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# Tectonic evolution of the Siberian paleocontinent from the Neoproterozoic to the Late Mesozoic: paleomagnetic record and reconstructions

D.V. Metelkin [a,b,*], V.A. Vernikovsky [a,b], A.Yu. Kazansky [a,b]

[a] *A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences,*
*pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*
[b] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090, Russia*

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## Abstract

In this paper we present the results of a generalization of paleomagnetic data for the territory of the Siberian craton and its folded framing that were obtained during the last fifteen years. We propose a new version of the apparent polar wander path for the Siberian continental plate, including the interval from the Mesoproterozoic–Neoproterozoic boundary up to the end of the Mesozoic. The constructed path forms the basis for new concepts on the tectonics of the Siberian paleocontinent and the paleooceans that surrounded it. We present a series of paleotectonic reconstructions based on paleomagnetic data, which not only displays the paleogeographic position of the Siberian continent, but also reveals the features of the tectonic evolution of its margins during the last billion years. In particular it has been established that large-scale strike-slip motions played an important role in the tectonic regime of the continental plate at all stages of its development.

*Keywords:* Siberian paleocontinent; paleomagnetic pole; paleotectonic reconstruction; strike-slip motions

## Introduction

The paleogeography of Siberia as one of the most ancient continental masses is a relevant issue regarding the reconstruction of the tectonic history and outlook of the Earth. The relative position and relationship of the craton with other lithospheric plates, as well as the kinematics of its drift raise an increased interest in the process of composing global and regional reconstructions. In solving these issues high-quality paleomagnetic data are very important, since they allow a quantitatively valid verification of existing theoretical plotting and abstract theoretical hypotheses. Increased interest in Siberian paleomagnetism today is also linked to the fact that a little over a decade ago this region was effectively a “blank spot” in this respect. It especially concerns the Precambrian and Mesozoic intervals. The paleomagnetic investigations results obtained during these last ten years for various Siberian rock complexes validate the paleogeographic position of the craton itself as well as that of microcontinents, island arcs and other terranes that compose its folded framing. At the same time it has been established that large-scale strike-slip faults played an important role in the tectonic regime of the continental plate on all its development stages. This study is an attempt to generalize the results from tectonic and paleomagnetic investigations concerning the evolution of the Siberian paleocontinent from the Neoproterozoic to the Late Mesozoic.

## Brief description of used paleomagnetic data

At the base of the proposed reconstruction that encompasses a long interval of geological history from the Meso-Neoproterozoic boundary to the end of the Mesozoic and centers around the Siberian paleocontinent we place our published models (Kazansky, 2002; Metelkin et al., 2005b, 2007a, 2009, 2010b; Vernikovsky et al., 2009). By analyzing the paleomagnetic data available today it is possible to reconstruct the sequential change in the paleogeographic position of the Siberian plate and reconstruct the main geodynamic particularities of its margins development during the last billion years. The general development tendencies are

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* Corresponding author.
*E-mail address*: MetelkinDV@ipgg.nsc.ru (D.V. Metelkin)

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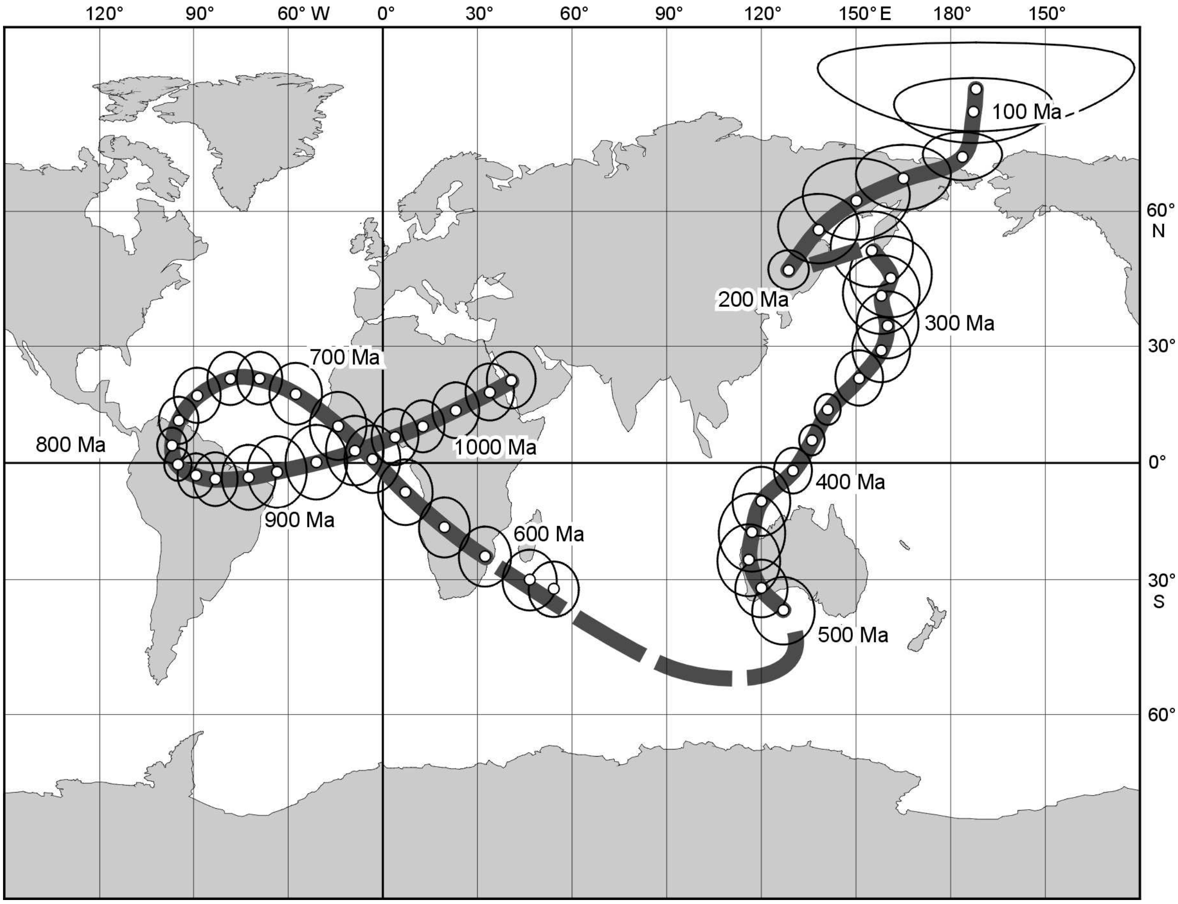

Fig. 1. The apparent polar wander path for Siberia. The pole coordinates are listed in Table 2. Dashed lines represent uncertain APWP with poor data, which need verification.

fairly distinct, even if for some time slices in the interval mentioned above the quantity and quality of paleomagnetic information is not complete enough and does not describe the regularities of the crustal evolution in the same adequate way.

