ISSN 0016-8521, Geotectonics, 2020, Vol. 54, No. 1, pp. 54–67. © Pleiades Publishing, Inc., 2020.
Russian Text © The Author(s), 2020, published in Geotektonika, 2020, No. 1, pp. 62–78.

# Geodynamic Model of the Neoproterozoic Evolution of the Yenisei Paleosubduction Zone (Western Margin of the Siberian Craton), Russia

**P. S. Kozlov[a, *], Yu. F. Filippov[b], I. I. Likhanov[c], and A. D. Nozhkin[c]**

[a]*Zavaritskii Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620016 Russia*
[b]*Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
[c]*Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
**e-mail: kozlov@igg.uran.ru*

Received June 30, 2019; revised September 16, 2019; accepted September 24, 2019

**Abstract**—The article proposes a model of collisional and accretionary events of the Neoproterozoic at the western margin of the Siberian Craton based on the results of geological, petrological, and geochronological studies of Precambrian complexes of the Yenisei Ridge and comprehensive geophysical data. Mineralogical and petrological evidence of paleosubduction is presented, represented by relicts of glaucophane-bearing high-pressure mineral assemblages in metabasites (630–620 Ma) within the tectonic mélange of the suture zone and by metamorphosed ophiolites and island arc complexes of the Isakovka and Predivinsk terranes (700–600 Ma) of the Sayan–Yenisei accretionary belt. The proposed geodynamic evolutionary model of the Yenisei paleosubduction zone includes reconstructions for time intervals of 740–700, 640–600, 580–540 Ma, during which a suture zone was formed as a result of collision of the Kas–Turukhansk microcontinent with the Siberian Craton. Tectonized fragments of the suture partially outcrop on the surface on the right bank of the Yenisei River. The bulk of the deformed and metamorphosed oceanic crust is buried beneath the Ediacaran and Phanerozoic sedimentary cover in the eastern part of the Kas–Turukhansk microcontinent, which is traceable by geophysical data. The history of the region's geological development in the Late Meso–Neoproterozoic correlates with synchronous endogenic events along the Arctic margin of the Nuna and Rodinia paleocontinents, which confirms the spatial proximity of the Siberian and North Atlantic cratons (Laurentia and Baltica) in a wide time range.

*Keywords:* Precambrian complexes, geodynamic model, suture zone, tectonic mélange, Yenisei paleosubduction zone, Kas–Turukhansk microcontinent, Yenisei Ridge, Paleo-Asian Ocean, Siberian Craton

**DOI:** 10.1134/S0016852120010069

## INTRODUCTION

The junction zone of the Pre-Mesozoic basement complexes of the West Siberian Plate with the Yenisei Ridge has long attracted the attention of geologists and geophysicists as a testing ground for deciphering the nature and paleogeodynamic evolution of the Yenisei tectonic belt on the western boundary of the Siberian Craton and the Paleo-Asian Ocean in the Neoproterozoic [18, 22, 28, 30]. Of particular interest is the zone of pronounced positive magnetic anomalies about 40 km in width, which stretches subparallel to the western margin of the Siberian Platform for hundreds of kilometers along the Yenisei River. The zone is confined to the western flank of the Sayan–Yenisei accretionary belt and to its northern continuation, the Yenisei tectonic belt; it is conventionally considered [4, 14, 17, 18, 26, 28, 36, 40] a collisional accretionary system on the margin of the Siberian Platform (Fig. 1).

The Pre-Yenisei paleosubduction zone is a fragment of a complex global tectonic structure on the western margin of the Siberian Craton, represented by Neoproterozoic tectonically crowded and metamorphosed island-arc and ophiolite complexes of the Isakovka and Predivinsk terranes, which, in geodynamic terms, constitute a united paleoceanic segment in the western part of the Yenisei Ridge. The studied zone also includes formations of similar genesis identified by geological and geophysical data west of the Yenisei Ridge that are buried under the Ediacaran and Phanerozoic sedimentary complexes of the basement of the West Siberian Platform. These formations are represented by a subvertical stratiform suture body, which can be traced by geophysical methods to a depth of 30 km.

The Yenisei paleosubduction zone extends hundreds of kilometers north of the Yenisei Ridge, plunging under the Mesozoic sedimentary strata of the West

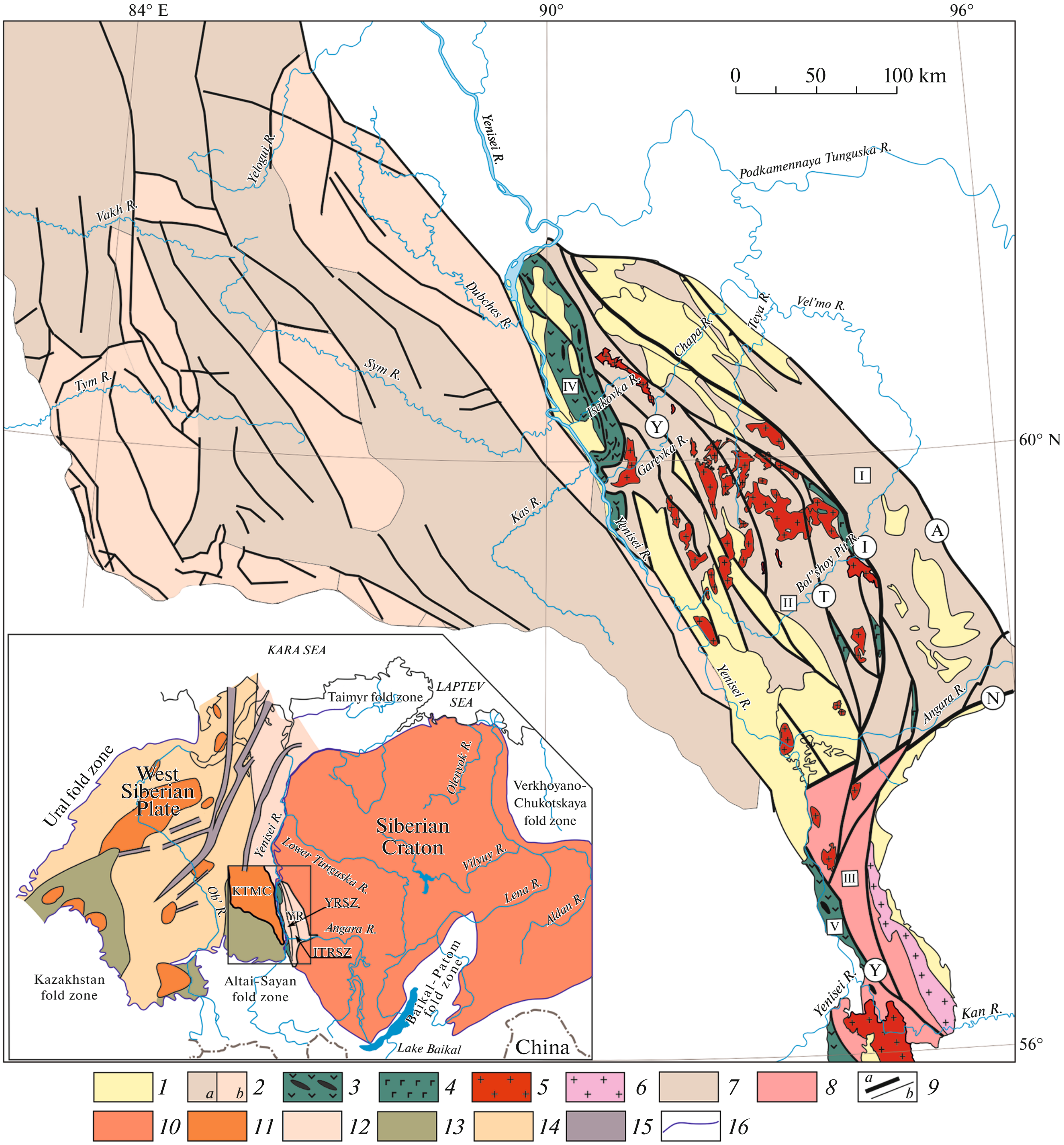



**Fig. 1.** Principal structures of Yenisei Ridge and basement blocks of Kas-Turukhansk microcontinent (KTMC). Inset: location of structures and basement blocks relative to position of Siberian Craton and est Siberian Platform. Legend (inset): YRSZ, Yenisei regional shear zone; ITRSZ, Ishimba–Tatar regional shear zone. Tectonic blocks of Yenisei Ridge (YR): I, East (EB); II, Central (CB); III, Kan island arc complexes: IV, Isakovka; V, Predivinsk. Regional faults: I, Ishimba; T, Tatar; A, Ankinovsky; Y, Yenisei; N, Nizhnyaya Angara. (*1*) cover ($NP_3$–PH); (*2*) basement blocks of KTMC: (*a*), sunken; (*b*), uplifted; (*3*) ophiolite and island-arc complexes with plagiogranites (NP); (*4*) basic volcanic rocks (MP–NP); (*5*) Neoproterozoic granitoids (NP); (*6*) Paleoproterozoic granitoids (PP); (*7*) metamorphic complexes from greenschist to amphibolite facies (NA?– $NP_{1-2}$); (*8*) metamorphic granulite-gneiss complexes (PP); (*9*) regional faults; overthrusts: (*a*), geological boundaries (YR); (*b*), boundaries of blocks (KTMC); (*10*–*12*) areas of basement consolidation (inset): (*10*) Siberian Craton; (*11*) ancient (NA–NP) hard-rock massifs; (*12*) Baikalides ($NP_3$); (*13*) Caledonides ($Pz_1$); (*14*) Hercynides ($Pz_3$); (*15*) rift grabens (P–T); (*16*) boundaries of West Siberian Platform and Siberian Craton.

