ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 411, No. 8, pp. 1313–1317. © Pleiades Publishing, Inc., 2006.
Original Russian Text © I.I. Likhanov, P.S. Kozlov, N.V. Popov, V.V. Reverdatto, A.E. Vershinin, 2006, published in Doklady Akademii Nauk, 2006, Vol. 411, No. 2, pp. 235–239.

## GEOCHEMISTRY

# Collisional Metamorphism As a Result of Thrusting in the Transangara Region of the Yenisei Ridge

**I. I. Likhanov[a], P. S. Kozlov[b], N. V. Popov[a],**
**Academician of the RAS V. V. Reverdatto[a], and A. E. Vershinin[a]**

Received May 18, 2006

**DOI:** 10.1134/S1028334X06080332

The Yenisei Ridge is one of the most interesting regions in the southwestern folded framework of the Siberian Craton with respect to geodynamics. The regional structure of the Transangara sector of the Yenisei Ridge is traditionally displayed as a NW-trending system of tectonic sheets divided by faults characterized by the collision of blocks and thrusting. Therefore, this region was subject to pressure-variable regional metamorphism expressed in the juxtaposition of low- and moderate-pressure metamorphic facies. Collision-related moderate-pressure metamorphism is locally superimposed on the low-pressure (presumably, younger) metamorphic rocks. As a result, andalusite is replaced with kyanite with the formation of new mineral assemblages and deformational structures. The prograde replacement of andalusite with kyanite in the Yenisei Tange is a rare phenomenon, because the stationary continental geotherm commonly does not intersect the andalusite–kyanite equilibrium line. Such replacements are usually referred to the retrograde stage of metamorphism, but this interpretation comes into conflict with the regional geological situation. Only a few examples are known in the literature (Northwest Cordillera in the United States and Canada, Dalradian in Scotland, central and northwestern Appalachians in the United States, and the Kola Peninsula and Yenisei Ridge in Russia), where prograde transformation of andalusite into kyanite is assigned either to the metastable state of andalusite in the *PT* stability field of kyanite or to an increase in pressure as a result of thrusting or magmatic loading characterized by different *PT* trends.

While studying collisional metamorphism in the Transangara sector of the Yenisei Ridge, we selected three (Chapa, Mayakon, and Angara) areas composed of Paleoproterozoic, Middle Riphean, and Upper Riphean rocks (Fig. 1). The Chapa and Mayakon areas are located in the Central uplift between the Ishimbino and Tatarka deep faults. The Angara area covers the junction of the Transangara structural units and the Angara–Kan block.

The *Angara area* is situated at the interfluve of the Angara, Belokopytovka, and Malaya Sploshnaya rivers. The reference sections are exposed in the Tatarka shear zone along the right bank of the Angara River between the mouths of the Babkin and Polovinkin creeks. The area is composed of the Upper Riphean low-pressure metasedimentary rocks (rhythmic intercalation of quartzites and phyllites of the Sukhoi Ridge Formation). In the study area, this sequence is largely made up of phyllites of the greenschist facies represented by quartz (Qtz), muscovite (Ms), chlorite (Chl), and ilmenite (Ilm). These rocks underwent high-pressure collisional metamorphism with the formation of new (kyanite-bearing) mineral assemblages. Metamorphism occurred simultaneously with the development of steep (80°–85° NW and SE) near-meridional cleavage. The increase in the metamorphic grade in the near-latitudinal direction is marked by the successive formation of chloritoid (apparent thickness 0.5–0.8 km) and kyanite (~1.5–1.7 km) zones. These minerals correspond to the conditions of kyanite schist facies. The eastern boundary of these rocks is hidden beneath unmetamorphosed Paleozoic rocks of the Pogromnino basin. In the Kulakovo uplift on the left bank of the Angara River, collisional metamorphism is expressed in the crystallization of kyanite (Ky), chloritoid (Cld), and ilmenite in metapelites consisting of staurolite (St), plagioclase (Pl), Ms, biotite (Bt), Qtz, and garnet (Grt) [2].

