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Physicochemical Model for the Genesis of Svecofennian Plagiomigmatites of the Belomorian Complex, Northern Karelia

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Abstract—A mechanism is proposed to explain the genesis of biotite–quartz–feldspar plagiomigmatite leucosomes as a consequence of the reaction of an amphibolite protolith with ascending fluid. The model is based on the analysis of the mineralogical and geochemical zoning of plagiomigmatite bodies and their outer contact aureoles. The model is underlain by the physicochemical simulations of interactions between a solution and rock in a system of sequential flow-through reactors. The development of the plagiomigmatites was related to the relief of mechanical strain in amphibolite strata and the ensuing origin of shear fractures. In these fractures, brittle hornblende was metasomatically replaced (under the effect of the fluid) by ductile quartz–biotite–plagioclase plagiomigmatite aggregates. Vein plagiomigmatites could have been produced at relatively low temperatures (590–630°C), when highly concentrated alkaline–silicic solutions affected amphibolites. The optimum fluid/rock ratio was equal to 30/1. The condition controlling the origin of the predominant mineral assemblage of the plagiomigmatites ($Qtz + Pl + Bt + Ttn$) was a local pressure decrease in shear fractures from 3.75–4.65 to 1.5–2.5 kbar. In regions with lower pressures (<1.5 kbar), the $Bt + Ttn + Qtz$ assemblage was formed. The solution in equilibrium with this assemblage of the plagiomigmatites had pH 4.5–5.5. An increase in the KCl and NaCl concentrations in the fluid was favorable for the expansion of the stability field of plagiomigmatites toward lower temperatures and higher pressures. The structural and textural heterogeneities in plagiomigmatite veins resulted from local silica dissolution at sites with higher mechanical strain and the redeposition of this component where the strain was relieved. The development of the mineralogical and geochemical zoning revealed in the outer-contact zones of the plagiomigmatite bodies and within these bodies themselves was controlled by the pressure gradient.

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INTRODUCTION

Amphibolite-facies metamorphism is ubiquitously associated with the extensive development of plagiomigmatites, as is also the case with the Belomorian Complex in northern Karelia. Migmatites of the Rebolian cycle are genetically related to regional plagiomigmatization at 2.5 Ga under amphibole-facies conditions: at $T = 590$–$620°C$, $P = 12.0$–14.0 kbar in the area of the ceramic-pegmatite deposit near the town of Khetolambino [1] and at $T = 700°C$, $P = 6.0$–7.0 kbar in the area of Seryak Lake [2–4]. The thick layers of homogeneous amphiboles and gneisses were transformed into a sequence of lenticular–banded rocks consisting of alternating layers and lenses of variably metasomatized amphibolites. In this publication, these rocks will be referred to as *substratiform* plagiomigmatites. The rock sequence is intersected by younger cutting and conformable leucocratic biotite–quartz–plagioclase veins, which were produced during the Svecofennian metamorphic stage (1.85 Ga) and will be referred to below as *vein* plagiomigmatites.

Svecofennian metamorphism in Belomorie was restricted to fault zones, most of which have northwestern, submeridional, and, more rarely, sublatitudinal trends. Salie et al. [5] recognized five deformation cycles in the Chupa segment of the Belomorian Complex and related the origin of numerous fields of ceramic and mica pegmatites to the fourth cycle (cycle IV). The vein plagiomigmatites are spatially associated with pegmatite bodies. Along faults of northwestern strike and in the fields of extensive deformations of cycle IV, the gneisses and amphibolites of the Khetolambino unit show traces of extensive metasomatic epidotization. Simultaneously with this process, the hornblende of the amphibolites was replaced by biotite. The boundaries of epidotization zones cut across the stratigraphic layering of the Khetolambino rocks, which were folded during cycles I–III. The metasomatically epidotized rocks are, in turn, deformed into folds of cycle IV. Hence, the onset of the prograde stage of deformational cycle IV and the metasomatic transformations of the Khetolambino rocks occurred simultaneously [5]. The temperature of the Svecofennian metamorphism of the Chupa pegmatite deposits was relatively low, 620–630°C, and the pressure reached 7.0 kbar [6].

Now most researchers of the Belomorian Complex believe that vein Svecofennian plagiomigmatites in the northern portion of the Belomorian Complex are of anatectic genesis [7–9]. The neosomes, which are close to plagiogranite in composition, were produced during ultrametamorphism accompanied by the partial melting of the protolith, whose composition corresponded to biotite gneisses.

Detailed results obtained on migmatization products in the Belomorian Complex indicate that they were formed in an open system, in the presence of a fluid flow. The initial stage of migmatization is commonly associated with Na–Si metasomatism, whereas the final stage of this process is accompanied by K–Si metasomatism [3, 4, 8]. The host rocks are thereby extensively metasomatized. Hence, a model of the migmatite process should involve the interaction of a siliceous alkaline fluid with the host rocks and the concurrent mechanical deformations of these rocks.

It is expedient to examine vein plagiomigmatites in the highly informative rocks that compose the lower part of the Khetolambino unit, were extensively deformed, and are now exposed in natural outcrops and the walls of open-pit mines at Veins 12, 96, and 196 of ceramic pegmatites at the Khetolambino deposit. This research was based on studying these veins and rocks.

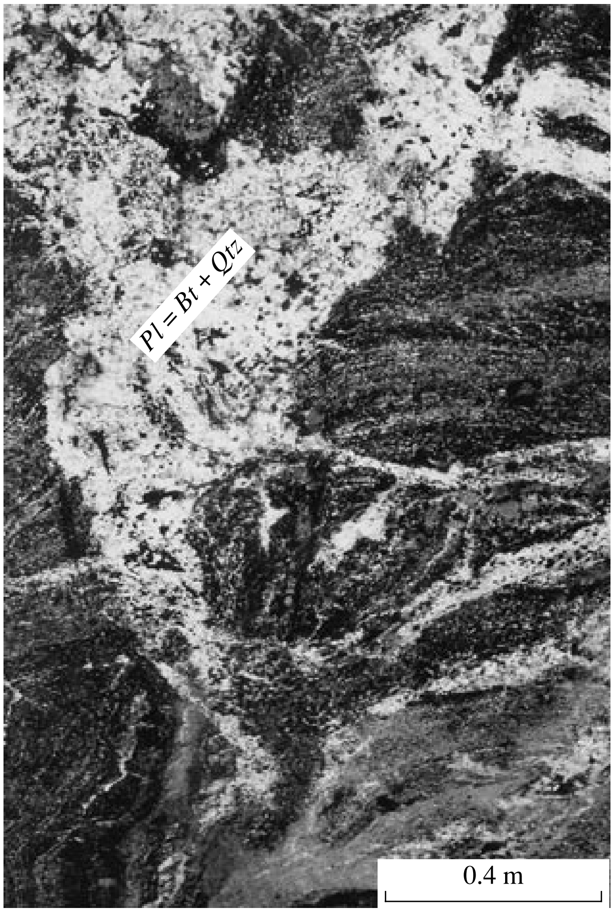

Fig. 1. Vein plagiomigmatites develop as complicatedly branching vein bodies that have swells and pinchings and bear xenoliths of the host rocks.

Considering the often contradictory interpretations of the genesis of migmatites, here we use the term *migmatite* in application to complicatedly structured heterogeneous rocks whose leucosomes either underwent melting or consist of the older metasomatic material.

