Russian Geology and Geophysics © 2020, V.S. Sobolev IGM, Siberian Branch of the RAS
Vol. 61, No. 1, pp. 1–13, 2020 DOI:10.15372/RGG2019125 *Geologiya i Geofizika*

Angara–Selenga Imbricate Fan Thrust System

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Received 31 December 2017; received in revised form 13 April 2019; accepted 22 May 2019

Abstract—We study Late Jurassic thrusting of the Archean craton basement over Jurassic sediments in Siberia, with the Khamar-Daban terrane as a rigid indenter. The study focuses on deformation and secondary mineralization in Archean and Mesozoic rocks along the thrusting front and the large-scale paleotectonic thrust structure. The pioneering results include the inference that the Angara, Posol'skaya, and Tataurovo thrusts are elements of the Angara–Selenga imbricate fan thrust system and a 3D model of its Angara branch. The history of the Angara–Selenga thrust system consists of three main stages: (I) detachment and folding of the basement under the Jurassic basin and low-angle synclinal and anticlinal folding in the sediments in a setting of weak compression; (II) brecciation and mylonization under increasing shear stress that split the Sharyzhalgai basement inlier into several blocks moving in different directions; formation of an imbricate fan system of thrust sheets that shaped up the thrusting front geometry, with a greater amount of thrusting in the front because of the counter-clockwise rotation of the Sharyzhalgai uplift; (III) strike-slip and normal faulting associated with the origin and evolution of the Baikal rift system, which complicated the morphology of the thrust system.

Keywords: thrust, Jurassic sediments, Khamar-Daban terrane, Siberian craton

INTRODUCTION

The first data on a thrust of the Archean craton basement over Jurassic coal-bearing sediments in Siberia were published more than one hundred years ago (Tetyaev, 1916). The following geological studies revealed multiple tectonic events in the southern margin of the Siberian craton, including large-scale thrusting (Danilovich, 1941; Salop, 1967; Popov, 1970; Klitin, 1974; Lobanov, 1977; Dobretsov, 1986; Mazukabzov and Sizykh, 1987; Alexandrov, 1990; Sizykh, 2001; etc.). Thrust tectonics in the southern Siberian craton ("Irkutsk amphitheater") has been associated with the evolution of the Central Asian Orogenic Belt (Zonenshain and Kuzmin, 1992; Dobretsov et al., 2019; Gordienko et al., 2019).

The earlier views of the southern craton margin and the adjacent orogens of Transbaikalia changed considerably as new lithological and tectonic evidence became available due to exploratory drilling for oil and gas, as well as to third-generation geological mapping. These data reveal multiple thrust sheets and their erosion outliers (klippes) and a multistage history of thrusting. It was established that the southern boundary of the Siberian craton are universally modified by a large number of subhorizontal structures represented a series of cover tectonical plates, multi-tiered thrusts and klippes.

This study addresses several key problems: (i) number of thrust sheets; (ii) mechanism of thrusting; (iii) tectonic control of the location of Lake Baikal; (iv) ongoing thrusting in the eastern side of Lake Baikal. The presented lithological-paleogeographic reconstruction of processes in the Angara-Selenga thrust system and its surroundings in the Baikal region based on data on rock compositions and tectonics aims at gaining insights into these issues.

STUDY OBJECTIVES AND MATERIALS

The study focuses on (i) lithology and petropgraphy of rocks in individual thrusts; (ii) paleotectonics of the large-scale thrust structure; (iii) deformation in Archean and Mesozoic rocks along the thrusting front; (iv) secondary mineralization in sedimentary and basement rocks involved in thrusting. Data were collected during four field campaigns in the western and eastern sides of Lake Baikal between 2015 and 2017 (Fig. 1) in the vicinities of Bol'shie Koty, Bol'shaya Rechka, Nikola, Listvyanka, Posol'skaya, Kamensk, and Tataurovo communities, as well as over 50 km along the left side of the Irkutsk hydroelectric water reservoir. Several video films were shot during the field trips: *The Angara Thrust Mistery* (https://youtu.be/NhCQrytBkNc); *Beyond the Frontier* (https://youtu.be/c73jIYwUK9M); *The Way to a Klippe* (https://youtu.be/p_jnvfgKusk); and *Tataurovo Conglomerate* (https://youtu.be/6adHWW9LQfg).

The new data extended the earlier knowledge based on documented core sections of L-1, L-2 and L-3 boreholes.

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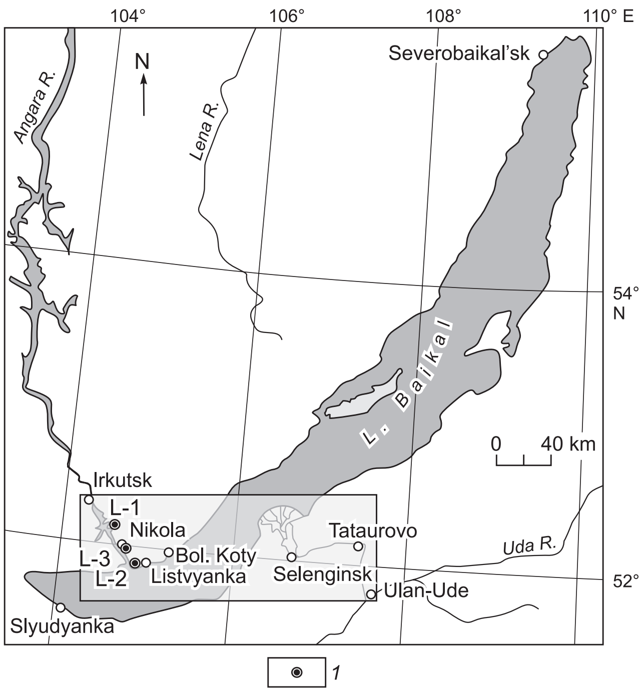

Fig. 1. Location map of the study area. *1*, borehole.

Borehole L-3 stripped a 50-m thick granitic sheet thrust on Jurassic sediments of the Irkutsk coal basin. The borehole penetrated into the basement through the sedimentary complex and the detachment and stopped at the depth 535.5 m. The 257 samples collected during the field trips include one from L-3, which has been described in detail by G.V. Orlova, a reputed petrographer.

The tectonic framework was studied by numerous structural measurements in thrust zones and their surroundings. Additionally, reference was made to previously published data on the Angara branch of the thrust system collected prior to the dam construction and impoundment in 1958.

RESULTS

The Siberian craton underwent multiple events through its long history. The milestones were associated with accretion of the Barguzin and Tuva–Mongolia microcontinents in the Late Neoproterozoic and in the Silurian–Devonian, respectively, as well as with the closure of the Paleoasian ocean followed by the formation of the Mongolia–Okhotsk orogenic belt (latest Jurassic–Cretaceous) and the Angara, Posol'skaya, and other thrusts (Zonenshain et al., 1990). Thrusts in the craton's southern margin and its folded periphery belong to five fold-thrust belts interpreted (Sizykh, 2001) as thrust roots (1); flanking mobile belts (2); thrust-related structures of the craton margin (3); structures of the thrust front (4) and behind it (5). The five belts grade successively from one to another inward the craton from the folded periphery.

The thrust system of the southern Siberian craton, the key object of this study, extends in a 15 km wide zone along the left side of the Irkutsk water reservoir to vicinities of Bol'shie Koty community in the western side of Lake Baikal and on as far as the Selenga Delta. By the time being, a 4 × 16 km granitic intrusion has been found (Sizykh, 2001) along the Baikal shore from the source of the Angara River and four granitic erosion outliers of thrusts (klippes).

More evidence of rock compositions was obtained from core samples of three deep boreholes L-1, L-2 and L-3 drilled near Listvyanka community for thermal water prospecting. The 1160 m deep borehole L-2 at the Angara source opposite the Shaman Rock stripped the craton basement composed of migmatites, granitoids, schists, and gneisses of the Sharyzhalgai uplift (basement inlier). Data from two other boreholes (Fig. 1), L-1 at Taltsy community and L-3 at Nikola community, which stripped sedimentary rocks, allow reconstructing the history of the imbricate fan thrust system.

