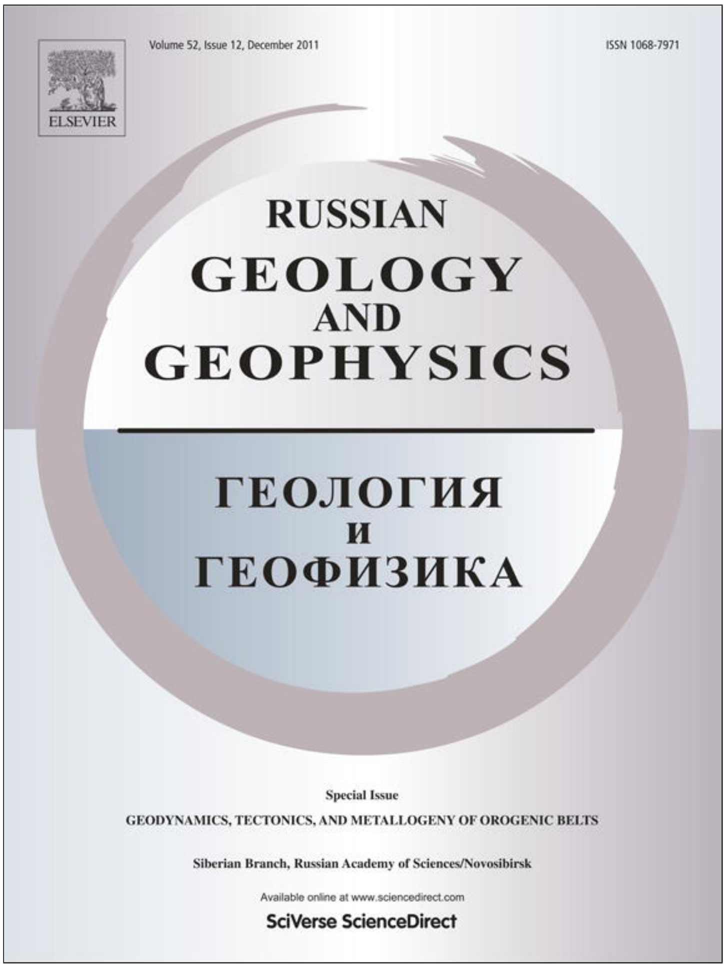
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# Relationship between the Ordovician and Carboniferous–Permian collisional events in the southeastern Tunka bald mountains, East Sayan (*southwestern framing of the Siberian Platform*)

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**Abstract**

Granites from the Tunka pluton of the Sarkhoi complex, located in the eastern Tunka bald mountains (East Sayan), have been dated at the Middle Ordovician (462.6 ± 7.8 Ma) by LA ICP MS. The granites of the Sarkhoi complex within the studied area cut a foldthrust structure consisting of deformed fragments of the Vendian (Ediacaran)–Early Cambrian cover of the Tuva–Mongolian microcontinent (Upper Shumak metaterrigenous formation, Gorlyk carbonate formation). The red-colored conglomerates and sandstones of the Late Devonian–Early Carboniferous(?) Sagan-Sair Formation overlie the eroded surface of the Tunka pluton granites in the eastern Tunka bald mountains. The Sagan-Sair Formation, in turn, is overlain along a low-angle thrust by a group of tectonic sheets, which comprises the volcanic and carbonate sediments of the Tolta Formation, biotitic schists, and plagiogneisses with garnet amphibolite bodies. Two nappe generations have been revealed on the basis of the described geologic relationships, the Middle Ordovician age of the Tunka pluton granites, and numerous Late Paleozoic Ar–Ar dates of syntectonic minerals from the metamorphic rocks in the area. The first thrusting stage was pre-Middle Ordovician, and the second, Late Carboniferous–Permian. The Lower Paleozoic thrust structure resulted from the accretion of the Tuva–Mongolian microcontinent to the Siberian Platform. The Late Paleozoic nappes resulted from intracontinental orogeny and the reactivation of an Early Paleozoic accretionary belt under the effect of the Late Paleozoic collisional events.


*Keywords:* tectonics; orogeny; geochronology; granites; U–Pb dating; Central Asian Fold Belt; East Sayan

## Introduction

The Tunka bald mountains (East Sayan) have a complex fold–thrust structure (Belichenko et al., 2003; Boos, 1991), made up of the Late Precambrian and Lower Cambrian variously metamorphosed terrigenous, volcanic, and carbonate rocks (Dobretsov, 1988; Letnikova and Geletii, 2005; Shkol'nik et al., 2009). It is universally accepted that the fold–thrust structure of the East Sayan, including its southeastern part, which is distinguished as the Tunka terrane (Belichenko et al., 2003) or Il'chir zone (Fedotova and Khain, 2002), formed in the Ordovician, when the Tuva–Mongolian microcontinent (TMM) was accreted to the Siberian Platform (Kuz'michev, 2004).

The Tunka terrane (Fig. 1) is located almost entirely within the TMM, forming a complex allochthonous structure on its northeastern margin. The autochthon is exposed in a window and consists of the Vendian–Cambrian carbonate and terrigenous sediments covering the TMM (Upper Shumak, Gorlyk, Ara-Oshei Formations) (Boos, 1991)). The allochthon contains volcanic and carbonate sediments, interpreted as paleoisland-arc and back-arc complexes (Belichenko et al., 2003; Shkol'nik et al., 2009). The Khamar-Daban terrane is overthrust upon the Tunka one in the south. It consists of high-grade rocks: mafic granulites, biotite gneisses, calciphyres, and marbles. The formation of the Khamar-Daban terrane is attributed to island-arc and back-arc basin activity (Belichenko et al., 2003). The multifacies metamorphism of the rocks in the Khamar-Daban terrane reaches the granulite facies and is 488–471 Ma old (Salnikova et al., 1998). The postmetamorphic granites cutting the metamorphic zoning of the Khamar-Daban terrane are 469 ± 2 Ma old (Barash et al., 2006).

