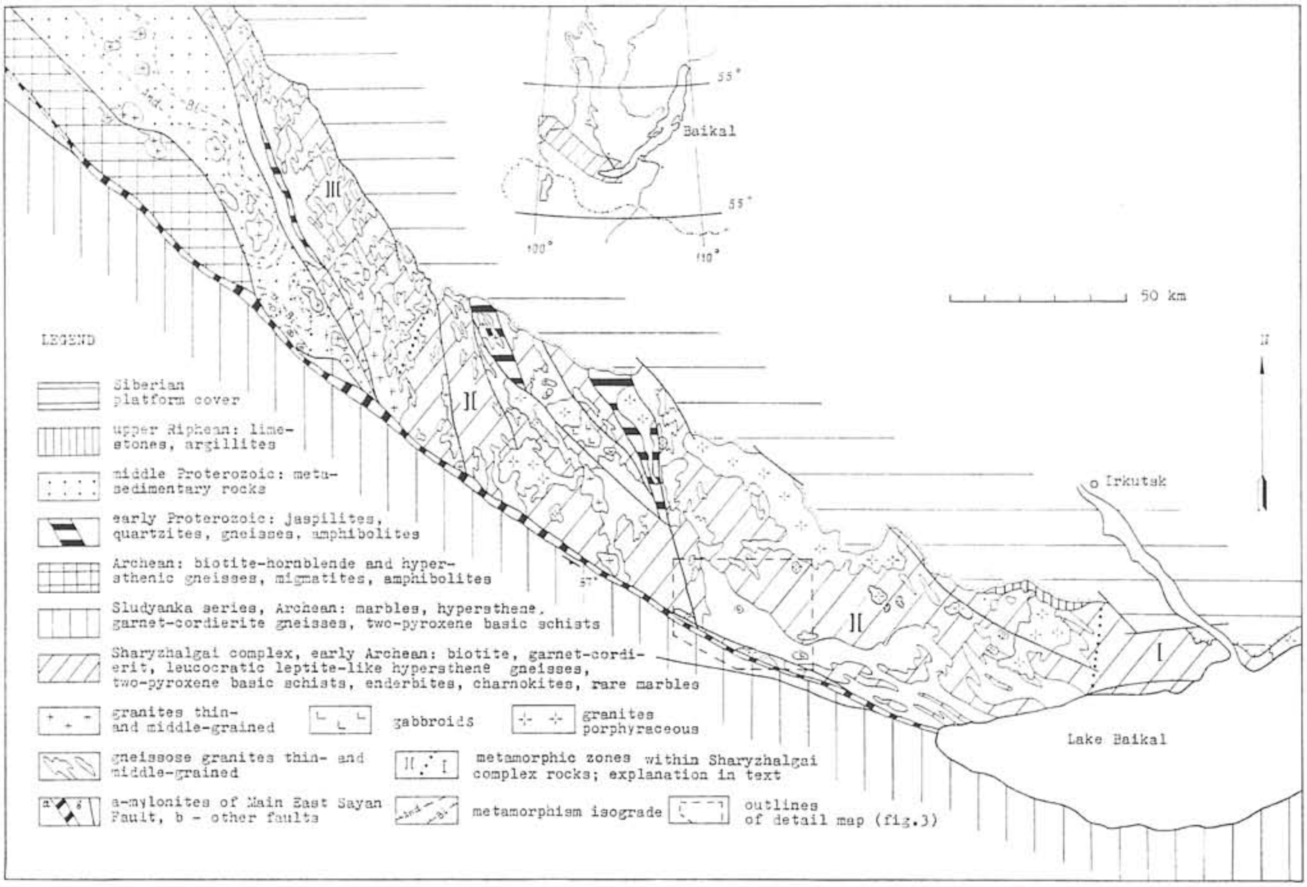

Fig. 1. Simplified geological map of Sharyzhalgai complex: South-West block of Siberian platform basement.