Currently the Paleozoic apparent polar wander path (APWP) for Siberia is the most valid. Today no less than five versions of the Paleozoic APW path are counted (Cocks and Torsvik, 2007; Khramov, 1991; Pechersky and Didenko, 1995; Smethurst et al., 1998). The differences are due to the approaches to existing data selection, the uneven data distribution on the time scale, and the "smoothing" procedure while composing the APWP. Nonetheless, while different in details, the general character of the apparent wander of Paleozoic poles in these trend versions is coherent. It describes the drift of the Siberian plate northwards from the equatorial region to high latitudes of the Northern hemisphere with a domination of clockwise rotation (Cocks and Torsvik, 2007; Pechersky and Didenko, 1995). The maximum drift velocity is estimated from 5 to 12 cm/year depending on the version of APWP analyzed, and the rotation amplitude is approximately 1 deg/m.y. In our version of the APWP for Siberia (Fig. 1) the Paleozoic interval is entirely borrowed and based on the analysis, given in (Pechersky and Didenko, 1995).

The Neoproterozoic interval of the APW path was based on an adjusted overview of Precambrian poles (Metelkin et al., 2007a), which is itself based on key paleomagnetic poles (reliability index (Van der Voo, 1990) more than 3) for the territory of the Siberian craton obtained in the last years (Table 1). In particular the analysis we performed (Metelkin et al., 2005b, 2007a) justifies the "eastern drift" of poles (from the direction of the Indian ocean) unconventional for Siberia, which in the Neoproterozoic forms a characteristic loop that can be compared to the well-known "Grenville loop" of the APWP for Laurentia (McElhinny and McFadden, 2000). The similarity of the APW paths for Siberia and Laurentia not only implies a tectonic connection of the cratons in the framework of the Neoproterozoic supercontinent, it also allows to reconstruct the dynamic of its breakup fairly confidently (Metelkin et al., 2007a; Vernikovsky et al., 2009). Nonetheless the "Siberian loop" per se is composed by only two determinations (Metelkin et al., 2005a, 2010a). Even though the reliability index of these poles is high, other interpretations and thus alternative paleotectonic models are technically possible. First and foremost the uncertainty is due to the determination of the true geomagnetic field polarity during the formation of the magnetization. Previously the directions of southeastern declination and positive inclination were traditionally considered as normal polarity (Pavlov et al., 2000; Smethurst et al., 1998). In such an interpretation the positions of these poles will correspond to the Early Paleozoic interval of the Siberian

Table 1. Identified paleomagnetic poles from Siberia used for the composition of the Neoproterozoic and Mesozoic APW paths

| Subject | Age, Ma | Pole | | | Reference |
|---|---|---|---|---|---|
| | | (ºN) | (ºE) | $A_{95}$ | |
| 1050–640 Ma | | | | | |
| Malga Fm., Uchur–Maya reg. | 1045 ± 20 | 25.4 | 50.4 | 2.6 | (Gallet et al., 2000) |
| Lakhanda Group, Uchur–Maya reg. | 1000–1030 | 13.3 | 23.2 | 10.7 | (Pavlov et al., 2000) |
| Uya Group including sills, Uchur–Maya reg. | 950–1000 | 4.9 | 357.7 | 4.3 | (Pavlov et al., 2002) |
| Karagas Group, Pre-Sayan trough | 800–740 | 4.2 | 292.1 | 6.2 | (Metelkin et al., 2010a) |
| Nersa complex, Pre-Sayan trough | 741 ± 4[1] | 22.7 | 309.8 | 9.6 | (Metelkin et al., 2005a) |
| Predivinsk complex, Yenisei Ridge | 637 ± 5.7[2] | –8.2 | 7.7 | 4.7 | (Metelkin et al., 2004a) |
| 600–530 Ma | | | | | |
| Aleshino Fm., Yenisei Ridge | 600–550 | –28.3 | 24.3 | 7.7 | (Shatsillo, 2006) |
| Carbonate rocks, Igarka reg. | 560–530 | –33.4 | 45.6 | 12.7 | (Kazansky, 2002) |
| Carbonate rocks, Lena–Anabar reg. | 560–530 | –28.0 | 66.5 | 8.2 | (Kazansky, 2002) |
| Aisin Fm, Pre-Sayan region | 600–545 | –39.9 | 75.1 | 12.1 | (Shatsillo et al., 2006) |
| Taseevo Group, Yenisei Ridge | 600–545 | –32.9 | 75.1 | 6.1 | (Shatsillo et al., 2006) |
| Taseevo Group, Yenisei Ridge | 600–545 | –41.0 | 91.0 | 15.4 | (Pavlov and Petrov, 1997) |
| Ushakovka Fm., Transbaikalia | 600–545 | –31.6 | 63.8 | 9.8 | (Shatsillo et al., 2005)[3] |
| Sedimentary rocks, Pre-Sayan region and Yenisei Ridge | 560–530 | –29.5 | 74.1 | 4.5 | (Shatsillo et al., 2006)[3] |
| Kurtun Fm., Transbaikalia | 560–530 | –25.3 | 54.5 | 12.0 | (Shatsillo et al., 2005)[3] |
| Irkutsk Fm., Transbaikalia | 560–530 | –36.1 | 71.6 | 3.2 | (Shatsillo et al., 2005)[3] |
| Minua Fm., Transbaikalia | 600–530 | –33.7 | 37.2 | 11.2 | (Kravchinsky et al., 2001) |
| Shaman Fm., Transbaikalia | 600–530 | –32.0 | 71.1 | 9.8 | (Kravchinsky et al., 2001) |
| AVERAGE | ~ 560 | –33.9 | 62.2 | 8.9 | |
| 200–80 Ma | | | | | |
| Sedimentary rocks, Lena River | 175–245 | 47.0 | 129.0 | 9.0 | (Pisarevsky, 1982)[4] |
| Tugnui depression basalts, Transbaikalia | 180–200 | 43.3 | 131.4 | 23.0 | (Cogné et al., 2005) |
| Sedimentary rocks, Verkhoyansk trough | 170–160 | 59.3 | 139.2 | 5.7 | (Metelkin et al., 2008) |
| Badin Fm., Transbaikalia | 150–160 | 64.4 | 161.0 | 7.0 | (Kravchinsky et al., 2002) |
| Ichetui Fm., Transbaikalia | 150–160 | 63.6 | 166.8 | 8.5 | (Metelkin et al., 2007b) |
| Sedimentary rocks, Verkhoyansk trough | 140–120 | 67.2 | 183.8 | 7.8 | (Metelkin et al., 2008) |
| Khilok Fm., Transbaikalia | 110–130 | 72.3 | 186.4 | 6.0 | (Metelkin et al., 2004b) |
| Intrusions, Minusa trough | 74–82 | 82.8 | 188.5 | 6.1 | (Metelkin et al., 2007c) |

[1] The age according to (Gladkochub et al., 2006); [2] the age according to (Vernikovsky et al., 1999); [3] "anomalous" (nondipole) field according to the viewpoint of data authors; [4] pole #4417 from the IAGA GPMDB (http://www.ngu.no/geodynamics/gpmdb/).