Siberian Plate on the left bank of the Yenisei River. The presence of subsided fragments of the collisional accretionary system (suture) and structural features of its exposed part shed light on the nature of Neoproterozoic tectonic processes on the western flank of the Siberian Craton.

According to geophysical [24] and geological data, as well as reconstructions of buried mafic volcanic island-arc belts and metavolcanogenic and metabasite–ultrabasite complexes of various stages of the Riphean occurring in sections along the right bank of the Yenisei River, part of the Yenisei tectonic belt west of the Yenisei River was interpreted as a Neoproterozoic subduction zone (Benioff zone) at the boundary between the West Siberian Plate and Siberian Craton [6, 14, 20].

Such an interpretation is consistent with geophysical data on the deep structure of the junction zone of the basements of the West Siberian Plate and Yenisei Ridge [23, 24]. However, the nature of the linear zone of geophysical anomalies, its boundaries, configuration, and formation age remain controversial, since Pre-Ediacaran folded metamorphic complexes of the Yenisei paleosubduction zone within the area of the anomaly are hidden under a thick sedimentary cover of Ediacaran and Phanerozoic rocks and hence remain unexplored.

In recent years, we have obtained new geological, petrological, and geochronological data on the western part of the Yenisei Ridge, which has the most complex geological structure; these data have made it possible to sort out ideas about the convergent border between the Paleo-Asian Ocean and paleocontinent of Siberia, the nature of tectonic and metamorphic events within the range 1.2–0.6 Ga, characterized by successive manifestations of metamorphic andalusite–sillimanite and kyanite–sillimanite rocks to high-pressure tectonites in the suture zone [17]. Discovery of metabasite tectonites with relicts of glaucophane-bearing high-pressure paragenesis can be regarded as a petrological and mineralogical indicator of the subduction nature of the boundary [40].

The results of large-scale geological and geophysical research in the last two decades by the Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences (Novosibirsk) in the southeastern part of the West Siberian Plate have substantiated the existence of a Pre-Yenisei Late Neoproterozoic–Paleozoic sedimentary basin that formed on a rigid crustal block (Kas–Turukhansk microcontinent) and adjoined the Yenisei Ridge at the Cryogenian–Ediacaran boundary [13, 26, 27]. Study of a volcanoplutonic complex opened by drilling sites near Tyn'yar (east of the Khanty-Mansi Autonomous Okrug) carried out by the Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences (Yekaterinburg) revealed the presence of an ancient sialic crustal block in the Pre-Jurassic basement in the east of the West Siberian Plate. It was shown that some of the zircons recovered from early Permian granitoids have an ancient age of 2050 Ma, which might have been inherited from the Paleoproterozoic sialic basement, the ancient periphery of the Siberian Plate. This was confirmed by parametric drilling data and a comparative analysis of the seismic waveform, which also prove that the sedimentary strata accumulated within the Kas–Turukhansk microcontinent (Pre-Yenisei sedimentary basin) during the Ediacaran and Cambrian also occur in the Yenisei part of the Siberian Craton [26].

The authors propose their own geodynamic model of Neoproterozoic collisional–accretionary events on the western margin of the Siberian Craton (age intervals of 740–700, 640–600, 580–540 Ma). The model is based on an analysis of the obtained geological and geophysical data, as well as reconstructions of the Yenisei paleosubduction zone [3, 4, 36, 37].

## GEOLOGICAL SETTING

The Yenisei Ridge is located on the western margin of the Siberian Craton, extending submeridionally along the Yenisei River for almost 700 km, 50–200 km in width (see Fig. 1). Geophysical data indicate crustal thickening, with the width of the fold zone of the Yenisei Ridge halved at depths exceeding 10 km, giving it a mushroom shape. The depth of the Moho under the Yenisei Ridge increases from 40 to 50 km compared to neighboring regions [23]. Thus, the fold belt has a structure with a thickened crust, preserved for a long geological time.

The regional accretion–collision model of the crust, consisting of Precambrian complexes of the paleoceanic and paleocontinental segments (Table 1), is confirmed by seismic profiling and substantiated by tectonic clustering of Neoproterozoic formations [19] that underwent tangential stresses. In the structure of the Yenisei Ridge, the northern (Cis-Angara) and southern (Kanskii) segments have been distinguished, separated by the sublatitudinal Nizhnyaya Angara regional fault (see Fig. 1). Two structural elements are distinguished south of this fault: the Early Precambrian Angara–Kanskii, formed by the Kanskii granulite–gneiss and Yenisei gneiss–schist complexes and granitoids, and the Neoproterozoic Predivinsk island-arc block. North of the Nizhnyaya Angara Fault, in the Trans-Angara part, the Yenisei Ridge consists of Paleoproterozoic and Meso–Neoproterozoic complexes of the continental margins making up the East (near-platform) and Central blocks. In the west, the Central Block borders the Yenisei regional shear zone with the Neoproterozoic Isakovka and Predivinsk tectonic blocks (terranes) of low-metamorphosed ophiolites and island-arc complexes. All tectonic blocks are separated by large regional faults of predominantly northwestern strike with a subvertical dip: the Ishimba, Tatar, Yenisei and Ankinov [37] (Fig. 1). These deep faults are often accompanied by higher-order feathering structures separating smaller blocks which used to collide, forming overthrusts [9]. Collision was accompanied by regional metamorphism that occurred under variable pressure, manifested as a

**Table 1.** Precambrian stratigraphy of western Yenisei Ridge (after [10, 16])

| Group | Paleooceanic segment | | Paleocontinental segment | |
|---|---|---|---|---|
| | series | sequence | series | formation, metacomplex, sequence |
| Neoproterozoic | Yukseev | Yuda<br>Predivinsk | Vorogov | Sukhorechenskaya<br>Mutna<br>Severorechenskaya |
| | Isakovka | Kiselikha<br>Firsov | Verkhnevorogovskaya | Lugov<br>Bystrinskaya<br>Kovriginskaya |
| | Unknown Formations | Unknown Formations | Shirokinskaya | Sukhokhrebtinskaya<br>Gorevka |
| | | | Tungusikskaya | Shuntarskaya<br>Potoskuyskaya |
| Mesoproterozoic | Unknown Formations | Unknown Formations | Sukhopit | Aladinskaya<br>Formation<br>Pogoryuyskaya<br>Udereiskaya<br>Gorbilokskaya<br>Cordinskaya |
| Paleoproterozoic | Unknown Formations | Unknown Formations | Teya | Penchenginsky<br>Formation of Karpinsky Range |
| | | | Yenisei | Garevka Metacomplex:<br>Malalogarevka<br>and Nemtikha sequences<br>Yenisei Metacomplex |
| Archean–Paleoprotero-zoic | Unknown Formations | Unknown Formations | Kanskaya | Kanskii Metacomplex:<br>Atamanovskaya<br>and Kuzeevskaya sequences |

combination of low- and moderate-pressure facies [39, 45].

The Yenisei and Ishimba–Tatar regional shear zones border the Central and Eastern tectonic blocks of the Yenisei Ridge and determine their tectonic pattern. These zones are represented by a system of adjacent subparallel strike-slip, reverse, and thrust faults, as well as combinations thereof, which concentrate shear strain, with manifestations of fault cataclasis, tectonic mélange, and dynamic metamorphism. Their length is estimated at hundreds of kilometers, while the width of dynamic metamorphism zones varies from hundreds of meters to the several tens of kilometers. Lineament zones divide the regional tectonic blocks and represent areas of their interaction. Displacements in near-fault areas of plastic deformations were accompanied by the formation of thick blastomylonite zones [38].

The laying of shear zones was established at the Mesoproterozoic–Neoproterozoic boundary, their development occurred in the range 1.3–0.54 Ga. Consideration of the long-term geodynamic evolution of the geological complexes genetically and spatially related to the zones is beyond the scope of this study: we only analyze the Yenisei regional shear zone and determine tectonic, thermal, and magmatic events, as well as the geodynamic evolution of the Yenisei paleosubduction zone in the range of 0.7–0.54 Ga.

In the geological structure of the western flank of the Yenisei Ridge, the Neoproterozoic paleoceanic and Neoarchaean – Paleoproterozoic paleo-continental segments are distinguished from west to east. Their junction zone is manifested as the Yenisei regional shear zone. In the east, Neoproterozoic formations of the Yenisei paleosubduction zone are in contact along the tectonic boundaries with Paleoproterozoic polymetamorphic complexes of the Central block and Neoarchaean(?)–Paleoproterozoic formations of the Kanskii block of the paleocontinental segment of the Yenisei Ridge. In the junction zones, we identified the Yenisei regional shear zone (about 80 km wide) [17], which extends across the entire Yenisei Ridge and covers both paleoceanic and partially paleocontinental Precambrian complexes. In the same manner, the

Ishimba–Tatar regional shear zone was identified in the junction zone of the Central and Eastern blocks of the ridge east of the Yenisei shear zone; this one was traced to the Kan River (in the south of the ridge). The Yenisei shear zone is interpreted as a likely continuation of the Baikal–Yenisei Fault (Main Sayan Fault) of the Sayan Region and, therefore, a fragment of the structure bordering the Siberian Craton from the west from Lake Baikal to the Kara Sea [18]. The discontinuous structure is clearly traced by geophysical data to great depth with the fault plane dipping to the west [7].

