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


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Abstract

The formation of the western margin of the Siberian craton in the Neoproterozoic is considered, with a focus on its transformation from a passive continental margin into an active one, accretion and collision processes, formation of island arcs and ophiolites, orogeny, and continent-marginal rifting. The evolution and correlation of sedimentary basins within fold-thrust belts of the Siberian Platform framing are considered. New structural and kinematic data on the Yenisei fault zone are discussed. On the basis of paleomagnetic data obtained for the structures in the zone of junction of the Siberian Platform and the West Siberian Plate, new models are proposed for the location of the Siberian craton relative to other paleocontinents and microcontinents in the Neoproterozoic. All these data provide a consistent evolution scheme for the western margin of the Siberian paleocontinent in the Neoproterozoic and constrain the position of the Siberian craton margin in Late Neoproterozoic (pre-Vendian) time.

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Introduction

Geologists have recently paid closer attention to the Predyenisei Petroleum Subprovince (Kontorovich et al., 2006), and as a consequence, the debatable questions on its geological structure are being discussed again: What sedimentary complexes do underlie the Mesozoic–Cenozoic cover? What is the basement on the left Yenisei riverside composed of? Are there buried structures of the Siberian craton? What is the age from which the sedimentary complexes on both riversides can be correlated? For the last ten years, sedimentary basin to the west of the Yenisei Ridge has been subjected to a considerable amount of seismic prospecting and drilling. This provided considerable progress in answering the above and many other questions (e.g., Kontorovich et al., 1999, 2008a,b; Saraev et al., 2004; Yolkin et al., 2001). The answers, however, are far from being exhaustive. The authors of this paper spent many years performing geologic-structural, sedimentological, petrological, geochronological, and paleomagnetic studies within the western folded framing of the Siberian craton, including the study of the Yenisei Ridge, the main folded structure separating the Yenisei Basin from the craton. This paper is an attempt to analyze all the available data and to propose a hypothesis on the geodynamic evolution of the western margin of Siberia and of its border.

Transformation from passive to active continental margin and evolution of magmatism-related events in the western framing of the Siberian craton in the Neoproterozoic

To draw the western boundary of the Siberian craton in a correct way, it is necessary to have an idea of its margins in Meso–Neoproterozoic time taking into account that the craton itself was formed in the late Early Proterozoic, 1.8–1.7 Ga, as a result of the amalgamation and collision of the Archean–Early Proterozoic terranes (Rosen et al., 1994; Zonenshain et al., 1990). The Mesoproterozoic sections on the Siberian craton start with beds of well-sorted, often monomict quartz
sandstones, the products of rewashing of highly mature crusts of weathering. However, on the basis of the analysis of sedimentary complexes, it was safely established that as late as the end of the Mesoproterozoic (1000 Ga), the whole (or nearly the whole) periphery of the platform was of passive type (Bogdanov et al., 1998; Pisarevsky and Natapov, 2003; Vernikovsky et al., 2004; Zonenshain et al., 1990).

For the western and northwestern margins (in modern coordinates) of the Siberian paleocontinent, Meso–Neoproterozoic sedimentary complexes typical of the passive continental margins are described in a number of papers (Bogdanov et al., 1998; Khabarov, 1999; Petrov and Semikhatov, 1997, 2001; Sergeev et al., 1997). For the Turukhan uplift the rocks referred to as passive margin deposits have been determined as Meso–Neoproterozoic by findings of microphytoliths and stromatoliths as well as after isotope Pb-Pb carbonate dating, which yielded an age of 1035±60 Ma (Ovchinnikova et al., 1995; Petrov and Semikhatov, 2001). Moreover, on the basis of the obtained paleontological, isotope-geochemical, and lithological data, the above-mentioned authors have revealed a good correlative similarity between the Turukhan uplift rocks and coeval deposits of the Uchur–Maya district.

However, as early as the Early Neoproterozoic the passive continental margin of northwestern Siberia began to transform into active margin. New geological, geochronological, and paleomagnetic data on the Central Taimyr accretionary belt show that the island-arc system began to form near the northwestern margin (in modern coordinates) of the Siberian craton at 960 Ma (Vernikovsky et al., 2007; Vernikovsky et al., 2008). The paleomagnetic pole we have calculated for island-arc volcanites and plagiograni tes of Tri Sestry (Three Sisters) Lake, Northeastern Taimyr, with a zircon U-Pb age of 960 Ma, is close to the pole of the same age for the Siberian craton obtained in the Uchur–Maya district (Pavlov et al., 2002). Ophiolites and island arcs continued to form near the northwestern margin of Siberia until the end of the Neoproterozoic: Chelyuskin and Stanovoi belts 750–730 Ma and Ust’-Taimyr belt 660 Ma (Khain et al., 1997; Vernikovsky, 1996; Vernikovsky and Vernikovskaya, 2001; Vernikovsky et al., 2004). Then, in the Vendian, they all together accreted to the Siberian craton and obducted on its margin to form the Central Taimyr accretionary belt.

