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PHYSICO-CHEMICAL CONDITIONS OF ANATECTIC MELTING AND THE ROLE OF ANATEXIS AND RHEOMORPHISM IN THE FORMATION OF A GRANITIC MAGMA (WITH EVIDENCE FROM THE ALDAN SHIELD)

(7 Figs.)

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Abstract: The following features have been established in granulite-facies migmatites formed by anatectic differentiation on the Aldan Shield: incomplete melting of the metamorphic association plagioclas + orthoclas + quartz, a higher proportion of anhydrous minerals among the dark-coloured constituents of the leucosome, and somewhat lower iron concetration in minerals of the leucosome as compared with the melanosome, similar leucosome amounts in gneisses of similar composition and degree of metamorphism, and chemical equilibrium between the leucosome and melanosome. All this evidence suggests that the solid products of incongruent melting reactions accumulated together with melt in the leucosome, that the leucosome was largely solid during its formation. It also indicates that the anatectic leucosome formed in situ and that melt did not separate during ultrametamorphism. Studies of ultrametamorphic granites and calculated P-T phase diagrams suggest that granitic magmas were formed by re-melting of compositionally similar metamorphic rocks under the effect of decompression and frictional flow heat release during their ascent.

Key words: ultrametamorphic granites, anatectic differentiation, migmatites, Aldan Shield.

Zones of ultrametamorphism are the only examples of mass partial melting accessible for direct observation, and their study is therefore of primary importance in understanding mechanism of magma generetion.

Recent studies in Aldan Shield have shown that even in the highest-tamperature migmatites the metamorphic association plagioclase + orthoclase + quartz has been retained in the melanosome. Numerous experimental results, show that in the presence of a hydrous phase this association melt in the range 650–700 °C. These rocks however contain the associations hypersthene + sillimanite and hypersthene + cordierite, and were thus metamorphosed at a tempereture of the order of 900 °C (Hensen – Green, 1972). In migmatites resulting from differentiation into leucosome and melanosome by partial melting, anhydrous minerals (garnet, cordierite, hypersthene) form a higher proportion of the dark-coloured constituents of the leucosome as compared with the melanosome. This is indicated by the location of points in the right-hand part of Fig. 1. Dark-coloured minerals of garnet-bearing leucosomes are in general slightly depleted in iron in comparison with the associated melanosome. This is illustrated by the fact that a majority of the points on Fig. 2 fall just above the bisectrix. These two phenomena appear paradoxical, since from many experimental results anatectic melt should, on the contrary, be more hydrous and richer in iron than the solid phases in

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eguilibrium with it. Fig. 3 shows that there is a direct relationship in isofacial migmatites between the amount of the anatectic leucosome and that of biotite in the melanosome at less than 15–20 % biotite.

These and other features of migmatites can only be explained water deficiency during anatexis processes (Brown – Fyfe, 1970; Robertson – Wyllie, 1971). The deficiency

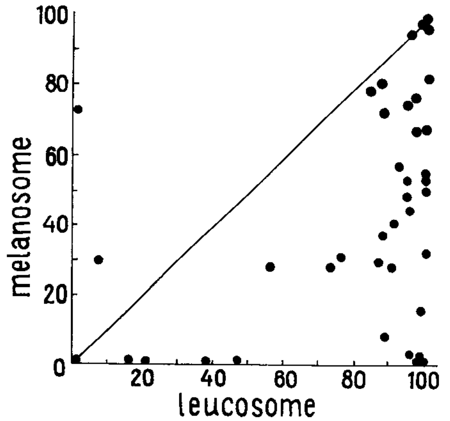

Fig. 1. Relation of abundances of anhydrous minerals in the dark coloured constituents of the leucosome and melanosome of migmatites resulting from differentiation by partial melting.

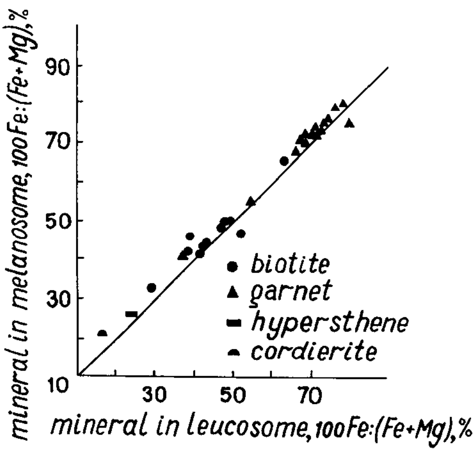

Fig. 2. Ratio 100 % Fe/(Fe+Mg) in biotites (1), garnets (2), hypersthenes (3), cordierrites (4) of the leucosome and melanosome (from chemical analyses).