GEOLOGY, MORPHOLOGY, INNER STRUCTURE, AND COMPOSITION OF VEIN PLAGIOMIGMATITES

Vein plagiomigmatites in the area of the Khetolambino deposit are hosted in a complicatedly structured and heterogeneous sequence of amphibolites, garnet amphibolites, and lenticular banded substratiform migmatites that developed after the amphibolites during the Rebolian cycle. These rocks include lenses of melanocratic amphibole-rich rocks and rare beds of biotite gneisses. The thicknesses of these beds range in most exposures from 15–20 cm to 3–5 m. The heterogeneous layered structure of the rocks predetermines the significant mechanical heterogeneity of the Khetolambino unit: brittle layers of amphibolites and melanocratic amphibole rocks alternate with more plastic layers of biotite gneisses and migmatized biotite-bearing rocks that replaced the amphibolites. Tectonic deformations and heterogeneities in the layered rock sequence were favorable for the development of faults, folds, flexures, and boudins.

Primary exposures of the plagiomigmatites were found mostly near veins of ceramic and mica–ceramic pegmatites. They occur as large vein bodies of complicated morphology that can branch and have swells and pinches. The veins are sometimes accompanied by numerous apophyses and contain small relics of the host rocks. Where pinching out, the migmatite veins branch into numerous thin veinlets (Fig. 1). The exposed areas of plagiomigmatite bodies may reach 4–8 m^2. The leucosome of the vein plagiomigmatites is spatially restricted to the most extensively deformed portions of the Khetolambino unit [10]. In virtually all of the examined exposures, vein plagiomigmatites are localized at contacts between rocks with different rheological characteristics.

The vein plagiomigmatites occur as rootless bodies, i.e., are not connected to any intrusive bodies. The contacts of the plagiomigmatites and their host rocks of the Khetolambino unit are of obviously reaction character, with amphibolites and melanocratic amphibole rocks in the contact zones displaying metasomatic alterations.

Plagiomigmatite bodies and outer contact aureoles around them can be regarded as the zones of a metasomatic aureole. The metasomatic rocks of the outermost zone (zone 1) are spread extremely widely in the Khetolambino unit. Salie et al. [5] ascribed them to near-fault epidote metasomatic rocks produced early in tec-

Table 1. Major-element composition (wt %) of the Khetolambino amphibolites and melanocratic biotite–amphibole metasomatic rocks (zone 1) replacing them

Component	Samples from the open-pit mine at Vein 12		Samples from the open-pit mine at Vein 96	
	amphibolite protolith (sample 12-7)	biotite–epidote metasomatic rock (sample 12-11)	amphibolite protolith (sample 96-4)	biotite–epidote metasomatic rock (sample 96-5)
SiO_2	45.25	50.62	50.57	50.44
TiO_2	1.06	1.65	0.67	1.50
Al_2O_3	16.38	18.41	14.42	13.57
Fe_2O_3	11.86	9.00	9.94	13.58
MnO	0.15	0.13	0.15	0.16
MgO	5.88	3.98	7.44	5.42
CaO	9.81	7.48	8.27	7.58
Na_2O	2.72	3.24	3.06	2.11
K_2O	0.66	2.11	0.87	1.64
P_2O_5	0.48	0.41	0.09	0.12
S	0.28	0.04	0.13	0.09
Total	94.53	97.07	95.61	96.21

Note: Analyses were conducted with a PHILIPS XRF spectrometer at the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), Russian Academy of Sciences.

Table 2. Trace-element composition (ppm) and indicator trace-element ratios of the Khetolambino amphibolites and melanocratic biotite–amphibole metasomatic rocks replacing them

Component	Samples from the open-pit mine at Vein 12		Samples from the open-pit mine at Vein 96	
	amphibolite protolith (sample 12-7)	biotite–epidote metasomatic rock (sample 12-11)	amphibolite protolith (sample 96-4)	biotite–epidote metasomatic rock (sample 96-5)
Ti	6356	9894	4018	8995
Nb	5	3	4	5
Zr	91	58	67	109
Y	28	18	19	22
Sc	26	20	28	16
V	215	146	180	136
Zr/Nb	18	19	17	22
Zr/Y	3	3	4	5
V/Sc	8	7	6	9
Y/Nb	6	6	5	4
Ti/Nb	1271	3298	1005	1799
Ti/Zr	70	171	60	83
Ti/Y	227	550	211	409
Ti/Sc	244	495	144	562
Ti/V	30	68	22	66

Note: Analyses were conducted with a PHILIPS XRF spectrometer at the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), Russian Academy of Sciences.

tonic cycle IV. These rocks are the most abundant in the outer contact zones of large plagiomigmatite veins, in which the replacement of hornblende in amphibolites gives rise to melanocratic biotite–epidote rocks ($Ep + Bt + Pl + Ttn + Qtz$). Epidote with quartz and biotite with quartz often develop as symplectitic aggregates, and large epidote crystals sometimes contain relics of unaltered hornblende. The major-component composition of the biotite–epidote rocks is close to that of the host amphibolites (Table 1). Samples taken from the walls of open-pit mines at two deposits of ceramic pegmatites (Veins 12 and 96) demonstrate similar Zr/Nb, Zr/Y, Y/Nb, and V/Sc ratios of the biotite–epidote metasomatic rocks and their host amphibolites (Table 2). This fact also suggests that the latter could be the protolith of the biotite–epidote rocks. The biotite–epidote metasomatic rocks are notably enriched in sphene compared with their amphibolite protolith and are higher in K and Ti (Table 1). The Ti/Zr, Ti/Nb, Ti/Y, Ti/Sc, and Ti/V ratios are notably higher in the biotite–amphibole rocks than in their amphibolite protolith (Table 2). Hence, the biotite–epidote metasomatic rocks were produced concurrently with the introduction of K and Ti, while the proportions of most other major elements were not modified as significantly.

In the inner contact zones of the vein plagiomigmatites and around some xenoliths in the veins, a melanocratic coarse-grained zone develops. This zone consists of randomly oriented thick platelets of biotite, with the interstitial space in between filled with coarse-grained quartz–plagioclase aggregates ($Bt + Pl + Ttn + Qtz$; zone 2).

The leucosome of large plagiomigmatite veins is also usually heterogeneous and consists of two zones: quartz–biotite–plagioclase ($Qtz + Bt + Ttn + Pl$; zone 3) and biotite–quartz ($Bt + Ttn + Qtz$; zone 4). Each of these zones contains sphene. The veins are made up predominantly of the quartz–biotite–plagioclase mineral assemblage with practically constant proportions of minerals: ~60–70% *Pl*, ~20–30% *Bt*, and ~5–10% *Qtz*). Plagioclase, quartz, biotite, and sphene compose equilibrium aggregates without evidence of reaction relations, and the compositions of these minerals vary within relatively narrow ranges. The plagioclase is oligoclase-andesine ($An_{27–30}$). The biotite from the leucosome is magnesian [$Fe^{2+}/(Fe^{2+} + Mg) = 0.31$] and close

Table 3. Average chemical compositions (wt %) and cation proportions of minerals from plagiomigmatites of the Belomorian Complex

Component	Hornblende	Biotite	Plagioclase
	n = 3	*n* = 9	*n* = 9
SiO_2	47.14	39.67	61.25
TiO_2	0.60	2.04	–
Al_2O_3	9.82	16.86	24.21
FeO	12.08	12.74	–
MnO	0.26	0.11	–
MgO	12.94	15.66	–
CaO	12.53	0.01	5.75
Na_2O	1.26	0.08	8.50
K_2O	0.69	11.12	0.06
Total	97.32	98.28	99.77
Si	6.91	2.92	2.73
Al^{IV}	1.09	1.08	1.27
Al^{VI}	0.61	0.38	–
Ti	0.07	0.11	–
Fe^{2+}	1.48	0.78	–
Mn	0.03	0.01	–
Mg	2.82	1.72	–
Ca	1.97	0.00	0.27
Na	0.36	0.01	0.73
K	0.13	1.04	0.00
O^{2-}	22.08	10.57	8.00
$(OH)^-$	1.92	1.43	–
Fe/(Fe + Mg)	0.34	0.31	–

Note: Analyses of minerals were carried out with a Cameca MS-46 microprobe at the Moscow State Geological Exploration University. The cation proportions of minerals were calculated by the cation technique.

to phlogopite in composition (Table 3). It is interesting that the iron mole fraction of biotite from the migmatites and the iron mole fraction of amphibole from the host melanocratic amphibolites [$Fe^{2+}/(Fe^{2+} + Mg) = 0.34$] are very similar.