The Ediacaran–Paleozoic Pre-Yenisei sedimentary basin is part of the basement of the West Siberian Plate on the left bank of the Yenisei River; it formed on the Kas–Turukhansk microcontinent, which accreted to the Yenisei Ridge at the Cryogenian–Ediacaran boundary [26].

According to outcrops near the Yenisei and its right tributaries (Garevka and Tis rivers), north of the Angara River estuary, the Yenisei shear zone includes the adjacent paleoceanic (terrane, allochthon) and paleocontinental (para-autochthon) segments [11]. The eastern boundary of the Yenisei shear zone in the north passes through the Paleoproterozoic complexes northeast of the Osinovskie rapids and comprises the lower reaches of the Verkhnyaya Surnikha, Garevka, and Tis rivers, south of the confluence of the Bol'shoy Pit and Angara estuaries. Further south, it is buried under the Phanerozoic sedimentary cover, after which, the boundary can again be traced southward to the Kan River estuary. The Yenisei shear zone is marked by thrusts, accompanied by local paragenesis of blastomylonites of moderate pressure (Mt. Polkan area). The western boundary of the zone is buried under the Phanerozoic sedimentary cover and can only be traced by geophysical methods.

The Yenisei shear zone includes part of the Garevka metamorphosed complex on the margin of the Siberian Craton and metamorphosed island-arc and ophiolite complexes of the paleosubduction zone west of the Siberian Craton. One part of the Yenisei shear zone has subsided to a depth of 20–25 km and is covered by sedimentary rocks of the Siberian Plate; another is exposed as part of the Isakovka and Predivinsk allochthons (terranes).

In the modern erosion section, the paleocontinental segment within the area from the Osinovsky rapids to the village of Kolmogorovo (see Table 1) is represented by the Garevka polymetamorphic complex of the Central Block, consisting by the Paleoproterozoic Nemtikha and Malalogarevka sequences (para-autochthon). Endogenic processes in the para-autochton are sequentially expressed intraplate extension, intrusive magmatism, and syntectonic metamorphism in the suprasubduction zone.

The tectonized rocks of the paleocontinental sector are characterized by kinematic shear or displacement indicators during deformation events, which are widely manifested both at the meso- (rock) and microlevel [41]. Kinematic shear indicators include:

(1) gneissoid structures caused by linear deformation;

(2) ordered plastic-flow structures;

(3) extension and rupture of echelon-like flow rock folds;

(4) “pressure shadows” of recrystallized quartz;

(5) S-shaped severely deformed garnet grains;

(6) ruptures and displacement of mineral grains with the formation of kink structures and fracture bands in micas;

(7) deformation twins and lamellae in plagioclase;

(8) parallel positions of fine-grained lenticular mineral aggregates;

(9) schistosity;

(10) cataclase;

(11) boudinage.

Viscous shear in fracture zones were accompanied by:

(1) the formation of thick deformation zones of submeridional strike, characterized by largely heterogeneous deformations;

(2) complex multiscale alternation of intensively deformed areas with completely undeformed ones.

This is expressed in the structural and textural features of rocks with a characteristic banded texture and the simultaneous presence of relict textures of source rocks with widespread blastomylonites. Banding of blastomylonites is associated with differentiation of a homogeneous substrate into layers enriched and depleted in quartz-feldspar and micaceous aggregates under regional shear conditions. Material was redistributed simultaneously with recrystallization of rock-forming phases and reorientation ordering [11]. Heterogeneous deformations in the suture zone are also expressed in the morphology of garnet porphyroblasts. The latter form two generations: large garnet early-generation porphyroblasts overgrown by small syntectonic garnet, forming clusters in pressure shadows or independent aggregations with lenticular–banded morphology [40].

In blastomylonite complexes, sinistral and dextral shear were recorded, with the later dominant over the former in a 60/40 ratio. The direction of rock mass movement in tectonites was established by analyzing the bending and rotation structures of porphyroclasts and porphyroblasts. Blastomylonite bodies are laterally bounded by faulting and abrasion surfaces and along the strike by scalloped structures. Steeply dipping zones are traced for tens and hundreds of kilometers, with a width from hundreds of meters to several kilometers, accompanied by orthoclase pegmatite veins and late microclinization and silicification zones. We believe that they reflect various deformation stages during extension (blastomylonites $D_1$) and compression (blastomylonites $D_2$) of the continental crust.

The paleoceanic segment of the Yenisei shear zone consists of paleosubduction complexes. Early Neoproterozoic fragments of oceanic crust were first found on the right bank of the Yenisei River, just upstream of the Verkhnaya Surnikha River estuary [2]. These formations were considered part of Riphean volcanic strata and the Surnikha intrusive complex of metabasites and ultrabasites within the structure of the Isakovka synclinorium [10, 16]. Paleoceanic complexes of the Isakovka belt (terrane, allochthon) include the Neoproterozoic Firsov and Kiselikha sequences. They border the Garevka complex along the mélange zone [21] and high-pressure blastomylonites. A large part of the rocks form a subduction–accretionary complex, where they occur as tectonic slabs, lenses, or blocks of different size and composition in the serpentinite mélange. The existence of the Middle Neoproterozoic Isakovka and adjacent Predivinsk island-arc systems to the west of the Siberian Craton at the latitudes of the Yenisei Ridge was substantiated in [3, 14, 17, 18, 36]. Study of the Isakovka ophiolite belt allowed the Late Neoproterozoic stage of the formation of the Paleo-Asian Ocean to be reconstructed [1, 3, 12, 14, 18, 26, 28, 36]. The absolute ages of the rock complexes within the island-arc system range from 700 to 640 Ma [3, 4, 14, 18]. A Neoproterozoic age of 692 Ma was obtained for island arc meta-rhyolites of the Kiselikha sequence for the first time by the U–Pb zircon method, confirming the previously established Lower to Middle Riphean age [10, 16]. The composition and age of buried Pre-Ediacaran oceanic complexes of the Yenisei paleosubduction zone have not been reliably established. Based on deep seismic sounding (DSS) data, the main body of the suture has a complex stratiform shape with a thickness of about 15–20 km and can be traced from the surface to depths of 30–40 km.

The Yenisei shear zone can be traced along the entire Yenisei ridge, and further, within the Turukhansk–Norilsk Ridge. On the western flank of the Yenisei Ridge, the fault zone is distinguished by potential field anomalies and seismic data. The conditions and age of faulting in the Yenisei regional shear zone have not been determined in detail. However, its long-term character, as well as its relationship with geodynamic extension and orogenesis, have been unequivocally confirmed by the tectonic accretion of heterogeneous terranes and blocks of highly and weakly metamorphosed crystalline rocks; the relationship of faults with metamorphic and magmatic complexes of different ages; and syntectonic zoning of dislocation processes [11, 25].

## STAGES OF GEODYNAMIC EVOLUTION OF THE PALEOCONTINENTAL SEGMENT

In the evolution of the paleocontinental segment, the following stages are most clearly distinguished: Mesoproterozoic, Late Mesoproterozoic–Early Neoproterozoic, Early Neoproterozoic, and Late Neoproterozoic.

### *Mesoproterozoic Stage (1.4–1.2 Ga ago)*

This stage reflects the earliest tectonic events of crustal extension within the marginal part of the craton. Within the Central Block, this is manifested in the formation of a pericratonic trough, subsequent formation in the Early Mesoproterozoic basin, and the accumulation of thick (4.5–7.5 km) terrigenous sedimentary strata of the Sukhopit series in the Early Mesoproterozoic [17]. In the Late Mesoproterozoic, the continental crust in deep zones was stretched and rift-related sodium series granitoids were intruded in the interval of 1.38–1.36 Ga (zircon, SHRIMP II) [38].

Within the Central Block, Mesoproterozoic rifting was manifested in the eruption of picrobasalt–basalt tuffs and lavas, the intrusion of associated subvolcanic bodies of gabbrodolerites and picrites of the Rybinsk–Panimba volcanic belt [17] in the Ishimba–Tatar segment of the regional shear zone. The age of their metamorphism, established by the Ar–Ar method for amphiboles, is 1.1–1.2 Ga [29], which is close to the age of regional low-pressure andalusite–sillimanite metamorphism, which occurred about 1.1–0.9 Ga in the Teya and Garevka metacomplexes. Endogenic activity in the west of the craton in the Late Mesoproterozoic can be inferred from the age (1262 ± 100 Ma) of presumably “oceanic metamorphism,” obtained by the Rb–Sr method for metagabbro, as well as from model estimates $T_{Nd}$ (DM-2st) = 1272 Ma of the magmatic source of island-arc plagiogranites [3]. Mesoproterozoic and Neoproterozoic tectonic events within the Yenisei regional shear zone were recorded in the geological history of the southern (Kanskii) block of the Yenisei Ridge [38]. Thus, the Early Precambrian crust of the western margin of the Siberian Craton underwent stretching, destruction, and rift-related magmatism about 1.4–1.2 Ga.