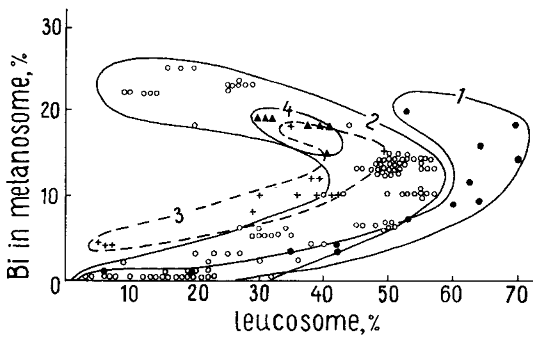

Fig. 3. Relationship of biotite abundances (%) in the melanosome to proportion of leucosome in biotite-hypersthene-garnet migmatites from the Sutam (1); Uchur, Gonam, Timpton (2); Aldan, Chuga (3); Amedichi (4) river basins.

of water caused incomplete melting of a granite minimum out of the melanosome, and the survival of the association plagioclase + orthoclase + quartz in the latter. The amount of water required for melting was extracted from hydroxyl-bearing minerals by altering them into anhydrous phases and hence to a markedly incongruent character of melting through reactions of the type $3nK_{0.85}Mg_{1.7}Fe_{1.1}Al_{1.6}Si_{2.74}(OH)_{1.8}O_{10.2}$ + 1.35 $nNaAlSi_3O_8$ + 1.67 nAl_2SiO_5 + (3.43−2.8 n)$Mg_{0.6}Fe_{2.4}Al_2Si_3O_{12}$ + 9.46 $nSiO_2$ = 3.43 $Mg_{0.6+n}Fe_{2.4-n}Al_2Si_3O_{12}$ + 1.2 $nKAlSi_3O_8$ + $9nK_{0.15}Na_{0.15}Al_{0.3}Si_{1.27}(OH)_{0.6}O_{2.84}$ or 3nBi* + 1.35nAb + 1.67Sil + (3.43−2.8 n)Gr + 9.46nQ = 3.43Gr_{Mg} + 1.2nOr + 9nL, where n is an increment of magnesium in garnet.

The newly-formed minerals mainly crystallized in the leucosome due to large scale diffusion of components through melt. This accounts for a high proportion of anhydrous minerals in the dark-coloured constituent of the anatectic leucosomes. The majority of the dark-coloured minerals in the leucosome formed synchronously with the melt and did ot crystallize from it. This explains their similar, and commonly lower, iron contents in the lecosome compared with the melanosome.

The amount of the newly-formed solid phases in the leucosome was probably much greater then that of the melt, since the anatectic melt has a much higher water content than the starting minerals. Using the above reaction as an example, the volume of the newly-formed solid phases is $2.8 \cdot 0.1 \cdot 115 + 3.43 \cdot 115 + 1.2 \cdot 0.1 \cdot 109 = 439.3$ cm^3, and that of the melt is $9 \cdot 0.1 \cdot 53 = 47.6$, using molar volumes of garnet, orthoclase and melt of 115, 109 and 53 cm^3, respectively, and at the most common increase in the magnesium content of the garnet of n = 0.1. If all of the newly-formed solid phases crystallized in the leucosome, the amount of the solid phases in it must have ben 92.3 %. The small melt fraction, however, must have been enough to provide a predominantly solid state of the leucosome during its formation and accounts for the absence of typical magmatic textures in the anatectic leucosome.

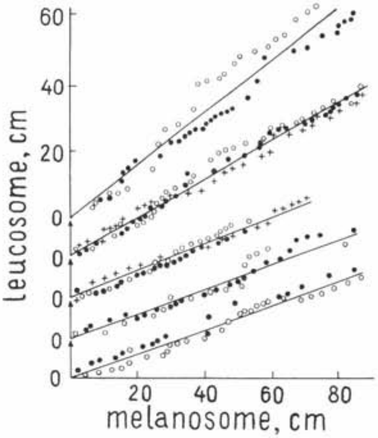

Fig. 4. Correlation between the cumulative thickness of the leucosome and melanosome in biotite--garnet migmatites.
Points show the relation of thicknesses of the first measured bodies of the leucosome and melanosome, the sums of the thicknesses of the first and second bodies, of the first, second and third bodies, etc. Each group of points of one type reflects meassurements along one line across the strike of the rocks.