APWP, which challenges the Neoproterozoic magnetization age and constitutes a separate problem. We discussed all these issues as well as some alternative models in a series of publications where we have shown that the available geological and paleomagnetic data conform best to the supposition that the identified magnetization was acquired during a time of mainly reversed geomagnetic field polarity and its origin is primary (Metelkin et al., 2005a,b, 2007a, 2010a). Thus normal polarity directions in the Neoproterozoic should include directions with northwestern declination and negative declination. In this case the APWP for Siberia will demonstrate this particular Neoproterozoic loop, whose existence solves the problem of Siberian–Laurentian relationships in the structure of Rodinia quite unambiguously.

Regardless of the relative complexity and abstruseness of the Neoproterozoic APW path its loop-like form actually reflects a rather simple movements of the Siberian plate. For the first third of the Neoproterozoic this motion corresponds to a southward drift from the equatorial region to the Southern hemisphere temperate latitudes with a counter clockwise rotation. In the second third of the Neoproterozoic it was characterized by a reverse—northern drift of the plate towards the equator with a clockwise rotation. The calculated drift velocity no more than 10 cm/year and the rotation amplitude is less than 1 deg/m.y., which is quite realistic. The cause for a gradual change in the drift direction of the continental plate is, no doubt, related to deep geodynamic mechanisms and reflects the directions of convective mantle flows that are

Table 2. Calculated APWP for Siberia

| Mesozoic | | | | Paleozoic | | | | Neoproterozoic | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time, Ma | PLat | PLong | $A_{95}$ | Time, Ma | PLat | PLong | $A_{95}$ | Time, Ma | PLat | PLong | $A_{95}$ |
| 80 | 81.3 | 188.2 | 6.7 | 240 | 52 | 155 | 8 | 560 | –32.2 | 54.3 | 6.7 |
| 100 | 77.8 | 187.4 | 5.2 | 260 | 46 | 161 | 9 | 580 | –30.0 | 46.7 | 7.4 |
| 120 | 70.2 | 183.9 | 4.2 | 280 | 42 | 158 | 9 | 600 | –24.1 | 32.5 | 7.5 |
| 140 | 66.3 | 165.2 | 6.0 | 300 | 35 | 160 | 8 | 620 | –16.7 | 19.6 | 7.7 |
| 160 | 62.1 | 150.3 | 7.8 | 320 | 29 | 158 | 8 | 640 | –7.6 | 7.2 | 8.6 |
| 180 | 56.3 | 138.3 | 7.1 | 340 | 22 | 151 | 7 | 660 | 1.0 | 356.8 | 8.9 |
| 200 | 47.7 | 128.8 | 4.3 | 360 | 14 | 141 | 4 | 680 | 9.7 | 345.9 | 8.9 |
| | | | | 380 | 6 | 136 | 4 | 700 | 18.0 | 332.4 | 7.9 |
| | | | | 400 | –2 | 130 | 6 | 720 | 22.0 | 320.9 | 6.7 |
| | | | | 420 | –10 | 120 | 9 | 740 | 21.9 | 311.7 | 6.7 |
| | | | | 440 | –18 | 117 | 10 | 760 | 17.6 | 301.2 | 7.1 |
| | | | | 460 | –25 | 116 | 9 | 780 | 11.2 | 295.3 | 6.1 |
| | | | | 480 | –32 | 120 | 7 | 800 | 4.6 | 293.2 | 4.7 |
| | | | | 500 | –36 | 129 | 8 | 820 | –0.4 | 295.1 | 4.3 |
| | | | | | | | | 840 | –3.3 | 300.8 | 5.8 |
| | | | | | | | | 860 | –4.2 | 306.9 | 7.1 |
| | | | | | | | | 880 | –3.7 | 317.5 | 8.5 |
| | | | | | | | | 900 | –2.3 | 326.5 | 9.4 |
| | | | | | | | | 920 | 0.2 | 339.0 | 9.8 |
| | | | | | | | | 940 | 3.2 | 351.2 | 9.1 |
| | | | | | | | | 960 | 6.8 | 3.9 | 7.4 |
| | | | | | | | | 980 | 9.6 | 12.7 | 6.8 |
| | | | | | | | | 1000 | 13.8 | 23.2 | 7.2 |
| | | | | | | | | 1020 | 18.4 | 34.0 | 7.3 |
| | | | | | | | | 1040 | 21.5 | 40.8 | 7.2 |

Note. The Paleozoic interval is taken from (Pechersky and Didenko, 1995); the Mesozoic and Neoproterozoic intervals are calculated of the basis of poles listed in Table 1. The data set was smoothed using the cubic spline (Enns, 1986; Torsvik and Smethurst, 1999) and then recalculated using a running mean (window length—50 Myr, poles through 20 Myr) (Besse and Courtillot, 2002; Irving and Irving, 1982); PLat, PLong—latitude and longitude of paleomagnetic pole; $A_{95}$, radius of 95% confidence oval.

controlled by the position of superplumes and subduction zones.

The Vendian (Ediacaran—from ~600 to ~540 Ma) interval of the APWP that connects the Neoproterozoic and Paleozoic trends discussed above (Fig. 1, Table 2) remains ambiguous. During the composition of the APWP the 560 Ma pole was accepted as the average from a group of poles located close to Madagascar Island (Table 1). A more southern position of this pole for this time—close to the Antarctic coast (Shatsillo et al., 2005, 2006) is not excluded. Despite significant progress in the study of the Late Precambrian and a large quantity of obtained determinations the problem of Vendian paleomagnetism and Vendian poles from Siberia is far from a definite solution. Several hypotheses have been put forward discussing an nonstationary and nondipole state of the geomagnetic pole in that time or anomalously high velocities of plates drift and other questions (Kazansky, 2002; Kirschvink et al., 1997; Kravchinsky et al., 2001; Meert, 1999; Pavlov et al., 2004; Shatsillo et al., 2005, 2006). One of the serious problems that if solved will possibly answer most questions on today's disagreements is the problem of absolute age determination for the rocks and for the magnetization preserved in them. Despite these difficulties, the identified poles from the Vendian–Early Cambrian interval are mainly distributed along the inferred trend.

