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Fluid control of charnockitization

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ABSTRACT

The reactions $Bt+Qtz=Opx+Kfs+H_2O$, $Bt_1+Qtz+(K_2O)=Or+Bt_2+(n\ H_2O)$, $Mg\text{-}Ts(Opx)+Qtz+(K_2O)=Or+En$, $Pl_1+(K_2O)=Pl_2+Or+(Na_2O)$ and $Prg+En+Qtz+(K_2O)=Or+Ed$ recorded in unique rock textures and mineral compositions from gneissic complexes of some granulite facies terrains have been studied. It is shown that chemical potentials of the perfectly mobile CO_2, H_2O and K_2O in a metamorphic fluid govern the charnockitization process along the retrograde P–T paths typical of granulite facies rocks. The sensors indicating the contribution of thermodynamic parameters to the process are discussed. In many complexes charnockitization took place at a $a^{fl}_{H_2O}$ similar to or even higher than that for initial gneisses.

The origin of arrested charnockites in the Precambrian gneissic complexes is considered to be CO_2–H_2O fluid/gneiss interaction, which causes migration of the majority of the basic components (MgO, FeO, CaO, TiO_2 etc.) from initial metamorphic rocks toward a transition zone; the scale of the migration depends strongly on the intensity of the interaction. The migration of the elements from a given rock volume propagates the shift of its bulk composition toward the charnockite (Kfs+Qtz+Fs) eutectic and subsequent melting. This model may explain the existence of zoned metabasite–enderbite–charnockite complexes of Precambrian granulite facies terrains. The arrested charnockites are a small-scale model for the formation of these complexes.

Abbreviations used

Thermodynamic symbols

P_s = lithostatic pressure, kbar
P = total pressure, kbar
t = temperature, °C
T = temperature, K
$a^{fl}_{H_2O}$ = activity of H_2O in a fluid (fl)
μ^{fl}_i = chemical potential of component i in a fluid
X_i = mole fraction of component i in a solid solution (ss)
N_i = $100 \cdot X_i$, mole% of component i in ss
a_i = activity of component i in ss or fl
γ_i = activity coefficient of component i in ss or fl
W_i = interaction parameter for component i in ss
G^e_i = excess partial molar free energy of component i in ss
K_D = distribution coefficient for isomorphic components i and j between two coexisting minerals
K_r = reaction constant of reaction r
f_i = fugacity of component i

Minerals

Ab = albite
Act = actinolite
Aln = allanite
Alm = almandine
Anc = ancerite
And = andalusite
Ann = annite
Brn = breunnerite
Bt = biotite
Cal = calcite

Chl = chlorite
Cpx = clinopyroxene
Crd = cordierite
Cum = cummingtonite
Dol = dolomite
East = eastonite
Ed = edenite
En = enstatite
Fa = fayalite
Fs = ferrosilite
Gln = glaucophane
Gru = grunerite
Grt = garnet
Hbl = hornblende
Ilm = ilmenite
Kfs = K-feldspar
Ky = kyanite
Mag = magnetite
Maf = mafic minerals
Ms = muscovite
Opx = orthopyroxene
Ok = "orthocorundum"
Or = orthoclase
Phl = phlogopite
Pl = plagioclase
Prp = pyrope
Prg = pargasite
Qtz = quartz
San = sanidine
Sid = siderophyllite
Spl = spinel
Sil = sillimanite
Tr = tremolite
Ts = tschermakite
Zrn = zircon

1. Introduction

The fluid regime of charnockitization of gneissic complexes from the Precambrian granulite facies terrains has been studied by a number of geologists on the basis of petrological and geochemical data (Newton, 1986; Stähle et al., 1987; Kröner, 1991). These data, combined with measurements of high-density CO_2 inclusions in minerals from these rocks (Dolgov et al., 1967; Touret, 1981; Hansen et al., 1984) provide strong evidence for an important role of CO_2 in the charnockitization process. It has been shown that trapping the CO_2 inclusions (Crawford and Hollister, 1986) and formation of many corona textures (Perchuk et al., 1985) occur along with the retrograde path of granulite facies metamorphism at which the fluid is mainly composed by CO_2, H_2O, N_2 and CO (Fig. 1).

Geothermobarometric studies (Perchuk, 1989) showed that the retrograde P–T paths for most non-isobaric granulite facies complexes are similar. The best fit gave the following equation:

$$P\text{, kbar} = 0.0176\ (\pm 9.768\times 10^{-2})\cdot t - 6.774\ (\pm 2.529) \qquad (1)$$

Along with geobarometric data, the best evidence for the late-stage charnockitization at shallow levels of the Earth's crust is the re-crystallization of gneissic rocks into patchy charnockites. In many outcrops of Sri Lanka and southern India, a loss of foliation is a common feature. Such structural homogenization of arrested charnockites is a direct petrological evi-