### *Late Mesoproterozoic–Early Neoproterozoic Stage (1.2–0.8 Ga)*

This stage is associated with tectonic events of Grenville age [17]. At the initial stage, granite gneiss domes of the Teya (Garevka) type and Garevka and Teya complexes of regional andalusite–sillimanite metamorphism with an age of about 1.1–0.9 Ga in the Central Block formed under the geodynamic conditions of synchronous extension and uplift of the crust. At roughly the same time, rapakivi granite intrusions occurred locally in the zone adjacent to the suture, controlled by the geodynamic crustal extension setting [15]. In the area of Ostrovok Island in the Yenisei River, rapakivi granites form a small subvertical blastomylonitized body of northwestern strike (several tens of meters thick), located on the map between Ostrovok Island and the lower reaches of the Garevka River.

The formation of ortho blastomylonites and boudinage zones in the rapakivi granites is associated with late metamorphism synchronous to shear with an age of about 890–880 Ma (zircon, SHRIMP II) under high-pressure amphibolite facies conditions. In the suprasubduction zone of the Garevka metamorphic complex, temperature increased locally near the suture, which was reflected by migmatization (840 Ma, zircon, SHRIMP II) and the formation of sillimanite + potassium feldspar paragenesis in muscovite of gneisses of the Nemtikha sequence [17].

In the interval of 850–800 Ma, the crust of the marginal part of the Siberian continent underwent further compression, which caused an inversion in the metamorphic pressure regime. The diversity of metamorphic pressure is manifested in the two regional metamorphic facies [45]. Polycyclic manifestations of various types of metamorphism, differing in thermodynamic regimes and metamorphic gradients, in the Trans-Angara Yenisei Ridge is confirmed by U–Pb SHRIMP II, U–Th–Pb and $^{40}Ar$–$^{39}Ar$ dating. At the first stage, high-gradient zoned pressure complexes of andalusite–sillimanite type with a Grenville age of ~1050–950 Ma formed with a metamorphic gradient of $dT/dH$ = 25–35°C/km, typical of orogenesis. At the second stage, these rocks underwent Neoproterozoic (with two peaks 854–862 and 798–802 Ma) collisional kyanite–sillimanite metamorphism under moderate pressure with a local increase in pressure near thrusts, resulting in progressive substitution: andalusite → kyanite ± sillimanite and the formation of new mineral assemblages and deformation structures. The formation of more ancient metamorphic kyanite–sillimanite complexes occurred as a result of thrusts of blocks of the Siberian Craton on the Yenisei Ridge at the age boundary of ~850 Ma, which was confirmed by direct field observations in outcrops, petrological and geophysical data, a tectonic crustal thickening model, and studies on the nature and age of clastic material sources [17]. Dyke swarms of bimodal associations of anorogenic granitoids and rift-related intraplate mafic rocks with the average age of 797–792 Ma, associated with Neoproterozoic crustal extension processes along the western margin of the Siberian Craton and onset of the Rodinia breakup [37], occurred during the final stages of the collisional orogen. Overprinted Late Riphean thermal metamorphism is expressed locally near granitoid plutons (areas of the Mayakon River, middle reaches of the Teya and Bolshoi Pit rivers), under hypabyssal conditions and a high metamorphic gradient with $dT/dH$ > 100°C/km. Additional heat from the Kalama and Chirimba intrusive massifs could have triggered the occurrence of a fibrolite ± sillimanite assemblage in moderate pressure metapelites, which initially did not correspond to the $P$–$T$ stability domain of these minerals.

In the western part of the craton, tectonic movements of eastern vergence intensified about 0.8 Ga ago, accompanied by the occurrence of apopelitic blastomylonites of the kyanite–sillimanite type (Mt. Polkan area) with an $^{40}Ar$–$^{39}Ar$ age of dislocation metamorphism of 800 Ma (obtained for biotite). Late recurring collisional metamorphism was caused by opposing eastward movements of small blocks in the zone of higher-order feathering faults. Accretionary and collisional events of the Valhalla folding produced a system of thrusts with fault planes generally dipping westward. Consequently, the main folded structures of the Yenisei Ridge formed in the interval 1.2–0.8 Ga. We believe that the peak orogenesis of 850–800 Ma was probably associated with the initial stage of evolution of the paleosubduction zone and movement of the Kas–Turukhansk microcontinent from west to east.

### *Early Neoproterozoic Stage (800–730 Ma)*

This stage is characterized by the prevalence of the geodynamic extension environment and anorogenic magmatism along with the manifestation of bimodal granitoid and mafic magmatism (797–792 Ma), and polychronous granitoid magmatism (the Ust'-Vyatka massif (780–770 Ma), Garevka, Chernorechenskii, and Strelkovka massifs (730–710 Ma)).

It was observed that geological events happened within a time period of about 40–50 Ma. It is important that during the period of 780–650 Ma in the north of the Ishimba–Tatar regional shear zone, continental rifting was accompanied by intraplate bimodal, subalkaline acid, basic and alkaline volcanism, and intrusive magmatism [17, 37, 38]. To the south (in the upper reaches of the Tatarka and Penchenga rivers), the fault zone is marked by the Penchenga carbonatite complex with an $^{40}Ar$-$^{39}Ar$ arfvedsonite age of 731 Ma [5]. Linear zones of apocarbonatite tectonites are controlled by large-block boudinage of carbonatites and deformation of large pyrochlore and magnetite crystals contained in them.

These data may indicate an early stage of activation of Neoproterozoic continental rifting on the western margin of the Siberian Craton. Extension of the crust and associated bimodal magmatism of this era, featured with plume activity, have also been detected in large igneous provinces of other regions of the world [32]. The formation of such magmatic complexes was associated with the Rodinia breakup and opening of the Paleo-Asian Ocean. Dyke swarms are believed to have formed branches extending from the northern regions of Laurentia, the center points of two hypothetical giant radial dyke swarms: Gunbarrel (790–780 Ma) and Franklin (725–715 Ma). Considering the peculiarities and close location of Laurentia and Siberia, it was assumed that the Yenisei–Sayan–Baikal dyke belt was one of the peripheral branches of the radial dike swarm [35, 38].

In the range of 730–630 Ma, there was a decrease in intrusive magmatism on the paleocontinental margin. Extension of the crust was accompanied by the formation of the Glushikha metarhyolite–basalt rifting depression with a rhyolite age of 717 Ma (zircon, SHRIMP II) [17], which was subsynchronous with plagiogranite magmatism in the paleo island-arc segment. The activation of volcanism is reflected in our model. The evolution of the Paleo-Asian Ocean 700 Ma ago is considered in reconstructions as the upper age limit for the formation of the island arc and ophiolites [4, 36].

### *Late Neoproterozoic Stage (630–600 Ma)*

Early Ediacaran tectonic processes in the Yenisei regional shear zone of the continental block were accompanied by cataclasis and phyllonitization of granitoids, which is well shown in the western endomorphic contact of the Chernorechenskii granitoid massif. The shear zones in rocks of the Garevka metamorphic complex controlled by local zones of quartz–feldspar–mica apogneiss and apogranitoid blastomylonites (thicknesses from several centimeters to several decimeters) with a northwestern strike, as well as regionally manifested late area microclinization with the formation of augen-gneisses and synshear microclinization of metamorphites of the Nemtikha sequence.

Thus, the continental crust of the western margin of the Siberian Craton within the Yenisei Ridge in 1.4–0.6 Ga underwent multiple and multiphase high tectonic impacts caused by the superposition of polychronous magmatic and metamorphic processes associated with global tectonic events and repositioning on the margins of the craton.

## GEODYNAMIC MODEL OF THE YENISEI PALEOSUBDUCTION ZONE

At the Mesoproterozoic–Neoproterozoic boundary, the western part of the Siberian Craton was subjected to stretching (formation of a pericratonic depression, destruction of crust, and granitoid magmatism). Based on ophiolites (as an indicator of paleogeodynamic settings characterizing fragments of ancient oceanic crust), as well as paleomagnetic data [4], it was presumed that the oceanic basin originated west (in present-day coordinates) of the Yenisei Ridge at the Mesoproterozoic–Neoproterozoic boundary. Opening of the ocean basin was possibly associated with the evolution of the Rodinia [28, 30–34]. During this period, rupture of the supercontinental crust and parting of its fragments in the intermediate zone between Siberia and Laurentia resulted in the formation of tectonic blocks and, later, a spreading zone, typical oceanic crust, and a subduction zone with a system of island arcs, back-arc basins, and terranes (microcontinents). The tectonic blocks and paleo island arcs are presumed to be a part of the Pre-Jurassic basement of the West Siberian Platform [1].

The most ancient structures of the paleosubduction zone are represented by fragments of oceanic crust and island arcs of the Isakovka Terrane with an age of 700–690 Ma. The aggregate zircon dates obtained for the igneous complexes of the Isakovka Terrane (701.6 ± 8.4, 697.2 ± 3.6, 691.8 ± 8.8, 682 ± 13, 672 ± 6 Ma) and those obtained for volcanic rocks of the Predivinsk Terrane in the south of the Yenisei Ridge (637 ± 5.7, 628 ± 3, 619 ± 3.9 Ma) indicate the formation of ophiolites and island arcs in the Yenisei paleosubduction zone and their further transformation during subduction in the period of 740–620 Ma. We reconstructed the Yenisei paleosubduction zone in accordance with time intervals of 740–700, 640–600, and 580–540 Ma.