The Late Neoproterozoic (Vendian) age of this accretionary event is proved by a complex of isotope-geochemical data (Sm-Nd, Rb-Sr, and Ar-Ar methods of dating) on garnet amphibolites (606–570 Ma) lying at the bottom of the allochthon, at the junction of Central and South Taimyr structures (Vernikovsky, 1996). This stage of evolution of the active continental margin was completed by continental-margin rifting accompanied by the effusion of trachybasalts solidified into thin beds (Bezzubtsev et al., 1986; Lopatin et al., 1991) as well as basalts and rhyolites of bimodal series referred to as the Laptev Formation (Zabiyaka et al., 1986). The zircon U-Pb age of rhyolites is 600 Ma (Pease and Vernikovsky, 2000).

Within the Yenisei Ridge the continental margin was transformed from passive to active at about 800 Ma, when the Central Angara terrane accreted to the Siberian craton (Fig. 1). The age of collisional Ayakhta and Chirimba granites that formed as a result of this collision is 760–750 Ma and the age of postcollisional Glushikha granites is 750–720 Ma (U-Pb data on zircons, after: Vernikovskaya et al., 2002, 2003, 2007). The collisional event was followed by the formation of island arcs along the western margin of the Siberian paleocontinent (700–630 Ma), first in the northern, Isakovka, part of the belt, and then somewhat later in the south, in the Predivinsk zone (Vernikovsky et al., 1999, 2001; Vernikovsky et al., 2003). These data are in agreement with the age of metamorphism of the obducted ophiolites and island arcs (685–600 Ma, after: Volobuev, 1993; Vernikovsky et al., 1994), as well as the Vendian age of the overlapping molasse complexes (Semikhatov, 1962; Sovetov et al., 2000).

Almost simultaneously with the formation of island arcs and their obduction upon the continental margin at the Yenisei Ridge, continental-margin rifting occurred with the formation of alkaline basaltoids, trachytes, syenites, and A-type granites, which is due to the continuing subduction of the oceanic plate beneath the continent and, when it reached the asthenosphere, to the formation of a new alkaline magma source (Nozhkin et al., 2007; Vernikovsky and Vernikovskaya, 2006; Vernikovsky et al., 2008b). Remarkably, at the same time (700–650 Ma), along the Yenisei Ridge and East Sayan to Lake Baikal (Yarmolyuk et al., 2005), the alkaline magmatism was accompanied by the formation of continental-margin rift-generated basins constraining the extension environments (Sovetov et al., 2007), which is in full agreement with the proposed model for the formation of a complex of alkaline rocks.

Thus, the accretion and continental-margin rifting events that occurred in the Late Neoproterozoic–Early Vendian were evidently very similar within the Taimyr folded area, Yenisei Ridge, East Sayan, and Baikal region, i.e., along the northwestern, western, and southwestern margins of the Siberian craton. This seriously constrains the position of the Siberian craton boundary in pre-Vendian time. The long history of Meso–Neoproterozoic passive continental margins along the western ending of the Siberian craton and Late Neoproterozoic island arcs and ophiolites from Taimyr to East Sayan, whose age was proved by numerous precision data obtained in different Russian and foreign laboratories (Dobretsov and Vernikovsky, 1997; Dobretsov et al., 2003; Khain et al., 1997; Vernikovsky, 1996; Vernikovsky et al., 2004), implies that the boundary of the Siberian paleocontinent must be drawn near these complexes obducted upon the craton, i.e., along the present-day Yenisei River.

At the same time, to follow the Neoproterozoic island arcs and ophiolites, other Precambrian terranes and/or microcontinents were accreted to the Siberian craton in the west. It is these terranes that made a consolidated basement for the formation of a single terrigene-carbonate and carbonate-evaporite plate complex demonstrated by Kontorovich et al. (2006) when characterizing the Preyndesis Petroleum Subprovince.
Fig. 1. A schematic tectonic map of the Yenisei Ridge. Compiled by Vernikovsky and Vernikovskaya (2006), with supplements; a fragment of the Batolit section, after: N.A. Goryunov (Detkov et al., 2007).