The *Mayakon area* is located in the Eruda and Chirimba river basins, where the Middle Riphean rocks of the Korda Formation subjected to low-pressure regional metamorphism were affected by Neoproterozoic moderate-pressure metamorphism. The low-pressure metapelites are represented by Ms + Chl + Bt + Cld + andalusite (And) + Qtz + Ilm ± cordierite (Crd)

[a] *Institute of Mineralogy and Petrography, Siberian Division, Russian Academy of Sciences, pr. akademika Koptyuga 3, Novosibirsk, 630090 Russia; e-mail: likh@uiggm.nsc.ru*

[b] *Zavaritsky Institute of Geology and Geochemistry, Ural Division, Russian Academy of Sciences, Pochtovyi per. 7, Yekaterinburg, 620151 Russia*

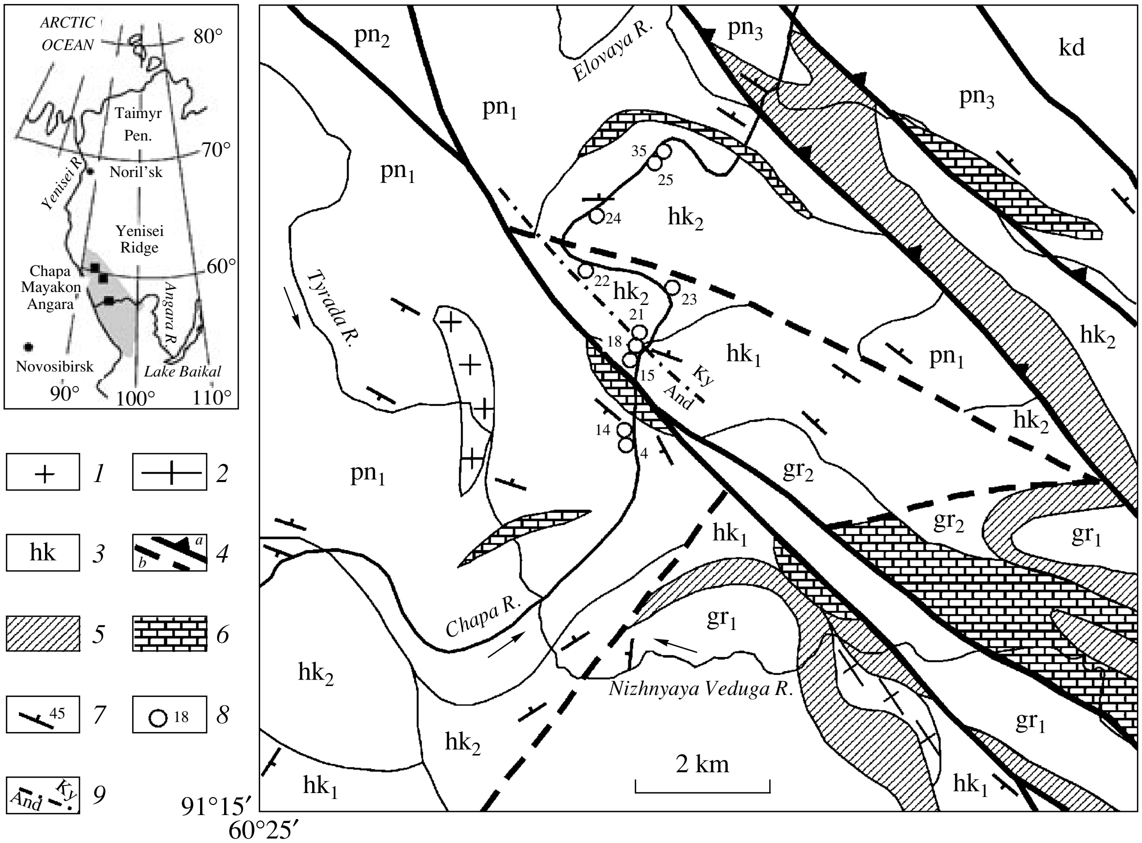


**Fig. 1.** Geological sketch map of the Precambrian metasedimentary rocks in the upper reaches of the Chapa River. (*1*) Subalkali granite of the Teya Complex; (*2*) granite gneiss of the Garevsky Complex; (*3*) metasedimentary rocks: (kd) Lower Riphean Korda Formation; schists of the Paleoproterozoic Penchenga Formation with ($pn_1$) actinolite, ($pn_2$) biotite, ($pn_3$) graphite; Paleoproterozoic Karpinsky Formation: ($hk_1$) schists with quartzite and marble interlayers, ($hk_2$) two-mica schists with andalusite, staurolite, and garnet (locally transformed into blastomylonite); Archean–Paleoproterozoic (undivided) Garevsky Formation: ($gr_1$) meso- and leucocratic gneisses, ($gr_2$) quartzites and mica schists; (*4*) faults: (*a*) major thrust faults (ticks indicate the direction of fault plane dip), (*b*) other faults; (*5*) amphibolite; (*6*) marble; (*7*) strike and dip of rocks; (*8*) sample location; (*9*) And–Ky isograd. Inset demonstrates areas with the manifestation of collisional metamorphism