Petrography

Borehole L-3 stripped the complete section of the Angara branch of the thrust system (Figs. 1–3) which represents the rock complex of the hanging wall. The footwall of the thrust consists of ortho-amphibolite and heavily deformed cataclastic biotite granite of the Archean craton basement. The ~10 m thick zone of detachment between the foot and hanging walls of the thrust is composed of chloritized mica schists (micalite) with abundant slickensides. The 381.9 m thick middle section of the hanging wall comprises slightly altered conglomerates and outsize sandstones with inclusions of carbonaceous plant detritus. The upper part of the section, 28.9 m in total, predominantly contains coarse conglomerates with hard siliceous cement. Deformation is recorded in numerous slickensides surrounded by zones of secondary chlorite and foliation where the pebble material is crushed and dispersed. Foliation and slickensides also appear in layers of gravelstone and sandstone.

The entire sedimentary unit is overthrust by a 61.3 m thick sheet of Archean plagiogranite gneiss which experienced deformation (fracturing and cataclasis), weak chloritization and leaching. The boundary between the sedimentary and basement units is marked by mylonite sutures, i.e., the detachment, which led lately to the formation of an imbricate fan system of thrusts, was originally along the base of the Jurassic strata. The Jurassic coal-bearing sediments stripped by L-3 belong to the Dabata, Cheremkhovo, and Sayan Formations; more data on the Angara branch of the thrust system come from composite sections in the vicinities of the Sobolev Cape, Mt. Skriper, and a klippe in the Nizhnyaya valley (Fig. 3). The rocks underwent low-temperature metamorphism, which led to the formation of low-temperature minerals associations under the influence of dynamic metamorphism in the contact zones of sedimentary formations and crystalline rocks..

Hornblende melanocratic granites are typical representatives of Archean allochthonous granitoids in the hanging wall of the Angara thrust. They are massive medium- and

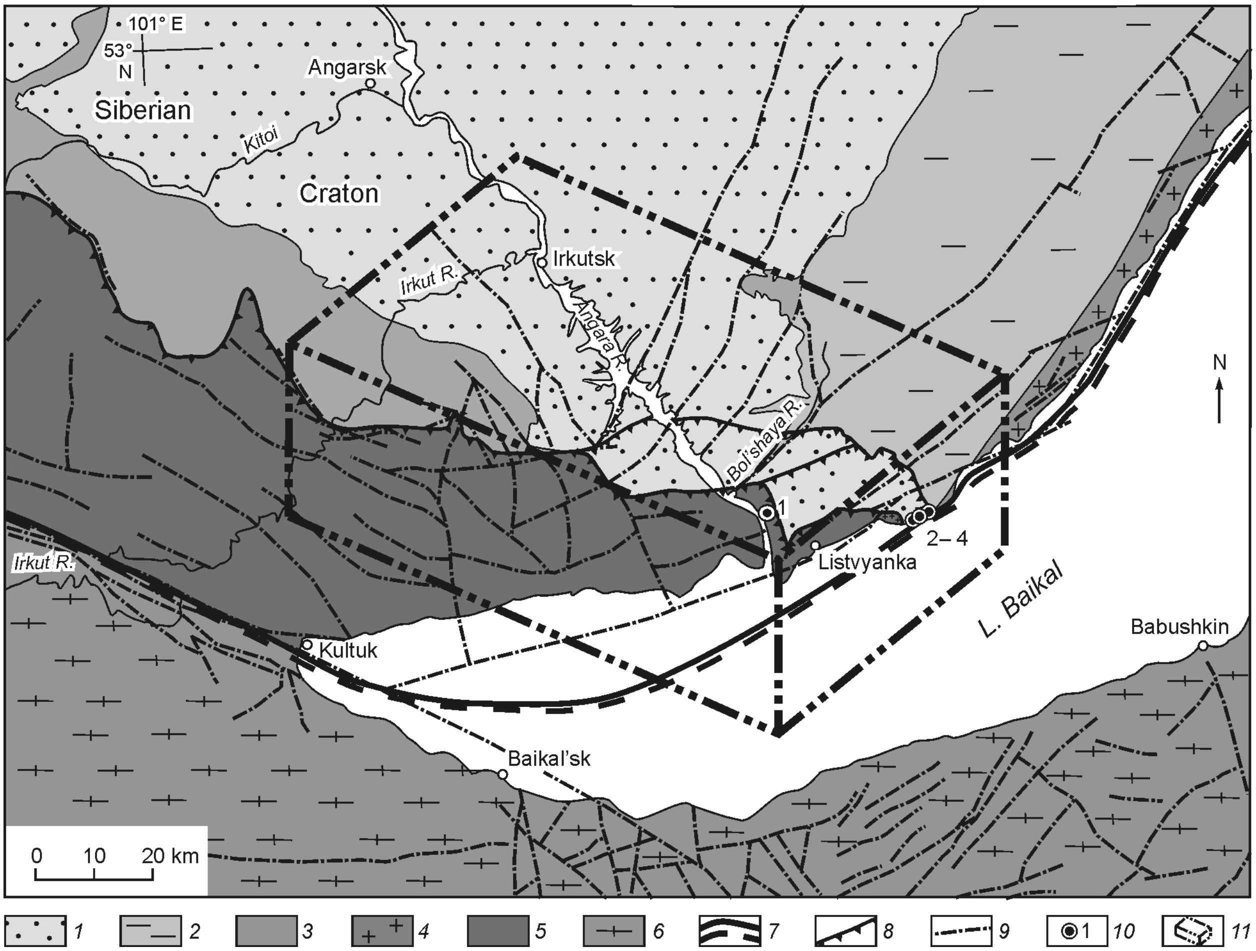

Fig. 2. Simplified geology of the southern Baikal region. *1–5*, Siberian craton: Lower–Middle Jurassic sediments (*1*), Paleozoic sediments (*2*), latest Precambrian–Paleozoic sediments (*3*), granitoids of the Primorsky complex (*4*), basement (Sharyzhalgai Group) (*5*); *6*, Sayan–Baikal fold belt; *7*, marginal suture of the Siberian craton; *8*, frontal line of the Angara thrust sheet; *9*, faults; *10*, sites of detailed studies (Fig. 3); *11*, location of the block-diagram shown in Fig. 10.

coarse crystalline metasomatic rocks consisting of plagioclase-antiperthite (up to 30%), microcline-microperthite (20%), quartz (25%), amphibole (20%), and biotite (3%), accessories of apatite, zircon, monazite, rutile, and opaques (2% in total), and secondary phases (sericite, calcite, epidote, limonite, and leucoxene).

Most of Jurassic sediments behind the frontal part of the Angara thrust near Bol'shie Koty community are conglomerates consisting of medium-size pebbles, cobbles, boulders, and lenses of gravelstone, sandstone, and siltstone. Currently the conglomerates are thrown up and make up a 1.5 km long system of cliffs with numerous slickensides; fragments of slickenside planes, up to 5 m across, appear in the shore of Lake Baikal near Mt. Skriper (Fig. 4).

Thin sections display melanocratic granites with signatures of intense postmagmatic alteration: cataclasis, metasomatism, and retrograde metamorphism with hornblende replacement by biotite. Cataclasis caused cracking and disintegration of rocks. Feldspar bears signatures of exsolution, with perthitic and antiperthitic textures. Microcline and plagioclase grains are separated by metasomatic quartz zones. The paths for percolating metasomatic fluids are marked by micrometer zones of shattering filled with flaky sericite and sometimes with fine grains of quartz or iron hydroxide.