enderbites intercalate here with two-pyroxene schists, hypersthene-garnet gneisses and marbles and form thick lenses and domes at the core of later anticlinal folds. This is suggested to be connected with the redistribution of enderbite melts into zones of decreasing pressure, and intrusion of these melts into the country rocks in uppermost part of domes or shear zones. Two-pyroxene schists form regular layers between and with "in situ" enderbites but are transformed into deformed boudines in the transitional zones and into blocks and xenoliths in domes and the central part of anticlines (Fig. 2, a, b). These basic schists which constitute 3–8 % of the rock volume, are usually suggested to be relics of substratum after magmatic substitution of basic schists, or "enderbitization-charnockitization" processes (Kurdukov and Berdnikov,

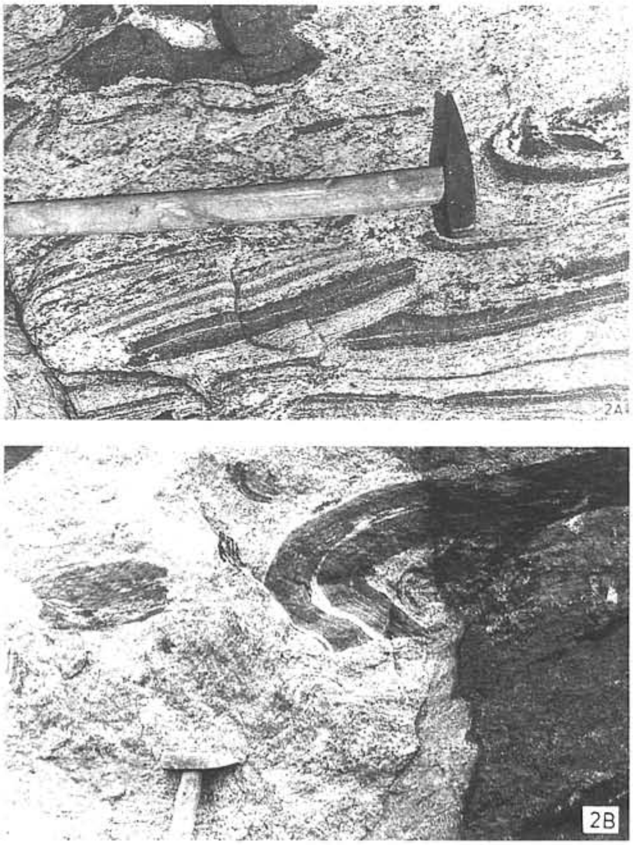

Fig. 2. Morphology of inclusions two-pyroxene-hornblende basic schists in enderbites.

A – enderbite "in situ" on initial stage of transfering. Thin layers of basic schists in swampy enderbite-migma are dismembered on blocks and bent.

B – xenolite-like boudins of basic schists in almost massive enderbite. There are no any chemical reaction between basic schist and enderbite in both cases.

Table 1. P-T estimation of metamorphism and anatexis of Sharyzhalgai complex, Baikal region (Kurdokov & Berdnikov, 1987; Shafeev, 1973)

Group	specimens No.	T1	T2	T3	T4	Tco2	Pco2
I	678	825—870	730	750	—	a) −23	7.4
	686	825	—	750	—	b) −15	5.5
	231	715	730—750	750			
	309	690—790	700	750			
	2	850	—	770			
II	681	760—790	730	770			
	244	—	—	—	650—705	a) −23	7.4
	11	—	—	—	700—750		
III	303	825	730	750	—	b) −13	5.0
	243	—	—	—	600—820	c) −7	3.0
	7	—	—	—	730—750		
IV	676	—	710	—	—	a) −5−10	3.0—4.0
	12	—	—	—	620—700	b) +2	2.0
						c) +12	1.2

I — basic schists; II — enderbites; III — charnockites; IV — biotite granites; T1 — opx-cpx (Wells, 1977); T2 — opx-amph; T3 — cpx-amph (Perchuk & Ryabchikov, 1976); T4 — Gr-Bi (Perchuk et al., 1983)