1, cover (PZ–KZ); 2, molasses (NP₂,₃); 3, predominantly carbonate deposits (NP₂,₃); 4, ophiolite and island-arc complexes of the Priyenisei belt of the Yenisei Ridge (NP₂), plagiogranites aged 700–630 Ma; 5, flyschoid deposits metamorphosed from greenschist to amphibolite facies MP(?–NP; 6, ophiolites of the Rybnaya-Panimba belt (MP–NP?); 7, granulite–amphibolite complexes (PP₃). Granitoids: 8, Tarak (1840 Ma); 9, Teya and Eruda (880–865 Ma); 10, Ayakhta (760–750 Ma); 11, Glushikha (750–720 Ma); 12, Tatarka (711–630 Ma); 13, Posol'nya and Nizhnekan (511–455 Ma); 14, faults (a) and thrusts (b), A, Angara, I, Ishimba, T, Tatarka, Ye, Yenisei, An, Ankinov; 15, terrane boundaries (dashed rectangles show location of schemes from Figs. 2 and 6); 16, complexes of intracontinental sedimentary basins; 17, complexes of passive continental margins; 18, collisional granitoids; 19, terrigene-volcanogenic and volcanogenic complexes of island arcs and marginal seas; 20, granite-gneiss complex; 21, granulite-gneiss complex; 22, basites, ultrabasites, granulites; 23, upper mantle; 24, metagabbro-dolerites, dolerites; 25, zones of saturation of the Earth’s crust with products of magmatism, of basalt composition, with ophiolite associations; 26, zones of intense manifestation of ultrametamorphism and migmatization in the consolidated Earth’s crust; 27, tectonic boundaries of global geostructures of the lithosphere (a) and regional megastructures of the lithosphere (b); 28, boundaries of large (a) and small (b) subdivisions. Regionally traced geophysical boundaries of the section of the Earth’s crust according to data of deep seismic sounding: F, surface of consolidated basement; C–M, crust–mantle transition zone; M, Moho discontinuity.
Analysis of the evolution of Neoproterozoic sedimentary basins of the western margin of the Siberian craton

The Neoproterozoic history of sedimentation on the Yenisei Ridge, in the East Sayan, and the Baikal regions confirms the conclusion that it was the period when the main geodynamic events took place, which led to the tectonic structure of the western and southwestern framing of the Siberian craton (Vernikovsky et al., 2004), and the analysis of the evolution of sedimentary basins can serve by its own as an additional tool for the interpretation of successive magmatism and metamorphism during accretion and collision (Sovetov et al., 2007). As shown above, sedimentation on the passive amagmatic Yenisei margin of the Siberian craton occurred in the Mesoproterozoic and Early Neoproterozoic. The sedimentary prism of the passive margin is recognized as the Kamenka-Chernaya Rechka structure-formational zone and is considered the East Angara terrane in the accretionary complex of the Yenisei Ridge (Vernikovsky and Vernikovskaya, 2006). Weakly metamorphosed sediments are represented there by deposits of underwater fans, slope contourites, shelf sandy waves and tempestites, forereef turbidite aprons andstromatolite reefs (Khabarov, 1999).

Within the Central Angara terrane of the Yenisei Ridge, separated from the East Angara terrane by the Ishimba thrust zone, only correlation analogs of sedimentary complexes of passive margin have been recognized. The deposits of the sedimentary basins of the Central Angara terrane bear signs of a deep-water regime of sedimentation (carbonate and terrigene-carbonate turbidites) at the continental rise. The deposits of sedimentary basins are heavily deformed there and are metamorphosed from greenschist to amphibolite facies of regional metamorphism, and the lower age limit of these basins exceeds 880 Ma (Vernikovsky et al., 2004).

A syncollisional deformed sedimentary complex, classified as a residual basin of closing ocean, lies in the northwest of the Yenisei Ridge in the Isakovka accretionary terrane (Fig. 2). The sedimentary basin is represented by a coarse-grained turbidite unit of deep-water fan with an arcosic source of clastics. Sedimentological and petrographic data prove the terrane origins of the clastics. The orogen terrane was situated west of the Yenisei Ridge and, probably, was a microcontinent (Sovetov and Romashko, 1999).