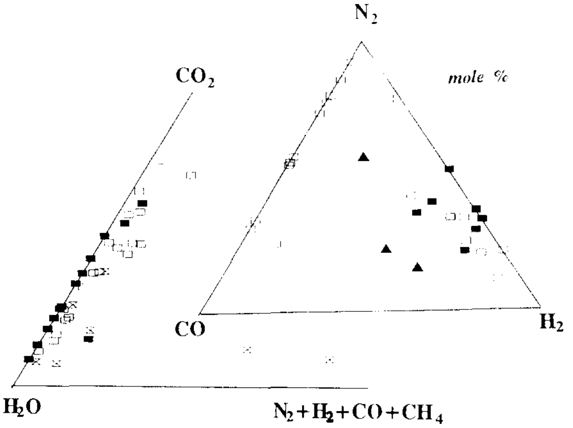


Fig. 1. Composition of fluid selected from cordierite, garnet and quartz in the rocks of granulite facies terrains from the Aldan shield and Sharyzhalgay complex, eastern Siberia. Empty squares: Crd from the Aldan shield (Popov and Tomilenko, 1987); filled squares and triangles: Crd and Grt+Qtz from the Sharyzhalgay complex (Berdnikov et al., 1990), respectively.

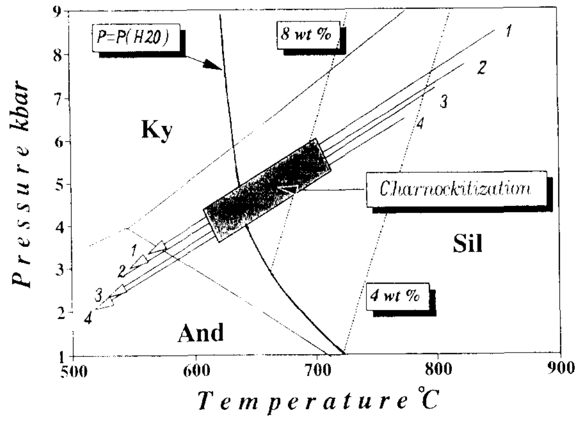


Fig. 2. P–T parameters of charnockitization process recorded by the Opx–Bt ± Grt exchange equilibria and CO_2 liquid inclusions in charnockite minerals with respect to the retrograde paths for four, 1–4, granulite facies complexes from eastern Siberia (Perchuk, 1987, 1989). Aldan shield: 1 = Sutam block, 2 = Western Aldan; 3 = Hankay massif, Primor'ye; 4 = Sharyzhalgay complex, S.W. Baikal. Curve and dotted lines represent the eutectic granite liquidus projection onto the P_s–T plane at given water contents of melt and saturated conditions ($P_s = P_{H_2O}$).

dence in support of the charnockitization process occurring at relatively shallow depths. Hiroi et al. (1990) gave petrographic evidence for the low-pressure conditions of this process, such as stability of the assemblages Opx + Kfs ± Crd and Opx + Grt + Kfs ± Crd, as well as andalusite and siderite in the charnockitized pelitic rocks of the SW-Group in Sri Lanka.

A relative decrease in $f^{fl}_{H_2O}$ in granulite facies rocks has been calculated at a constant $f^{fl}_{H_2O}/f^{fl}_{CO_2}$ ratio along with the path (Perchuk, 1989). At specific conditions, the fluid–rock interaction leads to formation of charnockites and associated rocks (enderbites etc.). The increase in CO_2 activity may cause transformation of garnet-bearing gneisses into orthopyroxene–cordierite rocks, while metabasites and biotite–hornblende gneisses can be transformed into charnockite series rocks. According to geobarometric studies such transformation occur at ~750–600°C and ~6–3 kbar (Fig. 2).

2. Water regime

Sen and Bhattacharya (1990) showed that the equilibrium water activity calculated for charnockites from Satnuru and Madras in Southern India is equal, $a^{fl}_{H_2O} = 0.1$–0.2 (Satnuru), or higher, $a^{fl}_{H_2O} = 0.2$–0.3 (Madras), than that in close-up metapelites. In view of these data, we have calculated the water activity in fluid for the S.W. Baikal gneiss/charnockite complex using the formula

$$a^{fl}_{H_2O} = \exp(\Delta G_{(2)}/RT)$$

for the reaction

$$\underset{\text{Phl}}{KMg_3AlSi_3O_{10}(OH)_2} + \underset{\text{Qtz}}{3SiO_2} = \underset{\text{En}}{3MgSiO_3} + \underset{\text{San}}{KAlSi_3O_8} + H_2O \qquad (2)$$

and using standard thermodynamic values ($\Delta H^\circ_{1000} = 24{,}048$ cal, $\Delta S^\circ_{1000} = 36.000$ e.u. and $\Delta V^\circ = -0.426$ cal/bar), $RT\ln f^\circ_{H_2O} + \Delta G^\circ_{(2)} + \Delta G^e_{(2)}$; $\Delta G^\circ_{(2)}$ is the difference in the excess Gibbs free energies for enstatite and phlogopite in the orthopyroxene and biotite solid solutions, respectively, at $X^{rock}_{Mg} = 0.5 \pm 0.05$, $X^{rock}_{Al} = 0.1 \pm 0.05$, $X^{Kfs}_{Or} = 1$ and P given by the best fit as the following