Water deficiency leads to buffering water activity during anatexis processes, that is, a considerable independence of f_{H_2O} on the initial water content of rocks. Anatectic and metamorphic reactions should be considered together in calculation P-T diagrams for migmatized metamorphic rocks (Shkodzinsky, 1976). Water deficiency and several other lines of evidence are at variance with the idea that anatexis and granitic magma generation

*Phase symbols: Ab − albite, Bi − biotite, F − fluid, Gr − garnet, Gr_{Mg} − magnesian garnet, L − melt, Or − orthoclase, Q − quartz, S − solid phases, Sil − sillimanite.

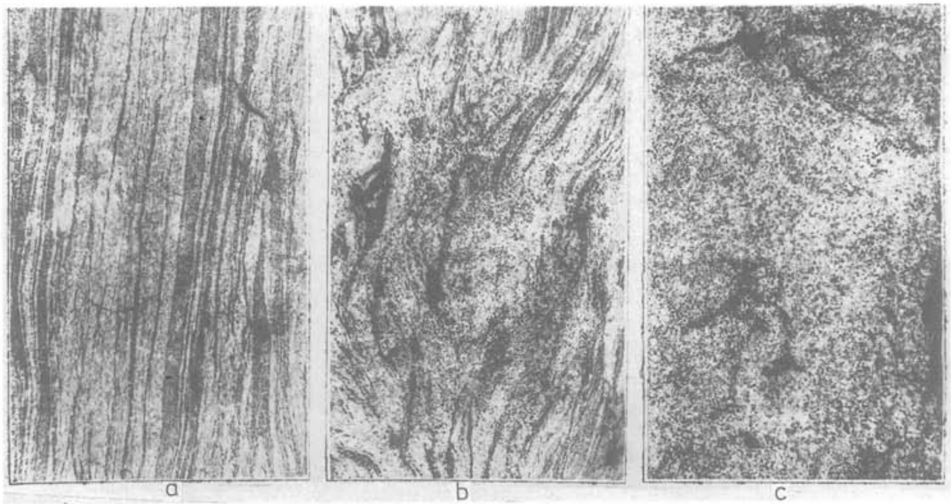

Fig. 5. Isotropization (a) of granite-gneiss (b) as a result of decompressive-dissipative melting to form inhomogeneous rheomorphic granite (c).

take place during ultrametamorphism under the effect of hypothetical flows of water, carbon dioxide and other components, and testify to the isochemical nature of these processes.

Also, the present study has failed to confirm the widely held view that granitic magma results from melt separation in migmatites during ultrametamorphism. The conducted measurements have shown that gneisses of similar composition and degree of metamorphism generally contain relatively similar amounts of the leucosome produced by anatectic differentiation. This is illustrated by relatively narrow fields of points of one type in Fig. 3. The straight line relationships between successive sums of the thickness for the leucosome and melanosome in Fig. 4 indicate a broadly uniform distribution of the anatectic leucosome in compositionaly homogeneous gneisses. The continuity and similarity of mineral compositions of the leucosome and melanosome (Fig. 2) are indicative of physico-chemical equilibrium of these parts of migmatites during their formation.

All of the above features confirm the autochthonous nature of the anatectic leucosome in migmatites and imply, little movement of anatectic melts in them. The presence of cross-cutting granitoid veins in migmatites does not contradict the above conclusions since most of the veins carry obvious signs of having been formed not by injection of melt but by injection of granite-gneisses with smal content of melt. This is indicated by lack of magmatic textures in them, the relatively high magnesium content of dark-coloured minerals and basicity of plagioclase comparable to those of metamorphic granite-gneisses, as well as the occasional, gradual transition of the veins along the strike into concordant granite-gneiss bodies. The autochthonous nature of the anatectic leucosome in migmatites contradict the assumption that granitic magmas were generated by separation of anatectic melts in ultrametamorphism zones.

Studies of ultrametamorphic granites of the Aldan Shield indicate a quite different genesis for granitic magma. The Aldan Shield, like many others, has a very thick, largely granite-gneiss complex in its basement (Dook et al., 1986). According to geological

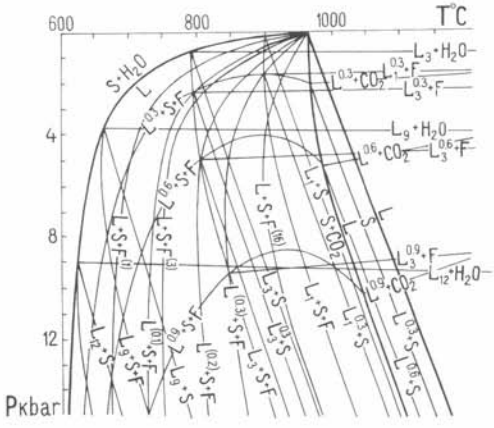

Fig. 6. P-T diagram of the state of the system eutectic granite-H_2O-CO_2.
Thin lines with H_2O contens as subscripts and CO_2 contents as superscripts are isoconcentrates (mass %) in a melt in various associations, and CO_2 to H_2O mass ratios (superscripts in brackets) in the melt and gas phase.