Biotite gneiss granite, typical rock in the contact zone of the Angara thrust, consists of quartz (35%), plagioclase (33%), biotite (20%), garnet (5%), microcline (5%), amphibole (2%), accessory minerals of titanite, apatite, zircon, ilmenite, and magnetite (up to 2% in total), and secondary phases of sericite, chlorite, limonite, and leucoxene. The well rounded boulders, cobbles, and pebbles in conglomerates are composed of altered granitoids (affected by cataclasis, gneissification, mylonitization, and replacement of primary phases by secondary muscovite, albite, and epidote), biotite plagiogranite, biotite granite gneiss, andesite, andesitic and rhyolitic porphyry, microquartzite, metamorphosed siltstone, muscovite-quartz metasomatic rocks, cataclastic milky-white vein quartz, orthogneiss, and glimmerite.

Sandstones are various poorly sorted polymictic types varying from gravel to rare fine grain sizes (0.1–3.0 mm),

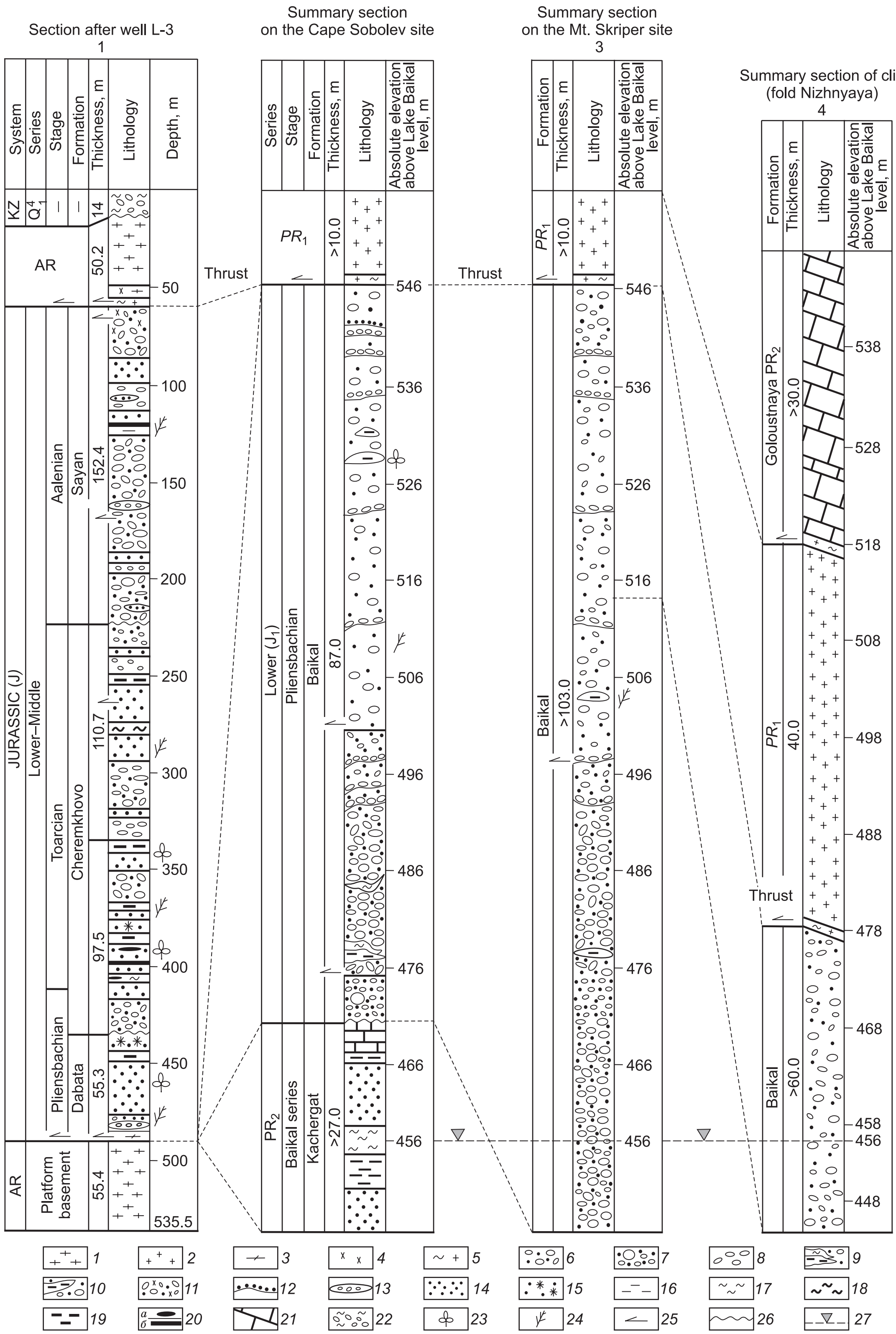

Fig. 3. Correlation of Jurassic rocks in the Angara thrust. *1–4*, sites of detailed studies. *1*, Archean ortho-amphibolite and biotite granite deformed by cataclasis; *2*, Archean–Proterozoic granitoids of the Primorsky complex; *3*, strongly altered rocks and micalites; *4*, chloritization; *5*, calcitized and cataclastic granitoids; *6*, conglomerate; *7*, coarse conglomerate; *8*, gravelstone; *9*, siltstone and mudstone lenses in conglomerates; *10*, siltstone lenses in conglomerates; *11*, conglomerates with signatures of chloritic alteration; *12*, layering produced by sand grains; *13*, gravelstone lens; *14*, sandstone; *15*, whitish weathered sandstone; *16*, siltstone; *17*, mudstone; *18,* coaly mudrocks; *19*, coaly siltstone; *20*, coal lenses (*a*) and layers of different thicknesses (*b*); *21*, dolomite; *22*, unconsolidated clay and pebble; *23*, fossil flora prints; *24*, plant detritus; *25*, thrust-related slickensides; *26*, stratigraphic unconformity; *27*, water level in Lake Baikal (456 m).