$$P = t\cdot(0.0279 - (7.9\times10^{-6})\cdot t) - 10.03$$

Mixing properties for biotite and orthopyroxene are

$$G^e_{Bt} = -3000\, X_{phl}X_{East} - 21967\, X_{Ann}X_{East}$$

$$G^e_{En} = X_{En}X_{Fs}(1.196\cdot T - 1720) + 1446 \cdot X_{OK}X_{En} - 1931\cdot X_{OK}X_{Fs}$$

where $X_{En} = Mg/(Mg + Fe + Al/2)$, $X_{Fs} = Fe/(Mg + Fe + 2Al)$, $X_{Ok} = Al/(2Mg + 2Fe + Al)$, $X_{OK} + X_{Fs} + X_{En} = 1$ in the orthopyroxene solid solution; $X^{Et}_{Mg} = Mg/(Mg + Fe)$ in biotite.

Figure 3 illustrates the results of our calculations based on mineral chemistry from charnockite series rocks collected from the Sharyzhalgay complex (Perchuk, 1989). In the diagram, the water activity for charnockites is

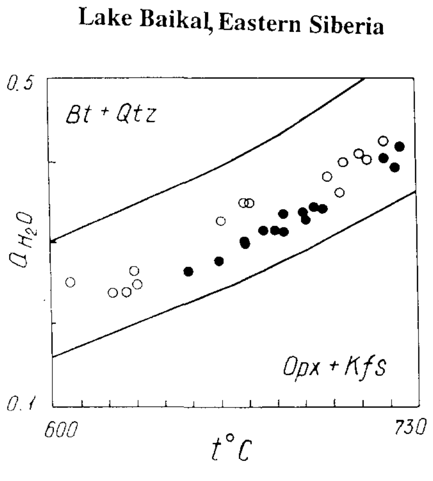


Fig. 3. The T-$a^{\text{fl}}_{H_2O}$ plot for charnockites (○) and gneisses (●) from S.W. Baikal along P–T path 4 in Fig. 2. It is clear that $a^{\text{fl}}_{H_2O}$ in charnockites is similar to or higher than that in gneisses.

similar to or slightly higher than that for the close-up gneisses. Consequently, in the course of charnockitization the fluid ws predominantly composed of H_2O and CO_2. The role of other components can be found through the reaction textures and mineral chemistry of adjacent minerals in coronas.

Thus, the problem arises as to how metamorphic charnockitization, along with an increase in the water activity and a decrease in T, P and $\gamma^{\text{fl}}_{CO_2}$ can be explained for some complexes. There is another important parameter, $\mu^{\text{fl}}_{K_2O}$, which governs reactions between biotite, orthopyroxene and quartz.

3. Unique reaction textures and perfect mobility of potassium

In contrast to granulites, the reaction textures reflecting charnockitization process have not been described yet. Examples of orthopyroxene coronas on biotite enclosed in a quartz matrix of gneiss are known from the Aldan shield, eastern Siberia (Korikovskiy and Kislyakova, 1975). However, such corona textures presumably resulting from an increase of the CO_2 activity (Newton, 1986) in a fluid occur extremely rarely in the gneisses of this area (Perchuk et al., 1985). Another example of the charnockitization reaction in gneisses from southern Finland is shown in Fig. 4. However, the CO_2 activity is not the only charnockitization factor able to form such rims. Analytical data show that they might result from an increase in $\mu^{\text{fl}}_{K_2O}$ during the charnockitization of the gneisses.

Korzhinskiy (1962) considered $\mu^{\text{fl}}_{K_2O}$ a factor of charnockitization of gneisses. He calculated the $\mu^{\text{fl}}_{K_2O} - \mu^{\text{fl}}_{H_2O}$ diagram and considered a field of the Opx+Kfs stability at low $\mu^{\text{fl}}_{H_2O}$ and high $\mu^{\text{fl}}_{K_2O}$. The role of potassium in the formation of some arrested charnockites from Kabbaldurga, southern India, has been demonstrated by Stähle et al. (1987). Using Orville's experimental data on the distribution of Na and K between feldspar and NaCl-KCl aqueous fluid, Newton (1990) calculated the isobaric phase diagram for the system Or–Pl_{25}–Phl-En-Qtz in the coordinates T–log(K/Na) and showed co-genetic relationships of charnockites from southern India with granites.

