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GEOLOGY

The Vendian Accretionary Event in the Southwestern Margin of the Siberian Craton

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The present-day southwestern margin of the Siberian Craton is represented by its Early Precambrian inliers (Angara–Kan and Sayan) and Mesoproterozoic–Neoproterozoic marginal continental region that includes the Yenisei Range and Sayan areas (Fig. 1). The Early Precambrian evolution of structures of the Siberian Craton culminated with formation of the Early Proterozoic Angara continental-margin foldbelt, intense intrusion of granitoids (1.87–1.84 Ga ago), and its general consolidation [1]. Mesoproterozoic–Neoproterozoic fold–thrust complexes in the trans-Angara part of the Yenisei Range and largely riftogenic complexes of the Sayan region demonstrate all features typical of the ensialic marginal continental and intracontinenal structures. Precambrian blocks and terranes in folded structures of the Central Asian foldbelt were united into the Sayan–Yenisei accretionary belt. The belt includes Early and Late Proterozoic island-arc and oceanic terranes (Central, Idar, and Shumikha–Kirel terranes in the Kan block; Arzybei, Isakovka, and Predivinsk) or terranes with substantially metasedimentary sections (Derba) and fragments of oceanic and island-arc structures (Kuvai Group) overlain by Vendian–Cambrian strata in the Man Trough.

The age of accretionary–collision processes, which promoted amalgamation of Precambrian terranes and their amalgamation with the Siberian Craton margin, remains an open problem. Nearly synchronous metamorphism and granite intrusions in two or more terranes, as well as formation of synchronous molasses in foreland basins, serve as indicators of the accretionary–collision processes. The purpose of this work is to determine, based on the above-mentioned criteria, the age of the main event that produced the Sayan–Yenisei accretionary belt and terminated the Neoproterozoic history of the Siberian Craton. We carried out complex Ar–Ar dating of amphiboles and biotites from metamorphic rocks in Precambrian terranes and from the marginal zone of the Siberian Craton, U–Pb dating of zircons from collision-related granitoids, and sedimentological studies in Vendian foredeeps. Given below is a brief characteristic of Precambrian terranes, which were the main objects of study.

Three terranes (Central, Idar, and Shumikha–Kirel) are recognized in the structure of the Kan block (Fig. 1). They differ from each other in lithology and age of the constituting rock associations and are characterized by tectonic boundaries [2].

The *Central Terrane* is represented by the Paleoproterozoic lithotectonic complex and constitutes an old “core” of the block under consideration. The lower part of the section is largely composed of metavolcanics of the tholeiitic–basaltic and calc-alkaline associations, while metasediments prevail in its upper part. Orthogneisses (metadacites) aged 2.3 Ga are characterized by positive ε_{Nd} (from 1.8 to 3.0) and T(DM) = 2.4–2.5 Ga values. Similar values of the model age (2.3–2.6 Ga) are established also for graywackes. Based on characteristic geochemical parameters, the metamorphosed volcanogenic–terrigenous complex is comparable with igneous associations and graywackes formed in subduction settings. The stratified complex is intruded by Late Vendian (555 ± 5 Ma) trondhjemites of the Verkhnii Kan Massif [2].

The *Idar Terrane* is separated from the Central Terrane by the thrust zone. The lower part of the stratified complex is composed of metamorphosed rocks of the komatiitic–tholeiitic series, which are comparable with oceanic volcanics in geochemical properties. They enclose intrusive ultramafic and ultramafic–mafic massifs crosscut by plagiogranite veins. The section is supplemented in the southeastern direction with a sequence of garnet-bearing biotite and amphibole paragneisses (metagraywackes), which are similar (in the composition of trace elements) to terrigenous sediments of island arcs. Paragneisses are characterized by a wide range of model Nd age varying from 1.3 to 2.5 Ma.