The period of 740–700 Ma in the geodynamic evolution of the Yenisei paleosubduction zone corresponds to the initial formation stage of the island-arc system west of Siberia [3, 4, 14], which includes the subduction zone, island arc, and back-arc basin (Fig. 2a).

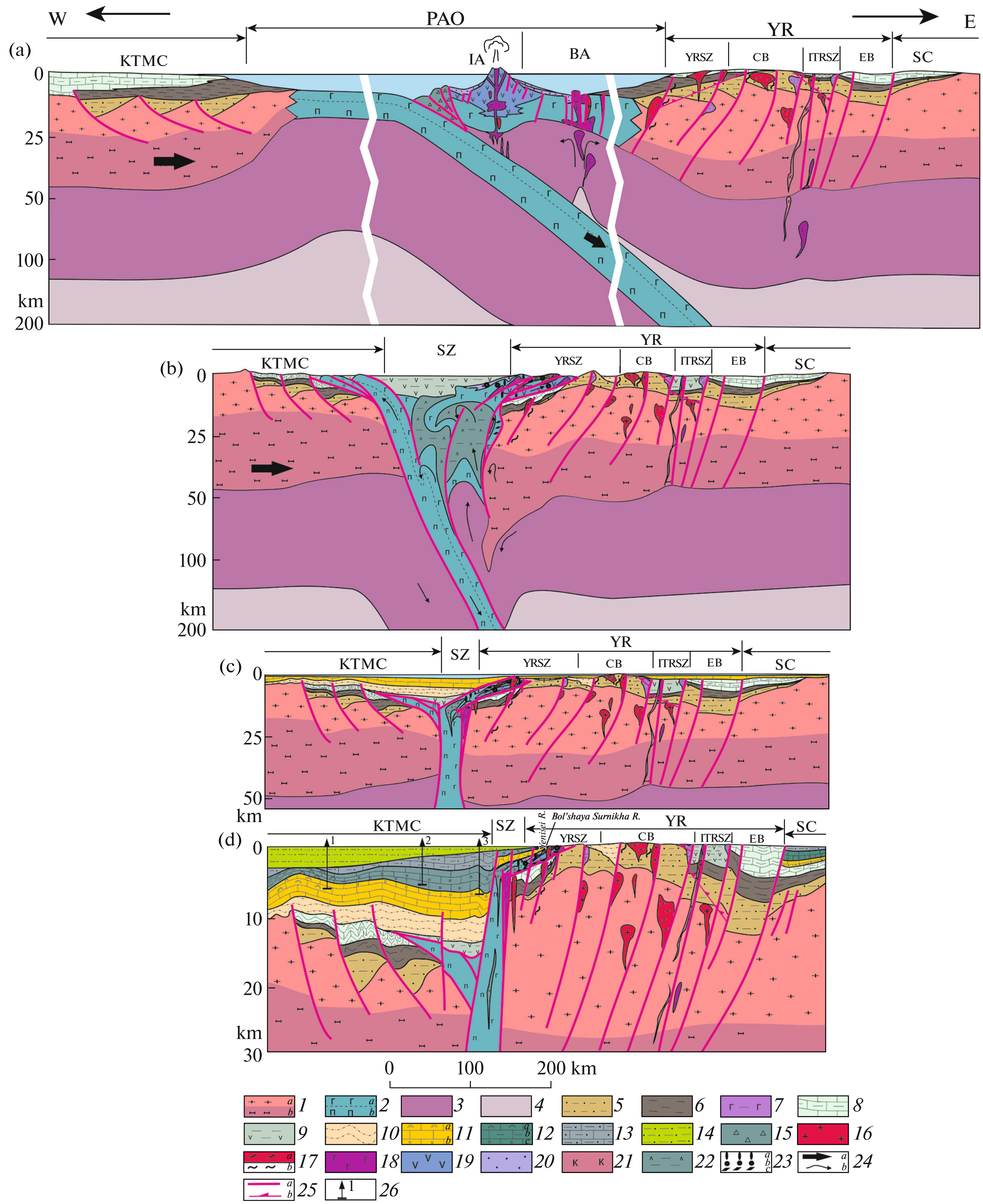
Repeat manifestations of mafic magmatism during this period recorded different stages of crustal extension along the western margin of the Siberian Craton. The formation of basalts more primitive in chemical composition occurred at the initial stages of spreading, when the upper horizons of the depleted mantle were melted. The basalts with higher titanium content were formed due to the melting of the enriched mantle substrate (less depleted mantle horizons) at later stages of spreading.

In Ediacaran time, about 640–600 million years ago, accretion and collision processes lead to collision of the Kas–Turukhansk microcontinent with the margin of the Siberian Craton along the subduction zone which caused a submersion of the latter under the continental crust (see Fig. 2b). The convergent border

$$\text{microcontinent} \rightarrow \text{paleoocean} \rightarrow \text{paleocontinent}$$

is marked by polychronous high-pressure tectonites in the suture zone, and by local zones of moderate-pressure metamorphism tectonites in the suprasubduction zone of the Siberian Craton near the suture. Their formation, most likely, is due to the movement of the Kas–Turukhansk microcontinent, which created stress directed eastward.

As a consequence of the evolution of the subduction zone and subsequent convergence of the Kas–Turukhansk microcontinent with the Siberian Craton (640–600 Ma), the Isakovka and Predivinsk oceanic and island-arc complexes were partially obducted (overthrusted) over the western margin, but mainly subducted (submerged) under Siberia [26, 36] along a system of tectonic faults, then dislocated and metamorphosed. The collision was accompanied by tectonic crowding and melting of accretionary, island-arc, and ophiolite complexes. Due to accretion to the Siberian Craton, oceanic crust was added to the continental crust; new continental crust was formed in the




Late Ediacaran. The accretion of the island-arc complexes of the Predivinsk Terrane to Siberia occurred later, about 610–600 Ma ago [18]. Syncollisional tectonic stress in the suture zone was accompanied by high-pressure polychronous metamorphism in the subduction zone with the formation of early (relict)

**Fig. 2.** Geodynamic model of evolution of Yenisei paleosubduction zone. a, 730–700 Ma; b, 640–600 Ma (based on modeled collision processes [34]); c, 580–540 Ma; d, current state (based on seismic tomographic section along Batolit seismic sounding profile [23]). Legend: KTMC, Kas–Turukhan microcontinent; SC, Siberian Craton; PAO, Paleo-Asian Ocean; IA, island arc; BA, back arc; YR, Yenisei Ridge; SZ, suture zone; YRSZ, Yenisei regional shear zone; ITRSZ, Ishimba–Tatar regional shear zone; CB, Central block; EB, Eastern block; (*1*) crystalline basement: (*a*) granite gneiss, granulite with felsic and intermediate composition; (*b*) granulite-basite (AR–PP); (*2*) oceanic crust (ophiolites): (*a*) dunites, peridotites; (*b*) matagabbros, metabasalts; (*3*) lithospheric mantle; (*4*) asthenospheric mantle; (*5–8*) metamorphosed and dislocated rift-depressive strata (PP–MP): (*5*) carbonate–volcanogenic–terrigenous sediments (Teya series, Malogarevka, Nemtikha sequences, PP–MP), (*6*) clayey, clay-carbonate deep-sea sediments (Sukhopit series, MP); (*7*) metapicrite–picrobasalt–basalts, orthoamphibolites (Shumikha and Rybinsk-Panimba volcanogenic complexes, MP); (*8*) mainly terrigenous–carbonate sediments of passive margins (Tungusik series, $MP_{1,2}$); (*9*) terrigenous–volcanogenic–carbonate (rift (?)) sediments (Glushikha, Verkhnevorogovka, Chingasanskaya, and Oslyanskaya series, $NP_2$); (*10*) predominantly terrigenous–carbonate sediments (Vorogovskaya series, $NP_3$); (*11*) predominantly carbonate sediments: (*a*) rift-related; (*b*) evaporites with salts) ($NP_3$); (*12*) carbonate sediments: (*a*) rift-related, (*b*) clayey deepwater; c, evaporites with salts) ($Є_{1-2}$); (*13*) terrigenous–carbonate sediments ($Є_{2-3}$); (*14*) terrigenous sediments (Mz); (*15*) accretionary wedge; (*16*) felsic intrusions; (*17*) metamorphosed granitoids: (*a*) granite gneiss complexes; (*b*) migmatites ($MP_3$–$NP_1$); (*18–19*) island arc complexes: (*18*) back-arc igneous, mafic composition; (*19*) volcanic; (*20*) island-arc volcano-clastic sediments; (*21*) carbonatites; (*22*) zones of partial melting of ophiolites, lower and upper crust; (*23*) tectonic elements: (*a*) protrusion; (*b*) mélange; (*c*) metabasites with glaucophane relicts; (*24*) shear direction in collision zone: (*a*) tectonic plates; (*b*) local shear; (*25*) faults: (*a*) major faults; (*b*) overthrusts accompanied by blastomylonites; (*26*) drilling sites: 1, Vostok-4; 2, Lemok-1; 3, Averniskaya-150.

glaucophane-bearing and late garnet–hornblende paragenesis with tectonic overpressure exceeding lithostatic pressure by 3–5 kbar [40] in the plastic subduction–shear zone.