If the effect of $\mu^{\text{fl}}_{K_2O}$ on the formation of charnockitic gneisses is real, then the Al content of biotite coexisting with K-feldspar and quartz should decrease in accordance with the following net-transfer reaction:

$$\begin{aligned}&(5+0.5n)K_2(Mg,Fe)_5Al_4Si_5O_{20}(OH)_4\\&\quad+21nSiO_2+(3nK_2O)=7nKAlSi_3O_8\\&\quad+5K_2(Mg,Fe)_{5+0.5n}Al_{4-n}Si_{5+0.5n}O_{20}(OH)_4\\&\quad+(nH_2O)\end{aligned}\tag{3}$$

or

$$\begin{aligned}&6K_2Mg_5Al_4Si_5O_{20}(OH)_4+12SiO_2\\&\quad+(6K_2O\text{ in fluid})\\&\quad=5K_2Mg_6Al_2Si_6O_{20}(OH)_4\\&\quad+14KAlSi_3O_8+(2H_2O\text{ in fluid})\end{aligned}\tag{3a}$$

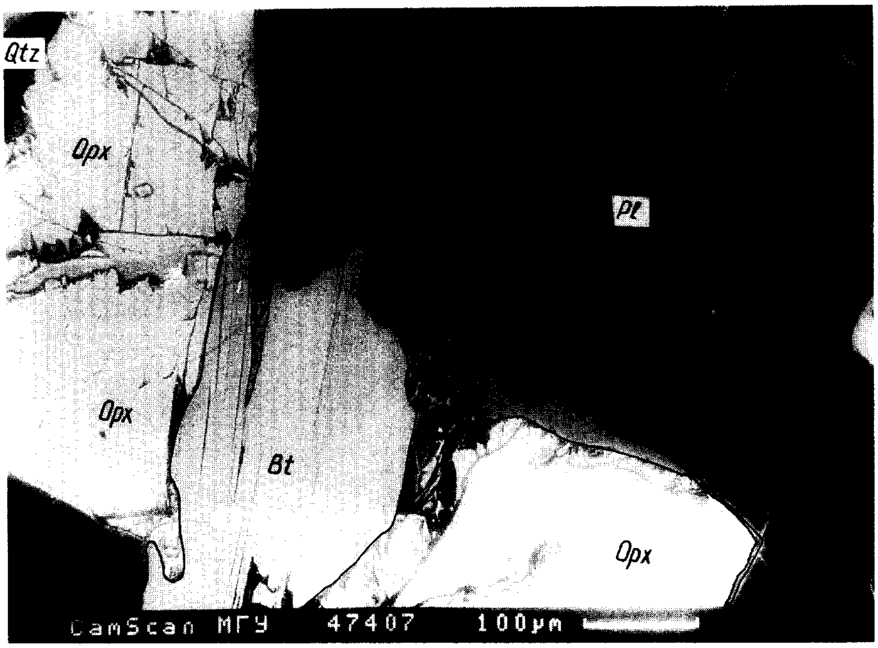


Fig. 4. The reaction rims in charnockitic gneiss from the Sulkava complex (southern Finland), reflecting an increase of the potassium activity according to reactions (4) and (5). The anorthite content of plagioclase grows to the contact with Kfs (reaction 4) while the Al concentration in Opx decreases to the Kfs rim because reaction (5) shifts to the right (profile 1 in Fig. 5a).

This reaction, however, depends on water activity as well. Incorporated with the following three reactions,

$$\begin{aligned} &\mathrm{CaAl_2Si_2O_8 \cdot \mathit{n}NaAlSi_3O_8} \\ &\quad + (0.5m\mathrm{K_2O\ in\ fluid}) = m\mathrm{KAlSi_3O_8} \\ &\quad + \mathrm{CaAl_2Si_2O_8 \cdot (\mathit{n}-\mathit{m})NaAlSi_3O_8} \\ &\quad + (0.5m\mathrm{Na_2O\ in\ fluid}) \qquad (4) \end{aligned}$$

$$\begin{aligned} &\mathrm{MgAl_2SiO_6 + 6SiO_2(K_2O)} \\ &\qquad = \mathrm{2KAlSi_3O_8 + MgSiO_3} \end{aligned}$$

i.e.

$$\text{Mg–Ts(Opx)} + \text{Qtz} + (\mathrm{K_2O}) = \text{Or} + \text{En} \qquad (5)$$

and

$$\begin{aligned} &\mathrm{NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2 + MgSiO_3} \\ &\quad + \mathrm{6SiO_2 + (K_2O) = 2KAlSi_3O_8} \\ &\quad + \mathrm{NaCa_2Mg_5AlSi_7O_{22}(OH)_2} \end{aligned}$$

i.e.

$$\text{Prg} + \text{En} + \text{Qtz} + (\mathrm{K_2O}) = \text{Or} + \text{Ed} \qquad (6)$$

reaction (3) reflects the effect of perfectly mobile potassium in the fluid on the transformation of gneiss into charnockite because reactions (4)–(6) are independent of the water fugacity. These three reactions (4, 5 and 6) proceed to the right with increasing $\mu^{\mathrm{fl}}_{\mathrm{K_2O}}$. According to reaction (4), the anorthite content of plagioclase should increase, whereas for reactions (5) and (6) the Al content of the coexisting orthopyroxene should decrease.

