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GEOCHEMISTRY

Neoproterozoic Age of Collisional Metamorphism in the Transangara Region of the Yenisei Ridge (Based on $^{40}Ar/^{39}Ar$ Data)

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In terms of geodynamics, the Yenisei Ridge is one of the most interesting regions in the southwestern folded framing of the Siberian Craton. Regional structures of the Transangara region of the Yenisei Ridge are traditionally depicted as a NW-extending system of tectonic sheets separated by faults located near the zone of collision of blocks. The collision was responsible for the regional process of heterogeneous (with respect to pressure) metamorphism expressed in the juxtaposition of two (low- and moderate-pressure) facies series. The moderate-pressure collisional metamorphism of the presumably younger stage is locally overprinted on low-pressure metamorphic rocks. Therefore, andalusite is progressively replaced with kyanite, resulting in the formation of new mineral assemblages and deformation structures [1]. The progressive replacement of andalusite with kyanite recorded in the Yenisei Ridge is a rare process, because the stationary continental geotherm usually does not intersect the andalusite–kyanite equilibrium line. Such replacements are commonly attributed to the retrograde phase of metamorphism. However, this interpretation contradicts the geological situation observed in the study region. Progressive transformations of andalusite into kyanite have only been reported from some regions (northwestern Cordillera, United States and Canada; Dalredian, Scotland; central and northwestern Appalachians, United States; Kola Peninsula and Yenisei Ridge, Russia), where these processes are attributed to pressure growth as the result of thrusting or magmatic loading with various *PT* trends [1]. Both the reconstruction of the *PT* evolution of metamorphic complexes and the isotope datings of rocks are essential for geodynamic modeling of regions with manifestations of collisional and contact metamorphism. Correct interpretation of these data provides insight into the interrelation and age correlation between processes of metamorphism, tectonics, and magmatic activity. Therefore, we carried out special geochronological investigations of metapelites related to collisional metamorphism. The results obtained are discussed in this paper.

We investigated Mesoproterozoic (1100 ± 50 Ma [2]) regional-metamorphic low-pressure rocks of the Korda Formation (Sukhopit Group) developed in basins of the Yeruda and Chirimba rivers (Transangara region, Yenisei Ridge). The rocks underwent moderate-pressure collisional metamorphism in some places (Fig. 1). In the study area, low-pressure metapelites (Ms + Chl+ Bt + Cld + And + Qtz + Ilm ± Crd assemblage) formed under conditions of the greenschist and epidote–amphibolite facies. Moderate-pressure rocks (Ms + Chl + Bt + Qtz + Ky + St + Grt + Ilm + Pl assemblage) with relicts of andalusite and rare sillimanite postdated the collisional metamorphism of the kyanite schist facies. They make up a zone (5–7 km wide and no less than 20 km long) bounded in the east by the NW-oriented Panimba thrust fault. Lower Proterozoic (~1600 Ma [3]) metacarbonates and crystalline schists of the Penchenga Formation are developed in the northeastern area beyond the Panimba thrust fault. Igneous rocks of the Tatar–Ayakhta Complex are composed of calc-alkaline (low-K) granitoids of the Yeruda pluton estimated at 878 ± 1.5 Ma [4]. In terms of geochemical characteristics, these rocks match granitoids of the intermediate *I–S* type. They crosscut the metamorphic zonality of low-pressure regional metamorphism. The regional-metamorphic rocks located near intrusive contacts are subjected to thermal metamorphism of a wide temperature range varying from muscovite to amphibole–hornfels facies at a pressure of ~3 kbar [5, 6].

The spatial transition from low-pressure regional-metamorphic rocks to younger moderate-pressure varieties is recorded by the kyanite isograde. We can identify three (outer, middle, and inner) metamorphic zones of the superimposed collisional metamorphism devel-