mineral assemblage of the greenschist and epidote–amphibolite facies. Moderate-pressure metamorphic rocks, which formed as a result of collisional metamorphism of the kyanite schist facies, are characterized by a Ms + Chl + Bt + Qtz + Ky + St + Grt + Ilm + Pl assemblage with relict andalusite and sporadic sillimanite (Sil). They compose a zone, 5–7 km thick and no less than 20 km long, bounded by the NW-trending Panimba thrust fault in the east. One can outline three (outer, middle, and inner) zones of superimposed collisional metamorphism that extend parallel to the thrust fault suture. They differ in the proportions of relict and newly formed minerals and the degree of rock deformation. The geothermobarometric estimates and the calculated *PT* trends testify to the gradual increase in pressure approaching the Panimba thrust fault: 3.5–4.0 kbar in metapelites of regional metamorphism, 4.5–5.0 kbar in the outer zone, 5.5–6.0 kbar in the middle zone, and up to 6.6–6.7 kbar in the inner zone without appreciable growth of temperature (from 550 to 580°C) [3].

The *Chapa area* embraces the middle reaches of the Chapa River between the mouths of the Nizhnyaya Veduga and Elovaya tributaries (Fig. 1). Paleoproterozoic metamorphic rocks make up the Chapa anticline with a hinge plunging to the northwest at 15°–30°. Quartzites and crystalline schists of the Karpinsky Ridge Formation (hereafter, Karpinsky Formation) crop out in the anticline core. The limbs consist of metaterrigenous and metacarbonate rocks (marbles with a subordinate amount of crystalline schists) of the Penchenga Formation. The anticline is complicated by the NW-trending Uvolzh'e fault system related to the northern segment of the deep Tatar fault. The distal (relative to the fault) crystalline schists of the Penchenga Formation are composed of the Ms + Chl + Bt + Qtz + Pl mineral assemblage of the greenschist facies. At 4–5 km from the thrust fault, metapelites of the Karpinsky Formation (Ms + Chi + Bt + Qtz + And + St + Grt + Pl assemblage) are metamorphosed up to the kyanite schist facies. When approaching the thrust fault, the rocks are affected by moderate-pressure collisional

**Table 1.** End member contents and iron mole fractions in minerals from metapelites in the Chapa area (based on microprobe data)

| Sample no. | Grt | | | | Bt | | Ms | Pl | Chl |
|---|---|---|---|---|---|---|---|---|---|
| | $X_{Alm}$ | $X_{Prp}$ | $X_{Grs}$ | $X_{Sps}$ | $X_{Ann}$ | $X_{Phl}$ | $X_{Ms}$ | $X_{An}$ | $X_{Fe}$ |
| Metapelites of the Penchenga Formation | | | | | | | | | |
| 4 | | | | | 0.42 | 0.38 | 0.79 | 0.26 | 0.62 |
| 14 | | | | | 0.42 | 0.37 | 0.73 | 0.27 | 0.61 |
| Metapelites of the Karpinsky Formation | | | | | | | | | |
| 15 | 0.73 | 0.09 | 0.03 | 0.14 | 0.51 | 0.33 | 0.78 | 0.16 | |
| 18 | 0.73 | 0.09 | 0.03 | 0.14 | 0.52 | 0.33 | 0.78 | 0.15 | |
| 21 | 0.74 | 0.10 | 0.05 | 0.11 | 0.51 | 0.33 | 0.82 | 0.22 | |
| 22c | 0.60 | 0.10 | 0.07 | 0.23 | 0.41 | 0.40 | | 0.48 | |
| 22 | 0.65 | 0.12 | 0.09 | 0.14 | 0.43 | 0.40 | 0.80 | 0.37 | |
| 23c | 0.70 | 0.10 | 0.07 | 0.13 | | | | 0.48 | |
| 23 | 0.72 | 0.12 | 0.09 | 0.06 | 0.43 | 0.36 | 0.81 | 0.37 | |
| 24 | 0.71 | 0.12 | 0.07 | 0.10 | 0.44 | 0.35 | 0.80 | 0.32 | |
| 25 | 0.71 | 0.12 | 0.10 | 0.06 | 0.44 | 0.35 | 0.78 | 0.42 | |
| 35 | 0.71 | 0.13 | 0.10 | 0.06 | 0.43 | 0.36 | 0.77 | 0.37 | |

