ISSN 1028-334X, Doklady Earth Sciences, 2007, Vol. 415A, No. 6, pp. 915–918. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © L.I. Khodorevskaya, S.P. Korikovsky, 2007, published in Doklady Akademii Nauk, 2007, Vol. 415, No. 4, pp. 539–543.

GEOCHEMISTRY

Metasomatic Garnet–Clinopyroxene–Orthopyroxene–Hornblende Veins in Metaanorthosites of the Kolvitsa Massif, Kola Peninsula: Mineral Composition and Relation with Syngranulite Granitization

L. I. Khodorevskaya[a] **and Corresponding Member of the RAS S. P. Korikovsky**[b]

Received March 12, 2007

DOI: 10.1134/S1028334X07060190

Forms and scales of transportation and redeposition of significant amounts of Mg, Fe, and Ca, which are removed during granitization and debasification of metamorphic (mainly mafic) rocks, is one of the least studied problems in the petrology of granite gneiss and migmatite complexes [1]. Study of these complexes revealed the absence of an uninterrupted basification front before granitization zones [2] inferred from idealized models. This is consistent with the conclusion of Korzhinsky [1] and subsequent studies suggesting that Mg, Fe, and Ca removed during granitization are commonly scattered far beyond the aureoles of anatectic granitization.

However, Fe–Mg–Ca metasomatism sporadically occurs at the periphery of granitized areas in the form of melanocratic Grt–Cpx–Opx–Hbl, Hbl–Cpx–Pl–Bt, Hbl–Grt–Pl, Cpx–Grt–Pl–Mag* and other concordant or cross-cutting veins [3–8]. Mineral assemblages and *PT* formation conditions of these metasomatites usually coincide with those of host granite gneisses and metamorphic complexes. However, the scales of Fe–Mg–Ca metasomatism are significantly smaller than those of complementary granitization and debasification.

The garnet–pyroxene–hornblende metasomatic veins considered in this paper were found within the Kolvitsa anorthosite massif, which experienced metamorphism and local granitization (charnockitization) under high-pressure granulite-facies conditions during Svecofennian orogeny [9]. Metaanorthosites preserve coarse- or giant-grained texture and primary magmatic minerals represented by pigeonite, pigeonite–augite, and bytownite (An_{83-85}). Metamorphism and high-temperature shearing of anorthosites gave rise to lineation, which was characterized by subparallel alignment of a newly formed fine-grained matrix composed of metamorphic uninverted ortho- and clinopyroxenes, garnet, and magnesian hornblende.

Relict, often inverted magmatic pigeonites (Opx^1) have an extremely low Fe mole fraction and fairly high Al content ($X_{Fe} = 0.13–0.20$, $X_{Al} = 0.33–0.44$ f.u.). They are commonly disintegrated and replaced by small rounded grains of higher Fe and lower Al metamorphic orthopyroxenes (Opx^2) ($X_{Fe} = 0.23–0.24$, $X_{Al} = 0.08–0.15$ f.u.), which reflects the difference in crystallization temperature.

Magmatic pigeonite–augite (Cpx^1) have $X_{Fe} = 0.15–0.20$ and $X_{Al} = 0.40–0.28$ (Jd 6.3–9.4%). They often contain thin orthopyroxene lamella and show zoning related to the formation of rim of noninverted metamorphic augite (Cpx^2). The augite has the same Fe mole fraction but lower X_{Al} value (0.2) and Jd content (3.6–4.5%). Magmatic pyroxenes are also replaced by light green high-Mg hornblende, which varies in composition from hornblende to tschermakite-pargasite [$(K + Na)_{A + B} = 0.2–0.6$ f.u.].

Large grains of magmatic bytownite are crushed and corroded by a finer aggregate of slightly Ca-depleted metamorphic Pl (An_{76}).