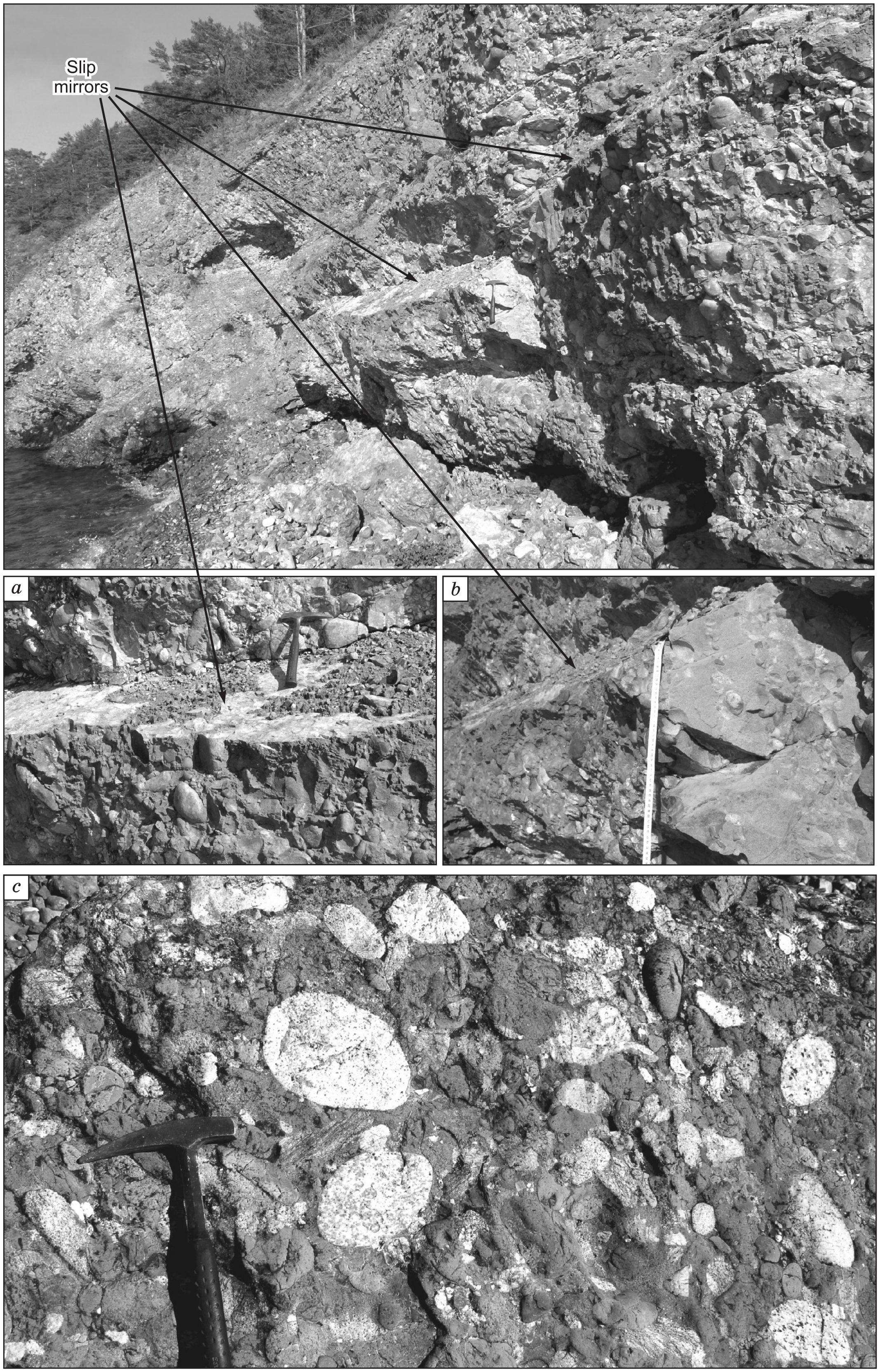

Fig. 4. Jurassic conglomerates from the thrust zone (3 km northeast of Bol'shie Koty community). *a*, outcrop along the shore of Like Baikal: general view; *b–d*, outcrop fragments: slickensides (*b*), vertical pebble layers (*c*), slickensides in coarse conglomerates: truncated boulders and granitoids, porphyrites, and quartzite pebbles (*d*).

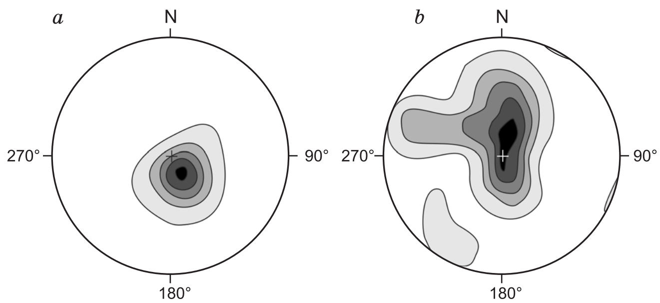

Fig. 5. Orientations of young low-angle zones of brecciation and cataclasis in the Sharyzhalgai uplift from the source of Angara to Kultuk community (*a*) and contacts of the Angara thrust (*b*). *a*, 153 measurements, contour lines > 4 > 8 > 12 > 15 > 20% Wulff net, lower hemisphere; *b*, 177 measurements, contour lines > 3 > 7 > 12 >15 > 18 > 20%, Wulff net, lower hemisphere.

consisting of quartz (70%), feldspar (15%), mica (10%), debris (5%), and cement (5%). The grain shapes are diverse, most often angular and subequant, some with irregular cuspate contours. Quartz grains are deformed and cracked almost everywhere. The rock debris is composed of granitoids, quartz, microquartzite, microgneiss, and other lithologies. Feldspar is represented by plagioclase and microcline that underwent sericitic and pelitic alteration. Biotite has an elongate platy habit, with heavily deformed and hydrated aligned plates, which occasionally form epigenetically deformed layers. The percentages of biotite and feldspar locally reach 40% while quartz is within 10%; biotite coexists with muscovite and chlorite aggregates.

Sandstone grains are cemented with unevenly distributed clayey-calcitic material. Calcite dissolves or sometimes fully replaces feldspar particles which remain as hardly identifiable relict grains. Calcite occurs also as cement filling interstitials or microcracks in garnet grains. Often clasts grow together at the account of dissolution along the boundaries.

Heavy fraction minerals are mainly garnet, monazite, apatite, epidote, rutile, ilmenite, and magnetite, with their percentage no higher than 1 wt.% of the total rock mass. Abundant chlorite, epidote, and hornblende impart a greenish-gray color to some sandstones.

Note that the rock clasts are most often subrounded (roundness grade 3 according to Rukhin's (1969) classification). Quartz grains preserve undulatory extinction and sometimes display granulation zones though being cracked in some layers of polymictic sandstone, with cracks healed by brown iron hydroxide. Fine sandstone grains are mainly cemented with aggregated or flaky clay and hydromica. Some clasts are cemented with material resulting from dissolution. Deformed biotite plates produce preferred orientations and intimate crumpling; locally they are decomposed by hydration and converted to cement.

Thin mudstone layers consist mainly of aggregated-flaky mud impregnated with iron hydroxide that produces dark brown staining. The clayey material contains minor silt consisting of approximately equal relative percentages of quartz, feldspar, biotite, muscovite, and chlorite, with up to 0.2 mm crystals of authigenic calcite and parallel microlayers of iron hydroxide.

Local zones of slickensides between sedimentary layers enclose lenses and inclusions of authigenic chlorite and disseminated pyrite, while the layers themselves contain epigenetically deformed fragments of fossil plant tissues replaced by carbonaceous material. Core samples from 347.0, 395.6 and 418.2 m depths in L-3 contain *Sphenobaiera* sp. and *Czekanowskia* ex gr. *rigida Heer.,* typical of Early and Middle Jurassic (Frolov, 2013).

TECTONIC FRAMEWORK OF THE ANGARA–SELENGA THRUST SYSTEM

As it was found out previously (Tetyaev, 1916, 1934, 1937; Maslov and Lavrov, 1933; Danilovich, 1941; Khrenov, 1969; etc.), the Angara–Selenga thrust system extends for more than 200 km northeastward along the Precambrian Sharyzhalgai basement inlier from the shore of Lake Baikal (Bol'shie Koty vicinity) to the Selenga Delta and consists of the Angara (western) and Selenga (northeastern) branches.

Angara branch. The Archean–Jurassic contact is traceable in outcrops along the Sharyzhalgai uplift on the left side of the Irkutsk water reservoir (as far as the Sosnovaya valley mouth 12 km far from the Angara source), in the Bannaya valley on the right side of the Irkutsk water reservoir, and on the shore of Lake Baikal in the area of Listvyanka (Krestovka valley) and Bol'shie Koty communities (Fig. 2).

The thrust system includes three clearly detectable main sheets densely cut by small faults. The primary rocks of the Sharyzhalgai basement inlier were mylonitized and partly recrystallized along the boundary with the Jurassic sediments as a result of dynamic metamorphism. Quartz is most strongly deformed and shows undulated extinction. Biotite grains are chloritized, form quasi-parallel diffuse clusters and are often grown together with plagioclase. Many plagioclase grains are replaced by clay minerals and sericite and have quartz rims.

The zone of granite-conglomerate contact is composed of granite gneiss and cataclastic migmatite. The most strongly altered granitoids were found among L-3 samples from the 54.6 m core depth (Fig. 2). Granite gneiss is chloritized, locally leached, and bears signatures of retrograde metamorphism (chlorite subfacies of greenstone facies). Cataclastic granite underwent calcitic and chloritic alteration and consists of feldspar (69%), quartz (30%), biotite (1.5%), accessories of apatite, zircon, titanite, and magnetite, and secondary chlorite, sericite and calcite. The alteration occurred in two stages: (1) retrograde metamorphism and (2) syntectonic chlorite and calcite secondary mineralization.

Dynamic metamorphism led to alteration of feldspar and its replacement with chlorite, clay minerals, and sericite. Many biotite plates were fully decomposed and replaced by chlorite. Granitoids became heavily fractured and crushed.

Thin sections display signatures of cataclasis in quartz grains, with formation of different extinction angles and blastesis. Later during the evolution, all fractured zones became healed with hydrothermal metasomatic calcite.