Note: Mole fractions of components: $X_{Alm}$ = Fe/(Fe + Mg + Ca + Mn), $X_{Prp}$ = Mg/(Fe + Mg + Ca + Mn), $X_{Grs}$ = Ca/(Fe + Mg + Ca + Mn), $X_{Sps}$ = Mn/(Fe + Mg + Ca + Mn), $X_{ann}$ = Fe/(Fe + Mg + Mn + Ti + $Al^{VI}$), $X_{Phl}$ = Mg /(Fe + Mg + Mn + Ti + $Al^{VI}$), $X_{An}$ = Ca/(Ca + + Na + K), $X_{Fe}$ = Fe/(Fe + Mg), $X_{Ms} = (X_k) \cdot (X_{Al}^{VI})^2$; (22c, 23c) cores of zonal minerals; other compositions characterize marginal zones of grains.

kyanite–sillimanite metamorphism. The spatial transition from low-pressure regional metamorphism to higher-pressure metamorphism is recorded in the simultaneous appearance of kyanite and sillimanite. The Ms + Chl + Bt +Qtz + Ky + St + Grt + Pl + Sil assemblage with relict andalusite was formed under conditions of the kyanite–staurolite subfacies of the kyanite schist facies. They make up a zone 4 km thick bounded by the NW-trending thrust fault in the east. Collisional metamorphism was accompanied by dislocations and deformations of rocks and minerals. This is evident from the development of shear- and kinkbands in minerals; pressure shadows of recrystallized quartz; S-shaped garnet grains with helicitic (snowball-type) textures; and ruptures of mineral grains with displacement, cataclasis, boudinage, and flattening. Blastomylonites zones developed near the thrust fault indicate crystal growth under pressure. This is also suggested by the lenticular–knotted fabric of rocks and granulated quartz veins. Based on the bulk chemical composition, the studied rocks are classified as metapelites enriched in Fe ($X_{Fe}$ = FeO/(FeO + MgO + MnO) = 0.6–0.7 mole fractions) and Al ($X_{Al}$ = $Al_2O_3$–3$K_2O$/($Al_2O_3$–3$K_2O$ + FeO + MgO + MnO) = 0.39–0.44 mole fractions) in comparison with typical metapelites ($X_{Fe}$ = 0.52 and $X_{Al}$ = 0.13).

The *PT* conditions of metamorphism and *PT* trends of metapelite evolution are based on the composition of rock-forming minerals (end member contents are presented in Table 1) and their zoning. The known mineral geothermobarometers, the respective mixing models, the matched thermodynamic data set, and the THERMOCALC [4] and PTPATH [5] software packages were used for this purpose. For metamorphic rocks of the Penchenga Formation, the temperature was estimated with Pl–Ms [6] and Bt–Ms [7] geothermometers. Pressure estimates were obtained with two modifications of the Bt–Ms–Chl geobarometer [8, 9]. For the garnet-bearing rocks of the Karpinsky Formation, the temperature was determined with the geothermometers mentioned above and two experimental calibrations of the Grt–Bt geothermometer [10, 11] with the respective mixing models. The pressure was estimated with two modifications of the Grt–Bt–Ms–Pl geobarometer [12, 13] with the application of composition–activity models for nonideal solid solutions of coexisting phases. The *PT* parameters of metamorphism were calculated based on all the geothermobarometers. The geothermobarometric results (Table 2) testify to the gradual increase in pressure of collisional metamorphism. Pressure increases approaching the thrust fault from the initial 4–5 kbar in the Penchenga metapelite zone to 5.0–5.5 kbar in the Karpinsky andalusite–sillimanite metapelite zone and finally to 8.1–8.4 kbar in the inner zone (kyanite blastomylonites of the kyanite–sillimanite type). The insignificant increase in temperature (from 620 to 710°C) toward the thrust fault indicates