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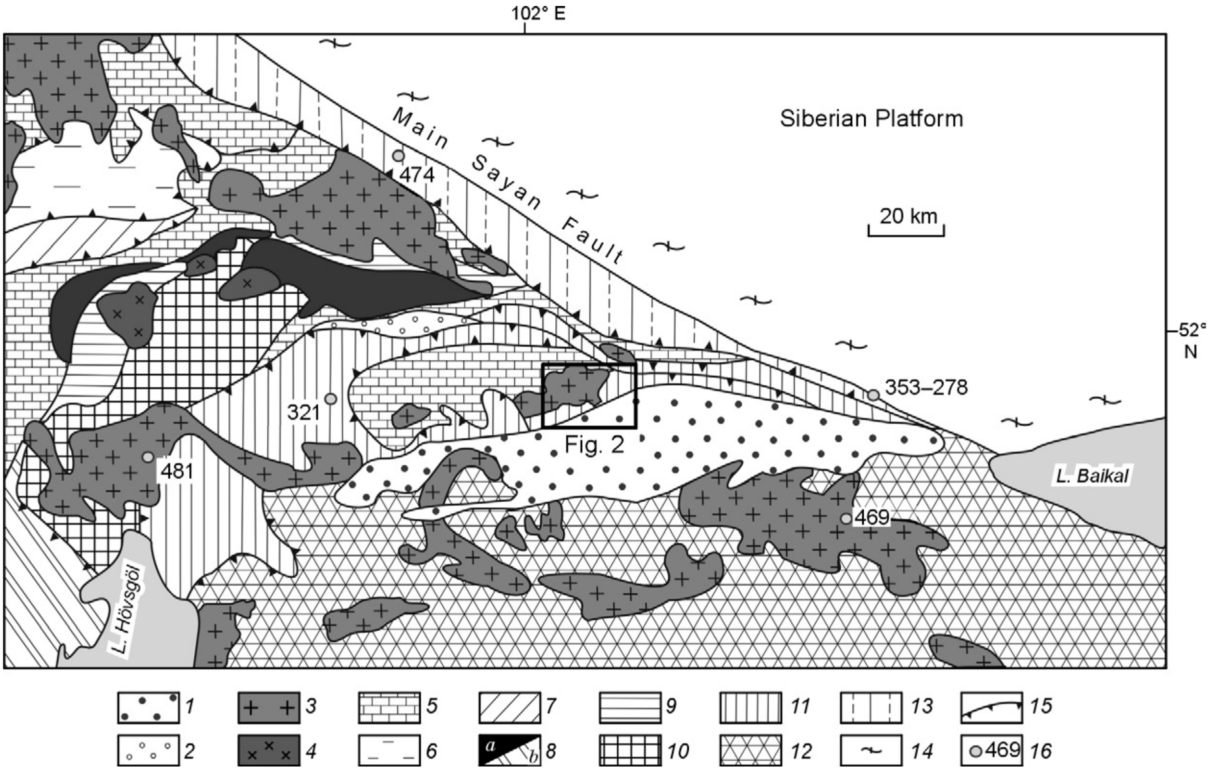


Fig. 1. Geological sketch map of southwestern Cisbaikalia, simplified and modified after (Belichenko et al., 2003). *1*, Cenozoic sediments of the Tunka basin; *2*, Late Devonian–Early Carboniferous(?) molassoid sediments (Sagan-Sair Formation); *3*, Ordovician and, partly, later (undifferentated) granitoids; *4*, Riphean granitoids; *5*, Vendian–Lower Cambrian cover sediments of the Tuva–Mongolian microcontinent; *6–10*, Riphean basement of the Tuva–Mongolian microcontinent: *6*, sedimentary and volcanosedimentary rocks of the Oka Group (Late Precambrian); *7*, volcanosedimentary rocks (Hugeyn Group); *8*, ophiolites (*a*), turbidites (*b*); *9*, carbonate sediments of the Riphean cover of the Gargan block; *10*, Early Precambrian metamorphic rocks of the Gargan block; *11*, Tunka terrane; *12*, Khamar-Daban terrane; *13*, Kitoi-Kin zone; *14*, basement of the Siberian Platform (Sharyzhalgai marginal salient); *15*, nappe boundaries; *16*, ages (Ma) of the granite and metamorphic complexes in the region (481 (Reznitskii et al., 2007); 474 (Donskaya et al., 2000); 469 (Barash et al., 2006); 353–278 (Savel'eva et al., 2010); 321 (Belichenko et al., 1988)).

The Khamar-Daban terrane, together with the Tunka one, forms a single fold–thrust structure, which predated the Ordovician zonal metamorphism, as evidenced by the superimposition of metamorphic isogrades on the nappe boundaries. The metamorphic isogrades cut the fold–thrust structures of the Tunka terrane and are cut by the granitoids of the Munku-Sardyk pluton, located in the western Tunka bald mountains. This pluton is a suture complex cutting the sediments of the TMM, Tunka terrane, and Khamar-Daban terrane and discordant with respect to the metamorphic zoning in the above-listed terranes. The age of the granitoids is placed at the upper limit of the accretion and metamorphism of the studied terranes. The granitoids of the Munku-Sardyk pluton were dated at the Middle–Late Ordovician (452 ± 16 Ma, Rb–Sr method) (Litvintsev and Kalmychkova, 1990). Later the U–Pb method yielded an age of 481 ± 2 Ma (Reznitskii et al., 2007), suggesting that the terrane accretion had ended as early as the Early Ordovician. For the eastern Tunka terrane, data on the age of the granitoids cutting the deformed cover of the TMM were absent until recently.