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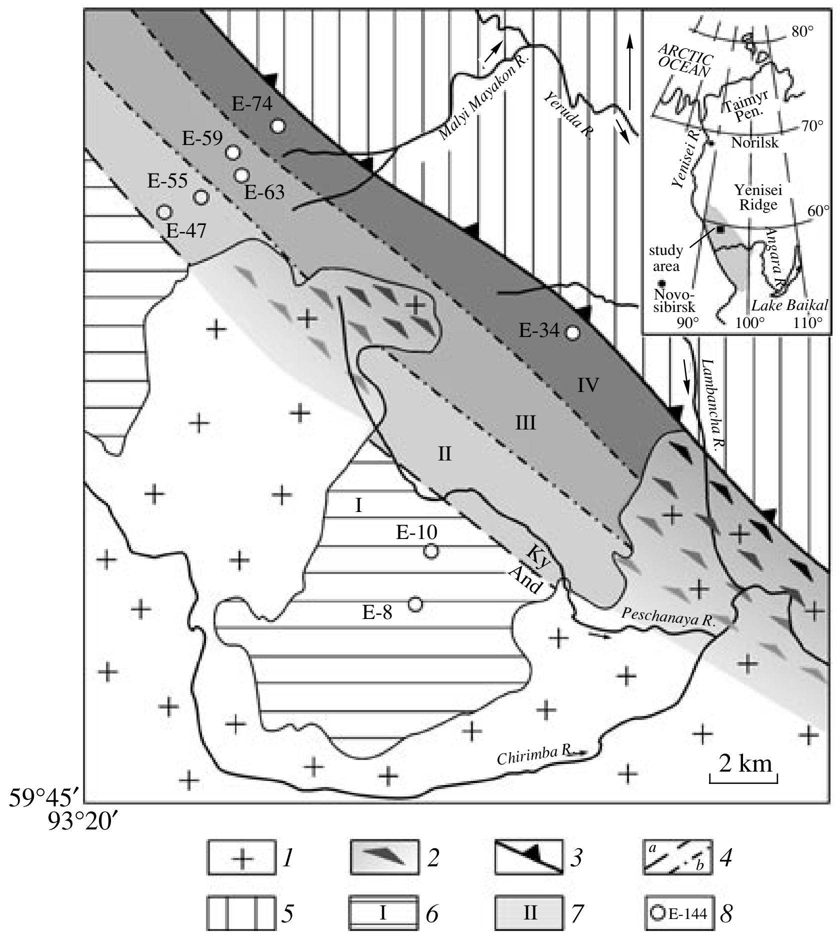

Fig. 1. Schematic geological map showing locations of collisional metamorphic zones at the Yeruda and Chirimba interfluve, Transangara region of the Yenisei Ridge. (*1*) Granites of the Chirimba pluton; (*2*) undifferentiated cataclastic and blastocataclastic zones in the granites; (*3*) suture of the Panimba thrust fault (ticks are oriented down along the dip); (*4a*) andalusite–kyanite isograde and (*4b*) boundaries between metamorphic zones in metapelitic rocks; (*5*) metasiltstones and metacarbonates of the Penchenga Formation; (*6*) metapelites of the Korda Formation (products of regional metamorphism); (*7*) collisional metamorphic zones in metapelitic rocks; (*8*) sampling sites.

oped parallel to the Panimba thrust fault. These zones differ in terms of the proportions of relict and newly formed minerals and the degree of rock deformation. The collisional metamorphism was accompanied by intense dislocations and deformations. This is evident from the appearance of crush and flexure bands in minerals, pressure shadows in the recrystallized quartz, S-shaped garnet grains with helicitic textures of the snowball type, and boudinage zones. The development of blastomylonites in the thrust-line sectors testifies to the stress-induced formation of minerals. This is also indicated by the lenticular-nodulous structure of rocks and the presence of strain-related granulated quartz veins [7]. In terms of the chemical composition, rocks of the Korda Formation are qualified as Fe- and Al-rich metapelites [8].

The results of geothermobarometric investigations indicate a gradual pressure increase upon approaching the Panimba thrust fault from 3.5–4 kbar in the regional-metamorphic metapelites to 4.5–5 kbar in the outer zone, 5.5–6 kbar in the middle zone, and 6.2–6.7 kbar in the inner zone. The increase in temperature is insignificant (from 550 to 580°C) [1]. Calculations of reaction equations and mass transfer showed that collisional metamorphism provoked mineral transformations with large volumetric and small entropic effects [9]. The calculated *PT* evolution paths confirm the gradual increase in lithostatic pressure in metapelites of the Korda Formation upon approaching the Panimba thrust fault (from 1 to 2.5 kbar) without significant increase in temperature (no more than 20 ± 15°C). This fact can suggest an almost isothermal subsidence of the rock sequence in the course of collisional metamorphism. In order to explain this scenario of metamorphic evolution, we proposed a tectonic model and performed thermophysical calculations that take into consideration the real physical parameters of metapelites and metacarbonates (radioactive heat emission and coeffi-