The Neoproterozoic rift sedimentary basins on the Yenisei Ridge are represented by the Vorogovka aulacogen as well as by Teya-Chapa and Oslyanka troughs, which form a system of autonomous structures developed on the heterogeneous basement: on the Meso–Neoproterozoic units of the passive margin of the Siberian craton and on the craton-obducted ophiolite complex in the Isakovka zone (Sovetov, 2001b). It is supposed that the sedimentation began at around 680–670 Ma, i.e., simultaneously with the manifestation of alkaline magmatism, as shown above. The rifting paleostructure was governed by a succession of sedimentary complexes, intense subduction of the basin’s bottom (more than 5 km deposits), bimodal paleotransport of clastics, initial and recurrent stages of rifting, and communication with open ocean. The Vorogovka Group is delimited from below and from above by regional disconformities. Before this group accumulated, the fold belt of the Yenisei Ridge had been denuded to a consolidated basement.

The Vorogovka aulacogen and the basin underwent four stages of evolution: (1) graben and accumulation of fluvial-delta deposits, (2) protobay, the first large sea transgression and formation of carbonate platform, (3) deep-water basin and accumulation of gravitites in the ramp fan, and (4) continental embankment, shallow-water shelf and tide-related carbonate formation (Fig. 3). The basin evolution was reconstructed through analysis of lithofacies and their associations, sedimentary systems.

The rift-related sedimentary basins coeval and sedimentologically identical to the Vorogovka basin were formed in the Kamenka zone of the Yenisei Ridge. The Teya-Chapa basin is filled with deposits of the Chingasan Group, and the Dashka basin, of the Oslyanka Group. It is characteristic for
these basins that the main source of clastics for them was the Siberian craton, the tectonic stages of the change of subsidence regime were simultaneous, the carbonate regional sedimentary systems were ramps and carbonate platforms. The three basins were eroded in the Early Vendian and were overlain by the Late Vendian continental molasse with a paleogeographical discordance.

Vendian molasse sedimentary basins

The regional Vendian peripheric foreland basin was formed in the west and southwest of the Siberian craton after the radical change of the paleogeographical position of the sources of clastics and regime of sedimentation. These changes were related to the formation of an orogen belt on the margin of the craton after the accretion of island arcs, terranes, and microcontinents from the west and southwest in Late Neoproterozoic–Early Vendian time. The beginning of the Vendian convergence stage coincides with the glaciation of the Siberian craton, a component of the global Marino glaciation. Glaciation traces have been found in the northeast and west of the Yenisei Ridge, and the Cis-Sayan glaciation deposits have been studied most thoroughly (Sovetov and Komlev, 2005). The regional correlation proves that, in the Vendian, the sedimentary systems changed in the same way over the vast territory of the southwestern Siberian Platform as components of a single marginal foreland basin of the Siberian Platform (Sovetov, 2001a; Sovetov and Blagovidov, 2004; Sovetov et al., 2007). After the Early Vendian glaciation, marginal sea basins were formed, with sources of clastics in the central areas of the Siberian craton, and in the Late Vendian the marginal sea basins disappeared, replaced by vast alluvium plains adjacent to outer orogens. The “molasse” stage of the foreland basin was just the time when the craton received a huge amount of siliciclastics which served then as a framework for hydrocarbon reservoirs (Fig. 4).

The Porozhnaya molasse sedimentary basin in the northwestern Yenisei Ridge and coeval basins, Chapa in the northeast and Taseeva in the south, were developed in separate lenses partly isolated from one another by elevated zones with slow rate of subsidence, as inferred from the direction of streams. The Porozhnaya, Kutukas, Surnikha, Stolby, and Isakovka lenses of the Chapa Group have been mapped on the Isakovka terrane. The Vendian sedimentary basin had a different orientation and was considerably larger in area than the preceding Vorogovka basin. The Chapa Group lies upon all gently tilted subdivisions of the Vorogovka Group and heavily deformed rocks of the Isakovka ophiolite complex. The basal part of the Chapa Group contains mixtite sand-gravelly deposits and breccias, which correlate with the glacial deposits of the Cis-Sayan Mama Formation (Sovetov and Komlev, 2005). The succession of shallow-sea and continental sedimentary systems in the Chapa Group is identical in the northwest and northeast of the Yenisei Ridge and is similar to the succession in the Taseeva Group in the south of this ridge and in the Cis-Sayan Oselok Group.

The Chapa molasse basin lies within the East Angara terrane, in the Chapa and Teya river basins. The Chapa Group overlaps the Chingsasan Group with a disconformity making up the rift-related Teya–Chapa sedimentary basin in many parameters similar to the Vorogovka basin. The Chapa Group
extends beyond the rift, overlaps its sides, and rests on the deformed deposits of the passive margin of the Siberian craton.