The theoretical prediction was tested using electron microprobe analyses of biotite, hornblende, orthopyroxene and plagioclase that associate with quartz and K-feldspar in gneisses and charnockites from the Sharyzhalgay complex and the Yenisey range, Eastern Siberia, and from the Sulkava complex, southern Finland (Perchuk, 1989, 1991; Perchuk et al., 1989). In particular, several profiles were probed in the sample Fin-21 (see Fig. 4) from

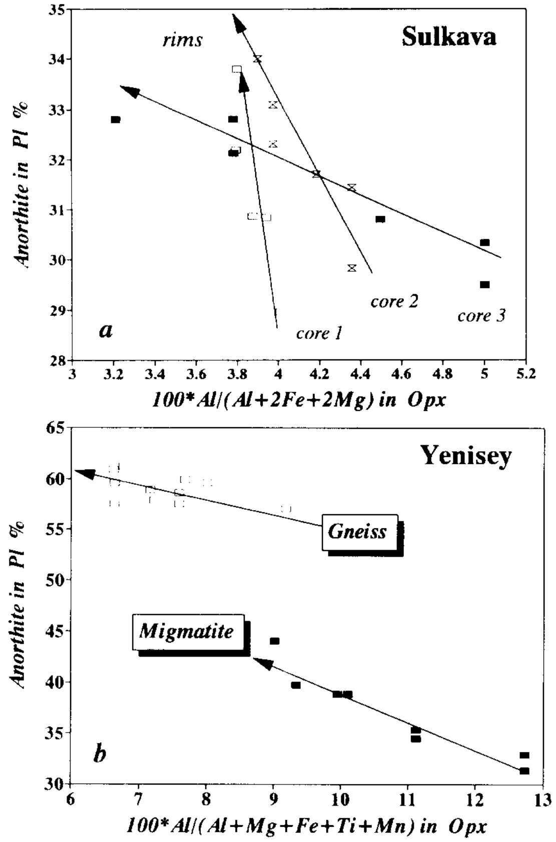


Fig. 5. Conjugate reactions (4) and (5) proceeding in charnockitic gneisses and charnockites from Central Finalnd (a) and S.W. Baikal (b). 1 = Grt-bearing charnockite gneiss with carbonates 2 = metapelites, 3 = migmatites.

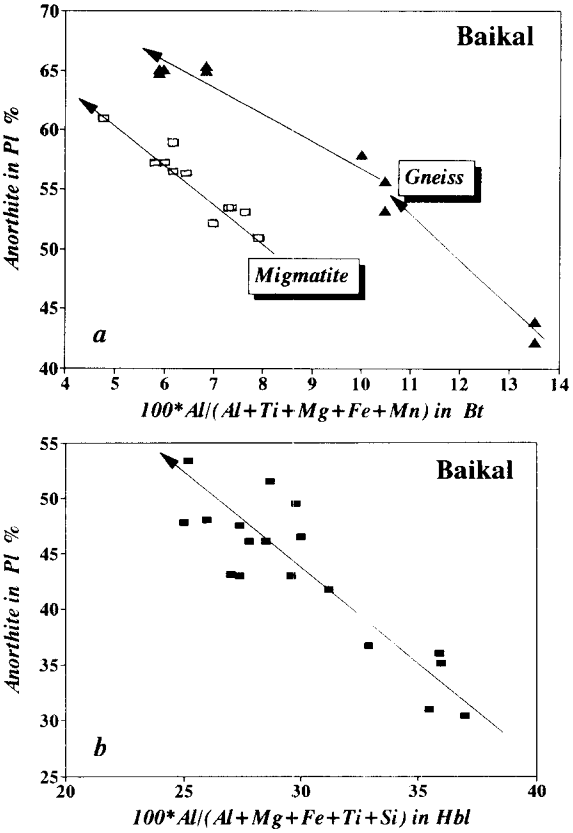


Fig. 6. Conjugate reactions (4) and (3), (4) and (6) proceeding in charnockitic gneisses and charnockites from Sharyzhalgay complex, S.W. Baikal, eastern Siberia. In diagram a: 1–3 are the same as in Fig. 5, and in diagram b filled squares relate to charnockitized basic gneiss.

the Sulkava complex. Diagram a in Fig. 5 shows the predicted inverse correlation between N_{Al}^{Opx} and N_{An}^{Pl} at the contacts of orthopyroxene and plagioclase (see Fig. 4). Similar relationships were obtained for the samples from S.W. Baikal (see Fig. 5b).

The Al content of biotite and hornblende associated with Kfs, as well as the anorthite content of the coexisting plagioclase, are good sensors for $a_{K_2O}^{fl}$ (see Fig. 6). Although reactions (3) and (3a) may be affected by $a_{H_2O}^{fl}$, the diagrams a in Fig. 6a illustrate an inverse correlation between N_{An}^{Pl} and N_{Al}^{Et}, reflecting a relatively strong influence of potassium activity on reaction (3).

Reaction (4) depends only on activities of alkalies. As a rule, X_{Ab}^{Pl} drops toward the contact with Kfs (increase of $a_{K_2O}^{fl}$) during an early stage of the charnockitization process (see Fig. 7b). Then a new phase, albite, appears and X_{Ab}^{Pl} grows (Fig. 7a) toward its contact because the sodium activity increases.