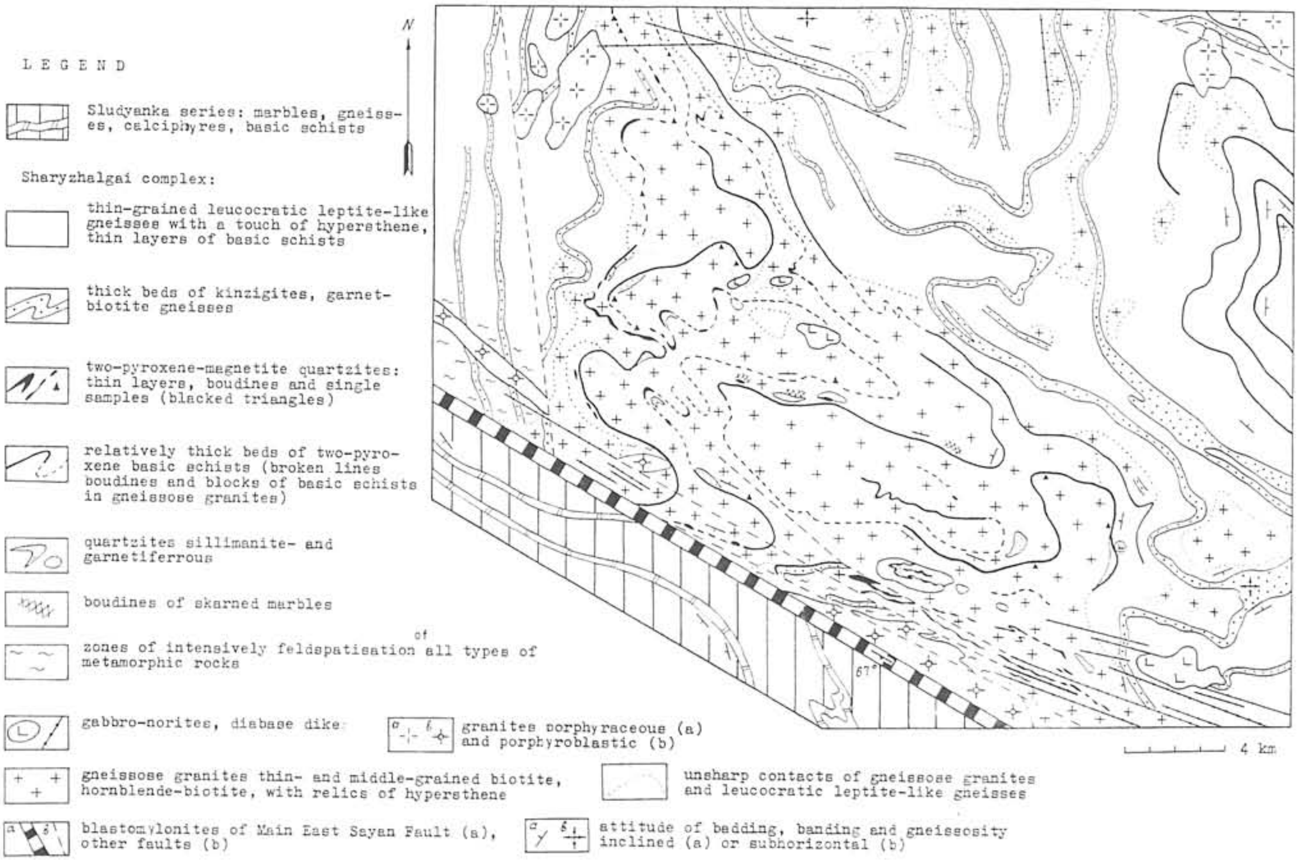

Fig. 3. Simplified geological map of typical part of Sharyzhalgai complex rocks and associated gneissose granites (by Shafeev, Buinov & Yalovik, 1978).

1987, etc.). However in many cases the enderbites are normal intercalations with basic or high-alumina rocks and marbles and have not reaction relations among them (excluding marbles) and the composition of the basic schists is very close to that of a normal tholeiites (Petrova and Levitsky, 1984). Such a picture is very difficult to be reconciled with the granitization or charnockitization point of view. The reaction relations of charnockite, enderbite and basic schist typical in the dome structures can be explained as migration of melts into such domes which promote homogenization of melts, disruption of stratified rocks, reaction with the country rocks. This is consistent with equilibrated CO_2 P-T-P_{CO_2} conditions in all types of rocks (Tab. 1). Basic schists and enderbite have higher temperatures (750–870 °C) and high carbon dioxide pressures (up to 7.5 kbar) than charnockites and granitic rocks (650–750 °C and 2–4 kbar).