The total stratigraphic succession of deposits in the Chapa Group is similar to the succession in the sections of the Porohzhaya basin. Its lower part hosts cyclic successions of alluvial deposits, which are overlapped with storm and shallow-sea terrigene-carbonate deposits, containing diancrites and breccia of glacial origin (Suvorov and Pod‘em Formations) in their basal part. Above lie various red alluvium deposits grading to variegated shallow-sea deposits (Taezhnaya and Uglovaya Formations), which correlate with stratigraphic analogs of the upper parts of the Taseeva Group sections and ushers in a new stage, the Late Vendian–Early Cambrian cycle of sedimentation on the Siberian Platform (Sovetov et al., 2007). Given multiple measurements of flow directions in the Chapa molasse trough, the rivers had carried the clastic materials from southwest to northeast and from northwest to southeast, i.e. on the craton as a whole. The regional correlation and interpretation of the age of glacial deposits at the base of the Chapa Group as products of the Early Vendian glaciation suggest that the Chapa molasse basin was formed in the Late Vendian (Sovetov et al., 2007).

The Taseeva molasse basin filled with the Taseeva Formation rocks has formed in the south of the Yenisei Ridge within the East Angara terrane. This basin illustrates its discordant position relative to the earlier plicative and ruptured structures, including the Rybnaya ophiolite zone and Ishimba overthrust (Vernikovsky et al., 2004). The Taseeva Group contains four genetic complexes (Sovetov and Blagovidov, 2004): two continental (Aleksino, Greben’, and Veselovo) and two marine (Chistyakovka and Redkii Les). Detailed analysis of lithofacies, facies models, cyclicity, and palaeogeographic zoning suggests that in the Early Vendian (Aleshino time) the sources of material were internal and external uplifts of the Siberian craton, whereas the Late Vendian (Greben’ and Veselovo) molasse was produced by the denudation of the external orogens. The alluvial deposits of the above-mentioned formations made a wide alluvial plain, which associated with coeval and similar plains of the Cis-Sayan and Baikal regions to form a belt of a foreland basin.

The Late Vendian Taseeva molasse as well as the coeval molasses of the northern Yenisei Ridge were accumulated in an asymmetrical trough with the greatest subduction and thickness of deposits in the foothill area and outwedging on the slopes of the intracratonic uplift.

Structure of the zone of junction of the Siberian craton and West Siberian Plate exemplified by the structure and kinematics of the Yenisei fault zone

The Yenisei fault zone can be interpreted as an extension of the Baikal–Yenisei Fault (Main Sayan Fault) (Datenson, 1984) and thus can be a structure limiting the Siberian craton in the west from Baikal to the Kara Sea. This large rupture is easily traceable from geophysical data. It is often documented in the left side of the Yenisei River by the disappearance of several seismic surfaces. As the fault plane dips westward, it goes to a great depth (Dekov et al., 2007, Krylov et al., 1967; Surkov et al., 1996). It runs along the whole Yenisei Ridge (Belyaev and Basharin, 2001; Konstantinov et al., 1999; Starosel’tsev et al., 2003) and extends into the Turukhan–Noril’sk tectonic zone (Egorov, 2004).

Within the Yenisei Ridge, the fault zone is distinguished by gravitational steps (Brovkov et al., 1985). These steps are quite distinct on seismic profiles (Fig. 5) traceable westward from the northern end of the Yenisei Ridge (Kontorovich et al., 2006; Sobornov et al., 2008). Moreover, the presence of the Yenisei Ridge, a large folded structure between the Siberian craton and West Siberian Plate, much complicates the configuration of the Yenisei fault zone (see Fig. 1). Geophysical data imply that at a depth of >10 km the folded area of the Yenisei Ridge is halved in width. As a result, it acquires a mushroom shape, which is explained by the establishment of strike slip–compression stresses combined with divergent overthrusts. The amplitudes of overthrust displacement are estimated from 10–20 to 80 km (Starosel’tsev et al., 2003).