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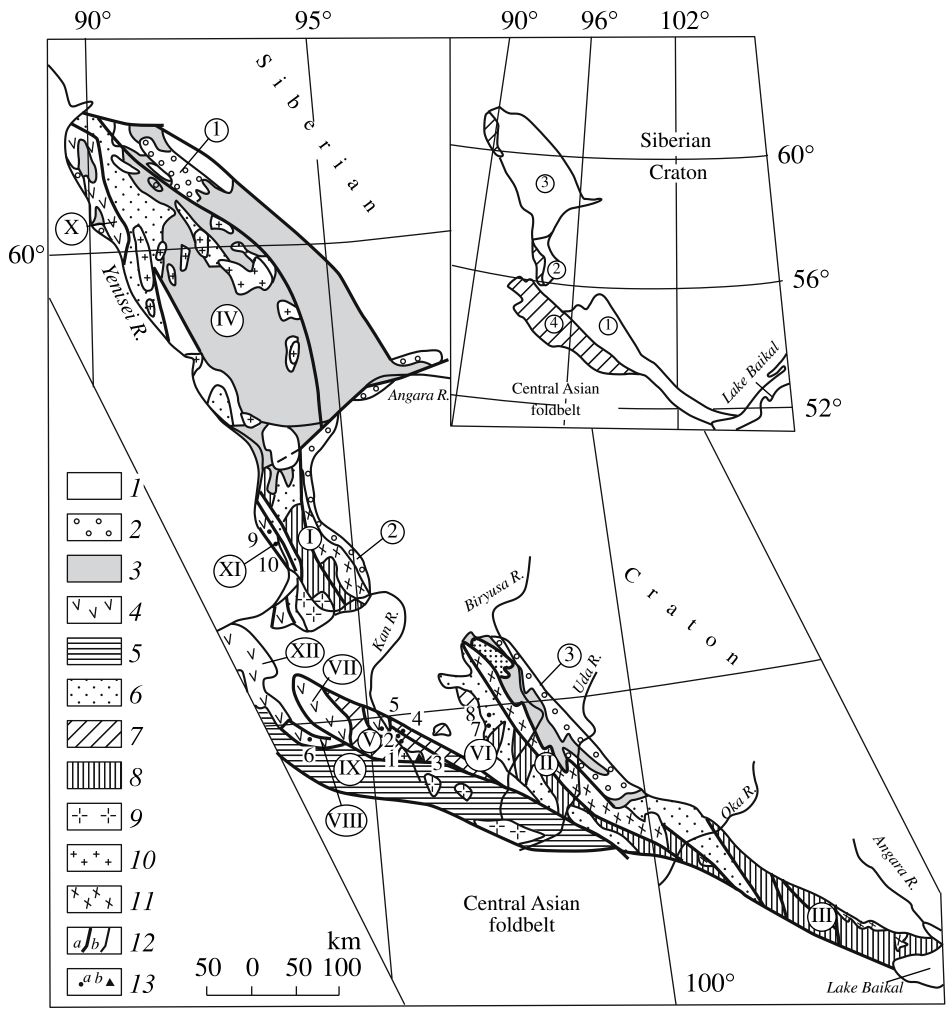