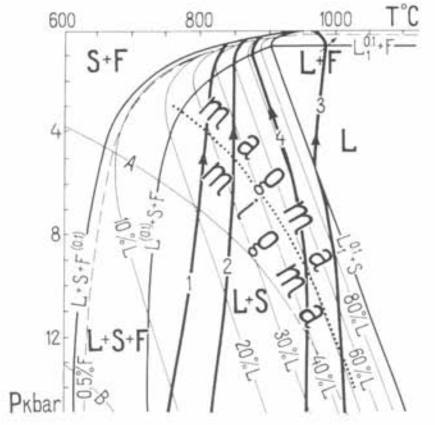

Fig. 7. P-T diagram of the phase composition of granitic magmas with 1 mass % H_2O and 0.1 mass % CO_2.
Thin liness: melt (solid lines) and fluid (dashed lines) isoconcentrates; heavy lines with arrows: models of magma evolution during ascent. A and B: lines of various geothermal gradients. L+S+F, L+S, L, L+F denote fields of different phase compositions of magmas and migmas. Lines 1 to 4 illustrate that, due to decompressive-dissipative melting during their rise, migmatized granite-gneisses containing 10 to 30 percent anatectic melt can be transformed first into migma than magma.

obsevations, granite-gneisses of the basement complex tend to rise and squeeze out as domes and diapirs during ultrametamorphism. As can be seen from Fig. 5, they become homogeneonus and increasingly similar in appearance to typical magmatic granites as they rise. Similar rheomorphic processes have also been described in other shields (Reynolds, 1958; Salop, 1977). It appears as if the uprise itself leads to remelting of granite metamorphic rocks.

To verify the assumption, a complete P-T diagram was construced for the system eutectic granite-water-carbon dioxide from published experimental evidence (Luth et al., 1964; Merril et al., 1970; Huang – Wyllie, 1973, 1975; Novgorodov – Shkodzinsky, 1974; Kadik – Eggler, 1975, and other). Unlike other diagrams available for this system in the literature (Perchuk, 1973; Kogarko – Ryabchikov, 1978), it also gives equilibria at water and carbon dioxide undersaturation. From it, a P-T phase diagram for a granitic magma containing 1 mass % H_2O and 0.1 % CO_2 (Fig. 7) was calculated. The procedure for constructing the diagrams and initial data are as given in a previous work (Shkodzinsky, 1985). Thin lines on the diagram show the amounts of melt and gaseous phase in magma under various P-T conditions. Heavy lines with arrows represent paths of temperature and magma phase composition variations. The path were calculated using the following equation (Shkodzinsky, 1981, 1985).

$$
\begin{aligned}
&(P_1 - P_2)(\varrho_e - \varrho_m)(\varrho_e \varrho_m I)^{-1} + C_e (T_1 - T_2) - \Delta H_m (A_{L_2} - A_{L_1})\, 10^{-2} + \\
&+ \Delta H_s (A_{F_2} - A_{F_1})\, 10^{-2} - 0.71 (P_1 - P_2)(A'_L + A'_S)\, 10^{-2} + \\
&+ P_1 V_1 A'_F [1 - (P_2 P_1^{-1})^{(k-1)/k}] [10^2 I(k-1)]^{-1} - \\
&- 0.8(T_m - T_e) [\lambda_e C_e \varrho_e (P_1 - P_2 - \Delta P)]^{0.5} (E^3_{\varrho_m} g)^{-0.5} = 0
\end{aligned}
$$

where T_1, T_2, P_1, P_2, A_L, A_{L_2}, A_{F_1}, A_{F_2} are, respectively, temperature, pressure, and melt and fluid content (mass %) at the beginning and at the end of the estimated ascent interval; A'_L, A'_S, A'_F, ΔP are mean contents of melt, solid phases and fluid, and pressure losses in the estimated ascent interval; ϱ_m, ϱ_e, C_m, C_e, T_m, T_e are, respectively, density, heat capacity and temperature of the magma and enclosing rocks; ΔH_m and ΔH_s are enthalpies of melting and separation of fluid from melt; I is a mechanical equivalent of heat; V_1 is a specific volume of the gas phase at pressure P_1; $k = C_p/C_v = 1.29$; λ_e is a thermal conductivity of the enclosing rocks; g is gravity acceleration; E is discharge of magma flow. The first term in the equation reflects potential energy released during ascent of lighter magmas through denser enclosing rocks; it is assumed to be completely consumed by frictional flow (i. e., by dissipative heat release). The others reflect energy variations with increasing/decreasing temperature of magmas (the second term), melting/crystallization in magmas (the third), gas phase separation (the fourth), expansion of condensed and gas phases (the fifth and sixth), heat transfer into the surrounding rocks (the seventh). Lines 1 to 3 were calculated for a case of voluminous magma ascent where specific heat losses into the enclosing rocks could be ignored; line 4 was estimated for a case of small magma volume ($E = 25\ m^3/s$) where specific heat losses during the ascent were high.