Chains of sufficiently high-Mg (coronal) garnets are formed along margins of pigeonite and pigeonite augites at the contact with Pl. They are occasionally amalgamated into individual larger grains (up to 200 μm in size) with the following zonal structure from core to rim: increase in Alm content from 27 to 34% and

---

*Abbreviations used in this paper: (Alm) almandine, (An) anorthite, (Bt) biotite, (Cpx) clinopyroxene, (Fsp) feldspar, (Grs) grossular, (Grt) garnet, (Hbl) amphibole, (Hem) hematite, (Ilm) ilmenite, (Mag) magnetite, (Opx) orthopyroxene, (Pl) plagioclase, (Py) pyrope, (Qtz) quartz, (Ttn) titanite.

---

[a] *Institute of Experimental Mineralogy, Russian Academy of Sciences, Chernogolovka, Moscow oblast, 142432 Russia*

[b] *Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 119017 Russia; e-mail: lilia@iem.ac*

Fig. 1. Metasomatic Grt–Cpx–Opx–Hbl–Mag vein cutting the lineation of metaanorthosites.

decrease in Py from 52 to 47%. The Grs content remains virtually constant. Garnet and hornblende are in equilibrium with metamorphic pyroxenes and grouped into a new mineral assemblage $Opx^2 + Cpx^2 + Grt + Hbl$. In general, the metamorphic transformation of anorthosites can be described by the reaction Opx^1 (or Opx molecule of pigeonite-augite) + $An_{83} \pm H_2O \rightarrow Grt + Cpx^2 \pm Hbl + An_{76}$.

The absence of quartz in the studied rocks makes it impossible to apply the reliable Grt–Cpx–Pl–Qtz and Grt–Hbl–Pl–Qtz geobarometers for the pressure estimate. The metamorphism temperature of gabbroanortosites calculated by the Grt–Cpx geothermometer [10] (core of Grt + Cpx^2) varies within 800–880°C. Similar temperatures were obtained using a Grt–Opx thermometer [11]. Thus, the peak of granulite metamorphism is estimated at 860°C. Temperatures obtained with the same geothermometers for retrograde fringes of Grt and with the Grt–Hbl thermometer [12] for the Grt (rim) + Hbl pair yield a wide range up to 650°C (retrograde *PT* path).

The quartz-free Grt–Cpx–Opx–Hbl ± Mag veins are from 0.5 to 10–12 cm wide (occasionally with swells and schlieren 20–25 cm across) and up to 20–30 m long. They gradually pinch out at termination. The veins are concordant or cross-cutting relative to lineation of metaanorthosites (Fig. 1) and distinguished by a dark color among light gray metaanorthosites. The veins have sharp outlines, with no wall rock alterations.

The mineral assemblages and compositions of mafic minerals (garnet, clinopyroxene, orthopyroxene, and hornblende) are similar to those produced by granulite metamorphism of anorthosites. As will be shown below, they were also formed at practically identical temperatures. Hence, the mafic veins are synmetamorphic bodies unrelated to magmatic or subsolidus evolution of host anorthosites. The veins have internal zoning expressed in the alternation of bands of different compositions parallel to selvage. Occasionally, the bands are symmetrical relative to the vein axis, but more often they demonstrate unsystematic alternation. Symmetrical veins can be divided into three types. The first type consists of garnet–magnetite core rimmed on both sides by a clinopyroxene–amphibole–magnetite zone. The second type consists of an orthopyroxene core with fine-grained garnet inclusions, which are successively replaced by the intermediate Cpx–Grt zone and Grt–Hbl zone in the selvage. The third type consists of a Cpx–Hbl core rimmed by Grt–Hbl–Pl bands. Mag–Ilm intergrowths are abundant in both zones. One can often see asymmetrical veins composed of randomly alternating parallel Grt–Opx–Pl–Mag, Hbl ± Mag ± Pl, Hbl–Bt–Cpx, Cpx–Mag, and Cpx–Grt–Mag bands. Other combinations are also possible.