Fig. 1. Schematic distribution of Proterozoic subduction–accretionary complexes and Vendian epicontinental sediments in the southwestern margin of the Siberian craton. (*1*) Phanerozoic sedimentary cover; (*2*) Vendian sediments of foredeeps; (*3, 4*) Proterozoic complexes: (*3*) marginal continental, (*4*) oceanic and island-arc; (*5*) Neoproterozoic metamorphosed terrigenous–carbonate complexes of the passive margin; (*6*) Paleoproterozoic continental-margin complexes of the Angara foldbelt; (*7*) Paleoproterozoic island-arc complexes; (*8*) Archean complexes of the craton; (*9–11*) granitoids: (*9*) Early Paleozoic, (*10*) Neoproterozoic, (*11*) Paleoproterozoic; (*12*) fault zones (*a*) and other geological boundaries (*b*); (*13*) sampling sites for Ar–Ar (*a*) and U–Pb (*b*) dating and their numbers. Terranes of the Kan block: Central Terrane: (1) Sample P-70-94, (2) Sample P-136-93, (3) Sample P-42-04 (Verkhnii Kan Massif); Idar Terrane: (4) Sample KH-7-92; Shumikha–Kirel Terrane: (5) Sample P-64-97; Arzybei Terrane: (6) Sample P-1-92; Biryusa block: (7) Sample A-59-81, (8) Sample A-76-81; Predivinsk Terrane: (9) Sample A-116-78, (10) Sample 16. Blocks: (I–III) Early Precambrian inliers of the craton basement: (I) Angara–Kan, (II) Biryusa, (III) Sharyzhalgai; (IV) Proterozoic continental margin of the Yenisei Range; (V–XI) terranes of the Neoproterozoic Sayan–Yenisei accretionary belt: (V–VII) terranes of the Kan block: (V) Central, (VI) Idar, (VII) Sumikha–Kirel, (VIII) Arzybei, (IX) Derba, (X) Isakov, (XI) Predivinsk; (XII) fragments of the Kuvai island-arc oceanic complex. Vendian foredeeps (encircled numerals): (1) North Yenisei, (2) South Yenisei, (3) Sayan. Legend for the inset. (1, 2) Sayan and Angara-Kan inliers, respectively, of the craton basement; (3) Proterozoic marginal continental folded region of the Yenisei Range; (4) Neoproterozoic North Yenisei accretionary belt (shaded).

This fact indicates different-age sources of terrigenous material and determines the lower age boundary of sedimentation at ±1.3 Ga. Metamorphosed rocks of two terranes are characterized by mineral associations of the amphibolite and epidote–amphibole facies. The maximal P values estimated for garnet-bearing amphibolites are 7.7–8.5 kbar, which are consistent with finds of kyanite. These values indicate elevated pressure and temperatures of 600 to 700°C during metamorphism [2].

The *Arzybei* and *Shumikha–Kirel terranes* are composed of Mesoproterozoic–Neoproterozoic island-arc complexes [3, 4]. The Shumikha–Kirel Terrane contains two Neoproterozoic rock associations: (1) calc-alkaline metavolcanics of the basalt–andesite–dacite series with comagmatic intermediate–acid volcanics represented by tonalities of the Shumikha intrusion (686 ± 32 Ma); (2) tholeiitic high-Ti metabasalts and low-K metadacites–rhyodacites. The latter rocks are compositionally similar to oceanic plagiogranites [3]. The rocks of the first and second associations are comparable with volcanics of ensimatic island arcs and back-arc basins, respectively. The stratified metamorphic complex of the *Arzybei Terrane* can be divided into two sequences. The lower metamorphosed volcanogenic sequence includes protoliths corresponding to island-arc tholeiitic basalts and calc-alkaline volcanics of the basalt–andesite series. The upper sequence is composed of metagraywackes intruded by granitoids of the tonalite–trondhjemite series (1017 ± 47 Ma) and postorogenic granites (560 ± 20 Ma) [4]. Mineral associations from gneisses and amphibolites of the Arzybei and Shumikha–Kirel terranes suggest conditions of amphibolite and epidote–amphibolite facies. Single quantitative estimates of the *PT* conditions of metamorphism available for biotite–amphibole gneisses of the Arzybei block are 2.5 to 3.0 (±1.2) kbar and 540–550 (±40)°C, respectively.

The Biryusa block comprises uplifts and troughs. The uplifts are composed of Late Archean gneisses, migmatites, and granulites (Khailoma Group) and Early Proterozoic granitoids. The protoplatform troughs are filled with Early Proterozoic metasedimentary sequences of the Neroi Group. Granitoids (1.87–1.75 Ga) [5] were intruded after Early Proterozoic high-temperature metamorphism (±1.9 Ga), which reflects collision of ancient blocks with the Siberian Craton. Regional metamorphism of the overlying carbonate–quartzite–schist complex (Neroi Group) is characterized by zoned patterns, kyanite specialization, and lower temperatures [6]. Thermometric data on mineral equilibriums obtained with account for chemical zoning of coexisting minerals indicate confinement of thermal (up to 680°C) and baric (up to 7 kbar) maximums to the central part of the Tumanshet Trough.