The Early Ordovician age of the terrane accretion is confirmed by geochronological studies of the adjacent areas. In the Oka zone (East Sayan), the quartz porphyry dikes cutting the thrust structure are 476 ± 4 Ma old (Rytsk et al., 2000). The metamorphic rocks of the Kitoi-Kin zone, located between the eastern Tunka terrane and the Siberian craton, are 474 ± 3 Ma old (Donskaya et al., 2000). Granulite metamorphism in the Slyudyanka metamorphic complex is 481 ± 2 Ma old, and the intruding postmetamorphic quartz syenites are 474 ± 5 Ma old (Kotov et al., 1997). To the northeast of Lake Baikal, the Barguzin terrane features gneissic granites with an age of 469 ± 4 Ma, which make up domes within an Early Paleozoic collisional system (Rytsk et al., 2009). In all these cases, high-grade metamorphism is attributed to the accretion of the terranes to the Siberian Platform. It has been found that the Tunka terrane is part of a Caledonian fold–thrust accretionary structure on the southern margin of the Siberian Platform.

In the Late Paleozoic, the region experienced tectonic activation, manifested in magmatism, metamorphism, sedimentation, and structuring. The thrust structure of the eastern Tunka bald mountains (Arshan area), studied in detail in (Ryabinin et al., 2011), is Late Carboniferous–Early Permian (Buslov et al., 2009). Kinematic (including petrofabric) and dynamic analyses, as well as the results of the $^{40}Ar/^{39}Ar$ dating of syntectonic minerals, were used in (Ryabinin et al., 2011) for distinguishing the following deformational stages in the region (Ma): 316–310, thrust faults; 305–303, fold deformation; ~286, strike-slip faults. The isotope-geochronological dating and structural analysis are confirmed directly by geologic relationships. In the eastern Tunka bald mountains, to the northwest of Arshan Village, a complex of tectonic sheets of different compositions is overthrust at a low angle upon the red-colored conglomerates and sandstones of the Sagan-Sair Formation. Numerous fish scales, plant impressions, spores, and pollen suggested the Late Paleozoic–Early Mesozoic (most probably Permian) age of the formation at the stratotype locality (Butov et al., 2001). The sediments of the Sagan-Sair Formation in the region form asymmetric V-shaped basins, partly overlain by N-verging thrusts (for example, the Sagan-Sair syncline (Arsent'ev, 1969)). Since the Sagan-Sair Formation is overlain by tectonic sheets with micaceous mylonites (306–285 Ma, Ar–Ar dating) at the bottom (Buslov et al., 2009; Ryabinin et al., 2011), it must be older than the Late Carboniferous.

The Late Paleozoic orogenic stage in the region included thrusting. This stage was reflected in deformations, magmatism, and metamorphism in the Tunka terrane and adjacent areas. The formation of the fold–thrust structure was simultaneous with the activation of shears along the Main Sayan Fault, which is the boundary between the Siberian Platform and the fold complexes of the Altai–Sayan region. The syntectonic metasomatic rocks in the Main Sayan Fault are Late Carboniferous (Savel'eva et al., 2003); Ar–Ar amphibole and biotite dating yielded the following ages: $321 \pm 5$, $317.0 \pm 1.7$, $310.5 \pm 1.7$, and $309.3 \pm 2.9$ Ma. The fault zone features several generations of granite veins of different chemical and petrographic compositions ($353 \pm 1.9$, $334 \pm 14$, $310.5 \pm 1.7$, $278.2 \pm 4.3$ Ma); the oldest ones are Early Carboniferous, and the youngest ones are Early Permian (Savel'eva et al., 2006, 2010).

Dikes and stocks of alkali and subalkalic granitoids formed along large faults in the Tunka and Khamar-Daban terranes and Oka zone in the Late Paleozoic. On the basis of Rb–Sr granitoid dating, four episodes of magmatism were distinguished: 319–317 (Rasskazov et al., 2003a), 307–304, 283–281, and ~261 Ma (Rasskazov et al., 2003b). They correlate with the ages of the granitoids and syntectonic metasomatic rocks from the Main Sayan Fault and the formation of the fold–thrust structure in the Arshan area (Tunka bald mountains). The predominant near-N–S orientation of the dikes suggests that the magmatic melts were emplaced during roughly N–S-trending crustal shortening; this agrees with the northern vergence of the Late Paleozoic nappes and dynamic analysis of the fold–thrust structure in the Arshan area (Ryabinin et al., 2011).

The central Tunka terrane features Late Carboniferous zonal metamorphism. In the central part of the Khongoldoi block, the metamorphic rocks corresponding to the disthene–staurolite zone of regional metamorphism were dated by the Rb–Sr radioisotope method at the Late Paleozoic ($312 \pm 20$ Ma) (Belichenko et al., 1988).

The geochronological, geological, and structural data suggest that a long-lasting Late Paleozoic orogenic stage took place in the Caledonian Tunka terrane. The deformational complexes of the variously aged Paleozoic orogenic stages are spatially related in the present structure of the terrane.

The study is devoted to the relationships between these stages within the eastern Tunka bald mountains. It is aimed at describing, dating, and interpreting two asynchronous nappe generations in the Tunka terrane.

## Geologic position of the granites of the Sarkhoi complex in the thrust structure of the eastern Tunka terrane

Two thrusting stages are well-defined in the geologic structure of the Arshan area in the Tunka bald mountains (East Sayan) (Fig. 2). The lower and upper complexes of tectonic sheets are separated by the Late Devonian–Early Carboniferous(?) Sagan-Sair Formation; the latter is neoautochthonous for the lower complex, and the upper one is overthrust upon it. The lower complex is cut by the granite plutons of the Sarkhoi complex.