There also is no decisive substantiation for the Early Mesozoic interval of the APWP because of the lack of reliable data for Middle and Late Triassic. The joining of the Paleozoic and the composed Late Mesozoic trends (Fig. 1, Table 2) indicates a clearly defined cusp in the APWP (an interval with abrupt change of the apparent polar wander direction). The existence of this cusp is basically not related to tectonic causes but is caused by the technique of APWP calculation during the smoothing of selected data over time intervals.

The Late Mesozoic interval of the APW path per se is based on paleomagnetic data obtained for the territory of the Verkhoyansk trough and the southwestern circumference of the Siberian Platform that were generalized in (Metelkin et al., 2010b). Among other things it has been shown that the Late Mesozoic poles from Siberia have a systematic deviation from the referential poles from Europe (Besse and Courtillot, 2002). The angular difference in the position of Jurassic Siberian and European poles reaches 45 degrees and gradually decreases to the end of the Cretaceous (Metelkin et al., 2008). The reason for such a difference is the strike-slip movements between the Siberian and European tectonic domains, with amplitudes estimated in several hundreds of kilometers. By "domain" in this case we mean a region that has an internally heterogeneous structure but can be considered as a rigid lithospheric block. We call a domain tectonically rigid if it lacks significant deformations that could lead to the mutual movements or significant rotations of the blocks of its internal structure. Judging by the APWP the Siberian domain within the framework of the Eurasian plate in the Jurassic, while being in the high latitudes of the Northern hemisphere, had a general southward drift (the maximum speed was 10–12 cm/year) with a gradual clockwise rotation (2.5 deg/m.y.). By the Jurassic–Cretaceous boundary Siberia reached its current coordinates and subsequently underwent at most a 0.5–1 deg/year clockwise rotation (Metelkin et al., 2010b).

## Paleotectonic reconstructions

**Neoproterozoic stage.** It is fitting to start the history of the Siberian continental plate or paleocontinent from the moment of the Rodinia breakup. The Neoproterozoic stage of tectonic history corresponds to this event (Li et al., 2008). The total of available geological and paleomagnetic data indicates that at the Meso-Neoproterozoic boundary the Siberian craton was a part of Rodinia and could represent a "giant peninsula" on the northeast of the supercontinent (Metelkin et al., 2007a; Pisarevsky et al., 2008). In modern coordinates Siberia was a continuation of Laurentia to the north, so that the western Siberian margin was the prolongation of the western Laurentian margin (Fig. 2, *A*). A review of geological information on the structural position, composition, and age of the Late Mesoproterozoic and Early Neoproterozoic complexes located on the margins of the Siberian craton, shows that this stage of its geological history was dominated by conditions of continental shelf almost on the entire perimeter of the continent (Khabarov, 2011; Kheraskova et al., 2010; Pisarevsky and Natapov, 2003; Pisarevsky et al., 2008; Vernikovsky et al., 2009). The current northwestern margin of Siberia as well as the western and eastern ones (Petrov and Semikhatov, 2001; Semikhatov et al., 2000) was a passive continental margin with a typical sedimentary rocks complex (Pisarevsky and Natapov, 2003). An active tectonic regime was probably only present in the southern margin (Gladkochub et al., 2007; Metelkin et al., 2007a; Pavlov et al., 2002; Rainbird et al., 1998; Yarmolyuk et al., 2005). Here during this time a series of rock complexes were formed, which can be compared to a regime of intracontinental rifting or an active stage of ocean development (Fig. 2, *A*). Among others those can include 1000–950 Ma sills and dykes of MORB-type, intruding the sedimentary sequence of the Uchur–Maya region on the south-east of the craton (Pavlov et al., 2002; Rainbird et al., 1998). The developing oceanic basin led to the formation of rock complexes of various geodynamic environments of the Baikal–Muya accretionary prism and framing of the Gargan block with ages ranging from 1050 to 850 Ma (Gordienko, 2006; Khain et al., 2003; Kuzmichev et al., 2001; Parfenov et al., 1996).

From the summation of paleomagnetic data we infer that the disintegration process along the southern margin of Siberia continued for more than two hundred million years from the east to the west (geographic Siberian coordinates) concurrently with a strike-slip dislocation due to the rotation of the craton (Metelkin et al., 2007a). Such an opinion has been voiced previously in (Yarmolyuk and Kovalenko, 2001). However, we suppose that a narrow basin of the Red Sea type existed as early as 950 m.y. ago elongating from the Baikal to the Uchur–Maya margin of the Siberian craton (Fig. 2, *A*). The relationships of the main structures in the ocean-continent transition zone near the Baikal margin could be similar to the Cenozoic tectonic setting of Eastern Yakutia, where divergent structures of the Gakkel Ridge are "truncated" by a large transform fault, while on the continent a large number of relatively small rift depressions (aulacogens) are formed whose strike corresponds to ancient suture zones (Parfenov and Kuz'min, 2001). In this respect the Akitkan suture appears as an important Neoproterozoic transtensional structure. We consider the entire Baikal margin as an area of riftogenic breakup above which a large continental margin sedimentary basin formed.

Some alternative, which also quite suits the available set of paleomagnetic data, can be provided if we recall the model of S.A. Pisarevsky and L.M. Natapov, in which a space of 20° (>2000 km) is reconstructed between the southern margin of Siberia and the northern margin of Laurentia (Pisarevsky and Natapov, 2003). According to the interpretation of the authors this space corresponds to a paleoocean, which implies that the Siberian craton had a tectonic history that was independent from Rodinia and was a separate paleocontinent as early as 1 b.y. ago. However, in the framework of this hypothesis the reasons for the similarity of the Neoproterozoic APW paths for Siberia and Laurentia are very unclear. Why did mutually independent continental plates, separated by an ocean, undergo concordant movements for hundreds of million years, which are recorded in a rather intricate paleomagnetic track? What regime did the separating oceanic basin function in?