Figure 2 presents results of the Ar–Ar studies. The Vendian stage of tectonothermal transformation reflected in metamorphism up to amphibolite facies is best manifested in volcanosedimentary complexes of three terranes constituting the Kan block with ages ranging from the Paleoproterozoic to the Neoproterozoic. The similar range of Ar–Ar ages (600–550 Ma) obtained for biotites and hornblendes from metamorphosed volcanosedimentary rocks of all terranes in this block and also for collision-related granitoids serves as a reliable argument in favor of their amalgamation into a single structure precisely in the Vendian. The identical value of the Ar–Ar age (555 ± 7 Ma) is also established for hornblende from amphibolites of the Arzybei Terrane. The upper age limit for metamorphism corresponds to the U–Pb age of igneous zircons from the Verkhnii Kan trondhjemite massif (555 ± 5 Ma) that intrudes rocks of the Central Terrane (Kan block) [2] and posttectonic granites of the Shirokii Log Massif (560 ± 20 Ma) in the Arzybei Terrane [4]. The Verkhnii Kan Massif represents a large pluton (±400 km^2) with intrusive contacts that are discordant relative to gneissosity and folded structure of the enclosing sequence. This fact implies the postorogenic origin of the massif.

Thus, the above-mentioned isotopic–geochronological data suggest that metamorphic (tectonothermal) transformations in three terranes of the Kan block and in the Azyrbei Terrane commenced approximately 600 Ma ago and culminated with intrusion of granitoid plutons 550–560 Ma ago. Nearly synchronous metamorphism and formation of granitoid plutons resulted from accretionary–collision processes that were responsible for amalgamation of different-age Precambrian terranes. However, the Vendian orogeny provoked not only the amalgamation of terranes of different ages, but also the collision of terranes with the margin of the Siberian Craton. This is evident from synchronous manifestations of thermal transformations in rocks of the Biryusa block. Hornblendes from two stratiform amphibolite bodies in the lower part of the Neroi section yielded an Ar–Ar age of 546 ± 6 and 577 ± 6 Ma. This age estimate corresponds to that of the event reflected in Precambrian blocks of the folded framing of the craton.

The temperature values obtained for the closure of the Ar–Ar isotopic system of hornblende and biotite [7] imply that regional heating of sequences in a large area (no less than 16 000 km^2) reached temperatures of 300–600°C, which accords with previously cited temperature estimates for metamorphism based on mineral parageneses. The thermal regime of collision is evident from genetic features of trondhjemites in the Verkhnii Kan Massif. Its rocks are characterized by high concentrations of Sr (1100–2100 ppm) and Ba (1000–2200 ppm) and high La/Yb_n and Sr/Y values (15–32 and 130–210, respectively) corresponding to Ba- and Sr-rich granites. The depletion of trondhjemites in heavy REE is explained by the formation of the initial melt in equilibrium with garnet. According to experimental data on melting of metabasites, this event occurred under P = 10 kbar and $T \geq 900$°C [8]. The isotopic composition of trondhjemites ($\varepsilon_{Nd} = -0.8$) and high Ba and Sr concentrations indicate formation of the acid melt largely from the juvenile basite source, which was comparable (in its geochemical characteristics) with intraplate Ba- and Sr-rich basalts with a limited (10–15%) contribution of material from the Paleoproterozoic crust of the Central Terrane [9]. The signs of the mantle–crust interaction during the formation of trondhjemites suggest underplating of basaltic melts beneath the base of the Early Proterozoic crust. Thus, the high-temperature regime of collision was probably provided by the rise of heated mantle material in response to the collapse of the newly formed orogen. This process was responsible for intense thermal transformations of Proterozoic volcanosedimentary sequences.