The geological structure of the Yenisei fault zone may be illustrated by its southern termination, at the junction of the Predvinsk and Angara–Kan terranes of the Yenisei Ridge (Figs. 1 and 6). Study was given to the deformed rocks of the island-arc and ophiolite complexes of Neoproterozoic age in the Predvinsk terrane and deformed gneisses of the Yenisei Group of Paleoproterozoic age in the Angara–Kan terrane, and the main tasks were to determine the morphology of ruptures, kinematics, and succession of deformations. The studied
complexes of the Predivinsk terrane belong to island-arc and ophiolite complexes of the southern part of the Priyenisei island paleoarc (Khain et al., 1997; Vernikovsky et al., 1999; Volobuev, 1993), which was accreted to the Siberian craton in the Late Neoproterozoic. Fragments of oceanic crust and volcanics of the southern part of the paleoarc are united into the Predivinsk terrane. Three tectonic slabs (zones) of sub-meridional strike have been recognized in the structure of the terrane (Fig. 6).

The western and central zones are represented by a paleoisland-arc complex of rocks. The complex is composed of carbonate-terrigenous sediments and volcanics of calc-alkaline series metamorphosed under the conditions of epidote-amphibolite and greenschist facies. These rocks are intruded by metagabbroids and metadiabases of the Yarlychikha pluton, metamorphosed gabbroids and diorites of the Shivera pluton, as well as by granodiorites and plagiogranites of the Yagun massif. The volcanogenic unit of calc-alkaline series is made up of calc-alkaline, high-Ti and subalkaline basalts, andesite basalts, dacites, rhyodacites, rhyolites, and tufts of acidic and basic compositions. Zircon U-Pb dating of metarhyolites and plagiogranites shows that they formed at $637\pm5.7$ Ma and $628\pm3$ Ma, respectively (Vernikovsky et al., 1999; Vernikovsky et al., 2003). The eastern slab is characterized by rocks of ophiolite complex: apoharzburgite serpentinites, metamorphosed gabbros, and tholeiitic basalts. The rocks of the Yenisei Group that make up the western part of the Angara–Kan terrane are amphibolites, two-mica gneisses and marbles metamorphosed under the conditions of the amphibolite facies of regional metamorphism (Nozhkin, 1999).

Thus, the Predivinsk terrane is delimited in the east and west by suture zones. It shares an anticlinorium structure and consists of three rupture-syndirectional slabs (zones). The structural studies show that the degree and character of deformations in each of the tectonic zones differ and regularly change from SW to NE, toward the zone of junction with the Angara–Kan terrane. Thus, the rocks of the western slab are characterized by metamorphic banding expressed in the orientation of crystals of amphibole and plagioclase (see Fig. 6, plot A). The banding is NNW-oriented; it dips ENEward at angles of 50–60°. The banded rocks are deformed into open parallel folds, measuring few centimeters (plication) to 1–2 m, whose hinges dip southward and northward at angles of about 10°. The axial planes of folds gently dip eastward. There, the rocks are complicated by cleavage steeply dipping chiefly northward. There are no unambiguous kinematic indicators in this zone, but the sublatitudinal (in modern coordinates) direction of tectonic compression is inferred from: general NNW orientation of banding and preservation of this direction (transformation into foliation) in other tectonic zones; steep dipping of the banding eastward and northward; the presence of folding of different orders up to plication with banding-syndirectional axial planes; delta structures around garnet grains from amphibolites.

Near the Yenisei fault, in the natural exposures of metagabbroids and metadiabases of the Yarlychikha pluton (see Fig. 6, plot B), the banding changes its dip to N and NNW. There is a system of cleavage fractures of SE dip, after which epidote develops. The 1–4 m thick dike-veined bodies filled with muscovite porphyroclastic granites also dip chiefly to the NNW, though they cut the banding. The dikes, in turn, are cut by the cleavage. In this area, ductile shear zones and ductile deformations in amphibolites are characterized by both vertical and horizontal components, the latter being as a rule of sinistral strike slip. The presence of cutting dike-veined bodies confirms that not only accretion-related but also later deformations occurred there. The sinistral component as well as the cleavage system were possibly due to the presence of a large NW-strike fault transversing throughout the Predivinsk terrane.