Later, in reconstructions published with the input of the same authors (Li et al., 2008; Pisarevsky et al., 2008) this oceanic space is "filled" by an unknown continental mass, supposedly representing the blocks of the hypothetical Arctida subcontinent whose relicts are now located in the Arctic sector. They include the Kara block, the New Siberian block (New Siberian Islands and the adjacent shelves), the block of Northern Alaska (to the north of Brooks Ridge) and Chukotka, and also small fragments of the Innuit fold belt on the north of Greenland (Peary Land, the northern part of Ellesemere and

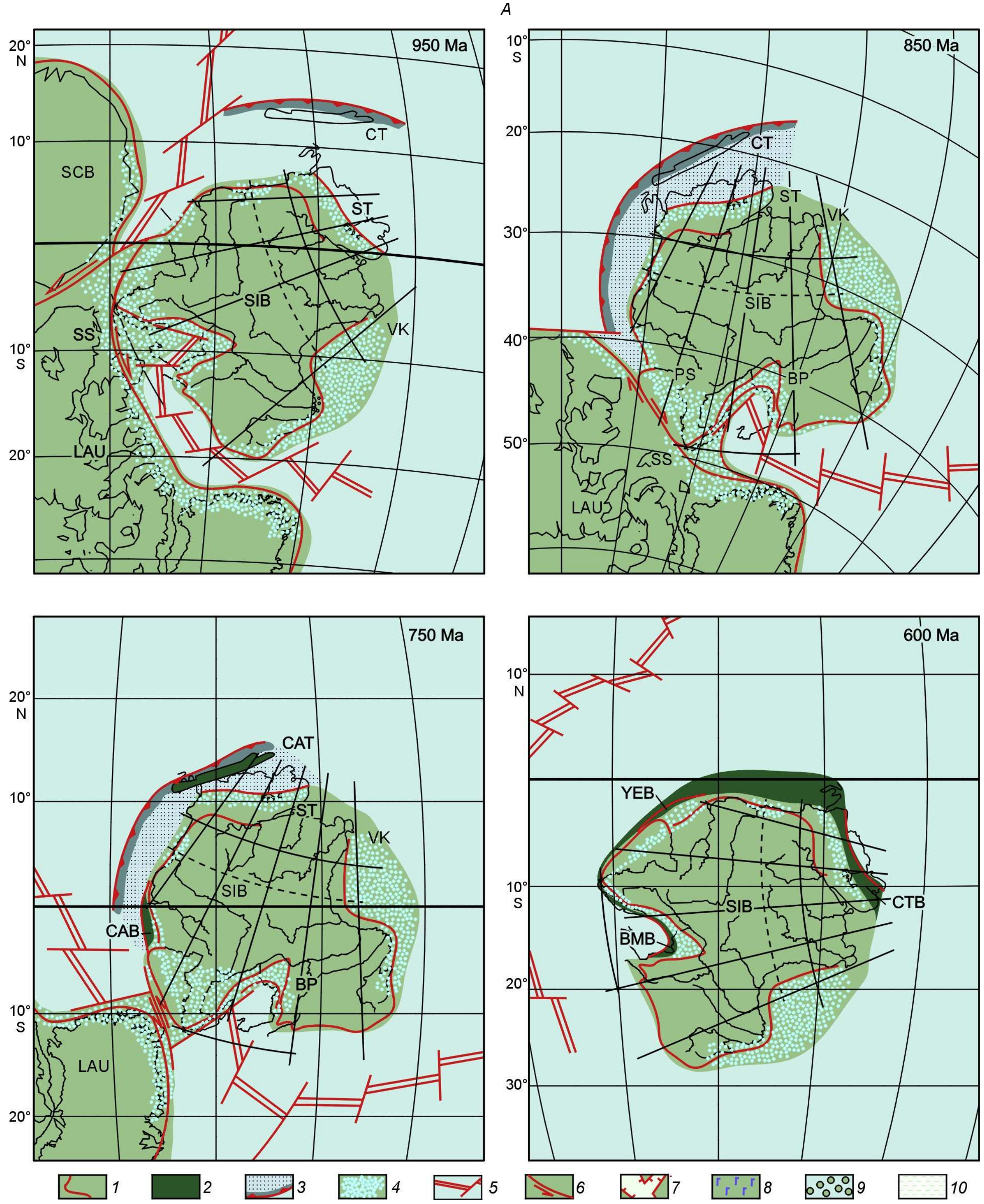

Fig. 2. Paleotectonic reconstruction of the evolution of the Siberian craton and its margins for the Neoproterozoic (*A*) and the Paleozoic (*B*). *1*, continental masses and most important contours; *2*, accretionary structures, orogenic belts of corresponding age; *3*, subduction systems, including volcanic belts and back arc basins; *4*, marginal seas, shelf basins of passive continental margins; *5*, inferred spreading zones position; *6*, principal strike transform-shear zones with their kinematic style; *7*, schematic area of continental crust thinning in limits of the West Siberian graben-rift system; *8*, schematic position of plateau basalts of the Siberian Permian–Triassic traps; *9*, sedimentary basins with suboceanic crust; *10*, schematic position of Meso-Cenozoic deposits of the West Siberian sedimentary basin. Alphabetic acronyms on figures: continental blocks: SIB, Siberian; EUR, Eastern European; KAR, Kara; KAZ, Kazakhstan; LAU, Laurentia; NCB, North China Block; TAR, Tarim; SCB, South China Block. Basins of passive continental margins, marginal seas: VK, Verkhoyansk; BP, Baikal–Patom; PS, Pre-Sayan; SS, South Siberian (hypothetical); ST, South Taimyr. Orogenic belts: ABO, Altai–Baikal orogen; BMB, Baikal–Muya belt; VCB, Verkhoyansk–Chukotka belt; MOB, Mongol–Okhotsk belt; YEB, Yenisei belt; TSO, Taimyr–Severnaya Zemlya orogen; URB, Ural belt; CAB, Central Angara belt; CASB, Central Asian (Late Paleozoic) belt; CAT, Central Angara terrane; CTB, Central Taimyr belt. Island arc terranes, active continental margin fragments and volcanic-plutonic belts: BT, Bateni; GA, Gorny Altai; ER, Eravna; ZK, Zolotoi Kitat; KI, Kiya; KT, Kurtushiba; NS, North Sayan; TS, Tersa; CT, Central Taimyr; OCVB, Okhotsk–Chukotka volcanic-plutonic belt. Other structures: CPD, Caspian depression; WSB, West Siberian basin.