Thus, a regular change in mineral compositions from the reaction textures is the major evidence for the perfect mobility of potassium in the course of the charnockitization process. In other words, not only a high CO_2-activity in the fluid, but also a high activity of the potassium component initiates the formation of charnockites to stabilize the assemblage Kfs + Opx.

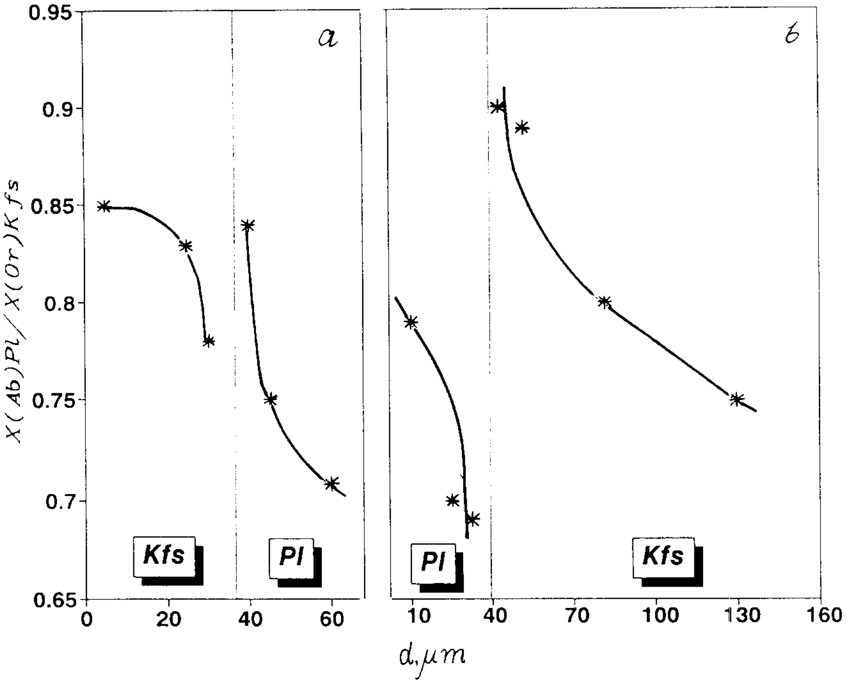


Fig. 7. Change of compositions of alkali feldspar and plagioclase at their contacts as a reflection of reaction (4) in charnockitized gneiss (sample BL2M4) from the Sharyzhalgay complex.

Fig. 8. Biotite-quartz intergrowths resulted from an increase $a^{fl}_{H_2O}$ and interaction between orthopyroxene and orthoclase in charnockite from Sharyzhalgay complex.

Finally, during a later stage of formation of charnockites, hydration and some carbonation reactions can be observed in the rocks. Figure 8 illustrates an example of reaction texture formed as a result of interaction between orthopyroxene and orthoclase in 1a charnockite from the Sharyzhalgay complex.

4. Mechanisms of charnockitization

4.1. Existing models

An increase in $\mu^{\text{fl}}_{K_2O}$ can result from interaction of the fluid with mafic rocks (Korzhinskiy, 1962). One cannot rule out the possibility that the composition of such a fluid is governed by crystallization of granites, which propagates charnockitization during the retrograde stage of metamorphism (see Fig. 2). As a result, both these factors, i.e. an increase in $\mu^{\text{fl}}_{K_2O}$ and $\mu^{\text{fl}}_{CO_2}$, may be responsible for the formation of the parageneses Opx + Kfs in gneisses with subsequent transformation into charnockites.

According to the Korzhinskiy model, the charnockitic gneisses and some charnockites may form by infiltration of the mantle-derived potassium-bearing aqueous fluids into metamorphic suites and their subsequent replacement, through melting and de-basification promoted by the fluid. Since K_2O is a perfectly mobile component, a charnockite fore-zone may form during the replacement of metabasites by the water-saturated granite magma, due to an increase of $a^{\text{fl}}_{K_2O}$ resulting from interaction of the fluid (liberated from the magma) with the wall rocks. The solubility of basic components such as Mg, Fe, Ca, etc. in the fluid initiates an increase in $\mu^{\text{fl}}_{K_2O}$ because potassium is a component of low electronegativity, i.e. relatively high basicity. Thus, $a^{\text{fl}}_{K_2O} = \gamma^{\text{fl}}_{K_2O} \cdot X^{\text{fl}}_{K_2O}$ increases due to the effect of "base–base interaction" on $\gamma^{\text{fl}}_{K_2O}$ in a H_2O–CO_2 fluid, even with a constant K_2O concentration. Korzhinskiy (1962) considered the mantle as a source of fluids, and granite magma as their carrier. A similar conclusion has been reached by Friend (1985) and Santosh et al. (1991) on the basis of studies of the relationships between arrested charnockites and Closepet granites from Kabbaldurga in Southern India.