Quartz–biotite–plagioclase zone 3 usually has a block texture. The plagioclase occurs as isolated equant monocrystaline blocks (up to 4 cm across), and biotite platelets and quartz grains occur in interstices. Some blocks of quartz–biotite–plagioclase zone 3 are surrounded by linear rims of fine-grained (0.5–3.0 mm) biotite–quartz aggregates (Fig. 2; zone 4). Biotite flakes in these aggregates are subparallel and conformably envelop nearby plagioclase cores. The thicknesses of the linear zones range from 1 to 30 mm.

Many crystals of the newly formed metasomatic biotite from central linear zone 4 crystallized during plastic deformations, which resulted in the deformed and distorted cleavage planes of these crystals (Fig. 3). Quartz in zone 4 often composes parallel columnar aggregates. Elongated quartz grains are oriented perpendicular to the walls of the fracture and completely fill it from one of its walls to the other (Fig. 4). All elongated quartz grains in these aggregates have a random crystallographic orientation; i.e., they did not undergo geometrical selection early in the course of their growing. This fact indicates that the crystals grew in the absence of free space, when silica gradually filled the fracture that simultaneously expanded (opened), and the growth rate of quartz crystals was commensurable with the opening velocity of the fracture (columnar aggregates of the second morphological type) [11]. The relations between minerals shown in Figs. 3 and 4 suggest that geochemical transformations during the migmatization of the amphibolites were synchronous with the tectonic deformations of the Svecofennian stage.

The textural heterogeneities identified in the vein plagiomigmatites suggest that these rocks were produced under the strong influence of the plastic flow of the quartz–biotite–plagioclase aggregate and the associated mechanical differentiation and recrystallization of the material.

The mega- and microscopic examination of the mineral aggregates and the morphology of mineral grains in both the plagiomigmatites themselves and their host rocks indicates that the mineral assemblage of the plagiomigmatites (*Qtz* + *Pl* + *Bt* + *Ttn*) developed at the sites of strong plastic deformations during the metasomatic replacement of hornblende in the host rocks. The protolith of the plagiomigmatites was melanocratic amphibole rocks, which are sometimes preserved as relics.

The vein plagiomigmatites started to develop in the melanocratic amphibole rocks with the origin of thin veinlets consisting of fine-grained aggregates of plagioclase (80–90%), quartz (5–10%), and biotite (no more than 5%). The veinlets contain newly formed sphene, whose amount can be as high as 3–5%, whereas the protolith (melanocratic amphibolite) is practically devoid of this mineral. The thicknesses of the veinlets do not exceed 1–1.5 mm. In contrast to large plagiomigmatite veins, these veinlets are very homogeneous and equigranular (Fig. 5).

The fine-grained aggregates of plagioclase, quartz, biotite, and sphene usually corrode hornblende crystals. Large plagiomigmatite bodies commonly bear hornblende crystals and grains that are not replaced by other minerals. When expanding and thickening, plagiomigmatite veinlets gradually lose their homogeneity and acquire the form shown in Fig. 2.

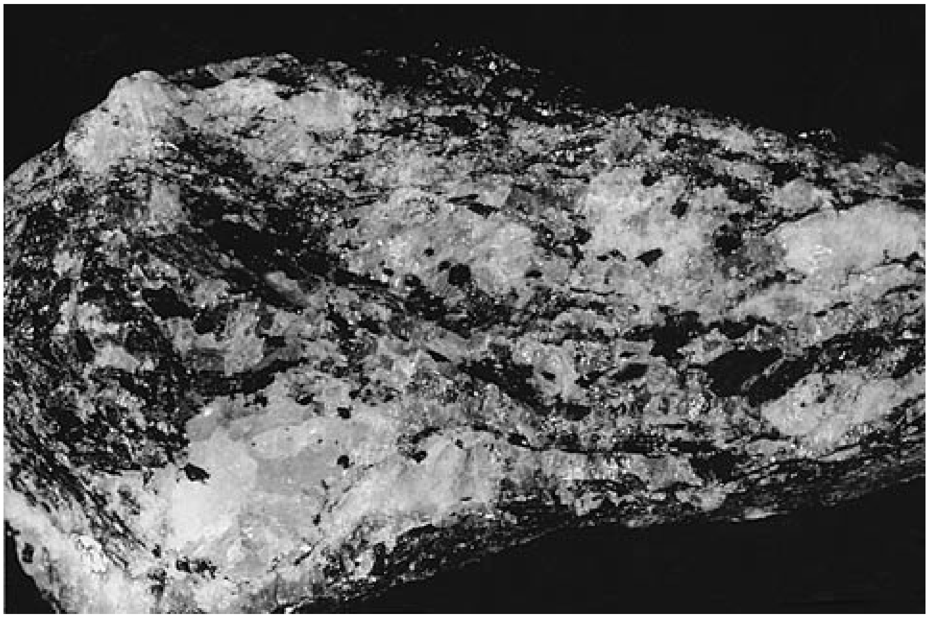

Fig. 2. Structural and compositional heterogeneity of plagiomigmatites. Large plagioclase blocks are surrounded by fine-grained biotite–quartz aggregates.

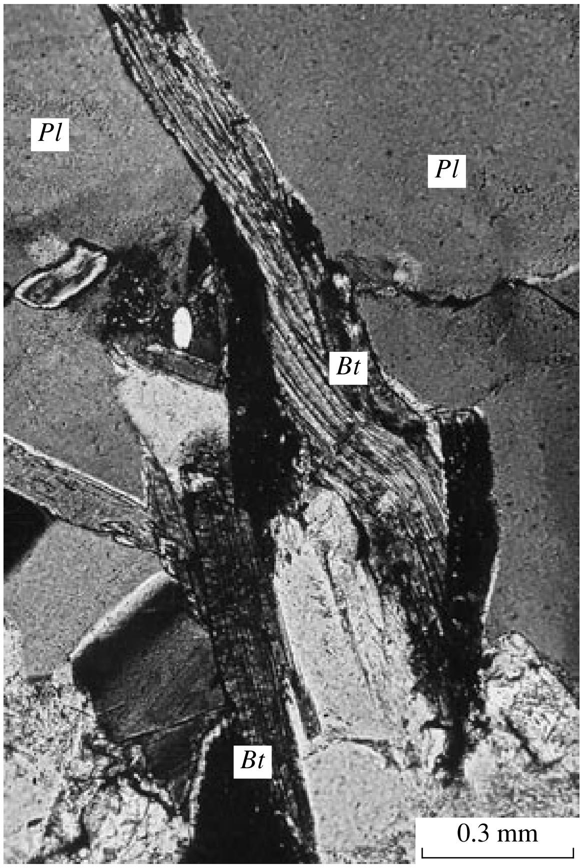

Fig. 3. Deformed biotite (*Bt*) crystals suggest that this mineral crystallized during plastic deformations, which were synchronous with the geochemical transformations of the Khetolambino amphibolites.