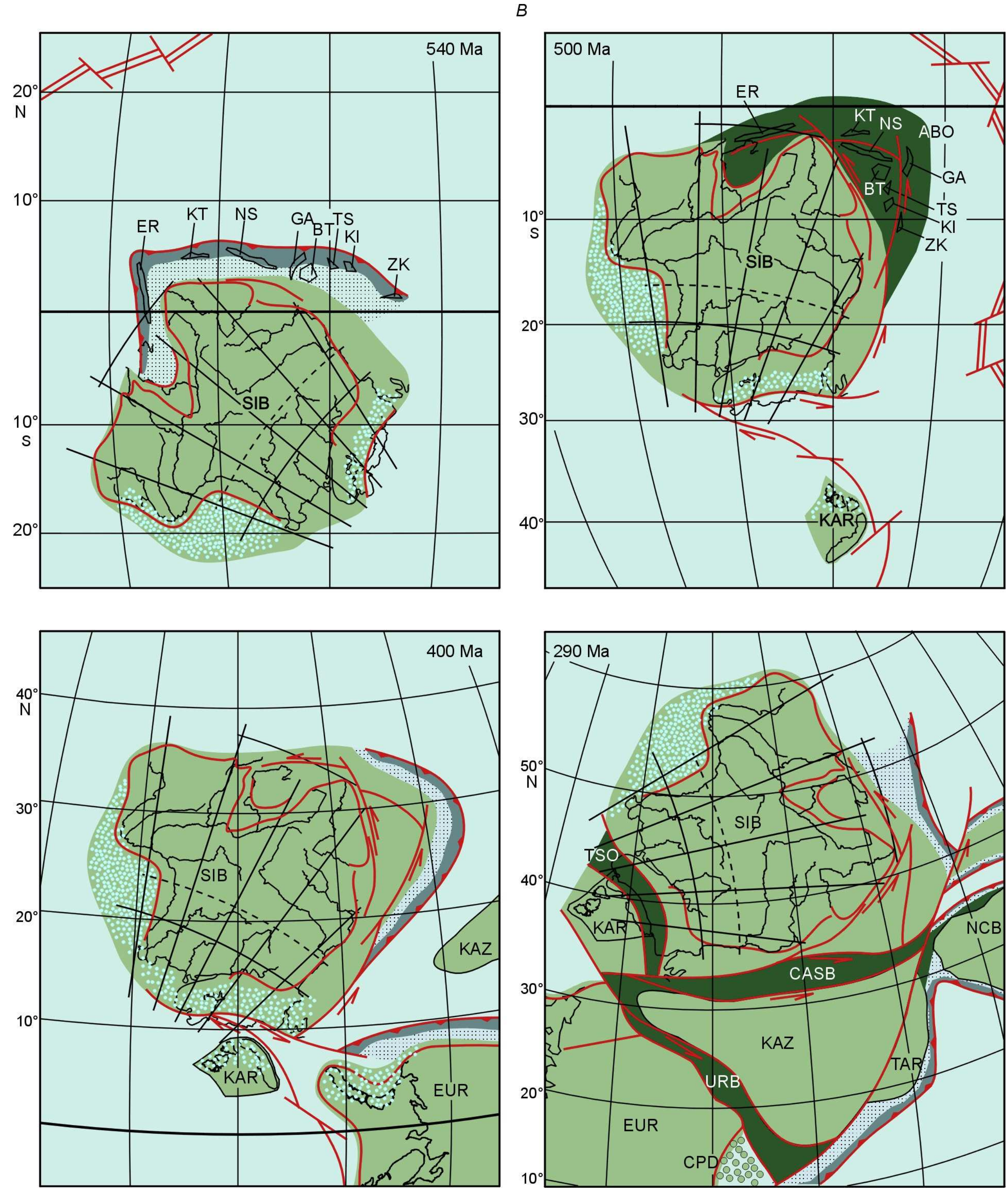

Fig. 2 (*continued*).

Axel Heiberg Islands) and possibly the structures of the Svalbard plate (Spitsbergen archipelago, Franz-Joseph Land, Novaya Zemlya) (Kuznetsov et al., 2010; Zonenshain and Natapov, 1987). Such a variant is quite acceptable according to our reconstructions. It will require a slight correction of the Euler poles used for the comparison of paleomagnetic data and current craton contours. However this will not significantly change the proposed model for the breakup of the Siberia–Laurentia system. The only difference will be that the reconstructed tectonic boundaries will link the southern margin of Siberia and the Arctida blocks, located on the northern perimeter of Laurentia.

From the model it follows that at 750 Ma Siberia was displaced along the northern margin of Laurentia on a distance of 2000 km and its southwestern border was in close proximity to the northern margin of Greenland (Fig. 2, *A*). At this time a transformation of the passive continental margin into an active one took place in the west, the north (Vernikovsky et al., 2003) and, possible, in the south of Siberia (Khain et al., 2003; Kheraskova et al., 2010; Kuzmichev and Larionov, 2011; Zorin et al., 2009) with the development of Late Neoproterozoic island arc systems. The active island arc magmatism belt was probably separated from the continental margin by a rather wide basin, providing the dominating regime of stable shelf in the western and northwestern Siberian margins that is identified almost everywhere (Pisarevsky and Natapov, 2003).

The stage of accretion of Neoproterozoic island arcs to the Siberian continent with the development of the Central Taimyr, Yenisei and Baikal–Muya belts took place in the beginning of the Vendian (Fig. 2, *A*) (Dobretsov et al., 2003; Kheraskova et al., 2010; Kuzmichev et al., 2001; Pease et al., 2001; Vernikovsky et al., 2004; Zorin et al., 2009). The age for this event in the west and north of Siberia has been proven by a complex of isotopic-geochemical data (Vernikovsky and Vernikovskaya, 2001, 2006). On the south of Siberia, in the Baikal area such data are rare for now, but the structural unconformity at the base of the Vendian–Cambrian terrigenous-carbonate sequence of continental margin genesis, which overlies the metamorphosed volcanogenic formations of the Neoproterozoic island arc, definitely indicates a pre-Vendian or Early Vendian phase of compression deformation (Zorin et al., 2009). It is possible that the Baikal margin had a somewhat peculiar tectonic history. The Neoproterozoic island arc system could develop rather far from the concerned territory (Kuzmichev et al., 2001). As a result of complex amalgamation processes a large superterrane was formed in the ocean, which included ophiolites, island arc and craton terranes. Before the Vendian its structural integrity was disturbed. One of the detached parts, corresponding to the Baikal–Muya accretionary belt was displaced and accreted to the Siberian craton (Belichenko et al., 2006; Kuzmichev et al., 2001). As a result of the superterrane's breakup, aside from the Baikal–Muya block, the Tuva-Mongolian, Dzhabkhan and Central-Mongolian blocks could have separated (Kuzmichev et al., 2001). These blocks are included in the structure of the Caledonian orogenic belts of the southwestern framing of the Siberian craton.