Models for the origin of granites and related charnockites from Precambrian granulite formations in India have recently been reviewed by Newton (1990). In the 1950s and 1960s, similar models were proposed by a number of petrologists in Russia and India. Two major theories were discussed at that time. Sudovikov (1954) considered the origin of granites as the result of H_2O–CO_2 fluid–rock interaction with the metasomatic transformation of granulite into the granite of eutectic composition and subsequent melting. This model is quite similar to that proposed by Radhakrishna for origin of Closepet Granite in India (for reference see Newton, 1990).

4.2. The model proposed

Apart of a typical magmatic series, the following two charnockite series rocks are widespread among granulite facies complexes:

(1) Granite–charnockite–enderbite–metabasite series. Monzonite, norite or different types of migmatites may also be formed in this sequence. The granite cores of domes, as a rule, are mantled by migmatites and gneisses. The transition from one rock of the above sequence to another is gradual, and the transition zones may be very narrow. Typical examples of the above genetic sequence include the Sharyzhalgay granulite complex, S.E. Baikal Lake (Perchuk, 1989), the Bug River complex, Ukraine and Belorussia crystalline massifs (Fairus al'Muhana, 1991), the Kanskiy complex of the Yenisey Range, eastern Siberia (Perchuk et al., 1989).

(2) The so-called arrested, patchy (incipient) charnockites within biotite–amphibole–garnet gneisses from southern India (Janardhan et al., 1982) and Sri Lanka (Raith et al., 1989). For the arrested charnockites, no regu-

lar correlations similar to those shown in Figs. 5 and 6 were found. Therefore, potassium does not appear to be a perfectly mobile component of the charnockitization process producing arrested charnockites.

Stähle et al. (1987) showed significant loss of many components, such as CaO, MgO, FeO, Al_2O_3 and TiO_2 combined with a gain of SiO_2 and K_2O from the central portions of charnockite patches. Milisenda et al. (1991) demonstrated a very weak change in potassium content across the 34.5-cm incipient "body" of charnockite within granitic gneisses at Kurunegala, Sri Lanka while a diffusive migration of Mg, Fe, Ca, Ti and Cs from the core of the charnockite patch to the gneiss–charnockite transition zone (Mn and Pb are the only elements of apparent inward migration) shown to be very likely. No evidence for K-metasomatism was found.

As mentioned above, replacement of biotite and/or amphibole by orthopyroxene in the arrested charnockite has not yet been found. To our knowledge, K-feldspar rims around biotite and plagioclase were also not observed in these rocks. These features, as well as the igneous texture, reflect a magmatic origin of this rock in the cores of charnockite patches. Thus, the eutectic composition of the rock resulted from preliminary metasomatic alteration (=metamorphic differentiation), i.e. a change in the bulk composition of the gneiss caused by the CO_2–H_2O fluid.

Figure 9 illustrates the variation of N_{Fe} along the profile probed by Milisenda et al. (1991). In contrast to the transition zone, the core of the patch shows relative iron enrichment that, along with enrichment in silica, provides a decrease of the melting temperature. Despite the fact that most of the major elements migrated from the core to the gneiss–charnockite transition zone, the central portion of the incipient charnockite patch becomes relatively iron-rich. This is the main argument for the magmatic origin of cores of arrested charnockites within gneisses of granitoid bulk composition.

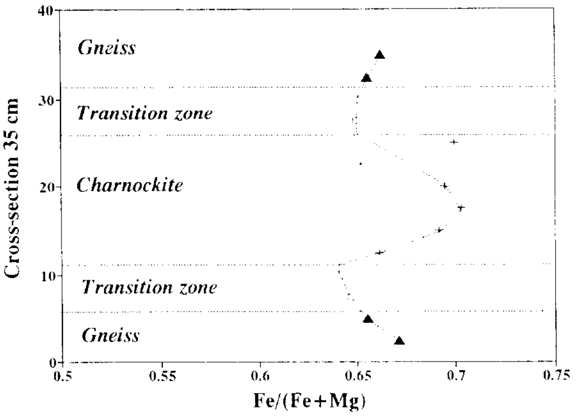
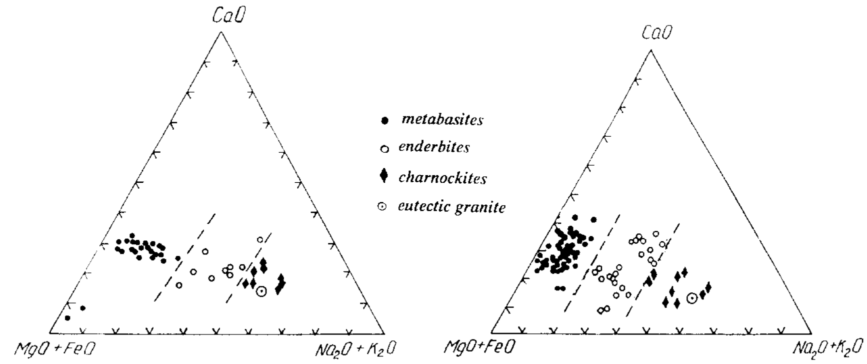


Fig. 9. Iron number variation in a 35 cm section across symmetrical rock sequence at the Kurunegala District, Sri Lanka [re-calculated from the diagrams by Milisenda et al. (1991)]. (▲) Gneiss, (□) transition zone, (+) charnockite.