The mineral composition in the veins shows a narrow variation range and depends little on the type of intravein zoning. Grt, Cpx, Hbl, Gr, Pl, and Mag have equilibrium relations. However, they are sometimes surrounded by very thin secondary Hbl or Hbl–Pl reaction fringes between Grt and Mag grains, as well as the finest Hbl ± Bt ± Ttn veinlets, occasionally with a calcite core, which crosscut lineation of veins and Cpx, Grt, and Mag bands. These reaction amphiboles reflect the retrograde recrystallization of the veins during cooling. Comparison of identical minerals in the metaanorthosites and veins revealed some minor but sometimes discernible distinctions.

Garnets from Fe–Mg–Ca veins are generally more enriched in Fe (20–30% Py) than those in metaanorthosites (40–53% Py). It is evident from Fig. 2 that they are also enriched in Grs (20–30% against 15–22% in metaanorthosite garnets). Both host gabbroanorthosites and veins contain zoned garnet: the Alm content at the rim is 3–5% higher than in the center. All garnets contain small clinopyroxene and amphibole inclusions, which allow us to determine their formation temperatures.

Clinopyroxenes of the augite series from the veins show wide variations in the Fe mole fraction from 0.15 to 0.34 ($Fe^{3+} \approx 0.1$ f.u.). The Jd content in Cpx is usually low (4–10.5%) (Fig. 3). This value is only insignificantly higher than that in the metamorphic augites from metaanorthosites (up to 7.5%). Vein Cpx is weakly zoned: one can see an appreciable decrease in the Jd content and an insignificant decrease in the Fe mole fraction from the center to the margins (Fig. 3).

Orthopyroxenes from veins have an Fe mole fraction (X_{Fe} = 0.24–0.25) similar to that in the orthopyroxenes of metaanorthosites. The Al mole fraction in these minerals is nearly similar (X_{Al} = 0.12).

Plagioclases of veins occur in interstices between mafic minerals and often form thin bands together with Grt and Cpx. They have a significantly more acid composition (34–55% An) relative to metaanorthosites (75–83% An), indicating a significant Na content in fluids that formed veins.

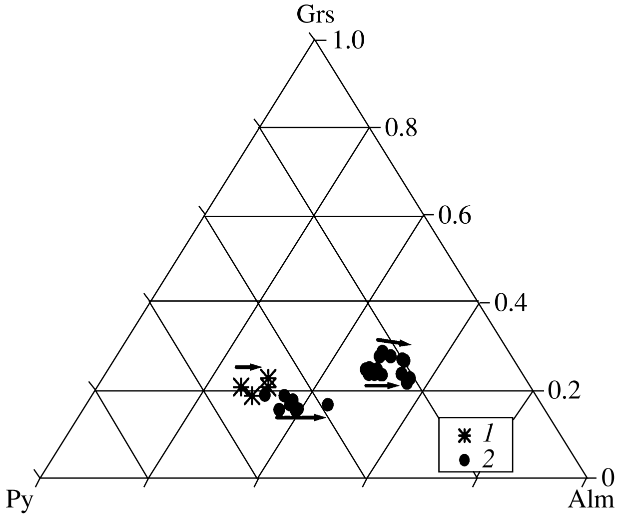

Fig. 2. Compositions of garnets from: (*1*) metaanorthosites and (*2*) Grt–Cpx–Opx–Hbl–Mag veins. Arrows indicate changes in the garnet composition from the core to the rim.

Amphiboles (pargasites) in the veins are in equilibrium with clino- and orthopyroxenes, garnet, and magnetite (Table 4). They typically have a higher Fe mole fraction (X_{Fe} = 0.35–0.52) than hornblendes from metaanorthosites (X_{Fe} = 0.1–0.3), with the exception of amphiboles from one vein. The total alkali content in the metasomatic amphiboles is higher than that in metaanorthosites (Fig. 4). This fact presumably reflects the relatively alkali composition of metasomatic fluid as compared to the metamorphic one. Intensely colored secondary hornblendes (ferropargasites) from crosscutting thin veinlets, which occasionally contain calcite grains in the core, make up a separate group. They are most enriched in Fe. The Cl content is up to 0.2% in the hornblendes and within measurement error in all other amphiboles. The appearance of Cl-bearing hornblendes with calcite marks some changes in fluid composition after the major stage of vein formation stage characterized by enrichment in CO_2 and Cl owing to precipitation of Ca, Mg, and Fe cations during formation of vein minerals.