As a result, the marginal Neoproterozoic complexes of the Siberian Platform and those of the adjacent microcontinent were brought together; at the place of the closed marginal sea, a subvertical suture zone was formed, the position of which was ascertained by geophysical methods [23, 24].

The synaccretionary metamorphism of paleo island-arc and ophiolite complexes is characterized by the greenschist facies and, locally, epidote–amphibolite facies conditions. The shear deformations of volcano-sedimentary rocks of the Kiselikha sequence were accompanied by the formation of folds with a vertical dip of the hinges; in the suture zone, they were controlled by high-pressure apopelitic and apobasitic blastomylonites (up to 13–15 kbar). The exhumed high-pressure polymetabasites of the suture zone contain relicts of glaucophane grains and coexisting minerals 620 Ma in age. The age of the glaucophane–schist metamorphism products that formed in the paleosubduction zone corresponds to a time interval of 640–620 Ma under *P–T* conditions of 8–10 kbar and 400–450°C. The overprinted formation of high-pressure tectonites in the suture subduction-shear zone ~600 Ma at 11–15 kbar and 550–640°C marks the final stage of accretion of the Isakovka block to the western margin of the Siberian Craton [40]. The Kiselikha sequence is penetrated by numerous protrusive bodies of carbonated and silicified serpentinites along the suture zone. Protrusion of serpentinite and exhumation of glaucophane-bearing blocks into the upper crust could be associated with the evolution of the fault system in the back-arc basin.

At the final stage (580–540 Ma) of the evolution of the Yenisei paleosubduction zone, formation of rift-related amygdaloid basalts (572 ± 6.5 Ma) and intrusion of postcollisional leucogranites of the Osinov massif (550–540 Ma) [18] occurred, which break through tectonized metadacites of the Kiselikha island-arc sequence (zircon, SHRIMP II, 692 Ma). The highly differentiated continental crust of the western margin of the Siberian Craton could have been a melt source for the Osinov granitoids, which indicates partial overthrust (obduction) of island-arc metacomplexes onto continental crust [18].

Thus, the established Late Neoproterozoic markers of the evolution of the Isakovka and Predivinsk terranes were compared with the final phase of the Rodinia breakup, detachment of the Siberian Craton, opening of the Paleo-Asian Ocean, and accretion of the Kas–Turukhansk microcontinent to the western (in present-day coordinates) margin of the Siberian Craton.

Late Ediacaran and subsequent Early Paleozoic events within the territory west of the Yenisei River mark the platform conditions for the accumulation of predominantly sedimentary (carbonate, evaporite, terrigenous-carbonate) complexes (Fig. 2c). The revealed similarities between the lithofacies and the vertical sequence of these Vendian–Cambrian cover formations of the Pre-Yenisei basin with coeval sediments in the southwest of the Siberian Craton are not limited only to drilling data. Their identical structure is revealed by comparative analysis of the waveform characteristic of the Ediacaran and Cambrian complexes in seismic sections of the central part of the basin and southwestern regions of the Siberian Craton [26, 27]. Moreover, in some cases, this similarity extends to the entire vertical section from the Vendian to the Cambrian inclusive, up to the coincidence of individual reflectors. This suggests that, from the Ediacaran and throughout the Cambrian, sedimentary complexes of the eastern parts of the Pre-Yenisei sedimentary basin formed synchronously with similar complexes in the southwestern regions of the Siberian Platform, under the influence of the same tectonic pulses, and identical transgressive–regressive cycles.

The Early Cambrian was predominated by deep-sea oceanic sedimentation conditions, corresponding to the active parts of the back-arc basin of the new Early Paleozoic island-arc system, located in the west of the Kas–Turukhansk microcontinent, which was consolidated with the Siberian Craton. Fragments of similar formations were discovered by drilling in the Vezdekhodnaya area in the southeast of the West Siberian Platform [26, 27], as well as in other areas in the southwestern frame of the Pre-Yenisei sedimentary basin. To the south of the back-arc basin, similar Ediacaran, Cambrian, and Ordovician complexes are common within the Kuznetsk–Alatau volcanic zone.

At the turn of the Late Carboniferous and Early Triassic, processes associated with closure of the Paleo-Asian Ocean (Hercynian diastrophism) began in the west. Due to these processes, the Yenisei Ridge was formed; under compression conditions, it rose along subvertical fault zones as a ramp arch elevation. Erosion processes here partially destroyed the Paleozoic and Vendian formations and the upper section of Riphean folded sediments and ophiolite allochthons. During the Mesozoic and Cenozoic, the Yenisei Ridge and adjacent parts of the Siberian Craton continued uplifting, while regions of the West Siberian Plate in the western part of the craton were subsiding, which led to the formation of the Mesozoic–Cenozoic cover (plate) complex (see Fig. 2d).

## DISCUSSION

The Pre-Mesozoic complexes in the southeastern part of the West Siberian Plate were affected by their rather deep location under a thick sedimentary cover, as well as by the peculiar position in the junction zone of folded structures of different ages and the marginal parts of the platform, which determined the tectonic development of the region.

Regional and global geodynamic reconstructions of the western marginal segments of the Siberian Craton are based on studies of polygenetic heterochronous folded and metamorphosed complexes of the Yenisei Ridge, which is the main structure of the craton's frame. However, buried fragments of the ancient basement of the West Siberian Plate adjoining from the west are not considered in many reconstructions. In addition, the numerous data obtained to date on various sedimentary, metamorphic, and magmatic complexes of the Yenisei Ridge, as well as their analysis and interpretation suggested by different experts, vary greatly, and the question of paleogeodynamic reconstructions and palinspastic models of accretionary collisional structures in the Yenisei frame of the Siberian Craton is still controversial. This is especially true for reconstructions of the earlier (up to the Late Neoproterozoic) stages of the geodynamic evolution of the structures of the Yenisei Ridge.

Geological, structural, tectonic, and paleomagnetic data on granitoids of the Eruda massif (Teya complex) [4] indicate significant distance and, accordingly, structural and tectonic disunity of the Central Angara Terrane from the Eastern block of the Yenisei Ridge up to the Cryogenian. However, we believe that the activity of the Grenville orogeny in these areas of the Yenisei Ridge and, therefore, the genetic proximity of the structures of the Central and Eastern blocks of the Yenisei Ridge is undeniable [17]. A close relationship between the Meso- and Neoproterozoic geological complexes in the Central and Eastern blocks of the ridge was revealed, and models for the evolution of the structures of the Yenisei Ridge were developed [10, 16, 37].

Our studies of the convergent paleocontinent–paleocean boundary and the geodynamic evolution of the Yenisei paleosubduction zone for the first time took into account the results of comprehensive studies of the Yenisei Ridge and materials of large-scale geological and geophysical studies, as well as geodynamic reconstructions of the Pre-Yenisei sedimentary basin (Upper Precambrian–Lower Paleozoic) that formed on the ancient Kas–Turukhansk microcontinent and is buried under the cover of the West Siberian Plate (Mesozoic).

The data obtained allow us to more thoroughly and reasonably interpret the Precambrian history of the tectonic development of the Yenisei Ridge and the junction zone with the basement of the West Siberian Plate bordering it from the west (in present-day coordinates).

The proposed geodynamic model of the evolution of the Yenisei paleosubduction zone in the Neoproterozoic is based on an analysis of abundant published and new geological, geophysical, and geochronological data obtained for the paleocontinental and paleoceanic segments. Our geodynamic model takes into account the results numerical modleing of similar convergent settings [8, 34] and includes: (1) analysis of the geodynamic conditions of magmatism and metamorphism within 1.4 to 0.54 Ga; (2) individual stages of the geodynamic evolution of the studied region in the intervals of 740–700, 640–600, and 580–540 Ma ago (see Figs. 2a–2d).

Such an comprehensive approach allowed us to distinguish five main tectonic stages as age boundaries controlled by the processes of extension and collision of the continental crust within the Yenisei regional shear zone: 1.4–1.1, 1.1–0.9, 0.9–0.85, 0.8–0.78, and 0.78–0.6 Ga ago.

The time interval of 1.4–0.8 Ga ago can be considered a very important period in the geological development of the western margin of the craton, indicating powerful endogenic processes. Accretion and collision processes that occurred about 0.8–0.6 Ga ago were genetically related to the formation and evolution of the Paleo-Asian Ocean [31]. The Paleo-Asian Ocean was formed between the North American and Siberian cratons as a result of the Rodinia breakup, according to various estimates, from 1000–900 to 720 Ma ago and lasted until the end of the Paleozoic [30]. Based on the geological data obtained for the rocks and structures of the Yenisei Ridge, we assumed that the origin of its spreading structures could have occurred at the Mesoproterozoic–Neoproterozoic boundary. This assumption was confirmed by conclusions on this age limit [6].

In the period of 1.1–0.9 Ga, the metamorphic pressure inversion at the periphery of the craton from low to moderate, in our opinion, could have been associated with tectonic processes occurring west of the Yenisei regional shear zone. A possible mechanism of orogenic processes leading to the formation of the Yenisei Ridge 900–800 Ma could have been a subduction zone plunging eastwards and a mosaic of microcontinents with eastern vergence approaching the Siberian Craton from the west.