Mylonites appear in cataclastic rocks as 0.5 to 2.5 m bands and lenses, especially abundant in the left side of the Irkutsk water reservoir where their zones are more than 60 m wide (Khrenov, 1969). The mylonite zones exposed in outcrops often exhibit thrusting and reverse slip in pegmatite veins, and mafic dikes along the faults and related fractures. Mylonites are foliated along contacts and consist of ultrafine particles of sericite, chlorite, kaoline, carbonate, quartz, and iron hydroxide. Coarser mylonites have fluidal textures and contain equant inclusions and clasts of quartz and feldspar, as well as lenses and fibrous bands of quartz-feldspar aggregates. All elements of the Archean structure, pegmatite veins, and dolerite dikes along the Baikal shore within the Sharyzhalgai inlier, from the Angara source to Kultuk community are crosscut by low-angle branching zones of breccias (Fig. 5*a* for their orientations), with 1.0–1.5 cm angular clasts in a fine-grained matrix (Grabkin and Melnikov, 1980). The breccias apparently mark the boundaries of sheets that formed while the Sharyzhalgai basement inlier was thrusting over the Jurassic sediments.

Jurassic coal-bearing sediments were heavily deformed near the Baikal shore under the dynamic effect of granitic masses, judging by the presence of numerous slickensides, thrusts, folds, and other deformation features. Slickensides and signatures of motion in the sediments within the thrust zone increase in number and magnitude toward the section top.

Tectonic stress that acted during the formation of the Angara branch of the thrust system displaced northwestward the beds of Jurassic rocks which became sheeted like a deck of playing cards. Most of faulting occurred in tightly cemented coarse massive conglomerates while folding mainly involved coarse to fine-grained coaliferous rocks.

The basement-sediment contact in the left side of the Irkutsk water reservoir (Maslov and Lavrov, 1933) is undulated and dips at 19° to 43°, with an azimuth of 140° (Fig. 5*b*). The Jurassic sequence near the contact is deformed by a few low-angle folds. Active thrusting occurred also along coal beds and converted thin shallow layers of brown coal into glossy and semiglossy black coal or locally to anthracite. The coal beds are strongly compressed and show slickensides and small (10–25 cm) drag folds (Fig. 6), which record rotation inside the layers during brittle-plastic flow parallel to the layer boundaries and related gliding along the coal layers. Rotation during thrusting in the area of Bol'shie Koty was mentioned in early publications as well (Danilovich, 1951; Khrenov, 1969).

The Angara branch of the thrust system has a more complex structure in the right side of the Irkutsk water reservoir (Fig. 2), where several large sheets are detectable in the sedimentary sequence. The dip azimuths at the contact of sedimentary bedding and bedrock foliation indicate thrusting from the south and the southeast (Fig. 5). The opposite northwestern dip may be due to warping of sediments by the thrusting front. The origin of granitic outcrops among Jurassic sediments in the headwaters of the Krestovaya and Banaya valleys, in the middle reaches of the Taltsinka and Shcheglovaya Rivers, as well as in the left side of the Irkutsk water reservoir opposite the Burduguz Bay, remains unclear. The outcrops were initially interpreted as tectonic windows but later they were rather considered as klippes, or remnants of an eroded thrust that formerly reached 15–20 km of horizontal displacement (Sizykh, 2001). Meanwhile, the idea of tectonic windows does not seem improbable given the curved contours and a stepped wedge-shaped structure of both the basin base and the thrust contact detectable in geophysical images. This structure may result from nonuniform gliding of neighbor basement units and their pressing into sediments, especially in the case of outcrops in the left side of the Angara River, along the Taltsinka and Shcheglovaya valleys. The zones of deformation trenched near klippes may have formed by gliding of sediments along the faces of granitic wedges.

The dip angles of well pronounced basement-sediment contacts in the Baikal shore vary from 10°–15° at the Angara source to 70°–80° in the area of Bol'shie Koty community.

Sizykh (2001) distinguished five sheets in the frontal part of the Angara thrust, but only from implicit evidence (satel-

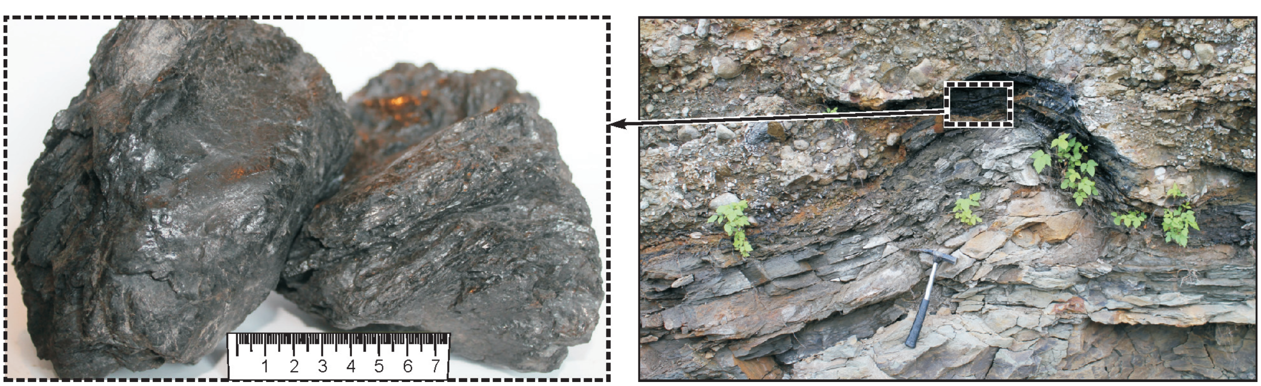

Fig. 6. Deformation of coal bed near the basement-sediment contact in the left side of the Irkutsk water reservoir.

lite images, topography, etc.). The thrust sheets are very poorly exposed and have never been traced along the strike.

Two sheets are especially prominent in the Jurassic sedimentary sequence. One separates conglomerates from sandstones and fine-pebble conglomerates intercalated with thin coal layers (Danilovich, 1941). It is exposed in bedrock outcrops in the Podorvikha valley, in the left side of the Irkutsk water reservoir, 6 km of the thrust front, downstream the Angara River. The outcrop exposes sediments heavily deformed in a >500 m zone, with low to high dip angles, a dense network of fractures, small bending folds, and shear joints aligned with the main thrust front. In general, the deformation zone is traceable from the lowest reaches of the Bol'shaya River into the Cheremshanka River catchment (Fig. 2). Small box folds and kink zones were found in trenches along the sheet on the road to the former village of Malyshkino (Fig. 7).

The other sheet is located 11 km farther to the north (Fig. 2) and runs from the left side of the Irkutsk water reservoir into the Scheglovaya River valley, where the Precambrian Scheglovaya basement uplift divides the Baikal and Irkutsk parts of the Jurassic basin. The thrust sheet separates a sequence of alternated sandstone, siltstone, and mudstone with thick economic coal seams from that of sandstone and fine conglomerate intercalated with siltstone and thin coal beds. The ~100 m thick shear zone displays heavily fractured plane- to cross-bedded (>40°) Jurassic rocks and turned-up layers.

Selenga branch. The Selenga branch of the thrust system is located in the eastern side of Lake Baikal between the Khamar-Daban and Ulan-Burgassy Ranges. Its segment called the Posol'skaya thrust (Shatskiy, 1933) extends from the Posol'skaya railway station to Kamensk town and continues the Angara thrust on the other side of Lake Baikal. It is a thrust of Upper Proterozoic marbled limestones and metamorphic rocks intruded by granitoids over Jurassic conglomerates, sandstones, siltstones, and mudstones containing Middle Jurassic *Czekanowskia rigida Heer* flora (Zamaraev and Samsonov, 1959). The thrust shifts northward when approaching the Posolskaya station and becomes traceable westward beneath the Selenga Delta sediments and emerges between Elan and Kamensk communities after being buried under the delta deposits east of Posolskaya (Sukhoi Ruchei valley). Trenching revealed a thrust contact between Jurassic sediments and marbled limestone dipping at 10° to 50° (Danilovich, 1960). According to Zamaraev (Zamaraev and Samsonov, 1959), the thrust would pinch out at that point, but Danilovich (1960) inferred that it rather extended eastward and graded into the Tataurovo thrust near Tataurovo community, along the Selenga River, where granites are thrust over conglomerates.