Early manifestations of Vendian accretion and collision at the western margin of the Siberian Craton are also established by the Ar–Ar dating of hornblendes from amphibolites of the Neoproterozoic island-arc complex in the Predivinsk Terrane [10] that adjoins the Early Precambrian Angara–Kan block (South Yenisei Range). According to our data, amphiboles from the Predivinsk and Yudinka sequences formed 614 ± 8 and 606 ± 8 Ma ago, respectively.

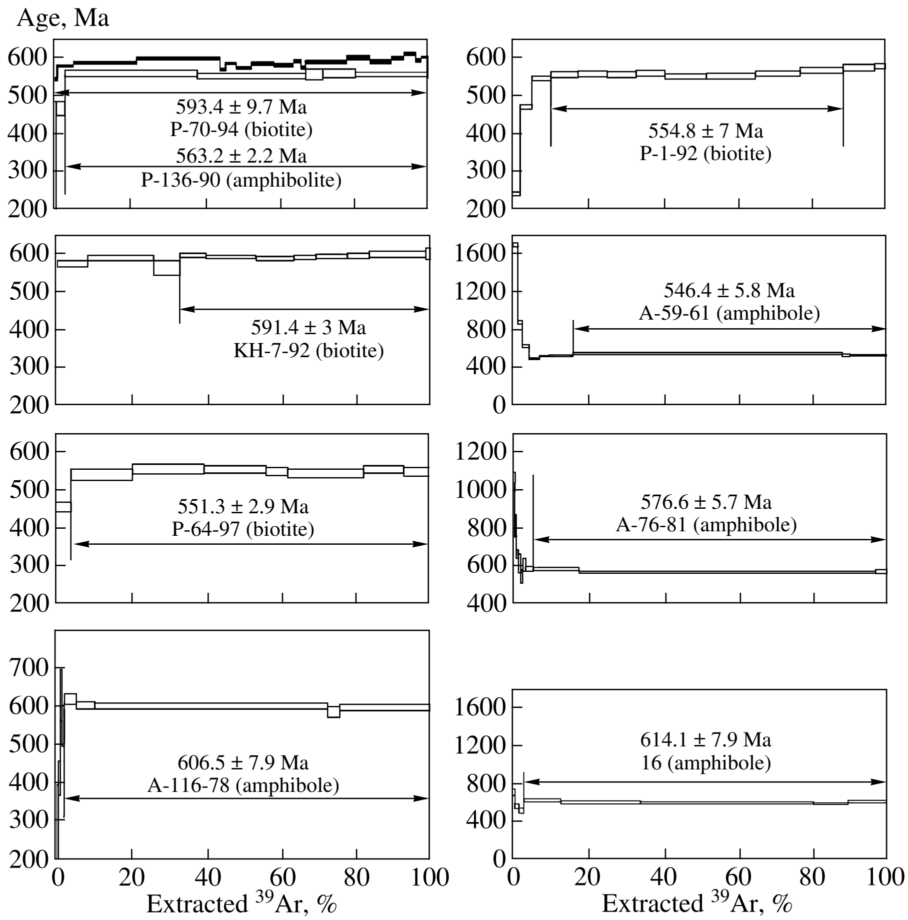

Fig. 2. Ar–Ar ages of minerals from metamorphic rocks in different blocks of the northwestern Sayan region.

The Vendian sedimentation history in the southwestern Siberian Craton is recorded by stratigraphically complete sedimentary sections in foredeeps in the Yenisei Range, Sayan and Baikal regions, and Patom Highland. The pre-Vendian regression of Late Riphean basins in aulacogens and the deep glacial erosion of the exposed shelf were followed by regional subsidence of the Siberian Craton and the formation of a peripheral foreland basin [11]. Based on chemostratigraphic correlation with the reliably dated Vendian foreland basin in the Kalahari Craton (Namibia), it is inferred that Vendian sedimentary successions are complete and their sedimentation stages may be correlated with the chronological scale [12]. The formation of the regional tillite unit and first subsidence phase are synchronous with the Early Varangian Glaciation (~600 Ma ago). The Early Vendian (largely marine) stage of the sedimentary basin development (Marnino Supersequence) related to the commencement of terrane accretion and subsidence of the craton margin was marked by orientation of clastic dispersion systems from the craton to marginal seas. The Late Vendian (largely continental) stage (Grebenskoi Supersequence) was characterized by the formation of external orogens and intense subsidence of foredeeps with progradation of alluvial complexes toward the craton.