Magnetite–ilmenite intergrowths are noted in variable amounts in all veins. The veins with low-Fe pyroxenes, amphiboles, and garnets (Figs. 2–4) have low contents of Mag and Ilm (1 or 2%). Their contents are maximum (~10%) in veins with the highest Fe silicates. Recalculation of ilmenite composition to formula units shows that the admixture of the hematite molecule in ilmenite varies from 1–4 to 17–21%. The correlation of the Fe mole fraction in clinopyroxenes, garnets, and amphiboles of veins with the amount of ilmenite–magnetite intergrowths indicates that veins were formed at the same temperatures but from solutions with different contents and oxidation states of Fe.

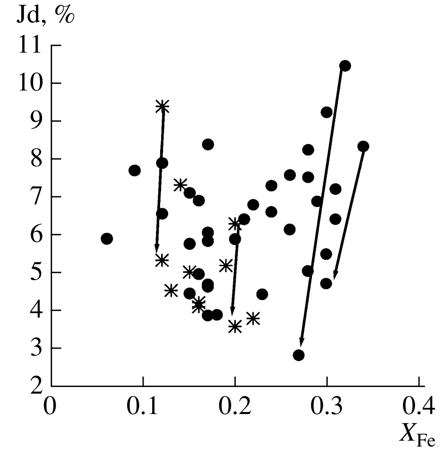

Fig. 3. X_{Fe} vs. the jadeite end member relationship in clinopyroxenes (symbols are as in Fig. 2). Arrows indicate the compositional change of pyroxenes from the core to the rim.

Grt–Hbl and Grt–Cpx thermometry of veins based on Hbl and Cpx inclusions in the garnet cores [10, 12] yielded approximately 850°C. Compositions of retrograde fringes of garnet grains and adjacent amphiboles define temperatures within 700–650°C. Thus, the peak metamorphic temperatures of anorthosites coincide with temperatures of the major stage of vein formation and temperatures of the subsequent retrograde stage in both rock types. This fact confirms that Fe–Mg–Ca metasomatism and basification veins were formed at the unified parameters of the Svecofennian granulite metamorphism.

No manifestation of syngranulite granitization was found in exposures located at the hypsometric level of metaanorthosites with garnet–pyroxene–hornblende–magnetite veins. The source of the mafic components in the veins was established during study of exposures at the northern border of the Kolvitsa metaanorthosite massif. Enderbite and charnockite bands (up to a few meters wide) related to migmatization and charnockite granitization were recorded there among quartz-free garnet–two-pyroxene crystalline schists in the vicinity

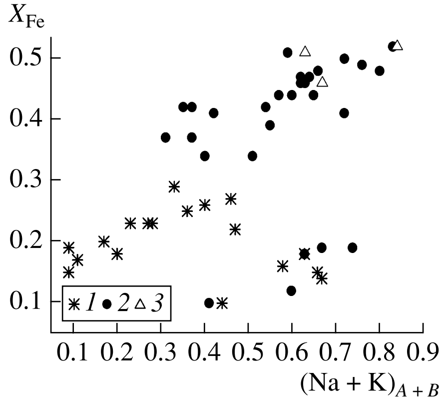

Fig. 4. $(Na + K)_{A+B}$ vs. X_{Fe} relationship in the metamorphic hornblende. (*1, 2*) See Fig. 2; (*3*) Cl-rich retrograde Ca-amphiboles from Hbl ± Cal veinlets.

of the metaanorthosite massif. The crystalline schists include numerous subparallel veins and veinlets of Grt-, Opx-, Cpx-, Hbl-, and Bt-bearing enderbite–charnockite granitoids. The veins up to 10*n* cm wide have clear-cut or indefinite contacts. The crystalline schists around the veins are subjected to feldspathization and silicification, with simultaneous formation of abundant brownish green high-Ti hornblende and brown Ti-rich biotite that are typical of granulite facies. Relative to pyroxenes, the hornblende and biotite have both reaction and new equilibrium relations, which are established near the veins in the course of charnockitization.