The lower sheet complex contains folded sheets of the metaterrigenous greenschists of the Upper Shumak Formation and the metamorphosed carbonate sediments of the Gorlyk Formation. The sediments of the Upper Shumak Formation are greenschist-metamorphosed metasandstones with lenses of deformed pebble metaconglomerate. The Gorlyk Formation is dominated by dolomites, which contain numerous lenticular bodies of alumina-rich quartz–garnet–sericite carbonaceous schists. The metamorphism was nonuniform: near the tectonic-sheet contacts, the rocks of the Upper Shumak Formation become quartz–biotite–amphibole schists, whereas slightly deformed conglomerates are preserved in the center. The Shumak and Gorlyk Formations are regarded as the sedimentary cover of the TMM and dated at the Vendian–Lower Cambrian (Anisimova et al., 2010; Letnikova and Geletii, 2005). The TMM cover is usually regarded as an autochthonous complex; however, considering its strong deformation, intense folding, metamorphism, and spatial isolation from the basement complexes, the detached and deformed cover is more of a para-autochthon (Dobretsov, 1989) or the lower allochthon. The tectonic origin of the contacts between the greenschist and carbonate sheets is evidenced by the presence of hydrothermal-alteration and crushed zones. In the core of a large antiform consisting of the sheets of the above-mentioned formations, biotitic plagiogneisses outcrop in erosional windows; they underlie the lower sheet complex and probably make up an autochthonous basement. The folded structure is violated by roughly E–W-trending steeply dipping shears.

The Ar–Ar dating of amphibole, muscovite, and biotite from the metamorphic rocks of the lower sheet complex yielded only Late Paleozoic ages ($310.7 \pm 3.0$ Ma for biotite and $286.8 \pm 4.8$ Ma for amphibole from the quartz–biotite–amphibole schists of the Upper Shumak Formation; $303.1 \pm 3.0$ Ma for biotite from the carbonaceous schists and $286.5 \pm 2.7$ for muscovite from the muscovitized carbonates

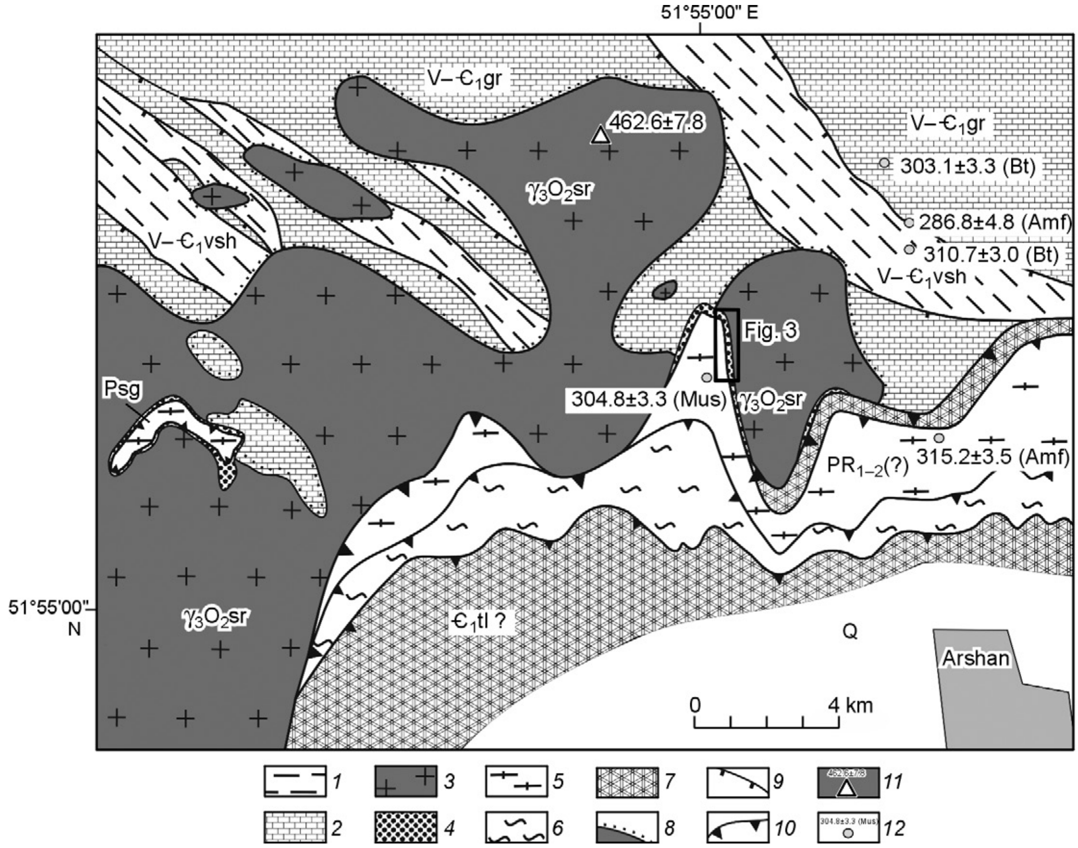


Fig. 2. Geological sketch map of the Arshan area. *1*, *2*, lower allochthon: *1*, Upper Shumak Formation (Vendian–Lower Cambrian): greenschists after sandstones and siltstones, metaconglomerate lenses; *2*, Gorlyk Formation (Vendian–Lower Cambrian): limestones, dolomites, interbeds of graphite–garnet–quartz schists; *3*, *4*, neo-autochthon-1: *3*, microcline granites and granosyenites (Middle Ordovician, third intrusive stage of the Sarkhoi complex); *4*, Sagan-Sair Formation (Late Devonian–Early Carboniferous(?)): red-colored conglomerates and sandstones; *5–7*, upper allochthon: *5*, Lower–Middle Proterozoic(?), gneisses with blocks of garnet amphibolites; *6*, biotitic schists; *7*, Tolta Formation (Lower–Middle(?) Cambrian): limestones interbedded with greenstone volcanics; *8*, intrusive contacts accompanied by hornfelsing; *9*, Cambrian–Early Ordovician thrusts; *10*, Carboniferous–Permian thrusts; *11*, site on which granites were sampled for U–Pb dating and the age obtained (Ma); *12*, sampling sites for Ar–Ar dating and the ages of amphibole (Amf), biotite (Bt), and muscovite (Mus) from the metamorphic rocks (Ma) (Buslov et al., 2009; Ryabinin et al., 2011).

of the Gorlyk Formation) (Buslov et al., 2009; Ryabinin et al., 2011).