In zone II the amphibolite facies rocks are often occur together with granulite rocks. In zone III the granulite relics are very rare, whereas the leucocratic biotite granite-gneiss and migmatites are predominant. The latter rocks are often intensively mylonitized.

In central part of Sharyzhalgai complex (zone II on Fig. 1, part of which is shown on Fig. 3) thick layer and beds of fine-grained leucocratic leptite-like gneisses with hypersthene, magnetite and hornblende are very typical. They have rhyolite or dacite-rhyolite compositions (SiO_2 71.2; Al_2O_3 12.6; FeO 5.7; MgO 0.5; CaO 2.15; Na_2O 3.13; K_2O 3.55; H_2O 0.24; average from 3 analysis) and may represent initial rocks before anatexis and origin of granites. The leptite-like gneisses show transitions change into granite-gneisses in anticlinal cores or shear zones.

Field mapping (Fig. 3) shows that two-pyroxene schists layers are present in leptite-like gneisses, but in the inner parts of granitic lenses and domes the chain of boudines of basic schists, complicated folding, with randomly oriented gneissosity can be observed. These structures are similar to those produced by turbid melt flow. In the high-alumina rocks (kinzigites, biotite-garnet gneisses) „granitization" is not typical and only venitic migmatites are observed. Such regularly layered kinzigite and biotite-garnet gneisses are often preserved within the granite-gneiss areas.

The three zones of Sharyzhalgai complex may correspond to the simplified vertical zonation of gneiss-granitic continental crust, in which the concentration of the K-rich granites in the upper part and enderbites in the lower part are typical. This redistribution of melt is correlated with the change of pressures and composition of fluid inclusions in comparison to those enriched in CO_2 within granulite facies of Sharyzhalgai complex (Kurdukov and Berdnikov, 1987, Tab. 1).

These features are very similar to the granulite-amphibolite facies section in the Aldan shield (Dook et al., 1986) and South India (Condie and Allen, 1982; Hensen et al., 1984).