According to paleotectonic and sedimentological criteria, the Vendian orogeny along the southwestern and southern boundaries of the Siberian Craton is evident from the following data: (1) formation of a chain of intensely subsided narrow 2500-km-long foreland (molasse) troughs with sharply reduced thickness of the wedge of clastic sediments on synchronous uplifts; (2) wide development of interlaced and reticulate fluvial systems that formed spacious piedmont alluvial plains with centripetal flows of clastic material; (3) lithoclastic low-feldspar sources of recycled sandy and fine-grained clastic material provided by erosion of slightly metamorphosed sedimentary sequences developed in Riphean margins of the Siberian Craton; and (4) synchronous activation of orogens, reflected in incision and progradation of river valleys.

In the North Yenisei foredeep (Fig. 1), the Late Vendian molasse is represented by the red-colored Nemchan Formation (2.5–3.0 km) composed of alluvial cyclic sediments transported toward the north, northeast, and southeast. In the eastern Baikit foreland uplift, its stratigraphic analogue (the Oskobin Formation of sandy and carbonate sediments) is a few tens of meters thick and pinches out at its arch. In the South Yenisei foredeep, Upper Vendian fluvial sediments of the Grebenskaya and Veselovskaya formations form a red-colored thick sequence (up to 1.5 km) that is reduced to 70 m in the adjacent Udorong Uplift. Numerous observations revealed that the flows are mainly oriented in the NNE direction. In the Sayan foredeep, variegated Upper Vendian alluvial sediments constitute the Aisin (Ikei) Formation (up to 1.5 km thick) with a similar vector of the material transport. Approximately 100 km away from the trough, the thickness of analogues of the Aisin Formation is a few tens of meters. The sedimentological analysis of the Upper Vendian molasses revealed the uniform structure of the clastic basin: a narrow peripheral zone of intense subsidence and the internal zone of a thin apron an order of magnitude wider. Along with the above-mentioned peculiarities of the material dispersion system and sediment composition, this regularity is considered as a typical feature of synsedimentary orogenesis and formation of the foreland basin at the margin of the lithospheric plate in response to its underthrusting beneath another lithospheric plate.

The coeval foreland basin that developed in the northeastern East European Platform may be considered as an analogue of the Vendian peripheral foreland basin of the Siberian Craton. In terms of sedimentary succession and chronology, the Vendian foreland basin of the East European Platform [13] is similar to its Siberian counterpart [11]. Judging from the age of igneous alkaline rocks and granitoids of hinterland, diorites, and cleavage-crossing dikes [14], tectonothermal processes in Timan, which were responsible for the formation of the thrust–fold belt (Timanides) in the northeastern margin of the East European Platform, commenced approximately 610–600 Ma ago and terminated 560–550 Ma ago. The presented data demonstrate that the Vendian orogenesis and succession of tectonothermal and sedimentological events were likely synchronous along the periphery of large Precambrian cratons of Baltica and Siberia, which implies their interrelationships during that epoch.

Thus, the accretionary-collision event resulted in development of the accretionary belt and lateral accretion of the continental crust to the margin of the Siberian Craton by the terminal Vendian as well as in reworking and recycling of the newly formed crust during the formation of the peripheral foreland basin. Similarly to adjacent parts of the Central Asian foldbelt, the final cratonization of the structures under consideration occurred during the Caledonian epoch and was accompanied by large-scale granite intrusion. In the Sayan–Yenisei accretionary belt, these events are distinctly manifested in metamorphism and formation of syncollision granitoids (500 Ma ago) in the Derba Terrane [15].

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