The granites of the Tunka pluton of the Sarkhoi (Dobretsov, 1989) (Sayan (Arsent'ev, 1969; Samburg, 1971)) complex cut the folded structure formed by the tectonic sheets of the Upper Shumak metaterrigenous and Gorlyk carbonate formations. The rocks of these formations are altered near the contact with the granites. They are marked by hornfelsing, limestone and dolomite marmorization, migmatization, apophyses injection, and the formation of magmatic contact breccias.

The Sarkhoi complex formed in three stages: the first one is represented by diorites and quartz diorites; the second one, by granodiorites, biotitic granites, and binary granites; the third one, by microcline granites, leucocratic granites, and granosyenites (Samburg, 1971). The plutons are irregular and elongated along the strike of the folded structures; the late phases are often subisometric. Primary linear and gneissose structures are sometimes observed at the periphery of the plutons. Gneissosity coincides with the host rock orientation, and the contacts dip steeply. The complex shape of the bodies, the presence of host rock blocks among the granitoids, and the localization of the latter among slightly metamorphosed rocks suggest that the plutons of the Sarkhoi complex (Tunka bald mountains) have a shallow erosional truncation. The plutons formed in and after the final stage of the host rock folding (Arsent'ev, 1969; Samburg, 1971).

The upper complex of tectonic sheets is overthrust from the south upon the lower sheet complex and the intruding granitoids. It comprises sheets of the carbonate rocks of the Tolta and Urta-Gol Formations and biotitic schists and granite-gneisses with garnet amphibolite boudins. The Tolta and Urta-Gol Formations consist of limestones and dolomites; the Tolta one also contains greenstone volcanic units. The age of the formations is Cambrian (Dobretsov, 1988).

The heavily deformed biotitic granite-gneisses rich in amphibolite, including garnet amphibolite, bodies contain metamorphic zircons, whose cores are 2.7–2.4 Ga old and rims are 2.0–1.7 Ga old (Zhimulev et al., 2010). This gneiss sheet (Fig. 3) might be an exhumed fragment of an ancient continental block which was part of the TMM basement. The gneisses are permeated with numerous schistose zones, in which they become quartz–muscovite schists. The Ar–Ar dating of fine-grained muscovite yielded a plateau age of 304.8 ± 3.3 Ma (Ryabinin et al., 2011).

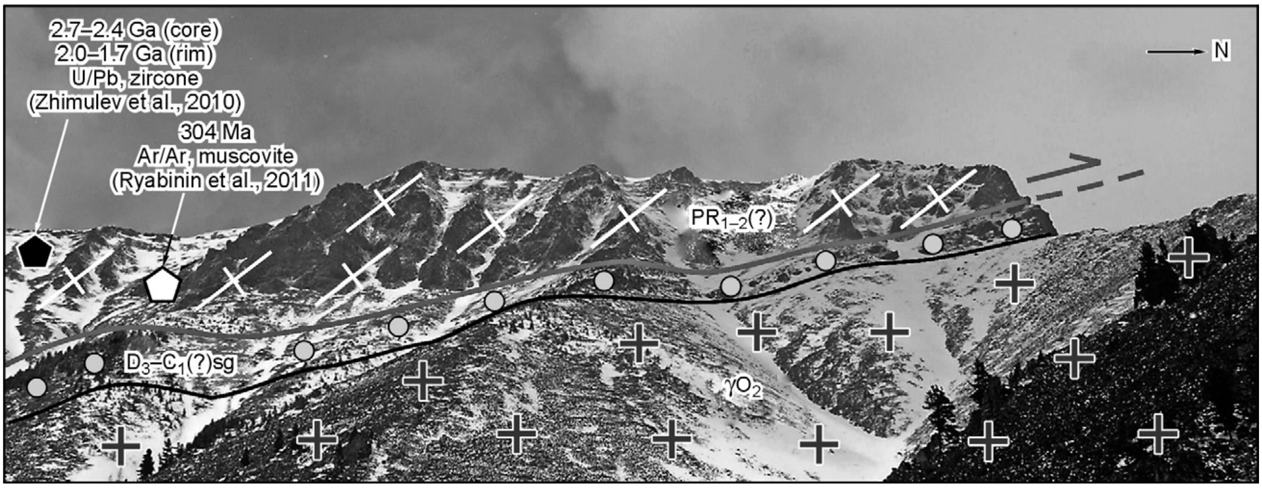


Fig. 3. Relationships of the granites of the Tunka pluton ($\gamma O_2$), the red-colored conglomerates and sandstones of the Sagan-Sair Formation ($D_3$–$C_1$(?)sg), and gneisses with the garnet amphibolite bodies from the upper sheet complex ($PR_{1-2}$(?)). Coordinates of the photographed place: 51°56′50″ N, 90°23′17″ E.

The Late Devonian–Early Carboniferous(?) Sagan-Sair Formation overlies (with a washout) the folded structure of the lower sheet complex and the intruding granites of the Tunka pluton. The upper sheet complex is overthrust upon the red-colored conglomerates and sandstones of the Sagan-Sair Formation (Fig. 3). In the western part of the area, it dips at only ~5°. In the case of dissected topography, tectonic outliers, with red-colored conglomerates and sandstones at the bottom, form on watersheds. The dip angles of the thrusts increase gradually westward to 25°–30°. The dip angles of bedding in the Sagan-Sair Formation vary in the same way; therefore, it is everywhere parallel to the nappe bottom. This suggests that the change in the dip angle of the thrust plane results from later folding. Many Late Paleozoic dates (316–286 Ma) were obtained by the Ar–Ar method for amphibole, biotite, and muscovite from the metamorphic rocks of the upper sheet complex. The geologic structure of the area and a model for its formation are discussed in detail in (Ryabinin et al., 2011).