The formation of the subduction zone 1.2–1.1 Ga was preceded by rifting of the continental crust of the Siberian Craton (several hundred kilometers west of the present-day location of the Yenisei River), which we interpreted as the onset of the spreading stage of the Paleo-Asian Ocean at the Mesoproterozoic–Neoproterozoic boundary (possibly more than 1 Ga). With an average spreading rate of 3 cm per year, the width of the Paleo-Asian Ocean after 100 million years could have reached about 3000 km.

We believe that the gradual formation of the suture was controlled by convergence of the Kas–Turukhansk microcontinent with the margin of the Siberian Craton along the subduction zone, which began about 800 Ma ago, possibly even earlier. Around 0.8–0.7 Ga, subduction boosted the eastward migration of the Kas–Turukhansk microcontinent, the formation of island-arc complexes, and the back-arc basin near the margin of the Siberian Craton. Extension zones on the margins of the craton could have been accompanied by subsynchronous dyke swarms with bimodal association of anorogenic granites and intraplate basites 797–792 Ma in age [37]. In the geodynamic convergence setting in the back-arc basin, a deep tectonic structure with a system of adjacent subparallel W trending deep faults could have been activated.

At subsequent stages, in the setting of the collision of the Kas–Turukhansk microcontinent with the Yenisei Ridge, in the eastern part of the back-arc basin, a tectonic subduction–shear zone was formed, genetically and spatially associated with the subduction zone (rejuvenated). At the Cryogenian–Ediacaran boundary, this led to tectonic crowding, merging of accretionary wedges, island-arc, and ophiolite complexes of the back-arc paleobasin to the Yenisei Ridge. Manifestations of accretionary tectonics were recorded by mélange zones, high- and moderate-pressure metamorphism of rock complexes accompanied by the formation of blastomylonites with relicts of glaucophane metamorphism (620 Ma), which are the first petrological evidence for the subduction zone and exhumation of glaucophane-bearing metabasites to the surface through the subduction channel [40].

Another feature of the junction of the paleoceanic and paleocontinental complexes in the suprasubduction zone in the western part of the Siberian Craton was a temperature increase up to a value typical of amphibolite facies metamorphism, controlled by the development of progressive paragenesis of potassium feldspar with sillimanite in muscovite, as well as by migmatization (840 Ma). Moreover, thrusts were accompanied by local collisional moderate-pressure metamorphism and late syntectonic microclinization (600 Ma) of the continental crust of the Garevka metacomplex.

## CONCLUSIONS

Our results on metamorphism of the suture and suprasubduction zones indicate polycyclic development of metamorphism 630–590 Ma. We believe that metamorphic complexes formed at an early stage (630–610 Ma) were similar in composition to paired metamorphic belts, characterized by joint manifestation of glaucophane HP/LT metamorphism and zonal LP/HT metamorphism of andalusite–sillimanite type, in the the subduction channel of the suture zone and on the western periphery of the Garevka complex, respectively. During the subsequent (610–590 Ma) accretionary–collisional deformation processes in the suprasubduction zone (the estuary part of the Garevka River), they experienced dynamic metamorphism with the formation of moderate-pressure garnet–staurolite–kyanite tectonites with an age of 600 Ma [40].

Thus, we believe that the Precambrian structures of the Yenisei Ridge and adjacent basement block of the West Siberian Plate were formed during collisional–accretionary movements (640–600 Ma), while the tectonic structures of the Yenisei Ridge arose under the influence of NW trending deep faults at the early stages of development of the Yenisei and Ishimba–Tatar regional shear zones.

The paleoceanic complexes of the Yenisei paleosubduction zone are a system of structures of different ages, which were formed within the oceanic lithosphere and accreted to the Siberian Craton in subsequent tectogenic epochs.

Geophysical methods revealed fragments of the Yenisei paleosubduction zone that tectonically subsided to depth and are buried under the sedimentary cover as a narrow suture block.

These events were recorded by continental margin, ophiolite, and island-arc rock associations of Precambrian terranes of different ages and nature, both tectonic and metamorphic [18].

The geodynamic history of the region in the late Mesoproterozoic and Neoproterozoic correlates with synchronous magmatic activity, concomitant rifting, and a similar sequence of the same type of tectonic and thermal events in the Arctic paleomargin of Nuna and Rodinia, which confirms the territorial proximity of the North Siberian and North Atlantic cratons (Laurentia and Baltica) [33, 42–44].

We believe that our model of the Neoproterozoic geodynamic evolution of the Near-Yenisei paleosubduction zone, which takes into account the aggregate geological and geophysical data, does not contradict available natural observations. In deciphering and constructing the key geodynamic settings of the collisional–accretionary system, we used modern software, experience, and the numerical simulation results for similar subduction zones.

## ACKNOWLEDGMENTS

The authors are grateful to the anonymous reviewers for valuable constructive comments that significantly improved the article.

## FUNDING

This work was carried out as part of the state tasks of the Institute of Geology and Mineralogy (project no. 0330-2016-0004) and the Institute of Petroleum Geology and Geophysics (project no. 0331-2019-0020), Siberian Branch of the Russian Academy of Sciences (both in Novosibirsk), and of the Institute of Geology and Geochemistry (project no. AAAA-A18-118052590032-6), Ural Branch of the Russian Academy of Sciences (Yekaterinburg). It was also supported by the Russian Foundation for Basic Research (project no. 18-05-00152) and the administration of Tomsk oblast (project no. 19-45-700009 p,a).

## REFERENCES

1. S. V. Aplonov, "Paleogeodynamics of the West Siberian Plate," Sov. Geol., No. 7, 27–36 (1989).
2. V. P. Belov, "Ultrabasic and basic rocks of the northwestern Yenisei Range," Vestn. Mosk. Univ., No. 1, 8–14 (1964).
3. V. A. Vernikovsky, A. E. Vernikovskaya, A. I. Chernykh, E. B. Sal'nikova, A. B. Kotov, V. P. Kovach, S. Z. Yakovleva, and A. M. Fedoseenko, "Porozhnaya granitoids of the Enisei ophiolite belt: Indicators of Neoproterozoic events on the Enisei Ridge," Dokl. Earth Sci. **381**, 1043–1046 (2001).
4. V. A. Vernikovsky, A. Yu. Kazansky, N. Yu. Matushkin, D. V. Metelkin, and J. K. Sovetov, "The geodynamic evolution of the folded framing and the western margin of the Siberian craton in the Neoproterozoic: Geological, structural, sedimentological, geochronological, and paleomagnetic data," Russ. Geol. Geophys. **50**, 380–393 (2009).
5. V. V. Vrublevskii, V. V. Reverdatto, A. E. Izokh, I. F. Gertner, D. S. Yudin, and P. A. Tishin, "Neoproterozoic carbonatite magmatism of the Yenisei Ridge, Central Siberia: $^{40}Ar/^{39}Ar$ geochronology of the Penchenga complex," Dokl. Earth Sci. **437**, 443–446 (2011).
6. V. M. Datsenko, Yu. S. Aleksandrovskii, A. P. Kosorukov, O. I. Pyatov, and A. G. Rublev, "Key epochs and geodynamuc settings of granitoid magmatism and endogenous mineralization in structures of the southwestern framing of the Siberian Platform," Otechestvennaya Geol., No. 10, 27–39 (1994).
7. V. A. Detkov, V. I. Val'chak, N. A. Goryunov, and A. A. Evgrafov, "Structural peculiarities of the crust and upper mantle of the southern Siberian Platform inferred from the Batolit and Altai Severnaya Zemlya reference transects," in *Models of the Crust and Upper Mantle from the Results of Deep Seismic Profiling* (VSEGEI, St. Petersburg, 2007), pp. 26–31.
8. N. L. Dobretsov, *Fundamentals of Tectonics and Geodynamics* (Novosibirsk. Gos. Univ., Novosibirsk, 2011) [in Russian].
9. A. S. Egorov, *Deep Structure and Geodynamics of the Lithosphere of North Eurasia Inferred from Geological-Geophysical Modeling along Russian Geotraverses* (VSEGEI, St. Petersburg, 2004) [in Russian].
10. L. K. Kachevskii, G. I. Kachevskaya, and Zh. M. Grabovskaya, *Geological Map of the Yenisei Range, Scale 1 : 500000*, Ed. by A. K. Mkrtych'yan and M. L. Sherman (Krasnoyarskgeols"emka, Krasnoyarsk, 1998).
11. P. S. Kozlov, I. I. Likhanov, V. V. Reverdatto, and S. V. Zinoviev, "Tectonometamorphic evolution of the Garevka polymetamorphic complex (Yenisei Ridge)," Russ. Geol. Geophys. **53**, 1133–1149 (2012).
12. M. M. Konstantinov, R. F. Dankovtsev, G. S. Simkin, and S. V. Cherkasov, "Deep structure of the North Yenisei gold district (Russia) and setting of ore deposits," Geol. Ore Deposits **41**, 387–397 (1999).
13. A. E. Kontorovich, V. A. Kontorovich, Yu. F. Filippov, S. Yu. Belyaev, V. A. Kashtanov, A. V. Khomenko, L. M. Burshtein, V. I. Val'chak, A. A. Evgrafov, A. S. Efimov, A. A. Kontorovich, and V. N. Petrov, "Fore-Yenisei petroleum subprovince as a new object promising for searching of oil and gas in Siberia," Geol., Geofiz. Razrab. Neft. Gaz. Mestorozhd., Nos. 5–6, 9–23 (2006).
14. A. B. Kuz'michev, Candidate's Dissertation in Geology and Mineralogy (Moscow, 1987).
15. A. M. Larin, *Rapakivi Granites and Associating Rocks* (Nauka, St. Petersburg, 2011) [in Russian].
16. *State Geological Map of Russian Federation, Scale 1 : 200000 (Second Edition), Yenisei Series*, Ed. by L. K. Kachevskii (PGO Krasnoyarskgeologiya, Krasnoyarsk, 2002).
17. I. I. Likhanov, A. D. Nozhkin, V. V. Reverdatto, and P. S. Kozlov, "Grenville tectonic events and evolution of the Yenisei Ridge at the western margin of the Siberian Craton," Geotectonics **48**, 371–389 (2014).
18. I. I. Likhanov, A. D. Nozhkin, and K. A. Savko, "Accretionary tectonics of rock complexes in the western margin of the Siberian Craton," Geotectonics **52**, 22–44 (2018).
19. G. L. Mitrofanov, T. V. Mordovskaya, and F. V. Nikol'skii, "Crustal compression structures in some marginal parts of the Siberian Platform," in *Tectonics of Platform Regions*, Ed. by O. A. Votakh and V. A. Solov'ev (Nauka, Novosibirsk, 1988), pp. 169–173.
20. G. I. Musatov, "Evolution of the Yenisei–Turukhan mobile belt and its metallogeny as a result of interaction between lithospheric plates," in *Metallogeny and New*