Parallel to feldspathization, selvages of some veins show the opposite phenomena: formation of mafic Grt–Cpx–Opx–Hbl–Pl fringes (1–5 cm), which are identical in composition to the Grt–Cpx–Opx–Hbl–Mag metasomatic veins in metaanorthosites described above. Minerals of these "microbasification" fringes are much coarser than those in crystalline schists. Garnet crystals are up to 1–1.5 cm in size and characterized by the presence of growth textures. Judging from the confinement to selvages of leucocratic quartz–feldspar veins, the melanocratic fringes are zones of direct redeposition of Mg, Fe, and Ca, which are complementary with vein charnockitization of the major crystalline schists.

Such interrelations of near-vein Fe–Mg–Ca metasomatism with the formation of quartz–feldspar veins during charnockite migmatization are the only reliable explanation for the genesis of separate Grt–Cpx–Opx–Hbl ± Mag veins in the granulite–charnockite complex of this region. Manifestation of the mafic metasomatism associated with charnockitization can differ in the mechanism and scale of matter migration. Fe, Mg, and Ca can be redeposited away from the debasification zone (in our case, Qtz–Fsp veins) over a few centimeters or tens of meters. In the latter case, the independent mafic Grt–Cpx–Opx–Hbl–Pl–Mag veins are formed at a significant distance from the source. Therefore, their genetic linkage with granitization is not always evident.

ACKNOWLEDGMENTS

We are grateful to E.V. Sharkov and A. V. Chistyakov (Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry) for great help in field works.

This work was supported by the Russian Foundation for Basic Research (project nos. 06-05-64645 and 05-05-64831).

REFERENCES

1. D. S. Korzhinsky, Izv. Akad. Nauk SSSR, Ser. Geol., No. 2, 56 (1952).
2. D. Reynolds, Quartz. J. Geol. Soc. London. **102**, 389 (1946).
3. G. M. Belyaev and V. A. Rudnik, in *Ferromagnesian Metasomatism and Ore Formation* (Nauka, Moscow, 1980), pp. 13–29 [in Russian].
4. S. N. Utenkov, in *Geology of Metamorphic Complexes* (Sverdlov. Gorn. Inst., Sverdlovsk, 1989), pp. 62–72 [in Russian].
5. B. M. Ronenson, in *Geology of Metamorphic Complexes* (Sverdlov. Gorn. Inst., Sverdlovsk, 1989), pp. 72–85 [in Russian].
6. V. V. Zhdanov, in *Ferromagnesian Metasomatism and Ore Formation* (Nauka, Moscow, 1980), pp. 29–40 [in Russian].
7. N. G. Sudovikov, *Regional Metamorphism and Some Petrological Problems* (LGU, Leningrad, 1964) [in Russian].
8. V. I. Levitskii, *Petrology and Geochemistry of Metasomatism during the Formation of Continental Crust* (GEO, Novosibirsk, 2005) [in Russian].
9. L. A. Priyatkina and E. V. Sharkov, *Geology of the Lapland Deep Fault in the Baltic Shield* (Nauka, Leningrad, 1979) [in Russian].
10. R. J. Powell, Metamorph. Geol. **3**, 327 (1985).
11. L. L. Perchuk and I. V. Lavrent'eva, Int. Geol. Rev., No. 5, 486 (1990).
12. L. L. Perchuk, Geokhimiya. **12**, 1 (1989).