In Fig. 2 the equilibrium temperature for arrested charnockites ranges from ca. 750 to ca. 600°C, while the pressure varies within a range of ca. 6 to 3 kbar. These values fall outside the field of eutectic granite melting, even under water-saturated conditions. However, Peterson and Newton (1990) showed experimentally that at pressures above 6 kbar, melting of the Phl+Qtz and Phl+Qtz+San assemblages in the presence of equimolar H_2O–CO_2 fluid "...occurs at temperatures as low as, or even lower than, in the presence of pure H_2O fluid." (p. 1029). In the case of the iron-rich mineral assemblage, Ann+Qtz+San±Fs, the melting temperature may decrease to ca. 650°C at a pressure of about 5 kbar.

Thus, the zoning observed in charnockite patches shows a metasomatic zone accumulating the majority of mafic components, and presumably a magmatic inner zone of eutectic composition. This can be a small-scale model for formation of the charnockite series rocks of group 1 discussed above. On a larger scale, an example of such kind of zoning is known from many granulite facies terrains, where granites and charnockites are located in the core of dome structures and mantled by enderbites,



Southern Bug complex
Ukraine & Belorussia

Lake Baikal complex
Eastern Siberia

Fig. 10. AC(MF) diagram for metabasites, enderbites and charnockites from the Bug River complex (after Fairus al'Muhana, 1991) and Sharyzhalgay + Yenisey range inliers from the western side of Baikal Lake (Perchuk, 1989; Perchuk et al., 1989). Dashed lines show provisional boundaries between zones in the complexes.

and migmatites at "the contacts" with metabasites (Perchuk, 1989).

According to the theory of metasomatic zoning, the inner zone must have a monomineralic composition (Korzhinskiy, 1970). However, in the case of the charnockite series, the inner zone (core) can be formed by the rock or a fluid-saturated melt of eutectic composition (granite, charnockite or enderbite). A low viscosity of this melt allows its migration upwards through a fault network. As a result, magmatic (allochtonic) granites, charnockites and enderbites occur in many granulite facies terrains. The magmatic origin of these rocks can easily be confirmed using structural, geochemical and petrographic methods. In addition, we should mention again that replacement of hornblende by orthopyroxene in enderbites or charnockites of eutectic composition has not yet been observed. This provides mineralogical evidence for their magmatic origin in situ.

Melting phenomena widely occur in many charnockite complexes related to granulite facies gneisses. This can result from an intense infiltration of potassium-bearing H_2O–CO_2 fluid through the metabasite suite. This fluid propagates migration of basic elements towards the transition zone (marginal metasomatic zone) and de-basification of the inner zone to the eutectic composition. This mechanism might be very similar to that described above for the arrested charnockite formation. Examples from the Ukrainian crystalline shield and S.W. Baikal are shown in Fig. 10. These are typical metabasite–enderbite–charnockite complexes with a well-exposed magmatic granite/charnockite zone (or dome core) formed as a result of infiltration of a CO_2–H_2O high alkali fluid/metabasite interaction. The composition of charnockite rocks in Fig. 10 shows similarity to the granite eutectic. This rock can form separate intrusive bodies whose margins contain xenoliths and relics of host metamorphic rocks.

5. Conclusions

The charnockitization proceeds over *P–T* ranges of about 6–3.5 kbar and 750–600°C at the retrogression stage and follows *P–T* paths typical of the granulite facies rocks. Within these parameters, the H_2O activity in charnockite might be similar or even higher than the H_2O activity in fluid equilibrated with the initial close-up gneiss.

The reactions involving Pl+Kfs and Opx_{Al}+Kfs, Hbl+Opx+Kfs and Opx_{Al}+Kfs+Bt, allow the role of potassium in the process to be qualified as irrespective of other reactions. The role played by this component is unequivocally established from variations in alumina contents of orthopyroxene, hornblende and biotite associated with feldspars in zoned metabasite–enderbite–charnockite Precambrian complexes, such as the Sharyzhalgay complex (S.W. Baikal), the Bug River complex (the Ukrainian shield) and Central Finland.

The charnockitization process is propagated by influx of the CO_2–H_2O fluid, which causes migration of most major basic elements from the initial metamorphic rock towards transition zones. The scale of these zones depends on the intensity of the fluid–rock interaction. Migration of the elements from a given volume of the rock leads to the shift of its bulk composition towards the granite eutectic and to subsequent melting forming the charnockite itself.

The role of the thermodynamic variables discussed above promises applications to many granulite facies terrains. They may provide an alternative explanation of the charnockitization process in Southern India, Sri Lanka, S.W. Baikal and many other regions.

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