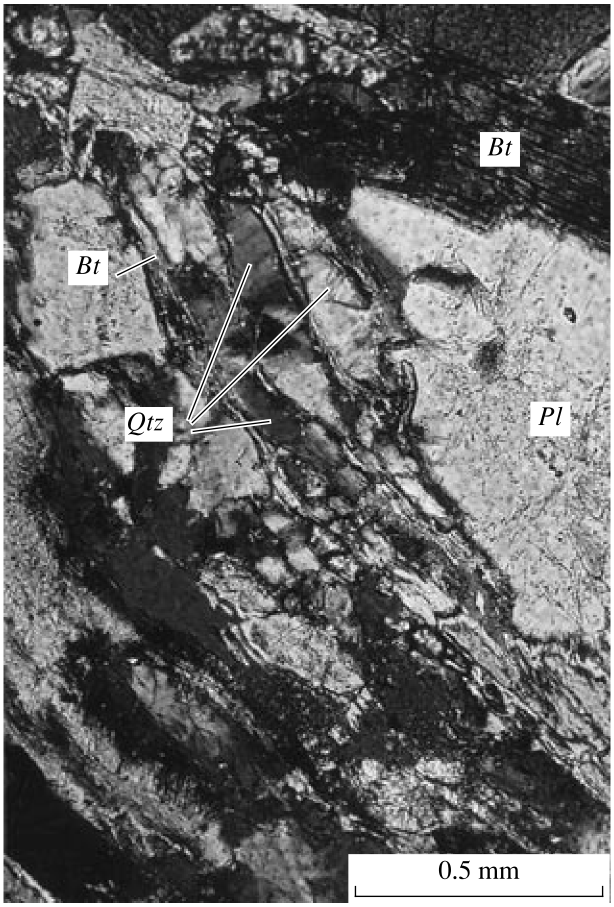

Fig. 4. Columnar quartz (*Qtz*) aggregates of the second type (formed when silica filled an opening fracture).

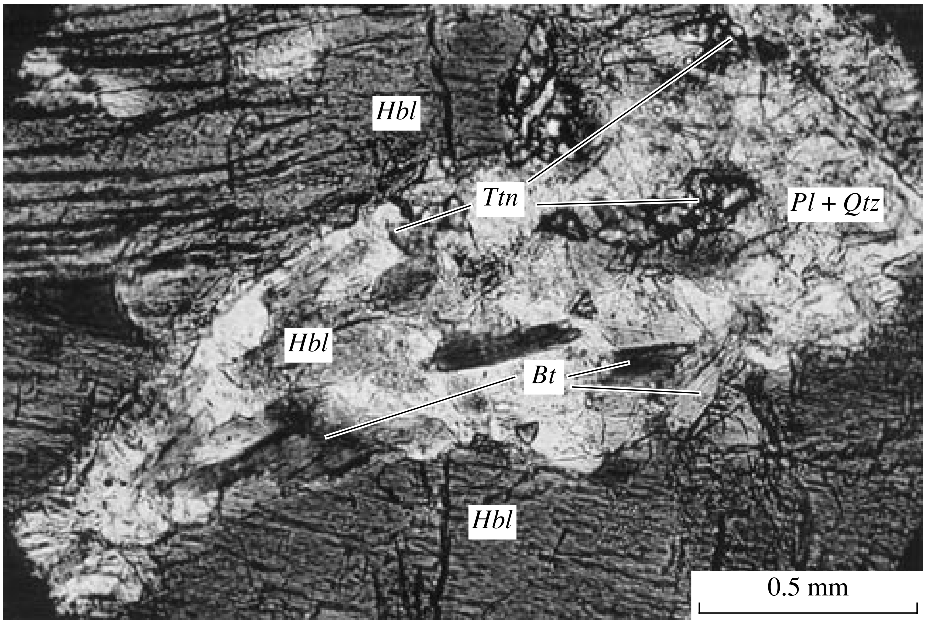

Fig. 5. Initial plagiomigmatite veinlets filling fractures in brittle melanocratic amphibole rocks. A large hornblende (*Hbl*) crystal is corroded by a plagiomigmatite aggregate (*Pl* + *Bt* + *Qtz*). The veinlet contains a xenolith of unaltered hornblende.

FORMULATION OF THE PROBLEM FOR PHYSICOCHEMCAL SIMULATIONS

Most vein plagiomigmatites in the Belomorian Complex are genetically related to folds or faults in the heterogeneous stratified sequence of gneisses, amphibolites, and substratiform migmatites that developed in the amphibolites. As a consequence, the Khetolambino rocks are cut by fracture zones, which could be marked by a local pressure decrease. Because of this, one of the tasks of our physicochemical analysis was the elucidation of the role played by decompression in the genesis of the plagiomigmatites.

The mineralogical transformations of the Khetolambino rocks and the thermodynamic parameters of their metamorphism and migmatization are now known in detail only for the northern part of the Chupa segment, in the area of Tupaya Bay and Seryak Lake [3, 4, 8]. According to Glebovitskii [6], this area is the deepest and highest temperature (700–720°C) zone of Svecofennian diaphthoresis, for which it is realistic to suggest the origin of autochthonous migmatite melts. Our vein plagiomigmatites in the vicinity of the town of Khetolambino are located 50 km southeast of Tupaya Bay and Seryak Lake, within the field of the Chupa mica pegmatites. The temperature of the Svecofennian metamorphic stage was much lower there: 620–630°C according to [6, 12, 13] or 590–600°C according to [9, 14]. This puts forth the problem of the possibility of the origin of the quartz–biotite–*Pl* leucosome at relatively low temperatures (590–630°C) without melt participation.

Geological reaction relations between the vein plagiomigmatites and their host amphibolites, as well as numerous corrosion microtextures testify to the unequilibrated character of the newly formed quartz–biotite–plagioclase leucosomes and the amphibolite protolith. The petrographic–mineralogical and structural–geological characteristics of the large plagiomigmatite bodies suggest that their genesis was related to the recrystallization of amphibolites and melanocratic amphibolites under the effect of a fluid flow simultaneously with intense and extensive tectonic deformations.

The leucosome of the migmatite contains four equilibrium minerals: plagioclase, biotite, quartz, and sphene. This mineralogy of the rocks did not allow us to apply traditional techniques of mineralogical thermobarometry to quantify the *P*–*T* parameters of these rocks. Because of this, these parameters and the composition of the fluid were assayed by means of thermodynamic simulations. The latter involved the evaluation of the *P*–*T*–*X* parameters of the reacting solution at which hornblende could be replaced by a biotite–quartz–plagioclase aggregate.

As was mentioned above, a notable genetic feature of the migmatites is the participation of Na–Si metasomatism during the early evolutionary stages of these rocks and K–Si metasomatism during their later stages [4, 15]. Because of this, in order to develop a model for the interaction of amphibole rocks with an ascending fluid, one should know the salt composition of this fluid. The extensive analytical material available now on the composition of gas–liquid inclusions in migmatites and accompanying metasomatic rocks pertains mostly to the older Rebolian migmatites (2.8 Ga), whose leucosomes were determined to contain highly concentrated aqueous inclusions with 5–35 wt % $CaCl_2$ [3, 16]. Quartz from the 2.7-Ga enderbite massif near the village of Pon'goma bears crystal–fluid inclusions of complicated $CO_2 + H_2O + KCl + NaCl + MgCl_2 + N_2 + CH_4 + H_2S$ composition [17].