The fault planes of the Posol'skaya thrust show signatures of dynamic metamorphism: cracks, brecciation, disintegration of pebbles, and alteration of rocks: silicification of marbled limestones, conglomerates, and mudstones, as well as chloritization and sericitization of sandstones and siltstones. The rocks are strongly altered within a >100 m thick zone while the amount of displacement reaches a few tens of kilometers. Pebbles in conglomerates are often aligned with the basement-sediment contact near the Tataurovo fault plane, crushed and dispersed, locally disintegrated and mixed with crushed granitic material (Fig. 8). In the hanging wall of the fault, the mixture gives way to kakiritized granites. In general, deformation is unevenly distributed along the thrust system, being more prominent in the west than in the east.

Thus, the Angara–Selenga thrust zone is a system of deformed slightly bending sheets displaced along distinct surfaces of listric faults, which fits the definition of an imbricate fan structure according to the classification of Boyer and Elliot (1982). The thrust zone is composed of Archean massive basement rocks of the Sharyzhalgai complex and lies over numerous detachment surfaces with slickensides which commonly coincide with layers of most easily deformable rocks (coal or foliated sandstones, shales, and conglomerates). Locally the apparent normal bedding is interrupted by downwarping and upthrow of beds, with vertically oriented layers of sandstone and conglomerate. The thrust system most likely formed in a setting of regional compression and flow.

Note that similar processes occurred elsewhere in the southern periphery of the Siberian craton affected by closure of the Paleoasian ocean. For instance, the bedrocks of the

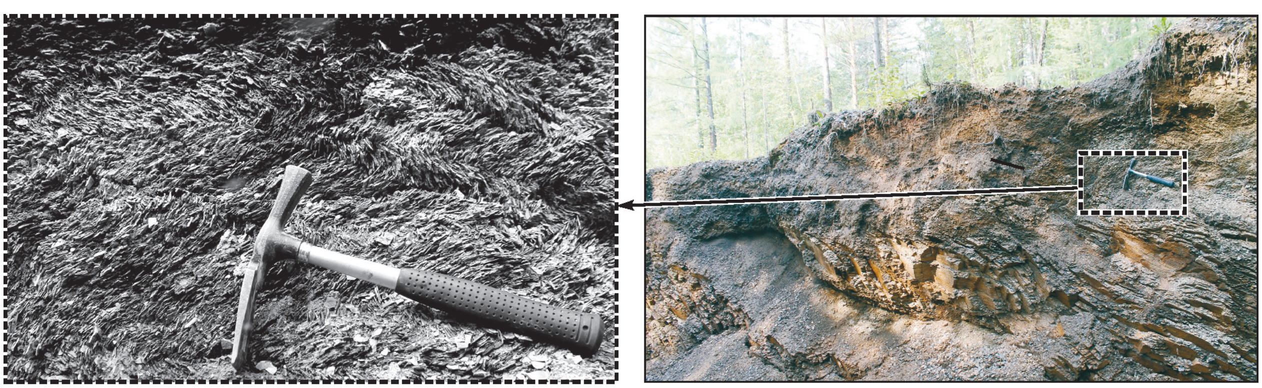

Fig. 7. Small kink zones in foliated Jurassic sandstones and carbonaceous siltstones (vicinity of Malyshkino community).

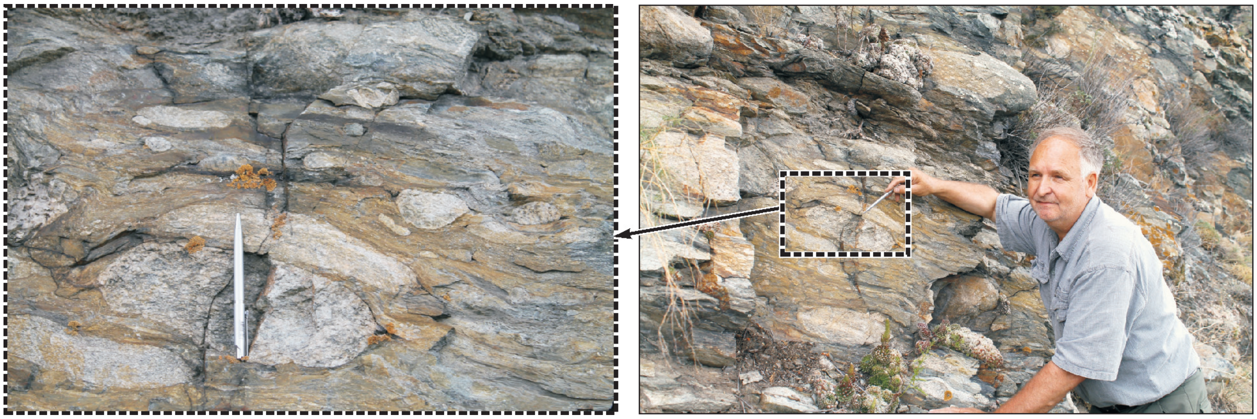

Fig. 8. Tataurovo coarse conglomerates deformed and metamorphosed during Mesozoic–Cenozoic tectonomagmatic activity.

Aldan shield are thrust over Jurassic volcanic-sedimentary rocks that fill the Chulman basin and its satellites along the South Yakutsk thrust zone (Pavlov and Parfenov, 1973), under the indentation effect of the rigid Stanovik terrane. Similar thrust structures occur also in the Verkhoyansk fold area (Prokopiev et al., 2001), as well as in the foothills of mountains in Scotland, Scandinavia, and elsewhere (Boyer and Elliott, 1982).

The thrusting process was accompanied by successive northwestward displacement of imbricated sheets, at a rate of ~0.3 mm/yr, as one can estimate from the 15 km distance between the craton edge and the mapped thrust remnants and the duration of thrusting from the Late Jurassic to the earliest Late Cretaceous. The initial contours of the sheets and the amount of thrust masses in the Angara–Selenga system are hard to estimate because the sheets underwent warping and folding with formation of complex structures. Note that trust sheets in the Inner Carpathians moved 90 km for 7.5–15.0 myr, at 12 mm/yr (Andrusov, 1961). Similar calculations were reported for thrusts in the Dinaric Alps (Belostotskii, 1961) which moved at 19 mm/yr. Unlike the smooth thrusting of the Angara system on the edge of a Precambrian craton, that in the Alpian and Carpathian mountains occurred in a few discrete events typical of Phanerozoic orogenic settings. Namely, five such events were inferred (Belostotskii, 1961) for the case of the Dinaric Alps. The relatively slow thrusting rate in the Angara system may be due to high rigidity of the craton basement.

Gladkov et al. (2000) distinguished elliptical concretions of hard sandstones with limestone cement, with concoidal farcture, in the sandstone sections on the left side of the Irkutsk water reservoir; they authors identified the concretions as pseudoboudins and used them to estimate the ductile component of deformation. However, this interpretation appears to be wrong, for several reasons. The term “pseudoboudinage” refers rather to tectonic formation of lens-like features in fault zones, when lenses of disrupted bodies rotate in a fine-grained matrix, whereas the concretions reported by Gladkov et al. (2000) result from postdepositinal alteration of sediments. Furthermore, no signatures of deformation have been found upon detailed examination of the concretions: they originally had elliptical or less often spherical shapes and have no bearing on ductile deformation.

DISCUSSION

The Angara thrust in the Angara headwaters distinguished about one hundred years ago (Tetyaev, 1916) by analogy with the Alpine system still arouses vivid interest as a clue to the deformation history in the Irkutsk coal basin and to the mechanisms of Mesozoic thrusting along the southern craton margin. Its origin still remains unclear though a wealth of data has been collected.