Northeast of the Yarlychikha pluton, the banding in volcanogenic rocks is chiefly of NW strike, subvertical and upturned dip (see Fig. 6, plot C). Plicative deformations remain in the form of folds and flexures, with the hinges dipping NNW at different angles. The axial planes parallel the banding, which is evidence of the SW–NE direction of...
Fig. 6. Geological-tectonic scheme and kinematic characteristics of the Predivinsk terrane, after (Vernikovsky et al., 1999) with additions. 1, Cover deposits (MZ–KZ); 2, 3, oceanic complex (NP); 2, metamorphosed tholeiitic basalts and andesite basalts; 3, harzburgite serpentinites; 4, metamorphosed gabbroids and diorites of the Yarlychikha complex (NP); 5, volcanites of calc-alkali series of the central slab (NP); high-Ti and subalkaline basalts, andesite basalts, dacites, rhyodacites, rhyolites, acid and basic tuffs; 6, gabbroids, diorites, and granodiorites of the Shiverka complex; 7, calc-alkali basalts, andesite basalts, dacites, rhyolites, carbonate-clayey deposits of the west slab (NP); 8, granitoids of the Yagunov complex (NP); 9, Kan Group (PP3), Kuzeev and Ataman units: amphibolites, gneisses, marbles, and migmatites; 10, faults: established (a), supposed (b); 11, Yenisei fault (a), thrusts (b); 12, localities of paleomagnetic sampling; 13, areas of structural studies.
The structural studies show the following succession of deformations in the zone of junction of the Predivinsk and Angara–Kan terranes and the Yenisei fault. The first stage of deformations is the formation of primary banding and folding, resembling the tectonic style in the western slab (plot A). The change of the banding strike from submeridional to NNW at site A and to NW at sites B–E is indicative of NE compressive strain. Then, most probably, dike-veined bodies formed. The next stage is bearing on the action of strike-slip stresses complicating both folded and monoclinic sequences. The ubiquitous overlapping cleavage steadily dipping SE seemed to be produced by rupturing stresses under strike-slip faulting. This succession of deformations comply in general with the interpretation by Smit et al. (2000), though these authors believe that this succession is bearing on the exhumation and thrust of the Angara–Kan terrane upon the Predivinsk terrane.

The data obtained agree with the paleomagnetic studies of volcanogenic deposits in the western and central zones (Metelkin et al., 2004). These studies show that at around 640 Ma the Predivinsk terrane was part of the Priyenisei island arc, immediately close to the margin of the Siberian craton (Fig. 7). During the accretion of the terrane and obduction of ophiolite and island-arc complexes upon the craton’s margin this block was rotated clockwise by 20° relative to the craton.

This rotation might promote the formation of the sinistral strike-slip component in the upthrows. Transpression combined with deformations of strike-slip kinematics can lead to the formation of the palm-tree structure in an orogen (Ramsay and Huber, 1987). Orientation of banding, foliation, and syndirectional faults on plots B to D suggests that the Predivinsk terrane seems to have such a structure which is expressed in NE and SW dipping in the southwest and northeast, respectively. In the central zone (plot C) the foliation orientations are equally distributed between NE and SW directions, and the SE and NW dipping of cleavage indicates either decompression strike-slip faulting or transpressional conditions.

Position and character of the west boundary of the Neoproterozoic Siberian craton according to paleomagnetic data

Analysis of the available paleomagnetic data (Li et al., 2008; Metelkin et al., 2007; Pavlov et al., 2002; Pisarevsky and Natapov, 2003; Pisarevsky et al., 2008) suggests that in the early Neoproterozoic Siberia could have been a giant peninsula of the Rodinia supercontinent. According to our
reconstructions (Fig. 8), the southern margin of Siberia (in modern coordinates) was oriented toward Laurentia, which in turn formed the “core” of the supercontinent and was situated south of Siberia. The western “shore” of Siberia was a continental-margin space “open” to ocean. At that time, the paleogeographical position of the western margin of the Siberian craton corresponded to the equator with a north-eastern strike of its margin (Metelkin et al., 2007).

The reconstruction is based on paleomagnetic data obtained for the southeast of the craton for a rather short interval of time, 950–1050 Ma (Pavlov et al., 2000, 2002; Gallet et al., 2000) corresponding approximately to the time of the complete assembly of the supercontinent. These suggest a southward drift with a counterclockwise rotation of Siberia during the Early Neoproterozoic. At about 800 Ma, the outlines of the western margin of Siberia had a sublongitudinal strike at about 30° S (see Fig. 8).