Samorukova [9] mentioned that the Svecofennian migmatites contain water-rich inclusions with relatively low CO_2 concentrations, as is typical of amphibolite-facies metamorphic rocks. Detailed data on the salt composition of fluid from the Svecofennian metasomatic rocks coeval with our migmatites were obtained by Vol'fson et al. [18–21] for rocks from the Maiskoe gold deposit, ~200 km northwest of our study area. Quartz from the biotite–quartz metasomatic rocks was found to contain primary three-phase inclusions (gas + solution + isotropic phase) with $T_h = 473–436°C$ and high NaCl concentrations (up to 28.5–29.1 wt %) [19–21]. Quartz from quartz–oligoclase metasomatic rocks contains two-phase (gas + solution) inclusions with 21.3–21.7 wt % $MgCl_2$ [19–21]. Quartz from epidote–quartz metasomatic rocks bears inclusions that homogenize at $T_h = 489–480°C$ and contain 21–35.3 wt % $MgCl_2$ [21].

These analytical data led us to suggest that circulating chloride Mg–Ca–K–Na solutions played a significant role in the petrogenetic processes throughout the whole geological history of the Belomorian Complex. However, this high salinity was atypical of the magmatic fluids. Hence, this fluid was probably genetically related to seawater. In modern concepts concerning the Precambrian evolution of the Belomorian Complex, the Khetolambino unit, which hosts the migmatites in question, was a fragment of an ancient protooceanic slab that was subducted in the Late Archean (2.8 Ga) beneath the margin of the Karelian craton [22]. The subduction process was associated with the inflow of significant amounts of seawater into lower crustal levels along the Benioff zones. In the course of metamorphism, the captured water was incorporated into the rocks not only in the form of gas–liquid inclusions but also as tiny inclusions accommodated at structural defects in minerals [23]. The Svecofennian collision at 1.8 Ga was marked by the remobilization of the captured chloride solutions. They mixed with ascending K- and Ti-rich mantle fluids in fracture and fault zones and gave rise to "composite" chloride fluids that facilitated the development of the Svecofennian plagiomigmatites. A similar conclusion about the mixed juvenile–metamorphic nature of the fluid that produced the Svecofennian gold-bearing metasomatic rocks at the Maiskoe deposit was drawn by Krylova et al. [18] from materials on the oxygen, carbon, and sulfur isotopic composition of the fluid.

PHYSICOCHEMICAL MODEL FOR THE GENESIS OF VEIN PLAGIOMIGMATITES

Our physicochemical model for the genesis of plagiomigmatites is underlain by the concept of interaction of an ascending K–Na chloride fluid with the Khetolambino rocks.

The evolutionary succession of the mineral assemblages was studied by the method of sequential flow-through reactors. The simulations were conducted by the BALANS computer program, which was developed by N.N. Akinfiev at the Department of Chemistry of the Moscow State Geological Exploration University. This program makes use of an algorithm for the minimization of the free energy of the thermodynamic system [24]. The thermodynamic constants of the solid phases and species in the aqueous solution under standard conditions used in the simulations are stored in the SUPCRT-98 thermodynamic database. The characteristics of aqueous species at high temperatures (up to 1000°C) and pressures (up to 5.0 kbar) were calculated by the Helgeson–Kirkham–Flowers (HKF) model. The number of independent components was equal to 10, the number of species in aqueous solution was 29, and the number of solid phases was 8. The assumed solid phases were pure mineral end members taken in the same proportions as in the analogous naturally occurring minerals: phlogopite, annite, ferrous and magnesian hornblende, albite, and anorthite.

The model included two reactors. The first of them corresponded to the passage of the initial fluid through the stratified sequence of apoamphibolite rocks along cracks, fractures, and pores in these rocks. Because of this, the fluid/rock ratio was relatively low and was assumed to be equal to 5. The interaction of the ascending fluid with the host rock was assumed to have taken place under higher metamorphic pressures and temperatures than those determined for the Chupa and Khetolambino pegmatite deposits. Temperatures of 700–720°C and pressures of 7.0–7.5 kbar were determined for the deep zone of Svecofennian metamorphism exposed north of our study area [6]. Because of this, the temperature and pressure in the first reactor were assumed to be equal to 700°C and 5.0 kbar (the maximum values that can be used for simulations by the BALANS computer program). The proportions of the solid mineral phases corresponded to the average mineralogical composition of the Khetolambino rocks. The KCl concentration in the initial solution was varied from low (0.1 mol/kg) to average (0.3 mol/kg) and high (0.5 mol/kg). The NaCl concentrations were 8.5–9 times higher than the KCl concentrations (i.e., 0.9, 2.6, and 4.2 mol/kg). The solution also contained 0.5 mol/kg HCl.

The interaction of the fluid and rocks caused the dissolution of hornblende and the crystallization of phlogopite and plagioclase concurrently with the partial dissolution of quartz. The resultant mineral assemblage,