The relationships described above show that the fold–thrust structure comprising the Gorlyk and Upper Shumak Formations developed before the accumulation of the Sagan-Sair Formation; this was followed by the emplacement of the granites of the Sarkhoi complex. By the time the Sagan-Sair Formation accumulated, the upper part of this structure had been eroded and the sealing granite plutons had outcropped. The age of the ancient fold–thrust structure in this area remained uncertain, because all the Ar–Ar isotope-geochronological age determinations for the lower structural stage belonged to the Late Paleozoic (Buslov et al., 2009; Ryabinin et al., 2011). According to the geological, structural, and geochronological data, the rocks of the ancient structural stage underwent retrograde metamorphism in the Late Paleozoic and the structure strongly altered. We determined the age of the sealing granites of the Tunka pluton (Sarkhoi complex) (Dobretsov, 1989) to date the deformation predating the intrusions and the Sagan-Sair Formation. Pink third-stage microcline granites from the Tunka pluton (sample T09051) were taken for dating from Mt. Trekhglavaya, in the upper reaches of the Kyngarga River, north of Arshan Village (51°58′08″ N, 102°22′13″ E). The rock has a massive structure and a medium-grained granitic texture. It consists of microcline (35–40%), quartz (35–40%), felsic plagioclase (20–25%), and biotite (5–7%). The chemical composition of the microcline granites from the Tunka pluton near the sampling site is the following (wt.%): $SiO_2$, 73; $Al_2O_3$, 13; $Fe_2O_3$, 0.9; FeO, 1.1; MgO, 1.4; CaO, 1.1; $Na_2O$, 3.0; $K_2O$, 5.3 (Samburg, 1971).

## Dating of the granites from the Tunka pluton (Sarkhoi complex)

The dating was conducted for zircon grains with the least inclusions or cracks. Handpicked grains were embedded in epoxy, ground off approximately by half, and polished. Optical and cathodoluminescence images (CL) were used to select points on the grain surface. Cathodoluminescence photography was conducted under a JEOL JSM-6400 SEM. The dating was conducted by LA-ICP-(SF)-MS (Department of Analytical Chemistry, Ghent University, Belgium). The U(Th)–Pb ratios were determined on Thermo Scientific Element XR Sector Field ICP MS detectors. The data were preprocessed by PepiAGE software (Dunkl et al., 2009), and the final concordant age was calculated by Isoplot (Ludwig, 2003). The dating and processing procedure is the same as in (Glorie et al., 2010, 2011).

Zircon consists of semitransparent pinkish brown euhedral crystals of prismatic and long-prismatic habits (elongation index 2–3.5), 250–300 μm long. They show a distinct oscillatory zoning in the CL images (Fig. 4).

The concordant and subconcordant ages of zircon from the leucocratic granites of the Sarkhoi complex are 462.6 ± 7.8 Ma (MSWD = 0.34, probability 0.56, within 97–108%). The Th–U ratio is 0.4–0.8, as is typical of igneous zircons.

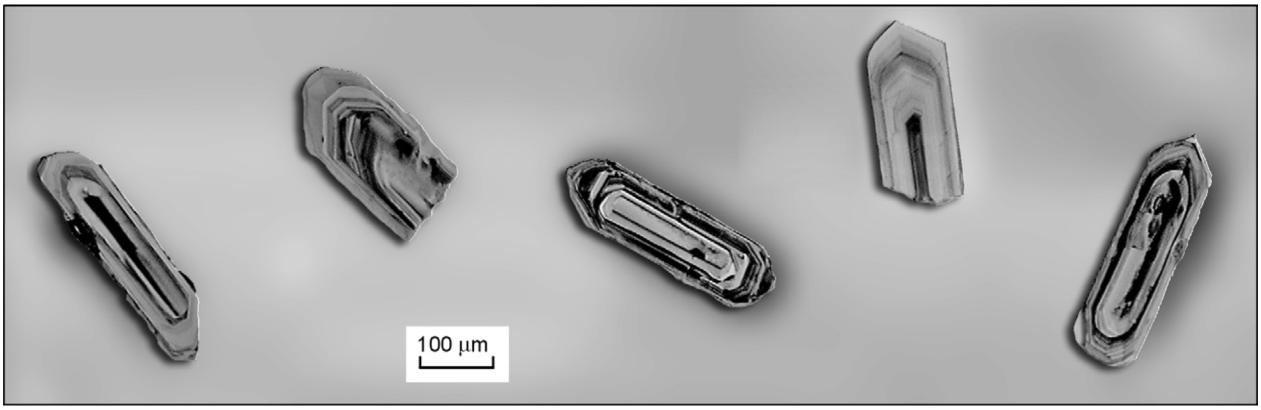


Fig. 4. Cathodoluminescence image of zircon grains (sample T09051) from the granites of the Tunka pluton.

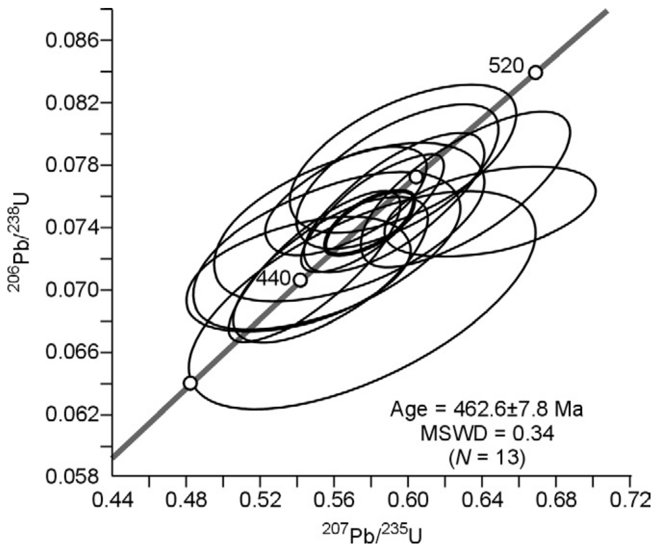


Fig. 5. Concordia diagram for zircons (sample T09051) from the granites of the Tunka pluton.