The new paleomagnetic data for the Middle Neoproterozoic include results of paleomagnetic studies of Neoproterozoic dike complexes within the Sayan–Yenisei margin of the Siberian craton (Nersa and Ust’-Angara complexes (Metelkin et al., 2005, 2007). The Ar-Ar isotopic age of the Nersa dolerites is 741±4 Ma (Gladkochub et al., 2006). Positive results of baked-contact, reversal, and fold tests indicate that the directions of primary components of magnetization established of the Nersa and Ust’-Angara dolerites correspond to that time (Metelkin et al., 2005, 2007). Based on geochemical data, we can suppose that the formation of these mafic intrusions occurred under rift-related conditions (Gladkochub et al., 2007; Sklyarov et al., 2003). On the other hand, the results of petrological–geochemical and isotope-geochronological studies unambiguously show that, at the time 750 Ma is related to accretion-collision events, which took place at the boundary of the Central Angara terrane and the
Siberian craton (Vernikovsky et al., 2003). It is not ruled out that the rift-regime and related magmatism manifested themselves in southwestern Siberia just as the result of this tectonic event. The described dikes mark the western margin of the Siberian paleocontinent, which, as inferred from paleomagnetic data, then rotated through nearly 90° counterclockwise relative to its Early Neoproterozoic position and again came to the equator (see Fig. 8). The considerable reorganization of plates at 750 Ma follows from the fact that the dominating dextral motion of the plate (drift with counterclockwise rotation) gives way to the sinistral, clockwise, motion (Metelkin et al., 2007).

As noted above, the important data characterizing the position of the western margin of the Siberian continent in the Late Neoproterozoic (beginning of the Vendian) include the results of paleomagnetic studies of the Predivinsk island-arc terrane (Metelkin et al., 2004). This structure bears direct information on the position of the western margin of Siberia at the stage of the pre-Vendian transformation of passive continental margin into an active one. Given the formation of rocks of the Predivinsk island arc is nearly coeval with the time of its accretion, at about 640 Ma this terrane was near the craton (Fig. 7). Then, the paleomagnetic poles of the Predivinsk terrane and Siberia should not differ very much. The prefolding i.e. primary nature of the stable magnetization is confirmed by fold test (Metelkin et al., 2004). The calculated paleomagnetic pole is in agreement with the available paleomagnetic data on the Vendian of Siberia (Kravchinsky et al., 2001; Pisarevsky et al., 2000). Our tectonic model and paleomagnetic data suggest that an extended system of island arcs developed along the entire western margin of the Siberian craton at that time (Vernikovsky et al., 2003), which had a sublatitudinal strike conform to the Siberian margin. By that time, Siberia turned clockwise to occupy a corresponding spatial position, still in the equatorial area.

Discussion and conclusions

The above-reported structural-geological, sedimentological, isotope-geochemical and paleomagnetic data are in agreement and provide a consistent picture of the evolution of the western margin of the Siberian paleocontinent in the Neoproterozoic. In the Early Neoproterozoic the western passive margin of the Siberian paleocontinent (in modern coordinates) begins to transform into an active margin. The process begins at the northwestern margin of the Siberian craton (960 Ma), then moves southward, to the Yenisei Ridge (about 760 Ma) and to the southwestern margin, and continues throughout the Late Neoproterozoic. Our model for the geodynamic evolution of the western framing of the Siberian craton provides solid geochronological support for each stage, with the tectonic and magmatic events complying with the formation of sedimentary basins. More correct global palynoplastic reconstructions on the basis of paleomagnetic data undoubtedly require that the database be continuously supplemented. However, on the one hand, the reconstructions of the Neoproterozoic location of Siberia and its western margin as given in this article are in agreement with the data on tectonics, magmatism, and sedimentary basins. On the other hand, they are supported by the international geological community and used in the largest projects, e.g., on the formation and breakup of Rodinia.

Moreover, taken together, the reported data seriously constrain the position of the boundary of the Siberian craton in pre-Vendian time. As the passive continental margins that developed along the western boundary of the Siberian craton in the Meso–Neoproterozoic and the island arcs and ophiolites that developed from Taimyr to East Sayan in the Late Proterozoic had a long history (Dobretsov and Vernikovsky, 1997; Dobretsov et al., 2003; Khain et al., 1997; Vernikovsky et al., 2004), the boundary of the Siberian paleocontinent should be drawn near these craton-obducting complexes, i.e., along the present-day Yenisei River.

At the same time, in addition to the Neoproterozoic island arcs and ophiolites, other Precambrian terranes and/or microcontinents accreted to the Siberian craton in the west either simultaneously or somewhat later. It is they that made, in pre-Vendian time or in the earliest Vendian, a basement for the formation of a single terrigene-carbonate and carbonate-evaporite plate complex described by Kontorovich et al. (2006) to characterize the Predyenisei Petroleum Subprovince. However, this basement of the sedimentary basin west of the Yenisei Ridge accreted in pre-Vendian time cannot be homologated with the basement of the Siberian Platform.

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