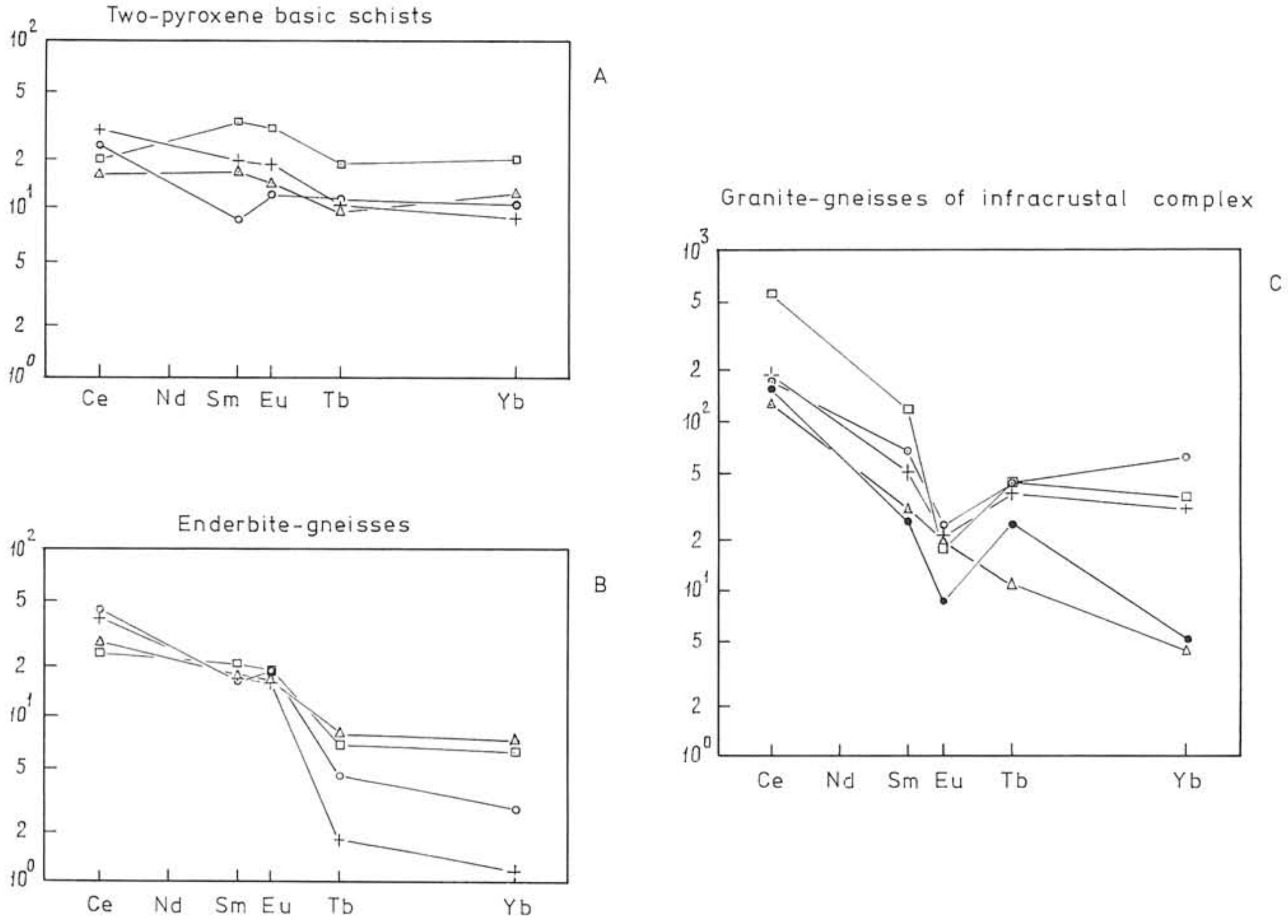

Fig. 4. Chondrite normalized REE pattern for three types of rocks from Aldan shield ultrametamorphic complex (Dook et al., 1986).

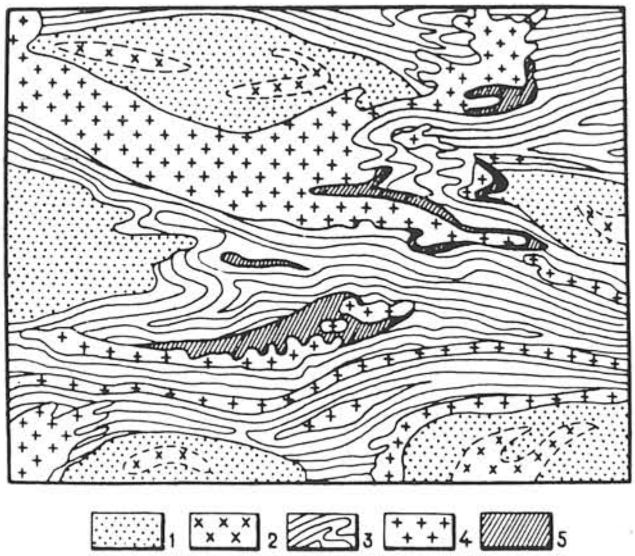

Fig. 5. The scheme of two-stage of migmatites in the granulitite facies rocks of SE Pamir.
Dots and crosses (x) show the massive melanocratic granulites and garnet leucogranulites (migmatites) of first cycle. lines and crosses (+) – garnet-kyanite gneisses and granitic veins with biotite rims of second cycle.