The results of the dating are shown in Fig. 5 and Table 1. Considering that the zircons belong to one morphologic type, show a distinct magmatic zoning, and have concordant and subconcordant ages, we think that the age obtained is coeval with the crystallization of the granites of the Tunka pluton.

## Discussion and conclusions

The dating of the granites sealing one sheet complex and overlain by the other one confirmed the existence of pre-Middle Ordovician folding and thrusting in the same small area in which the Late Paleozoic nappes and folding had been found. The observed structure of the eastern Tunka bald mountains results from at least two large orogenic stages: Ordovician and Late Carboniferous–Early Permian. Both show a wide regional distribution.

The Early Paleozoic structures (Late Cambrian–late Ordovician, 500–440 Ma) were traced and studied in the enormous area of the southern folded framing of the Siberian Platform, from Gorny Altai in the west to northern Transbaikalia in the east (Dobretsov and Buslov, 2007). The best studied Early Paleozoic collisional systems in the region such as the Early Paleozoic fold–thrust structures in the Ol'khon area or Sangilen have a long multistage history. For the Caledonian rocks of Sangilen, the collisional stage as such took place at 535–490 Ma and the subsequent transform faulting took place at 490–430 Ma (Vladimirov et al., 2005). The collisional system in the Ol'khon area developed at 500–450 Ma (Fedorovsky et al., 2005; Gladkochub et al., 2010a); for example, granulite metamorphism is $485 \pm 5$ Ma old (Bibikova et al., 1990). The age of the postfolding granites from the Arshan area ($462.6 \pm 7.8$ Ma) is very close to that of the postmetamorphic granites from the Zun–Murin pluton ($469 \pm 2$ Ma) (Barash et al., 2006), which cut the metamorphic rocks of the Khamar-Daban terrane. This can be further evidence for the common structural history of these terranes, which are now separated by the sediments of the Cenozoic Tunka basin (Fig. 1).

The Early Paleozoic collisional tectogenesis was manifested throughout the Caledonian rocks of the Altai–Sayan Fold Region in the formation of granitic batholiths. The following peaks of magmatism were distinguished on the basis of the statistical processing of many dates: $495 \pm 5$, $475 \pm 5$, and $450 \pm 5$ Ma (Rudnev et al., 2004a). The largest granitoid plutons are multiple: they comprise several intrusive complexes, which formed in the accretionary, collisional, and postcollisional (shear) stages (Rudnev et al., 2004b). High-temperature metamorphism and large-scale granitization are typical of the Caledonian orogenic stage in the southern folded framing of the Siberian Platform.

The Late Paleozoic metamorphism and magmatism were more or less intense in the enormous area including not only Hercynian folded areas (eastern Kazakhstan, basement of the West Siberian Plate, southern Mongolia) but also a considerable part of the Caledonian rocks in the Altai–Sayan Fold Region.

Hercynian geologic events within the Caledonian accretionary belt are hard to identify, because the complexes of the

Table 1. U-Pb isotope data on zircons from the granites of the Tunka pluton (Sarkhoi complex)

| Point no. | $^{207}Pb^a$ (cps) | $U^b$, ppm | $Pb^b$, ppm | $Th^b/U$ | $^{206}Pb/^{204}Pb$ | $^{206}Pb/^{238}U^c$ | ±2σ, % | $^{207}Pb/^{235}U^c$ | ±2σ, % | $^{207}Pb^c/^{206}Pb$ | ±2σ, % | *Rho* | $^{206}Pb/^{238}U$ ±2σ, Ma | $^{207}Pb/^{235}U$ ±2σ, Ma | Concordance$^d$ | $^{207}Pb/^{206}Pb$ ±2σ, Ma |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2450 | 377 | 30 | 0.42 | 1297 | 0.0751 | 3.2 | 0.6446 | 7.2 | 0.0623 | 6.5 | 0.44 | 467 ± 14 | 505 ± 29 | 108 | 683 ± 139 |
| 2 | 1485 | 241 | 21 | 0.60 | 641 | 0.0765 | 5.3 | 0.6309 | 7.4 | 0.0598 | 5.1 | 0.72 | 475 ± 24 | 497 ± 29 | 105 | 597 ± 112 |
| 3 | 1731 | 299 | 25 | 0.59 | 7799 | 0.0773 | 4.9 | 0.5950 | 7.6 | 0.0558 | 5.8 | 0.64 | 480 ± 23 | 474 ± 29 | 99 | 444 ± 129 |
| 4 | 3523 | 612 | 50 | 0.54 | 2322 | 0.0750 | 4.2 | 0.5811 | 5.4 | 0.0562 | 3.3 | 0.78 | 466 ± 19 | 465 ± 20 | 100 | 461 ± 74 |
| 5 | 877 | 166 | 14 | 0.74 | 543 | 0.0725 | 5.8 | 0.5557 | 10.5 | 0.0556 | 8.8 | 0.55 | 451 ± 25 | 449 ± 39 | 99 | 435 ± 196 |
| 6 | 2945 | 558 | 45 | 0.60 | 7465 | 0.0716 | 5.6 | 0.5495 | 6.9 | 0.0557 | 4.1 | 0.80 | 446 ± 24 | 445 ± 25 | 100 | 440 ± 91 |
| 7 | 828 | 144 | 13 | 0.79 | 410 | 0.0785 | 4.9 | 0.5975 | 8.4 | 0.0552 | 6.8 | 0.59 | 487 ± 23 | 476 ± 32 | 98 | 421 ± 152 |
| 8 | 2825 | 512 | 43 | 0.57 | 5481 | 0.0756 | 4.9 | 0.5926 | 6.7 | 0.0568 | 4.5 | 0.73 | 470 ± 22 | 473 ± 25 | 101 | 485 ± 100 |
| 9 | 1246 | 240 | 19 | 0.66 | 1402 | 0.0710 | 4.2 | 0.5403 | 9.2 | 0.0552 | 8.2 | 0.46 | 442 ± 18 | 439 ± 33 | 99 | 420 ± 183 |
| 10 | 2385 | 436 | 37 | 0.59 | 4791 | 0.0758 | 3.8 | 0.5664 | 6.3 | 0.0542 | 5.0 | 0.61 | 471 ± 17 | 456 ± 23 | 97 | 380 ± 112 |
| 11 | 587 | 109 | 9 | 0.77 | 2076 | 0.0743 | 5.6 | 0.5680 | 10.5 | 0.0554 | 8.9 | 0.53 | 462 ± 25 | 457 ± 39 | 99 | 429 ± 199 |
| 12 | 1061 | 201 | 16 | 0.64 | 415 | 0.0713 | 5.4 | 0.5583 | 7.7 | 0.0568 | 5.5 | 0.70 | 444 ± 23 | 450 ± 29 | 101 | 483 ± 122 |
| 13 | 482 | 95 | 8 | 0.77 | 613 | 0.0693 | 8.3 | 0.5757 | 13.4 | 0.0602 | 10.5 | 0.62 | 432 ± 35 | 462 ± 51 | 107 | 611 ± 227 |