The model of Danilovich (1960) attributed the thrust system to arching (Pavlovskiy et al., 1948; Florensov, 1960) associated with tectonomagmatic activity and the related long-term formation of linear systems of arch uplifts separated by basins in the western Baikal and Transbaikal regions since the Middle Jurassic. The arching was thought to be especially active in the margins of Precambrian cratons and accompanied by magmatism, with injection of dikes and lava outpourings. According to the model of Danilovich (1960), the Angara thrust is located in the northwestern limb of the Sayan–Baikal dome, which underwent linear warping and the ensuing fracture and faulting of different slip geometries. The dome base was thought to be the most favorable place for thrusting. Later that model implying conversion of vertical forces to horizontal ones by spreading of the arch was refused, even though it was supported by experiments (Gzovskii, 1963).

Another model, suggested by Sizykh (2001), predicted thrusting-related zoning at the junction of basement and sedimentary structures in the craton margin. Sizykh (2001) distinguished five sheets in the front of the Angara thrust and attributed the zoning to collisional events, but did not specify their ages and nature.

The model we suggest (Fig. 9) relates the origin of the Angara–Selenga thrust system with the evolution of the Pa-

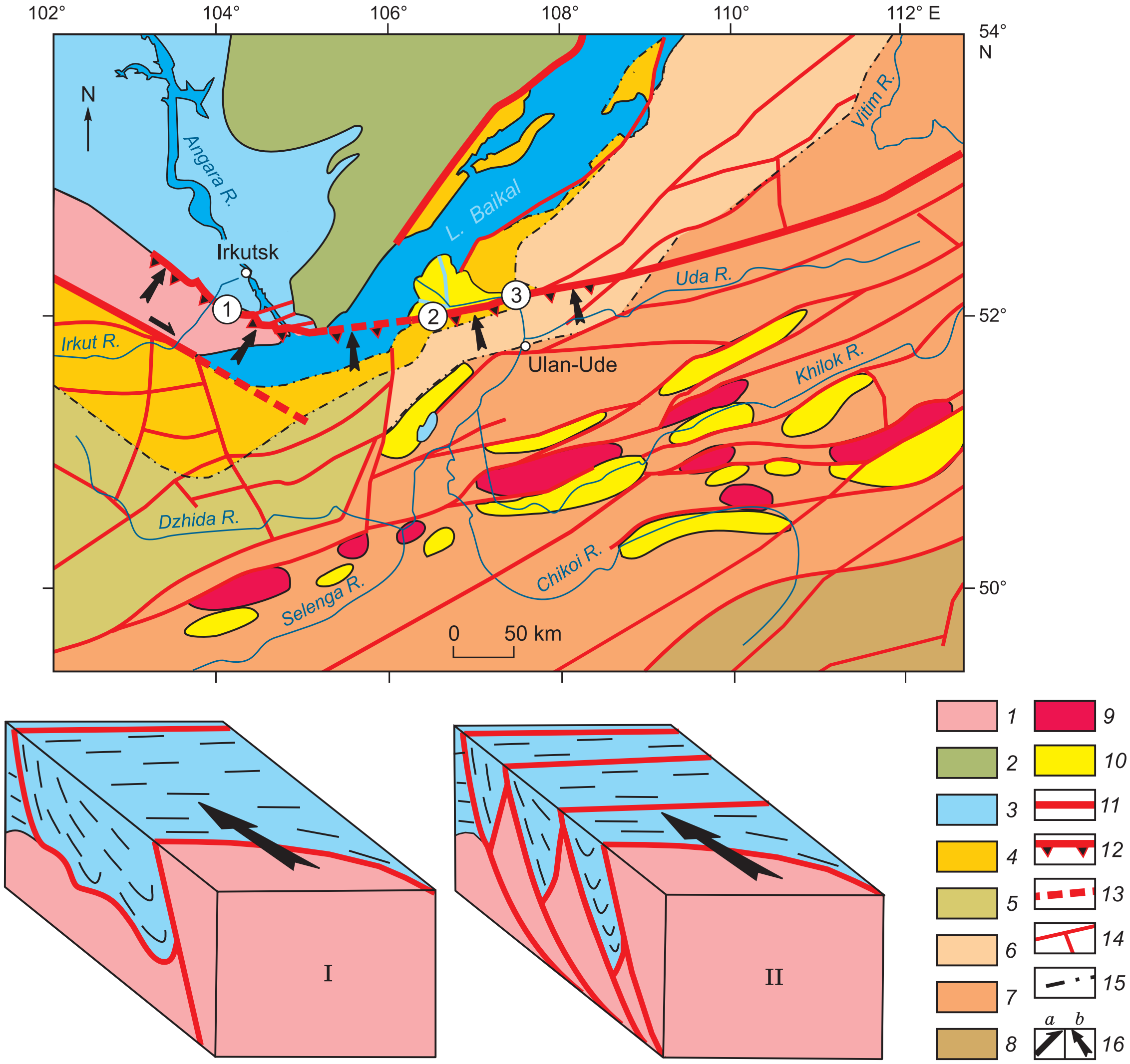

Fig. 9. Geodynamic zoning of Transbaikalia, modified after (Sklyarov et al., 1997), and two stages in the history of the Angara–Selenga thrust system. *1–3*, Siberian craton: Sharyzhalgai basement inlier (*1*) and Lower Paleozoic (*2*) and Mesozoic (*3*) sediments; *4–6*, Central Asian orogenic belt: Late Precambrian Khamar-Daban island arc terrane (*4*); latest Cambrian–Cambrian Dzhida terrane (*5*), Barguzin microcontinent (*6*); Cambrian–Ordovician Eravnoe terrane; *8–10*, Mongol–Okhotsk orogenic belt: Hentiyn island arc terrane (*8*), mylonite gneiss domes (metamorphic core complexes) (*9*), Early Cretaceous basins (*10*); *11*, marginal suture of the Siberian craton; *12*, Angara–Selenga thrust system and its segments (labeled by numerals in circles: 1, Angara, 2, Posol'skaya, 3, Tataurovo); *13*, inferred faults; *14*, other faults with different slip geometries; *15*, contours of terranes; *16*, directions of strike slip (*a*) and compression (*b*). Block diagrams I and II show two stages in the history of the Angara–Selenga thrust system: detachment of basement under the Jurassic basin (initial stage I) followed by formation of the imbricate fan structure (main stage II).

leo-Asian ocean (Sklyarov et al., 1997) which closed in the Late Jurassic. At the time of ocean closure, the territory of Transbaikalia comprised uplifts and basins of clear geomorphic expression, presumably resulting from vertical motions superposed on general horizontal extension. The extension setting was especially prominent in the Eravnoe terrane, which is evident in the presence of numerous Mesozoic–Cenozoic basins, intrusions, and exhumed Cordilleran-type metamorphic core complexes (Sklyarov et al., 1997). The collisional processes were localized at the junction of the Siberian craton with the structures of the Paleo-Asian ocean, while the neighboring Khamar-Daban and Dzhida terranes acted as a rigid indenter that pushed the Sharyzhalgai basement inlier. These processes reactivated right-lateral strike-slip motions on the Main Sayan Fault and counter-clockwise rotation of the basement inlier (Fig. 9) and led to detachment along the base of the Irkutsk coal basin with subsequent thrusting of the basement on Jurassic sediments (Fig. 9, Stage I).

The Baikal Formation Jurassic conglomerates were also found in the eastern side of Lake Baikal (Zamaraev and Samsonov, 1959) and must have formed in a single basin which became later split by the Baikal rift. The paleogeographic conditions during the deposition of the Baikal Formation Jurassic conglomerates have never been described in the literature. Our data from the right side of the Selenga River show that the Jurassic coarse conglomerates make up a natural extension of a large paleoriver which presumably flew from the foothills of old mountains in the Khamar-Daban terrane and transported the boulders and pebbles of the Tataurovo and Baikal Formation conglomerates (Akulov et al., 2015). The evident postdepositional rework of the Tataurovo conglomerates occurred during Mesozoic–Cenozoic tectonomagmatic activity in Transbaikalia.