The infracrustal complexes of *Aldan shield* include:

a) enderbite-gneisses; b) biotite-amphibole plagiogneisses; c) biotite and amphibole biotite granite-gneisses (Dook et al., 1986). Many authors have suggested that these rock types are the result of granitization of metabasites, which are represented by layers, lenses and boudines at amounting to not more than 10 % of the area. However, recent investigations including, for example, REE distribution data (Fig. 4) show that the first and the second complexes are very homogeneous, similar to the „grey gneisses" of other Precambrian shields, and are most likely to be the metamorphosed equivalents of the andesitic-dacitic series, originated from the upper mantle. In some rocks we can see Eu-maximum as indication of restite origin. The granite-gneisses complex may be the result of the secondary melting (palingenesis) of enderbite-gneisses particularly the complementary Eu-minimum can be observed (Fig. 4). The layers of basic rocks in the infracrustal complexes of Aldan shield correspond in composition to normal basalts unaffected by any pervasive metasomatic processes (Dook et al., 1986; Petrova and Levitsky, 1984). Trend of REE of basic schists (Fig. 4) corresponds to undifferentiated tholeiites and shows close relations with enderbite-gneisses of andesitic composition.

The interesting melt inclusions was found by V. Chupin (pers. communication) in minerals of the granulites from xenolithes in alcaline basalts of East Pamir. Melt inclusions show granitic composition of glass (SiO_2 69–72 %, K_2O 4–5 %, Na_2O – 3 %) and was observed in all minerals (quartz, sanidime, garnet, kyanite, zircone, apatite). Melt inclusions in kyanite are very surprising. Fluid component of melt inclusions in quartz is pure CO_2 with density 0.85 g/cm^3. The estimations of temperatures and pressure (1050–1100 °C and 10 kbar) are highest for such inclusions.

The regular distribution of H_2O and CO_2-rich inclusions in the metamorphic minerals and migmatites of *South India* is correlated with the metamorphic conditions and the character of "granitization" (Condie and Allen, 1982; Hansen et al., 1984). The earliest, relatively rare inclusions are enriched by H_2O and are followed usually by liquid CO_2-inclusions which fix the pressures of 7–8 kbar in charnockite areas and 5.3–6.0 kbar in the transitional zone. The change from H_2O-rich to CO_2-inclusions and the depletion of charnockite rocks in mobile elements (Rb, U, Th, etc.) may be connected with the removal of portions of acidic melts which are concentrated in the transitional and amphibolite facies zones. The latest H_2O-rich inclusions in these granulites and charnockites near the transitional zone mark the retrogressive crystallization of acidic melts (Friend, 1981; Hansen et al., 1984; Jarnardhan et al., 1982).

In the *south – western Pamirs* high pressure granulite facies conditions were dominant. Fig. 5 and Tab. 2 show features of

Table 2. P-T estimations of granulite metamorphism and anatexis in the rocks of SE Pamir (Budanova, 1989)

	Number of spec.	X mg			$\ln K_D^{Gr\text{-}Bi}$	$\ln K_D^{Gr\text{-}Cord}$	T °C			P, kbar		
		Gr	Bi	Cord			T_1	T_2	T_3	P_1	P_2	P_3
I	2126	0.37	0.55	—	0.73	—	845	919	—	10.5	10.5	7.1
	2169	0.28	0.48	0.66	0.87	1.61	780	885	835	9.5	4.6(?)	7.8
	2179	0.21	0.47	0.66	1.19	1.97	700	725	684	7.0	5.6	5.3
	2	0.33	0.51	0.66	0.78	1.39	817	913	970	9.2	3.4(?)	9.6
	3	0.24	0.45	0.64	0.97	1.77	755	811	774	7.5	5.6	7.1
	2139	0.26	0.54	0.65	1.20	1.71	713	720	778	6.8	5.2	7.1
	average	—	—	—	—	—	768	829	808	8.1	5.7	7.3
II	2169	0.31	0.55	—	1.05	—	734	778	—	7.0	4.1	—
	2	0.30	0.59	—	1.20	—	713	720	—	9.0	2.0(?)	—
	3	0.34	0.59	—	1.02	—	742	790	—	7.5	5.6	—
	2030	0.29	0.55	—	1.11	—	720	754	—	6.8	4.8	—
	average	—	—	—	—	—	727	761	—	7.6	4.1	—

T_1, T_2, P_1, P_3 — Perchuk, 1970; Perchuk et al., 1983; T_3 — Thompson, 1976; P_2 — Ghent, 1976.
I — restites: $Gr+Bi+Cord+Ky(Sil)^{+Pl}+Q\pm KFsp$; II — migmatites and granites: $Gr+Bi+Q+Pe+KFsp$ (+Hyp in spec. 2169 and 2).