*Global Tectonics: Abstracts of the All-Union Scientific and Technical Meeting "Problems of Metallogeny in the Light of Ideas of the New Global Tectonics,"* Leningrad, Soviet Union, 1973 (VSEGEI, Leningrad, 1973), pp. 89–92.
21. E. S. Postel'nikov and N. I. Museibov, "Peculiarities of deep structure of the Trans-Angarian region," Byull. Mosk. O-va. Ispyt. Prir., Otd. Geol. **67** (2), 20–32 (1992).
22. N. S. Priyatkina, N. B. Kuznetsov, S. V. Rud'ko, A. V. Shatsillo, A. K. Khudoley, T. V. Romanyuk, and A. V. Maslov, " The Proterozoic Pogor'uy Formation of Yenisei Ridge: Age and provenance sources according to U/Pb dating of detrital zircons," Dokl. Earth Sci. **484**, 28–31 (2019).
23. A. S. Sal'nikov, *Seismological Structure of the Earth's Crust of the Platform and Fold Zones of Siberia Inferred from the Data of Regional Refracted-Wave Seismic Studies* (Sib. Nauchno-Issled. Inst. Geol., Geofiz. Miner. Syr'ya, Novosibirsk, 2009) [in Russian].
24. V. S. Surkov, V. P. Korobeinikov, and S. V. Krylov, "Geological and sedimentation formation conditions of the Riphean petroleum-bearing complexes in the western margin of the Siberian Paleocontinent," Geol. Geofiz. **37** (8), 154–165 (1996).
25. *Tectonics and Metallogeny of the Lower Angara Region*, Ed. by A. I. Zabiyaka (Krasnoyarsk. Nauchno-Issled. Inst. Geol. Miner. Syr'ya, Krasnoyarsk, 2004) [in Russian].
26. Yu. F. Filippov, Doctoral Dissertation in Geology and Mineralogy (Novosibirsk, 2018).
27. Yu. F. Filippov, "The Fore-Yenisei sedimentary basin: Seismic-geological model and geodynamic evolution," Russ. Geol. Geophys. **58**, 371–383 (2017).
28. T. N. Kheraskova, S. A. Kaplan, V. P. Bubnov, and V. I. Galuev, "New data on the structure of the Kas Block in the basement of the West Siberian Plate," Geotectonics **47**, 101–114 (2013).
29. A. I. Chernykh, Candidate's Dissertation in Geology and Mineralogy (Novosibirsk, 2000).
30. V. V. Yarmolyuk, V. I. Kovalenko, V. P. Kovach, E. Yu. Rytsk, I. K. Kozakov, A. B. Kotov, and E. B. Sal'nikova, "Early stages of the Paleoasian Ocean formation: Results of geochronological, isotopic, and geochemical investigations of Late Riphean and Vendian-Cambrian complexes in the Central Asian Foldbelt," Dokl. Earth Sci. **411**, 1184–1189 (2006).
31. P. A. Cawood, R. A. Strachan, S. A. Pisarevsky, D. P. Gladkochub, and J. B. Murphy, "Linking collisional and accretionary orogens during Rodinia assembly and breakup: Implications for models of supercontinent cycles," Earth Planet. Sci. Lett. **449**, 118–126 (2016).
32. R. E. Ernst, M. A. Hamilton, U. Soderlund, J. A. Hanes, D. P. Gladkochub, A. V. Okrugin, T. Kolotilina, A. S. Mekhonoshin, W. Bleeker, A. N. LeCheminant, K. L. Buchan, K. R. Chamberlain, and A. M. Didenko, "Long-lived connection between southern Siberia and northern Laurentia in the Proterozoic," Nat. Geosci. **9**, 464–469 (2016).
33. R. E. Ernst, M. T. D. Wingate, K. L. Buchan, and Z. H. Li, "Global record of 1600–700 Ma Large Igneous Provinces (LIPs): Implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents," Precambrian Res. **160**, 159–178 (2008).
34. M. Faccenda, T. V. Gerya, and S. Chakraborty, "Styles of post-subduction collisional orogeny: Influence of convergence velocity, crustal rheology and radiogenic heat production," Lithos **103**, 257–287 (2008).
35. D. P. Gladkochub, S. A. Pisarevsky, T. V. Donskaya, R. E. Ernst, M. T. D. Wingate, U. Söderlund, A. M. Mazukabzov, E. V. Sklyarov, M. A. Hamilton, and J. A. Hanes, "Proterozoic mafic magmatism in Siberian craton: An overview and implications for paleocontinental reconstruction," Precambrian Res. **183**, 660–668 (2010).
36. A. B. Kuzmichev and E. V. Sklyarov, "The Precambrian of Transangaria, Yenisey Ridge (Siberia): Neoproterozoic microcontinent, Grenville–age orogeny, or reworked margin of the Siberian craton," J. Asian Earth Sci. **115**, 419–441 (2016).
37. I. I. Likhanov and M. Santosh, "Neoproterozoic intraplate magmatism along the western margin of the Siberian Craton: Implications for breakup of the Rodinia supercontinent," Precambrian Res. **300**, 315–331 (2017).
38. I. I. Likhanov and M. Santosh, "A-type granites in the western margin of the Siberian Craton: Implications for breakup of the Precambrian supercontinents Columbia/Nuna and Rodinia," Precambrian Res. **328**, 128–145 (2019).
39. I. I. Likhanov, V. V. Reverdatto, P. S. Kozlov, V. V. Khiller, and V. P. Sukhorukov, "*P-T-t* constraints on polymetamorphic complexes of the Yenisey Ridge, East Siberia: Implications for Neoproterozoic paleocontinental reconstructions," J. Asian Earth Sci. **113**, 91–410 (2015).
40. I. I. Likhanov, J.-L. Régnier, and M. Santosh, "Blueschist facies fault tectonites from the western margin of the Siberian Craton: Implications for subduction and exhumation associated with early stages of the Paleo-Asian Ocean," Lithos **304–307**, 468–488 (2018).
41. N. J. Price and J. W. Cosgrove, *Analysis of Geological Structures* (Cambridge University Press, Cambridge, 1990).
42. N. Priyatkina, A. K. Khudoley, W. J. Collins, N. B. Kuznetsov, and H.-Q. Huang, "Detrital zircon record of Meso- and Neoproterozoic sedimentary basins in northern part of the Siberian Craton: Characterizing buried crust of the basement," Precambrian Res. **285**, 21–38 (2016).
43. N. Priyatkina, W. J. Collins, A. K. Khudoley, D. Zastrozhnov, V. Ershova, K. Chamberlain, V. Proskurnin, and A. Shatsillo, "The Proterozoic evolution of northern Siberian Craton margin: A comparison of U–Pb–Hf signatures from sedimentary units of the Taimyr orogenic belt and the Siberian platform," Int. Geol. Rev. **59**, 1632–1656 (2017).
44. N. Priyatkina, W. J. Collins, A. K. Khudoley, E. F. Letnikova, and H.-Q. Huang, "The Neoproterozoic evolution of the western Siberian Craton margin: U–Pb–Hf isotopic records of detrital zircons from the Yenisey Ridge and the Prisayan Uplift," Precambrian Res. **305**, 197–217 (2018).
45. V. V. Reverdatto, I. I. Likhanov, O. P. Polyansky, V. S. Sheplev, and V. Yu. Kolobov, *The Nature and Models of Metamorphism* (Springer, Cham, Switzerland, 2019).

*Translated by M. Hannibal*