The Late Neoproterozoic accretionary structures of the Central Taimyr belt on the northern framing of the Siberian craton are also unconformably overlain by the Vendian–Paleozoic passive continental margin complex with a typical platform development regime (Vernikovsky, 1996). The same geodynamic regime is typical for the western Yenisei marginal region of the Siberian paleocontinent in the Vendian–Cambrian (Sovetov et al., 2000; Vernikovsky and Vernikovskaya, 2006; Vernikovsky et al., 2009). Synchronously with the accumulation of shallow marine carbonate and carbonate-slate deposits at the Central and Southern Taimyr boundary a deep-water basin formed in the Early Vendian with distinct features of a linearly elongated depression, which was supposedly (Khain, 2001) connected in the east with a similar depression in the inner regions of the Verkhoyansk system. The axis of this deep-water trough was located to the south of the suture zone between the Central Taimyr accretionary block and the continent, in the frontal zone of the large Pyasina–Faddey thrust, which gives us reason to consider its development as a foredeep (Vernikovsky, 1996). The conclusion of the Early Vendian orogenic stage was in a regime of continental-margin rifting and associated magmatism that is widely manifested in the southwest of the Siberian paleocontinent (Vernikovsky et al., 2008).

**Paleozoic stage.** The Neoproterozoic transform/strike-slip kinematics in the development of the oceanic basins around Siberia went on into the Paleozoic (Fig. 2, *B*). Strike-slip dislocations played an important role in the course of Paleozoic accretionary-collisional events. From the end of the Neoproterozoic up until the Mesozoic Siberia evolved as an independent interaction system between an oceanic and a continental plate. During this time the craton underwent a mainly northward drift from the equatorial latitudes of the Southern hemisphere (~10° S) at the end of the Cambrian towards high latitudes of the Northern hemisphere (~50° N) at the end of the Paleozoic (Cocks and Torsvik, 2007; Pechersky and Didenko, 1995). According to paleomagnetic data the continental plate was gradually rotated ~180° clockwise and by the beginning of the Triassic the northern margin of Siberia was directed westward (Fig. 2, *B*).

After a relatively short time period in the beginning of the Vendian the active continental margin regime in the southwest (geographic coordinates) of the Siberian paleocontinent was resumed (Dobretsov, 2011; Dobretsov et al., 2003). The oldest subduction rocks associations within the Early Caledonian part of the Altai–Baikal sector of Central Asia are 570 m.y. old, however the main island arc magmatism stage undoubtedly took place in the interval 540–520 Ma (Khain et al., 2003). According to the available paleomagnetic data (Metelkin et al., 2009) the Vendian–Cambrian island arcs reconstructed for this region were fragments of a single system and marked an elongated subduction zone along the entire western (geographic coordinates) circumference of the Siberian continent, similarly to today's Pacific boundary of Eurasia (Fig. 2, *B*). Deformations of this island arc system at the stage of accretion to the craton in the Late Cambrian–Ordovician were due to a clockwise rotation of the Siberian paleocontinent. Such kinematics in a compression setting at the continental-oceanic plates boundary led to the development of strike-slip zones on the circumference of the continent and, as a result, to the deformation of the island arcs system formed in the Late Vendian–Early Cambrian. Movements of fragments of this system could take place along strike-slips, located in the back as well as along zones of oblique subduction (Fig. 2, *B*). Because of the rotation the structures of the continent's perimeter "dragged behind" and were displaced, forming separate tectonic sheets, which through interaction underwent complicated drifts (Berzin, 1995; Kungurtsev et al., 2001; Metelkin et al., 2009).

By the Late Cambrian–Ordovician, after the accretion of island arcs, the tectonic framework on the west–southwest of Siberia (geographic coordinates) acquired the features close to

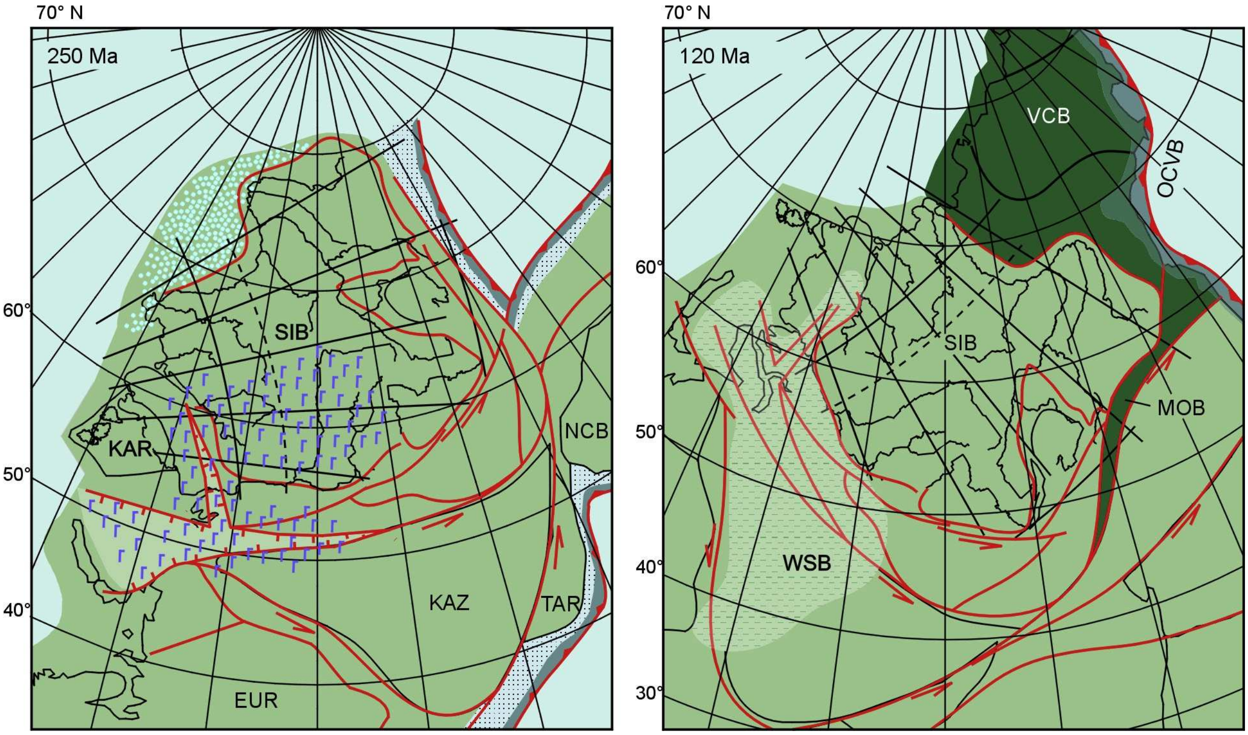

Fig. 3. Paleotectonic reconstruction of the Mesozoic evolution of the territory of Siberia. The legend and alphabetic acronyms are given on Fig. 2.

the present-day state. Paleomagnetic poles from Siberia and the terranes of the Altai–Baikal region are close, although they do not completely match (Metelkin et al., 2009). Small differences in the pole positions indicate that the intense, mostly strike-slip deformation of the paleoisland arc system and back arc basins that started in the Cambrian continued during the entire Paleozoic (Buslov, 2011; Buslov et al., 2003; Fedorovsky et al., 2010; Filippova et al., 2001; Korobkin and Buslov, 2011).