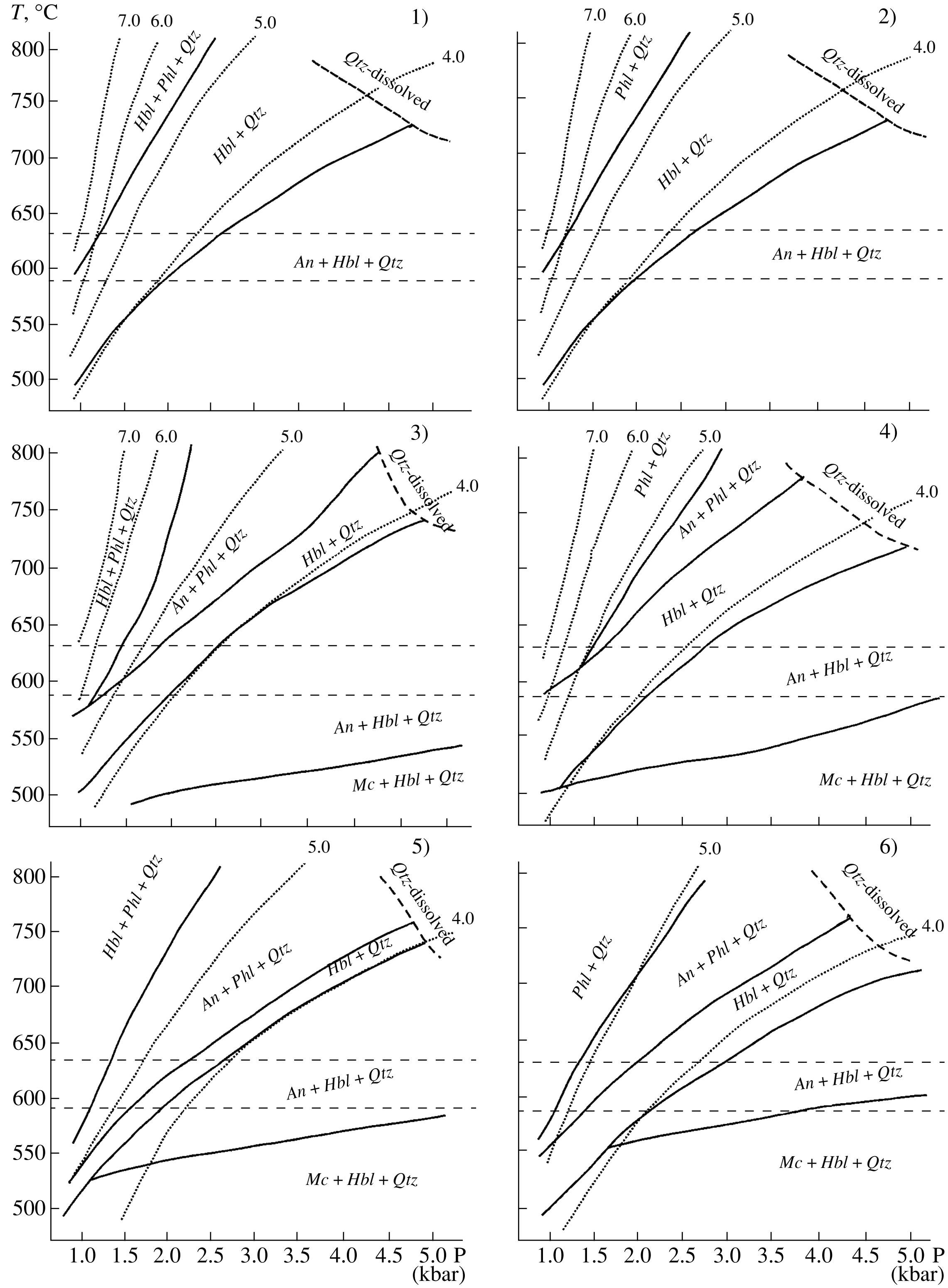

Fig. 6. Mineral assemblages formed in fracture zones under the effect of fluid on the Khetolambino rocks (according to our simulations for the second reactor). The KCl, NaCl, and HCl concentrations in the initial fluid are, in experiments 1 and 2, 0.1 μm for KCl, 0.9 μm for NaCl, and 0.5 μm for HCl; in experiments 3 and 4, 0.3 μm for KCl, 2.6 μm for NaCl, and 0.5 μm for HCl; and, in experiments 5 and 6, 0.5 μm for KCl, 4.2 μm for NaCl, and 0.5 μm for HCl. The fluid/rock ratio was 30/1 in experiments 1, 3, and 5 and 50/1 in experiments 2, 4, and 6. Dotted lines show the pH of the equilibrium fluid; horizontal dashed lines constrain the temperature range of 590–630°C, within which the leucosomes of the plagiomigmatites were produced.

corresponding to the initial migmatization of the host rocks, was consistent with the naturally occurring mineral relations. After its reaction with rocks, the fluid was enriched in Si, Fe, Mg, and Ca. The higher KCl/NaCl ratio of the initial solution brought about the microclinization of the rocks, a process that was not observed in nature. At lower fluid/rock ratios, magnesian hornblende was not dissolved. The simulations yielded a solution that was in equilibrium with the migmatized Khetolambino rocks in the first reactor.

Tectonic deformations of rocks inevitably create weakened and fracture zones in them, which are characterized by a lower pressure on the solid phase and are more permeable to fluid percolation. These zones act as drainage systems for pore solutions. The second reactor corresponds to the origin of plagiomigmatite veins and reflects the interaction of the rock and solution in an open fracture. Because of this, the fluid/rock ratio was significantly increased, to 30/1 and 50/1. The assumed starting solid material corresponded to the melanocratic amphibole rocks, whose hornblende is often corroded by biotite–quartz–plagioclase aggregates. The reacting solution came from the first reactor. The simulations were carried out within the temperature range of 500–800°C (at a step of 50°C) and within the pressure range of 1.0–5.0 kbar (at a step of 0.5 kbar). The results of the simulations were used to delineate the *P–T* stability fields of mineral assemblages (Figs. 6-1 through 6-6).

In attacking the rocks, solutions with relatively low KCl and NaCl concentrations (0.1 and 0.9 mol/kg, respectively) formed no plagiomigmatite assemblage (*Qtz* + *Pl* + *Bt*; Figs. 6-1, 6-2). At low pressures (<2.5 kbar), the diagrams show the fields of the assemblages *Qtz* + *Phl* + *Hbl* (at a fluid/rock ratio of 30/1, Fig. 6-1) and *Qtz* + *Phl* (at a fluid/rock ratio of 50/1, Fig. 6-2), which correspond to quartz–feldspathic mineral associations. As was mentioned above, these mineral assemblages occur within migmatite bodies in the form of narrow zones with traces of the plastic flow of the material. In addition, analogous mineral aggregates compose small veins associated with plagiomigmatites in zones of Svecofennian diaphthoresis in the Khetolambino rocks. The original *Qtz* + *Hbl* assemblage becomes enriched in plagioclase at low temperatures and high pressures. At high pressures (>4.0–4.5 kbar) and temperatures (>700°C), the silica solubility in fluids increases drastically, and quartz-free assemblages are formed.

An increase in the KCl and NaCl concentrations to 0.3 and 2.6 mol/kg, respectively, resulted in the appearance of a field where the plagiomigmatite association was stable at low fluid contents (fluid/rock = 30/1), low temperatures (590–630°C), and low pressures (<1.7 kbar) (Figs. 6-3, 6-4); i.e., the original assemblage of the melanocratic amphibolites (*Qtz* + *Hbl*) was replaced by the plagiomigmatite assemblage (*Qtz* + *An* + *Phl*). In this situation, calcic plagioclase (anorthite) and magnesian mica (phlogopite) are formed. Sodic plagioclase should likely be produced at lower KCl/NaCl ratios in the initial fluid. Under low pressures (<1.5 kbar), quartz veins with phlogopite and hornblende were formed, as in the region with lower KCl and NaCl concentrations.

As the fluid/rock ratio was increased to 50/1, the stability field of the plagiomigmatite assemblage notably diminished and shifted toward higher pressures and temperatures (Fig. 6-4). Simultaneously, the field of the feldspar-free assemblages of the biotite–quartz veins expanded. A pressure decrease to 1.4 kbar resulted in the replacement of the quartz–hornblende protolith by plagioclase-free biotite–quartz aggregates throughout practically the whole temperature range of 590–630°C.

A further increase in the KCl and NaCl concentrations in the fluid to 0.5 and 4.2 mol/kg, respectively, expanded the fields of plagiomigmatites toward higher pressures: to 2.2 kbar at a fluid/rock ratio of 30/1 and to 1.8 kbar at a fluid/rock ratio of 50/1 (Figs. 6-5, 6-6).

DISCUSSION

The results of our simulations demonstrate that plagiomigmatites could have been formed in a metasomatic system within the temperature range of 590–630°C, when the Khetolambino amphibolites were affected by highly concentrated K–Na chloride solutions. The relief of strain in amphibolite layers during the tectonic deformations of the heterogeneous stratified rock sequence brought about zones of shear fractures, along which the pressure could have locally decreased from 6.0–7.0 to 3.75–4.65 kbar. These pressure values were determined by the hornblende geothermometer with the use of amphibole relics in plagiomigmatite veins: 3.75 kbar according to [25] and 4.65 kbar according to [26]. The fracture zones served as conduits for solutions. Under the effect of fluid and further decompression from 3.75–4.65 to 1.5–2.0 kbar, brittle hornblende was replaced by more plastic quartz–biotite–plagioclase plagiomigmatite aggregates. The further deformations of the heterogeneous rock sequence proceeded in compliance with the mechanism of plastic flow.

Vein plagiomigmatites were formed in a fluid-dominated environment, at an optimum fluid/rock ratio of no less than 30/1. Higher fluid contents in the system (fluid/rock = 50/1) were favorable for the development of the feldspar-free biotite–quartz assemblage (in place of the plagiomigmatite association) during decompression. An important role was also played by the NaCl and KCl concentrations in the ascending fluid. At low concentrations of salts, no plagiomigmatites were formed. The favorable conditions occurred at concentrations of KCl > 0.3 mol/kg and NaCl > 2.6 mol/kg. The solution in equilibrium with the plagiomigmatite association had pH 4.5–5.5.