Lines 1 to 4 demonstrate that granitic compositions contain higher proportion of solid phases at higher pressure so that at great depths (5−15 kb) they are largely solid (10−30 % melt) migmas. As noted from observations in ultrametamorphic zones, granitic rocks with small contens of a melt, but not entirely molten, began to ascend. During their ascent they were re-melted under the effect of decompression and frictional flow heat release, i. e. dissipative heat release. Thus, granitic magmas must have been generated through decompressive-dissipative re-melting during floating and squeezing out along fracture zones of compositionally similar substrates with small initial melt content. A similar conclusion has been made from calculated phase diagrame for magmas of intermediate, basic and ultrabasic compositions (Shkodzinsky, 1985).

The decompressive-dissipative generation of granite magmas is envisaged as follows. During anatexis, the gneisses closer in composition to granites would fuse most readily, thereby becoming less viscous. Due to lower density they would floating or squeeze under the influence of stress along tectonic rupture zones. According to Stokes formula, the rate of ascent is proportional to a squared radius of rising body, therefore it would be much greater for large diapirs of granite-gneisses than for droplets of anatectic melt in them. Thus for a viscosity of $\eta_1 = 10^{20}$P for the enclosing ultrametamorphic rocks-containing 10 % melt, a viscosity of $\eta_2 = 10^{19}$P for the granite-gneisses containing 20 % melt, density contrast of $\varrho_1 - \varrho_2 = 0.4 g/cm^3$ between the enclosing rocks and the granite-gneisses, and gravity acceleration of $981\ cm/s^2$ the rate of ascent of a granite-gneiss diapir with R=5 km, from Stokes formula, would be $W = 2R^2 g(\varrho_1-\varrho_2)(\eta_1+\eta_2)/3\eta_1(2\eta_1+3\eta_2)$ $= 2.25.10^{10}.981.(10^{20}+10^{19})/3.10^{20}(2.10^{20}+3.10^{19}) = 3.13.10^{-7}$ cm/s. Over a period of one million years ($3.16.19^{13}$s), the diapir would rise by $9.88.10^6$ cm or 98.8 km. Over the same period, a droplet of melt having a radius of one centimeter and a viscosity of $\eta_2 = 6.10^8$P would rise by $3.16 \cdot 10^{13} \cdot 2.981 \cdot 0.4(10^{19}+6 \cdot 10^{8})/3 \cdot 10^{19} \cdot (2 \cdot 10^{19} + 18 \cdot 10^{8}) = 4.13 \cdot 10^{-4}$ cm only in granite-gneiss. The above approximations explain the autochthonous nature of anatectic melts and a relatively rapid ascent of large masses of partially molten granite-gneisses.

As they rise, the granite-gneisses undergo gradual remelting (Fig. 7) and transformation first into migma, then into magma. Such transformations appear to reflect rheomorphic processes reported sometimes in ultrametamorphism zones. Rocks generated from migmas are intermediate in appearence between typical metamorphic and magmatic formations, due to melting, recrystallization and mixing of material of the granite-gneisses during ascent (Figs. 5b, 5c). With magmas of decompressive-dissipative origin, the deepest granites appear to have been formed from highly viscous magmas containing a low proportion of melt rather than from a melt. This provides an explanation for the characteristic features of ultrametamorphic granites: the absense of typical magmatic structures, crystallization and emanation differentiation phenomena and associated hydrothermal mineralization, as well as their structural and textural similarity to metamorphic rocks. The decompressive-dissipative model of magma generation implies compositional identity of primary magmas to their source substrates and early generation of material of most of the substrates, probably due to fractionation of a global magma ocean that appeared early in the Earth's history as a result of impact heat release (Hofmeister, 1983; Shkodzinsky, 1985, and other).

Thus, the present study suggests that granitic and perhaps other primary magmas were not generated by melt separation from mafic rocks but resulted from decompressive-dissipative re-melting of compositionally identical, weakly molten substrates during their floating and squeezing zones of tectonic disturbance.

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