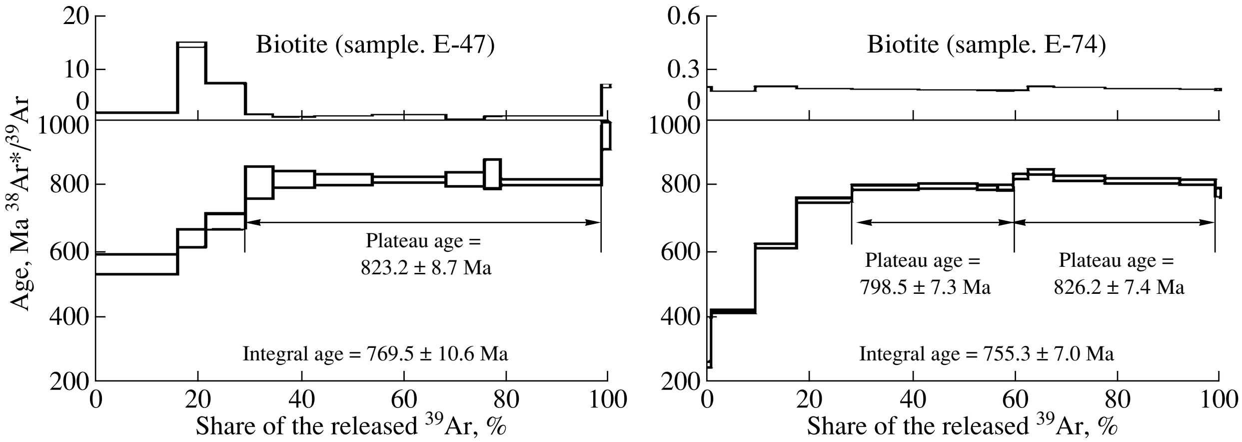

Fig. 2. Results of the $^{39}Ar/^{40}Ar$ dating of biotites from the outer (sample E-47) and inner (sample E-74) zones of collisional metamorphism. Each sample is furnished with the integral age and $^{38}Ar^*/^{39}Ar$ (Cl/K) spectrum. Arrows indicate ages based on the plateau method.

cients of thermal conductivity). The gradual increase in the lithostatic pressure was attributed to tectonic thickening of the Earth's crust in the Panimba fault zone. Consequently, the Korda metapelites initially located at a depth of 15–17 km were overlapped by the 5- to 7-km-thick metacarbonates of the Penchenga Formation. The absence of appreciable temperature increase in the course of thrusting is explained by specific features of the behavior of stationary geotherms in various types of rocks with contrasting heat-generating and thermophysical properties [1, 7]. The proposed model explains the metamorphic evolution of metapelites in the following way: the gradual replacement of andalusite by kyanite, the enrichment of garnet grains in the grossular component from the center to the edge of grains, the gradual increase in lithostatic pressure with an insignificant increase in temperature, and so on. Advancing the proposed interpretation of collisional metamorphism in the 1D approximation, we have developed a 2D model of deformation of the lithosphere in the course of thrusting [10].

Isotope dating occupies an important place in our investigations. Samples for geochronological investigations were taken from metapelites of the outer (II, sample E-47) and inner (IV, sample E-74) zones of collisional metamorphism (Fig. 1). The $^{40}Ar/^{39}Ar$ datings were carried out according to the procedure described in [11]. Together with weighed portions of standard biotite samples MCA-11 and LP-6 used as monitors, the mineral fractions (no less than 0.15 mm in size) were packed in aluminum foil. After the preliminary evacuation of air, the samples were sealed in quartz ampules and irradiated in the Cd channel of the research reactor (BBP-K type) at the Tomsk Polytechnic Institute. The neutron flux gradient did not exceed 0.5% of the sample size. The stepwise heating experiments were carried out in the quartz reactor with an outer heating furnace. The ^{40}Ar procedure blank (10 min at 1200°C) did not exceed $5 \cdot 10^{-10}$ ncm^3. The released Ar was subjected to twofold purification with Ti and ZrAl SAES getters. The Ar isotopic composition was measured in a Noble Gas 5400 (Micromass, Great Britain) mass spectrometer. Uncertainties are quoted at the $\pm 1\sigma$ level in the text and in Fig. 2.