**Table 2.** Estimates of *PT* conditions of regional and collisional metamorphism in the Chapa River area

| Sample no. | *T*, °C | | | | | *P*, kbar | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [10] | [11] | [6] | [7] | [4] | [13] | [12] | [8] | [9] | [4] |
| Metapelites of the Penchenga Formation | | | | | | | | | | |
| 4 | | | 585–594 | 584–592 | | | | 4.0–4.3 | 3.9–4.4 | |
| 14 | | | 588–603 | 588–602 | | | | 4.25–4.6 | 4.5–4.9 | |
| Metapelites of the Karpinsky Formation | | | | | | | | | | |
| 15 | 617 | 618 | 612 | 621 | 623 ± 14 | 5.48 | 5.51 | | | 5.6 ± 1.1 |
| 18 | 625 | 627 | 630 | 630 | 635 ± 16 | 5.74 | 5.66 | | | 5.9 ± 1.1 |
| 21 | 661 | 635 | 654 | 638 | 636 ± 15 | 6.93 | 6.71 | | | 6.1 ± 0.80 |
| 22 | 664 | 621 | 664 | 640 | 635 ± 16 | 7.01 | 6.78 | | | 6.8 ± 0.65 |
| 23 | 665 | 622 | 667 | 648 | 638 ± 16 | 7.36 | 7.01 | | | 7.0 ± 0.66 |
| 24 | 682 | 637 | 676 | 652 | 681 ± 24 | 7.37 | 6.96 | | | 7.2 ± 0.85 |
| 25 | 695 | 641 | 687 | 660 | 652 ± 20 | 7.76 | 7.68 | | | 7.4 ± 0.71 |
| 35 | 710 | 645 | 699 | 670 | 675 ± 21 | 8.42 | 8.10 | | | 8.1 ± 0.97 |

Note: Numerals in brackets correspond to the numbers of geothermobarometers in the list of references.

that a low geothermal gradient existed in the course of collision (<10°C/km). To estimate the reliability of the geothermobarometric results, the calculated values were compared with estimates of *PT* conditions based on the THERMOCALC program [4]. All results are in good agreement within the error limits of the geothermobarometers. The parameters of the initial stage of garnet growth obtained for cores of zonal grains were used for substantiation of *PT* trends of kyanite–sillimanite metamorphism. The prograde zoning of garnet with depletion in the spessartine component and the gradual enrichment in the grossular component from the grain core to its margin indicate the gradual increase in pressure at the late stage of garnet growth. The calculated *PT* trends confirm the gradual increase in pressure for metapelites of the Karpinsky Formation during transition from the southwest to the northeast (up to 3 kbar near the thrust fault), but the temperature growth is insignificant (Fig. 2). This specific feature of collisional metamorphism during the overthrusting of continental blocks (independent of subduction) may testify to the plunging of rocks under the load of a cold overthrust plate [14]. The results obtained are in agreement with *PT* evolution of metamorphic rocks from other collisional orogens, where the prograde transformation of andalusite into kyanite was assigned to tectonic thickening of the crust as a result of thrusting (Fig. 2).

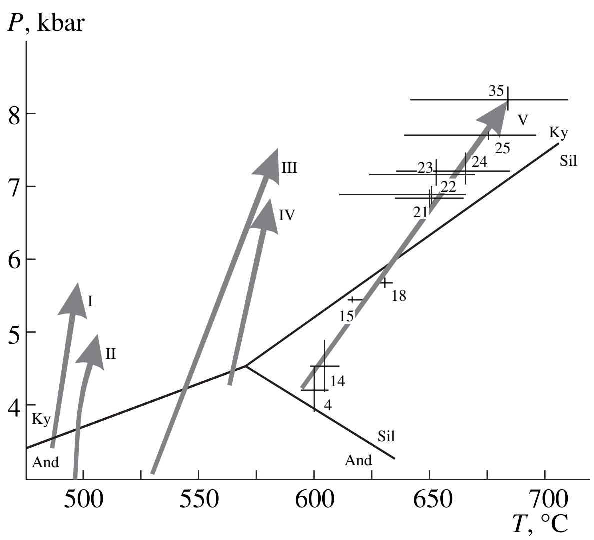


**Fig. 2.** *PT* conditions and metamorphic trends of metapelites in the Chapa River area in comparison with *PT* evolution of collisional metamorphism in other regions with thrust tectonics. For each sample, average *PT* parameters (crosses) and their range based on different geothermobarometers (Table 2) are shown without the consideration of uncertainties. Numerals at crosses are number of samples (see Table 2). Directions of *PT* trends based on zonal metamorphic minerals are shown as solid arrows directed from core to margins of garnet grains. Coordinates of the triple point and lines of monovariant equilibria of $Al_2SiO_5$ polymorphs are given after [4]. Regions: (I) Ballow Falls, Appalachians, United States; (II) Muskoma–Orfordville, Appalachians, United States; (III) Nason, Cordillera, Canada; (IV) Eruda–Chirimba interfluve, Yenisei Ridge; (V) Chapa area, Yenisei Ridge.