The plagiomigmatite association could also have been produced in another manner: by means of increasing the temperature to more than 700°C and the pressure to 3.75–4.65 kbar. The temperature could have

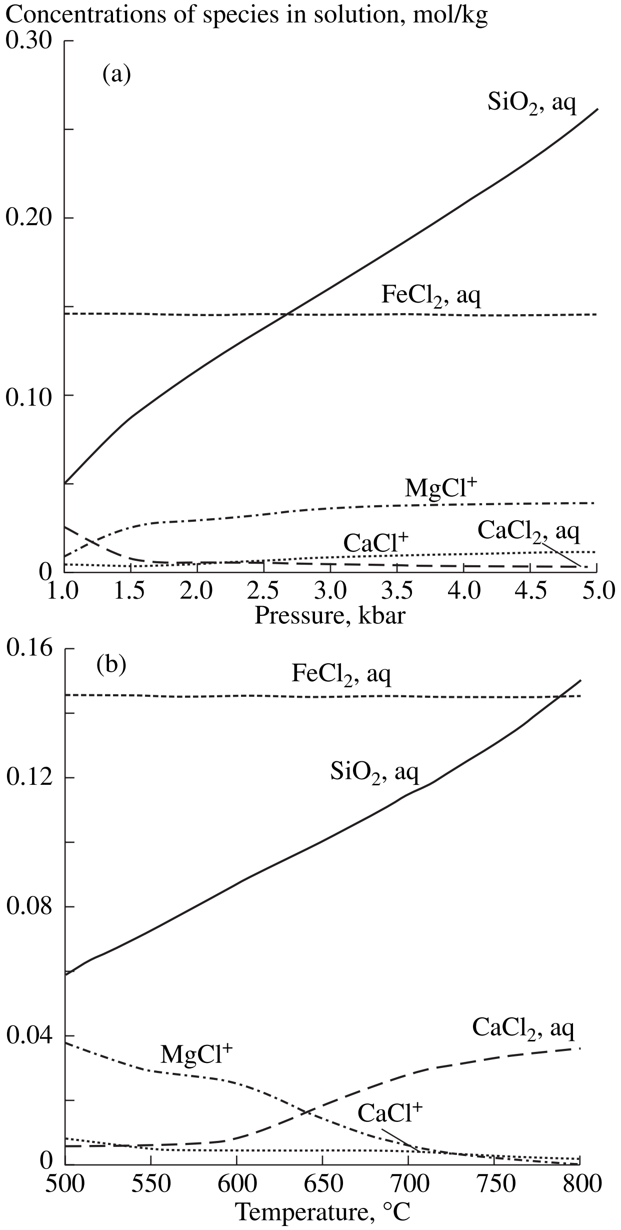

Fig. 7. Dependences of the concentrations of the SiO_2(aq), $FeCl_2$(aq), $MgCl^+$, $CaCl^+$, and $CaCl_2$(aq) species in the fluid in equilibrium with the plagiomigmatites on (a) pressure at $T = 600°C$ and (b) temperature at $P = 1.5$ kbar.

been generated by both mechanical friction during the deformations of the rocks and inflowing high-temperature fluid. The pressure decrease and rock heating in migmatization zones were likely concurrent. The role of heating seems not to be significant, because the leucosomes produced at 700–720°C underwent partial melting [8].

Our results suggest that plagiomigmatite leucosomes in the area of the Khetolambino deposit (in the central portion of the Belomorian Complex, where the upper, relatively low-temperature zone of Svecofennian metamorphism is exposed) could have been formed due to the reaction of ascending fluid with the host rocks. In the northern part of the Belomorian Complex, near Tupaya Bay, the probability of finding Svecofennian metasomatic leucosomes is very low, because the zone exposed at the surface is deeper sitting and higher temperature. This zone is characterized by anatectic leucosomes [6, 8].

The silica solubility in the equilibrium mineral-forming fluid was very sensitive to variations in the external parameters: pressure (Fig. 7a) and temperature (Fig. 7b). As can be seen in Fig. 7a, a pressure decrease from 5.0 to 1.0 kbar at $T = 600°C$ results in a more than fivefold decrease in the $SiO_{2(aq)}$ concentration in the solution: from 0.262 to 0.048 mol/kg. At the same time, the concentrations of other components of this solution ($FeCl_2$, $MgCl^+$, $CaCl^+$, and $CaCl_2$) changed very insignificantly. Because of this, the low-pressure region (<2.5 kbar) is occupied in Figs. 6-1 through 6-6 by the biotite–quartz assemblage, which composes the inner zones of the plagiomigmatite bodies. An increase in the fluid content in the system (fluid/rock = 50/1, Figs. 6-2, 6-4, and 6-6) expands the biotite–quartz field at the expense of the quartz–biotite–plagioclase field of plagiomigmatites. Hence, the origin of plagioclase-free and quartz-rich assemblages could be related to the further opening of fractures and a pressure decrease. Once a fracture or weakened zone appears in a rock massif (due to a pressure decrease), the corresponding decrease in the SiO_2 solubility causes the healing of the fracture with quartz. An analogous effect can expectedly be exerted by a temperature decrease (Fig. 7b).

Variations in the silica solubility in the mineral-forming fluid in response to pressure variations can account for the zoning in the leucosome of the vein plagiomigmatites. At extensive deformations of the rocks in fracture zones, rigid tiny rock blocks or domains could have been produced at which mechanical strain could have been locally accumulated. The high silica solubility in these domains could have caused the development of quartz-free feldspar-rich cores. The rigid blocks were separated by microfractures, along which these blocks could have moved. The relief of mechanical strain along these microfractures was associated with a decrease in the silica solubility and the ensuing crystallization of quartz. Consequently, narrow linear zones of biotite–quartz composition were formed, which contained practically no plagioclase (Fig. 2). Under the effect of directed pressure, the material of plagiomigmatites in these linear zones could have occurred in a plastic state. This follows from the structural and textural heterogeneity of the large plagiomigmatite veins, the shearing of the biotite–quartz aggregates, and the deformations of biotite crystals. The accumulation of biotite, a plastic mineral, in linear zones was favorable for a decrease in the friction between rigid rock fragments (like graphite lubrication in a bearing) and enhanced the plasticity of the material.

The origin of the melanocratic fine-grained biotite–epidote and coarse-grained quartz–plagioclase–biotite rocks in the contact zones of plagiomigmatites could likely be related to the interaction of the fluid with the host amphibolites at an elevated (as compared with that in the leucosomes) pressure on the solid phase (3.75–4.65 kbar). During compression, silica was removed, and basificates could have been formed [27]. Thus, mineralogical and geochemical zoning developed along long-lived tectonic fractures and weakened zones under the effect of the pressure gradient. For this zoning to develop, the pressure gradient should have existed for a long enough time, perhaps, due to long-lived deformations in the tectonized zones.

The solubility of silica could also have increased at increasing pressure and temperature. At high temperatures (750°C or higher) and pressures (of about 4.0 kbar), the high SiO_2 solubility in the fluid caused the complete dissolution of quartz and its leaching from the rocks. These conditions were favorable for the origin of quartz-free plagioclase-rich veins.

CONCLUSIONS

(1) Our physicochemical simulations demonstrate that the vein plagiomigmatites could have been produced when the Khetolambino rocks were attacked by highly concentrated alkali–silicic solutions. The origin of the vein plagiomigmatites at relatively low temperatures (590– 630°C) was controlled primarily by a local pressure decrease in shear fractures from 3.75–4.65 to 1.5–2.5 kbar and the associated inflow of fluid into the fractures. The optimum fluid/rock ratio was 30/1.