Thus, the two branches of the Angara–Selenga thrust system make a single large imbricate fan structure, given that thrusting of Precambrian basement rocks on Jurassic sediments occurred on both sides of Lake Baikal (in the eastern side, Precambrian metamorphic limestones thrust over Lower Jurassic sediments (Posol'skaya fault), while the older Taturovo thrust was reactivated). Note that the northeastern extension of the Angara–Selenga trust aligns with the Selenga–Vitim shear zone, a major element in the geodynamics of Transbaikalia. The activity of Stage I was followed by the formation of a fan of thrust sheets in the Angara and Posol'skaya segments of the system (Fig. 9, Stage II).

The tectonic framework of the Angara–Selenga thrust system changed further in the course of the Baikal rifting which produced new normal and strike-slip faults, slickensides, and zones of cataclasis (Stage III). Note that the tens of meters thick rocks (50.2 m in L-3) in the allochthonous part of the thrust underwent cataclasis, and their chaotic fracture, mylonitization, and mineralization (chlorite and limonite) increase toward the sheet margins, but the alteration processes did not involve the basement rocks in the thrust end 15 km far from its beginning, where only erosion remnants of the thrust are present (Fig. 10). They are unaltered Precambrian granitoids and massive black amphibolites ly-

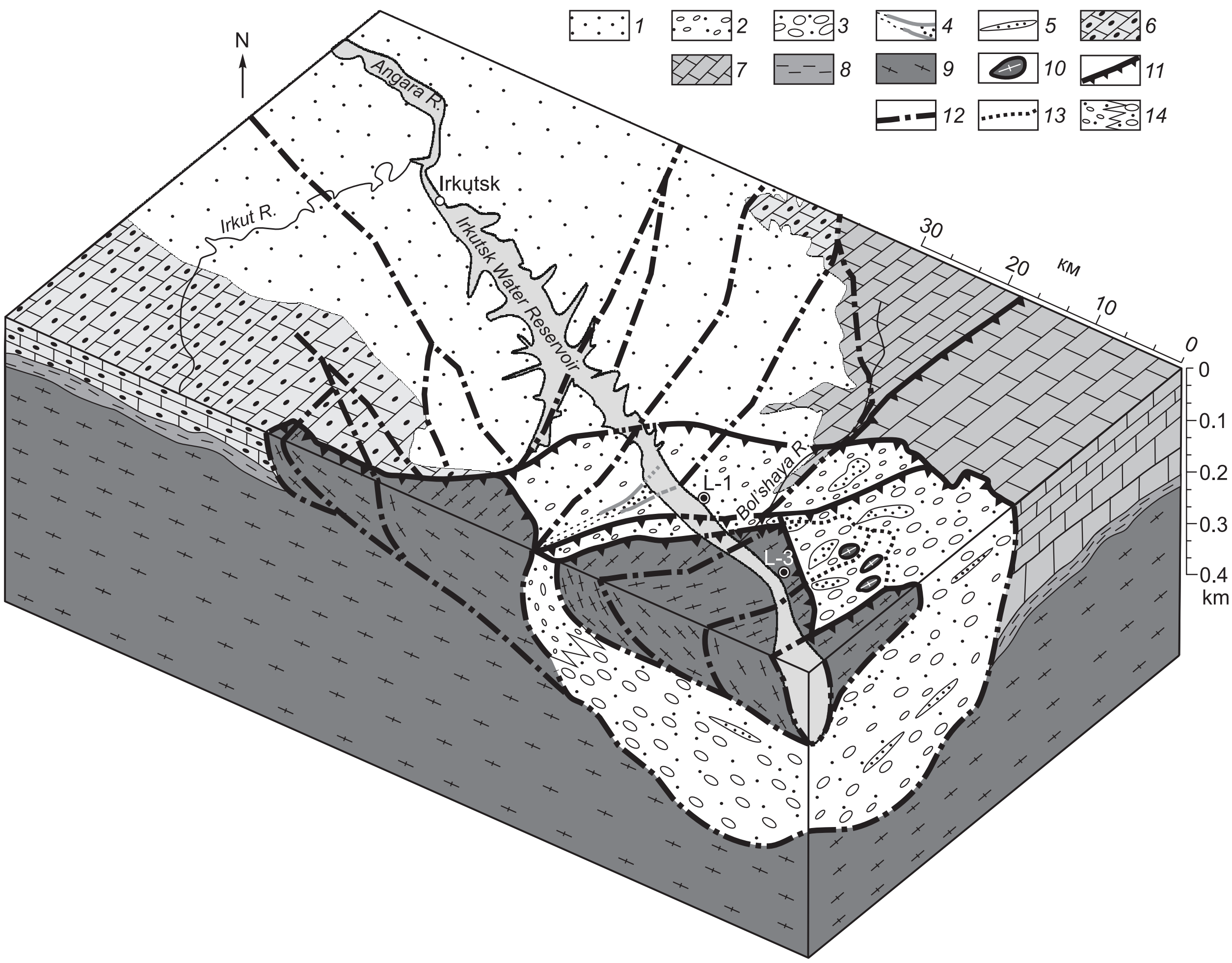

Fig. 10. Block diagram of the Angara thrust system (see Fig. 2 for location). *1–5*, Lower–Middle Jurassic rocks: alternated sandstone, siltstone, and mudstone with thick coal seams (*1*), sandstone and fine conglomerate interbedded with siltstone and thin coal beds (*2*), medium and coarse conglomerates enclosing well rounded boulders and lenses of sandstone with abundant carbonaceous plant detritus (*3*), sandstone and siltstone of a paleodelta (*4*), giant lenses and fields of silt-sand sediments (*5*); *6*, Lower Paleozoic clastic-carbonate complex; *7*, undifferentiated Late Precambrian–Paleozoic sediments; *8*, Late Neoproterozoic sediments; *9*, basement (Sharyzhalgai Group); *10*, erosion outliers of the Angara thrust sheet (klippes); *11*, thrusting front; *12*, faults; *13*, inferred limits of thrust sheets; *14*, inferred zone of facies change from Lower Jurassic coarse conglomerates to gravelstone, fine conglomerate, sandstone, and carbonaceous siltstone.

ing over light-brown Jurassic conglomerates consisting of well sorted and rounded medium-size pebbles, whereas the autochthonous rocks bear signatures of intense cataclasis.

CONCLUSIONS

The Angara, Posol'skaya, and Taturovo thrusts make up a single imbricate fan system at the junction of the Siberian craton with the structures of the Paleo-Asian ocean. The Angara–Selenga thrust system formed in three stages (Fig. 9).

Stage I: detachment and warping of the basement beneath the Jurassic basin and formation of low-angle anticlinal and synclinal folds in the sediments.

Stage II: increasing shear stress and formation of low-angle zones of brecciation and mylonitization that split the Sharyzhalgai basement inlier into several sheets, which then displaced at different rates and produced a fan structure. The amount of displacement at the thrust front shaped up during the imbrication was greater than behind it because of the rotation of the Sharyzhalgai uplift.

Stage III: normal and strike-slip faulting associated with the Baikal rifting which complicated the morphology of the thrust system.

We wish to thank A.M. Mazukabzov and V.S. Imaev from the Institute of the Earth Crust (Irkutsk) for discussions. Thanks are extended to G.V. Orlova for detailed description of thin sections. The manuscript profited from the thoughtful review and constructive criticism by A.V. Prokopiev.

The study was carried out as part of basic research programs run by the Institute of the Earth Crust (Irkutsk): Project 0346-2018-0004 Recent Geodynamics, Geospheric, and Biospheric Evolution and Catastrophic Global Changes and Project 0346-2018-0005 Evolution of Diamond-Bearing Lithosphere of the Siberian Craton Recorded in Kimberlite, Carbonatite, and Ultramafic-Alkaline Magmatism.

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Editorial responsibility: V.A. Vernikovsky