Note. *Rho*, Error correlation coefficient of the ratios $^{207}Pb/^{235}U$-$^{206}Pb/^{238}U$. [a] Correction for laser signal intensity within one sequence. [b] U, Th, and Th-U contents were calculated relative to the GJ-1 zircon standard. [c] The U-Pb age was calculated by Isoplot software (Ludwig, 2003). [d] ($^{206}Pb/^{238}U$ / $^{207}Pb/^{235}U$) × 100.

superimposed stage are subordinate in the geologic structure of the areas in which the crust consolidated in the Caledonian. Also, the superimposed orogenic events are ill-defined in the sedimentation; therefore, absolute geochronology is key to their explanation.

The importance of the Late Paleozoic geologic events in the geologic structuring of western Transbaikalia has been shown in recent years. Detailed geochronological studies have shown that the giant Angara–Vitim batholith and some other granitoid plutons in Transbaikalia (total area >200,000 km$^2$) formed at 330–275 Ma (Tsygankov et al., 2007, 2010; Yarmolyuk et al., 1997). Amphibolite metamorphic rocks 295.3 ± 1.6 Ma old were found near Mt. Mandrik (~30 km from Ulan-Ude) (Mazukabzov et al., 2010). In the Late Carboniferous–Early Permian, the Tocher flysch trough closed in the Ikat–Bagdarin zone of Transbaikalia and turned into a fold–thrust structure (the intruding Usoi granite pluton is Early Permian, 288 ± 2 Ma old) (Ruzhentsev et al., 2007). Mafic dikes 274 ± 3 Ma old are observed on the southern flank of the Siberian Platform (Gladkochub et al., 2010b).

The above-mentioned events are coeval with the Late Paleozoic nappes, shears, granitoids, and metamorphic rocks in the Caledonian Tunka terrane. Thus, the Late Paleozoic events in the terrane should be assigned to a large orogenic stage with a regional distribution.

While studying the geologic manifestations of variously aged orogenic stages in the Tunka terrane, note that the erosional truncation of the corresponding orogenic ensembles is located at different levels. In the Caledonian orogen, the upper parts of the granite batholiths are exposed by erosion and adjoined by outcrops of amphibolite (Kitoi-Kin zone, Khamar-Daban terrane) and granulite (Slyudyanka Group) metamorphic rocks. The Hercynian orogen retained small fragments of intermontane troughs, consisting of synorogenic molasse (Sagan-Sair Formation), and the exposed metamorphic rocks belong to the greenschist and epidote–amphibolite facies. Note that the Late Paleozoic deformations are temporally isolated from the accumulation of the sedimentary and volcanic complexes of the Tunka terrane. This makes the Hercynian orogenic stage dramatically different from the Caledonian one. The sediments of the Sagan-Sair Formation stratigraphically overlap with the Caledonian rocks and are overlain by tectonic sheets with 306–285 Ma old (Ar–Ar dating) micaceous mylonites at the bottom (Buslov et al., 2009; Ryabinin et al., 2011). These relationships suggest that it is older than the Late Carboniferous, but younger than the Ordovician.

According to the reconstructions available, the Tunka terrane was located inside the broad accretionary belt framing the Siberian Platform, far from the then ocean basins (Gordienko, 2006). The thrusting, shearing, metamorphism, and magmatism which took place in the Late Carboniferous–Permian in the Caledonian Tunka terrane might have been due to collision along the edge of a Caledonian accretionary margin, quite far from the study area. Collision-related deformations spread quite deep into the continent, and this led to a reactivation of the Caledonian accretionary–collisional fold–thrust structure, especially near its junction with the Siberian craton. Note that the deformations concentrated in large shears (Buslov, 2011), including the Main Sayan Fault. The mountain structures of the Alpine–Himalayan belt, which replaced older fold belts as a result of the Indo-Eurasian collision, are present-day equivalents of such orogens.

Note that the thrust and shear structures of the Tunka bald mountains were coeval with continental-margin calc-alkalic and shoshonite series (305–278 Ma) as well as the alkali and alkali-feldspar syenites and granites (281–278 Ma) of the Angara–Vitim pluton, which are attributed to the activity of the Tarim mantle plume (Borisenko et al., 2006; Dobretsov et al., 2010; Tsygankov et al., 2010). Most probably the plume favored the realization of tectonic strains far from the zone of tectonic-plate collision, as exemplified by the formation of the Cenozoic Himalayan–Central Asian orogen (De Grave et al., 2007; Dobretsov et al., 1996).

Thus, the structure of the Tunka terrane results from the superimposition of two collisional orogenic stages. The first one is related to the accretion of the TMM and some other terranes to the margin of the Siberian Platform, and the second, to intracontinental orogeny. The coeval formation of the Late Paleozoic deformational structures and plume magmatism in southern Siberia might be related to global geodynamic events resulting from tectonic-plate interaction and plume effect.

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