Thus, the Precambrian crystalline rocks of the Ishimbino and Tatarka deep fault zones (Transangara region of the Yenisei Ridge) represent polymetamorphic complexes that include both the rocks of low-pressure regional metamorphism (andalusite–sillimanite type) and the locally developed moderate-pressure metapelites (kyanite–sillimanite type). The metapelites are indicators of elevated pressure in the axial zone of the region. In the succession of collisional rocks, the highest pressure metapelites (*P* = 5.5–8.4 kbar at 620–710°C) are confined to the Paleoproterozoic Karpinsky Formation in the northern sector of the study region (Chapa area). In the south, the collisional rocks occur in the Middle Riphean Korda Formation (Mayakon area) as graphite-bearing metapelites formed at $P$ = 4.5–6.7 kbar and $T$ = 540–600°C. Farther to the south, products of collisional metamorphism are known in the Upper Riphean rocks as a fragment of prograde metamorphic zoning of kyanite–sillimanite type (Angara area) superimposed on low-temperature metapelites of the Angara–Tissa greenschist complex. Despite spatial separation of these areas, they show the following common attributes of collisional metamorphism in the Transangara sector of the Yenisei Ridge: (a) development of blastomylonites with kyanite, sillimanite, garnet, and staurolite, which replace andalusite-bearing mineral assemblages of regional metamorphism of the andalusite–sillimanite type; (b) insignificant apparent thickness (from 2.5 to 6–8 km) of the zonal collisional metamorphism near thrust faults; (c) low geothermal gradient during metamorphism (no higher than 10°C/km); and (d) gradual increase in pressure from the southwest to the northeast toward the thrust faults (from 1–2 kbar in the Mayakon area to 3 kbar in the Chapa area).

Thus, we can make the following conclusions. The Transangara sector of the Yenisei Ridge can be divided into three areas of collisional metamorphism, where andalusite is gradually replaced by kyanite with an increase in pressure. Metamorphism is related to the thrusting of older blocks over younger rocks. On a regional scale, metamorphism is probably related to the thrusting of the Siberian Craton over the Yenisei Ridge. This conclusion is supported by geophysical data [15].

## ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 05-05-64057 and 06-05-64676), the Foundation of the President of the Russian Federation for the Support of Leading Scientific Schools (project no. NSh-4922.2006.5), and the Russian Academy of Sciences (integration project no. 6 and 116 of the Division of Earth Sciences and Siberian Division, respectively).

## REFERENCES

1. I. I. Likhanov, O. P. Polyansky, V. V. Reverdatto, et al., J. Metamorph. Geol. **22**, 743 (2004).
2. P. S. Kozlov, I. I. Likhanov, V. V. Reverdatto, et al., in *Proceedings of Scientific Conference on Metamorphism and Geodynamics* (Yekaterinburg, 2006), pp. 42–45.
3. I. I. Likhanov, O. P. Polyansky, V. V. Reverdatto, et al., Geol. Geofiz. **42**, 1205 (2001).
4. R. Powell and T. J. B. Holland, Am. Mineral. **79**, 120 (1994).
5. F. S. Spear, Comput. Geosci. **12**, 247 (1986).
6. N. L. Green and S. I. Usdansky, Am. Mineral. **71**, 1109 (1986).
7. T. D. Hoisch, Am. Mineral. **74**, 565 (1989).
8. R. Powell and J. A. Evans, J. Metamorph. Geol. **1**, 331 (1983).
9. K. Bucher-Nurminen, Contrib. Mineral. Petrol. **96**, 519 (1987).
10. J. M. Ferry and F. S. Spear, Contrib. Mineral. Petrol. **66**, 113 (1978).
11. L. L. Perchuk and I. V. Lavrent'eva, in *Kinetics and Equilibrium in Mineral Reactions* (Springer, New York, 1983), pp. 199–239.
12. T. D. Hoisch, Contrib. Mineral. Petrol. **104**, 225 (1990).
13. E. D. Ghent and M. Z. Stout, Contrib. Mineral. Petrol. **76**, 92 (1981).
14. V. V. Reverdatto and V. S. Sheplev, Geol. Geofiz. **39**, 1679 (1998).
15. M. M. Konstantinov, R. F. Dankovtsev, G. S. Simkin, et al., Geol. Ore Deposits **41**, 387 (1999) [Geol. Rudn. Mestorozhd. **41**, 425 (1999)].