Figure 2 presents results of the $^{40}Ar/^{39}Ar$ dating of biotites. In the low-temperature region, spectra of both biotites are characterized by relatively low age values. High $^{38}Ar^*/^{39}Ar$ (Cl/K) ratios recorded at such temperatures in biotite E-47 can be related to late superimposed transformations. The spectrum of biotite E-47 shows a distinct plateau with an age of 823.2 ± 8.7 Ma that corresponds to 70% of the released ^{39}Ar. In the spectrum of biotite E-74, we can recognize two plateaus located in the middle sector with an age of 798.5 ± 7.3 Ma (32% of the released ^{39}Ar) and in the high-temperature region with an age of 826.2 ± 7.4 Ma (39% of the released ^{39}Ar). The plateau age values of biotite samples E-47 and E-74 are consistent with the error limits. The integral age includes the contribution of low-temperature steps characterized by lower age values relative to the plateau. Hence, datings based on the plateau method are closest to the age of rock cooling down to the temperature of closure of the K/Ar isotope system in biotite (330–360°C) [12]. This value is much lower than the temperature of the culmination stage of collisional metamorphism. The similarity of age values testifies to a virtually simultaneous exhumation and cooling of all zones in the rock block subjected to collisional metamorphism.

In order to determine the age of collisional metamorphism, we analyzed the possible thermal history of rocks in the course of their exhumation from a depth of 20–24 km. The calculations were based on the previous tectonothermal model of the metamorphic evolution of the study region [1]. According to this model, the stationary geotherm includes two sectors with different temperature gradients if the crust is thickened as the result of stacking of two tectonic sheets. The temperature of the K/Ar isotope system closure corresponds to a depth of ~15 km for the calculated stationary geotherm of the thickened crust. Hence, metapelites of the postcollision stage were exhumed over no less than 5–9 km. Our estimate of the thrusting rate of rocks of the Penchenga Formation is ~300 m/Ma [1]. This value is consistent with data reported by other researchers based on Ar/Ar dating [11] and the apatite tracking method [13]. According to these researchers, the exhumation rate of metamorphic rocks does not exceed 0.3–1.5 mm/yr. Using this range of the exhumation rate, we can calculate the time required for the uplift of Korda metapelites up to the isotherm level of 330°C: t = 5–9 (km)/0.3–1.5 (km/Ma) = 3–25 Ma. Thus, the collisional metamorphism was probably 3–25 Ma older than the stage of uplift and cooling of metapelites based on the Ar/Ar isotope method. If we use the maximal estimate of the duration of uplift, the culmination stage of collisional metamorphism should not be older than 848–851 Ma. These estimates indicate the Neoproterozoic age of collisional metamorphism. They are consistent with the K–Ar muscovite dating of collisional metamorphism (792–856 Ma) for the Transangara region of the Yenisei Ridge [14].

Our estimates indicate an insignificant time interval between processes of the exhumation of metamorphic complexes in the Panimba fault zone and the culmination stage of collisional metamorphism. This conclusion is consistent with the data reported by other researchers [15]. The exhumation of metamorphic complexes in real geodynamic settings is provided by the corporative effect of tectonic mechanisms with a significant endowment of erosional denudation.

The materials discussed above indicate that the emplacement and evolution of granitoids of the Yeruda pluton predated the collisional metamorphism of Korda metapelites by approximately 30–33 Ma. This conclusion does not contradict the geological data suggesting that the fault-line granitoids were subjected to crushing and gneissic alteration with the development of cataclasite and blastomylonite zones (Fig. 1). It should be noted that the emplacement of intraplate granitoids of the Chirimba pluton at the later postcollision stage (761.5 ± 8 Ma based on the U/Pb zircon dating [4]) did not lead to alteration of the K/Ar isotope system and heating of metamorphic rocks in the study region.

Thus, the $^{40}Ar/^{39}Ar$ biotite datings of metapelites in the outer and inner zones of collisional metamorphism near the Panimba thrust fault yielded age estimates of 823.3 ± 8.6 and 826.3 ± 7.4 Ma, which correspond to the stage of rock cooling down to temperatures below ~360°C. With allowance made for the rate of rock exhumation, these estimates indicate that the culmination stage of collisional metamorphism was not older than 848–851 Ma. The significant age discrepancy (~30–33 Ma) between the Yeruda granitoids (~880 Ma [4]) and the Korda collisional metamorphism suggests a younger age of the latter event.

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