(2) Under lower pressures (<1.5 kbar), the decrease in the silica solubility in the fluid caused transformation of the quartz–biotite–plagioclase assemblage ($Qtz + Bt + Ttn + Pl$) into the biotite–quartz assemblage ($Bt + Ttn + Qtz$) with hornblende. An increase in the fluid content in the system (fluid/rock = 50/1 or more) was favorable for the expansion of the stability field of the biotite–quartz assemblage toward higher pressures.

(3) The structural and compositional heterogeneity of the plagiomigmatite veins could have resulted from silica dissolution at local accumulations of mechanical strain and the redeposition of this component where the strain was relieved.

(4) The mineralogical and geochemical zoning of the plagiomigmatite bodies was formed under the effect of a pressure gradient, which was perpendicular to long-lived tectonic fractures.

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REFERENCES

1. T. F. Shcherbakova, *Amphibolites of the Belomorian Complex and Their Granitization* (Nauka, Moscow, 1988) [in Russian].
2. E. V. Bibikova, E. Yu. Borisova, G. M. Drugova, and V. A. Makarov, "Metamorphic History and Age of Aluminous Gneisses of the Belomorian Mobile Belt on the Baltic Shield," Geokhimiya, No. 9, 883–893 (1997) [Geochem. Int. **35**, 775–784 (1997)].
3. I. S. Sedova, V. A. Glebovitskii, and A. P. Semenov, "Evolution of Late Archean Metamorphism of Tupaya Bay, Kovdozero Lake, Northwest White Sea Region," Petrologiya **4**, 150–170 (1996) [Petrology **4**, 137–156 (1996)].
4. I. S. Sedova, A. P. Semenov, and E. I. Kravtsova, "The Nature of Migmatites of the Polymetamorphic Complex of Tupaya Bay, Kovdozero Lake," Petrologiya **6**, 197–224 (1998) [Petrology **6**, 180–206 (1998)].
5. *Geology and Abundance of Pegmatites in Belomorides*, Ed. by M. E. Salie, S.S. Batuzov, S.I. Dusheiko, et al. (Nauka, Leningrad, 1985) [in Russian].
6. V. A. Glebovitskii, Yu. V. Miller, G. M. Drugova, et al., "Structure and Metamorphism of the Belomoride–Lapland Collision Zone," Geotektonika, No. 1, 63–75 (1996) [Geotectonics **30**, 53–63 (1996)].
7. E. V. Bibikova, S. Klaesson, V. A. Glebovitsky, et al., "Isotope Dating of the Svecofennian Metamorphism of the Belomorian Belt, Baltic Shield," Geokhimiya, No. 10, 1116–1119 (2001) [Geochem. Int. **39**, 1023–1026 (2001)].
8. V. A. Glebovitskii and I. S. Sedova, "Anatexis and Formation of Crustal Magmatic Chambers: Petrological and Geochemical Evidence from Belomorian and Svecofennian Province, Baltic Shield," Zap. Vseross. Mineral. O-va **77**, 5–26 (1998).
9. *Migmatization and Granite Formation in Different Thermodynamic Conditions*, Ed. by V. A. Glebovitskii (Nauka, Leningrad, 1985) [in Russian].
10. V. M. Kozlovskii, "Origin of the Svecofennian Plagiomigmatites of the Belomorian Complex, Northern Karelia. Geological–Structural Position and Compositional Specifics," Izv. Vyssh. Uchebn. Zaved., Geol. Razved., No. 4, 24–29 (2004).
11. A. G. Zhabin, *Ontogeny of Minerals* (Nauka, Moscow, 1979) [in Russian].
12. *Geology and Pegmatites in Belomorides*, Ed. by M. E. Salie (Nauka, Leningrad, 1973) [in Russian].
13. M. E. Salie and V. A. Glebovitskii, *Metallogenic Specifics of Pegmatites* (Nauka, Leningrad, 1976) [in Russian].
14. A. M. Ruch'ev, "Precious Metals in the Gneisses of the Chupa Formation (Belomorian Complex, Northern Karelia)," in *Geology and Mineral Resources of Karelia* (Petrozavodsk, 2002), Vol. 5, pp. 47–58 [in Russian].

15. I. S. Sedova and V. A. Glebovitskii, “Evolution of Ultrametamorphism under Amphibolite Facies,” Izv. Akad. Nauk SSSR, Ser. Geol., No. 2, 46–60 (1984).
16. V. A. Glebovitskii, E. A. Vapnik, I. S. Sedova, and A. P. Semenov, “Significance of Fluid Inclusions and Fluid Compositions of the Rocks for Interpreting the Evolution of Polymetamorphic Complexes: Evidence from the Tupaya Guba Area, Kovdozero Lake,” Geokhimiya, No. 2, 222–236 (1993).
17. I. S. Sedova, V. S. Baikova, S. L. Klepinin, and K. I. Lokhov, “Distribution of Fluid Components in Intrusive Rocks of the Baltic Shield: Evidence from Pon’goma Navolok Island,” Zap. Vseross. Mineral. O-va **78** (5), 34–47 (1999).
18. T. L. Krylova, A. A. Vol’fson, and A. V. Volkov, “*PT* Parameters of Fluids during the Formation of the Precambrian Maiskoe Gold Deposit, Northern Karelia,” in *Proceedings of the 10th International Conference on Fluid Inclusions, Aleksandrov, Russia, 2001* (VNIISIMS, Aleksandrov, 2001), pp. 326–341.
19. Yu. G. Safonov, A. V. Volkov, A. A. Vol’fson, et al., “The Maisk Quartz Gold Deposit (Northern Karelia): Geological, Mineralogical, and Geochemical Studies and Some Genetic Problems,” Geol. Rudn. Mestorozhd. **45** (5), 429–451 (2003) [Geol. Ore Dep. **45**, 375–394 (2003)).
20. A. A. Vol’fson, V. L. Rusinov, T. L. Krylova, and A. V. Chugaev, “Metasomatic Alterations in Precambrian Metabasites of the Salla–Kuolajarvi Graben near the Maiskoe Gold Field, Northern Karelia,” Petrologiya **13**, 179–206 (2005) [Petrology **13**, 161–186 (2005)].
21. A. A. Vol’fson, Extended Abstract of Candidate’s Dissertation (Moscow, 2004).
22. Yu. V. Miller, “The Tectonics of the Junction Region between the Belomorian Mobile Belt and the Karelian Craton,” Geotektonika, No. 4, 14–25 (2002) [Geotectonics **36**, 267-277 (2002)].
23. I. S. Sedova, K. I. Lokhov, and E. A. Vapnik, “Composition of Fluid in the Rock-Forming Minerals of Ultrametamorphic Granitoids,” Petrologiya **1**, 235–248 (1993).
24. N. N. Akinfiev, “Computer Algorithm for the Calculation of Heterogeneous Equilibria,” Geokhimiya, No. 6, 882–890 (1986).
25. M. C. Johnson and M. J. Rutherford, “Empirical Calibration of Aluminium-in-Hornblende Geobarometer Applicable to Calcalkaline Rocks,” Geology **17**, 837–841 (1989).
26. J. M. Hammarstrom and E-An. Zen, “Aluminum in Hornblende: An Empirical Igneous Geobarometer,” Am. Mineral. **71**, 1297–1313 (1986).
27. A. B. Kol’tsov, Doctoral Dissertation in Geology and Mineralogy (St. Petersburg, 1996).