migmatites and geothermobarometry of these and country rocks (Budanova, 1989). Maximal P-T estimations (800–900 °C, 7–10.5 kbar, spec. 2126, 2169, 2) and pure CO_2-inclusions are characteristic of the first stage of metamorphism and migmatization. For the restites and charnockitic migmatites (garnet leucogranulites – see Fig. 5) the mineral reaction is typical: Gr+Pl=Gr>Ca+Pl<Ca+Ky+Q. For the second stage of metamorphism and migmatization P-T estimations are lower (700–800 °C, 4–7 kbar, spec. 3, 2139, 2030), the concentrations of H_2O in inclusions of quartz are higher and mineral reaction is typical: Gr+Cord+KFsp+H_2O = Bi+Ky+Q (Budanova, 1989; Glebovitsky et al., 1985). Such high pressures and pelitic compositions of rocks promotes the preservation of acidic melts "in situ" without migration to the upper parts of the crustal section.

One of the authors (N. L. Dobretsov) has seen all these examples (Baikal region, Aldan shield, Pamir block, South India) and could select most important facts for the estimation of possible models. A. A. Shafeev has studied in detail the structural geological and petrological features of Sharyzhalgai and some other ultrametamorphic complexes of South Siberia. We both made the conclusion that differential anatexis model with variable stages in redistribution of anatectic melt is the most favourable for the interpretation of the main facts obtained from ultrametamorphic complexes. But many aspects of this problem particularly the source of CO_2- rich and H_2O-rich fluids during anatexis do not yet solved.

Possibilities of fluid flow from mantle

For all considered and similar examples it is very important to consider the possibility of H_2O-rich or CO_2-rich fluids from the upper mantle. From experimental results (Nakamura and Kushiro, 1975; Ryabchikov and Boettcher, 1985; Shneider and Eggler, 1986) many Soviet petrologists (Zharikov, 1987, etc.) conclude that in the upper mantle is possible generation of fluids enriched by H_2O, SiO_2, Na_2O. However, consideration of the stability field of phlogopite and amphibole in the uppermost mantle leads us to suggest the disappearance or consumption of fluids containing H_2O, SiO_2, K_2O, Na_2O according to the following reactions:

(1) forsterite + spinel + fluid (H_2O + K_2O + SiO_2) = phlogopite + orthopyroxene;

(2) forsterite + spinel + diopside + fluid (H_2O + Na_2O + K_2O + SiO_2) = amphibole + orthopyroxene. The average content of K_2O and H_2O in the upper mantle may be near 0.3 % (Ryabchikov and Boettcher 1985). According to reaction (1) and composition of phlogopite all the K_2O and only half of the H_2O may be consumed. The rest of H_2O and only half of the Na_2O (+K_2O) can be consumed through reaction (2).

In deep continental lithosphere or close to active or relict subducted lithosphere the presence of carbonate and amphibole in mantle lherzolite may be expected (Wyllie 1978; Mysen et al., 1976; Taylor and Green, 1988). The crystallization of mantle carbonatite melt or reactions of decarbonatization in the "hot" Archean mantle can produce a flow of CO_2-rich fluids in the uppermost mantle and lower crust (Taylor and Green, 1988; Wallance and Green, 1988). This is a possible source for CO_2-rich fluid inclusions in granulites facies complexes in which carbonate rocks are often absent (Newton, 1986).

We can certainly suggest the possibility of the CO_2-rich fluid flow from the "hot" mantle but consider the possibility of H_2O-rich fluid flow from the mantle to be very remote. The source of H_2O for melting in the lower crust may be the biotite of the rocks (Shkodzinsky, 1985) or filtrating and crystallized H_2O-bearing melt from deeeper parts. In any case the anatectic model of granite melt origin is the most plausible one and the model of granitization with the previous Si-K metasomatism is possible only in specific conditions, perhaps connected with specific mantle magma enriched in H_2O (Litvinovsky and Podladchikov, 1990).

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