On the north of Siberia the Early Paleozoic (Vendian–Devonian) interval was characterized by the uplifting of the Anabar block and the development of large synforms around it that were occupied by epicontinental seas where mainly carbonate deposits formed (Bogdanov et al., 1998). Also the deep-water trough that formed in the end of the Precambrian in the place of the foredeep along the thrust front of the Central Taimyr belt continued its development. The change in tectonic regime on the Taimyr margin took place in the Carboniferous period when the collisional orogen started forming, which was accompanied by granitoid magmatism and regional metamorphism, and carbonate sedimentation was succeeded by terrigenous (Shipilov and Vernikovsky, 2010; Vernikovsky, 1996; Vernikovsky et al., 1995). The type change in sedimentation is recorded by the appearance of a new sediment provenance area. Our paleotectonic analysis performed using paleomagnetic data demonstrates that this event was conditioned by the initiation of the Siberian margin's interaction with the Kara microcontinent in a regime of oblique collision with a leading role of strike-slip dislocations (Metelkin et al., 2005c). Transform zones "connecting" the arctic margins of Siberia and Baltica had a defining importance in the Paleozoic tectonics of the Kara block. They determined the strike-slip northward movements of the Kara microplate from the subtropical zone of the Southern hemisphere towards the subequatorial zones of the Northern hemisphere with a simultaneous counter clockwise rotation. The strike-slip tectonics completely conditioned the deformation style of the Paleozoic margin on the north of Siberia during the Late Carboniferous–Permian collisional event (Metelkin et al., 2005c; Vernikovsky, 1996) and took place against the background of the oppositely directed rotation of the Siberian and Kara continental masses, which fits well into the general geotectonic framework (Fig. 2, *B*). There is a distinct problem in the lack of Paleozoic subduction complexes, which probably should occur in the Main Taimyr suture, if an oceanic crust space existed between Siberia and the Kara microcontinent. From the proposed model the evident explanation would be that the sialic masses interacted softly with a leading role of strike-slip faults in a setting of oblique transform approach and subsequent collision. The concluding stages of the orogen's development at the Permian–Triassic boundary saw the formation of large extension zones before the front of folded structures and predefined in this segment of the belt the formation of a large depression—the Yenisei–Khatanga basin.

**Mesozoic stage.** The continental rifting at the Permian–Triassic boundary was manifested mainly in Western Siberia (Fig. 3). By the beginning of the Mesozoic the fold-and-thrust structure of the Taimyr–Severnaya Zemlya region was not the only structure formed. As a result of the closure of the Precambrian–Early Paleozoic oceans the general structure of the Central Asian belt was formed, suturing the continental masses of the Siberian and East European cratons within the framework of the Eurasian plate, which in turn, formed the main structure of the Laurasian part of Pangea. This key moment in the tectonic history of Siberia was marked by dramatic trap magmatism, caused by the effect of one of the largest mantle plumes (Dobretsov, 1997). In the Siberian Platform the plateau basalts are concentrated in the Tunguska syneclise and spread under the Yenisei–Khatanga basin including South Taimyr. To the west, in the West Siberian plate traps have been recorded beneath the Meso-Cenozoic sediments cover as far as the East Ural basin. Here they are associated to rift zones of the Koltogory–Urengoy graben, but are also penetrated by boreholes in between those. The fields of plateau basalts spread further to the north, covering the floor of the Kara and Barents Seas (Dobretsov, 2005; Dobretsov and Vernikovsky, 2001). Manifestations of the Siberian traps have also been recorded on the New Siberian Islands (Kuzmichev and Pease, 2007). The structures of the Kuznetsk trough can be named as the southernmost satellite of the Siberian traps (Buslov et al., 2010; Dobretsov, 2005, Kazansky et al., 2005). Correlations of available paleomagnetic and geochronological data indicate that the development of the Siberian trap province happened exceptionally fast. The duration of intense magmatism in various regions was 1–5 Ma (Buslov et al., 2010; Dobretsov, 2005; Kazansky et al., 2005) and in the south (Kuznetsk trough) and probably the west (West Siberia) and the north (Yenisei–Khatanga trough) was controlled by large-amplitude strike-slip faults (Fig. 3). Our analysis of paleomagnetic data for the Permian–Triassic boundary allows the assumption that the intraplate strike-slip deformations due to the clockwise rotation of the Siberian tectonic domain of the Eurasian plate are the probable cause for the formation of a graben structures system in the basement of West Siberia, which started the development of a large Meso-Cenozoic sedimentary basin here (Bazhenov and Mossakovsky, 1986; Voronov, 1997). The eastern branch of this strike-slip system, which caused rifting in West Siberia, are extension structures associating with frontal thrusts of South Taimyr. The axial graben of the Yenisei–Khatanga basin and the coeval graben-rifts of the Koltogory–Urengoy system (Aplonov, 1989; Khain, 2001) form a some semblance of a triple junction, which fits well into the strike-slip model.

We believe that the strike-slip tectonics due to the rotation of the Siberian domain of the Eurasian plate relatively to the Eurasian domain were the cause for the compression regime and deformation that manifested in the Mesozoic on the southwest of Siberia within the Altai–Sayan folded area (Bazhenov and Mossakovsky, 1986; Metelkin et al., 2009, 2010b). Strike-slip movements of this kinematics inside the Eurasian continent continued until the end of the Mesozoic, which is confirmed by a systematic divergence of the Mesozoic poles of Siberia and Eastern Europe (Metelkin et al., 2008, 2010b). Our model (Fig. 3) infers that the deformation of the crust of Central Asia during the general clockwise rotation of the Eurasian plate is related to movements of separate constituents of its composite structure (Siberian, European and Kazakhstan tectonic domains) along a system of large sinistral strike-slip zones (Metelkin et al., 2010b). The deformation of the Mongolia–China territory of the plate was also related to the functioning of a series of strike-slip zones, along which crustal lamination took place. This happened against the backdrop of a gradual west to east migration (geographic coordinates) of the closure of the Mongol–Okhotsk gulf in the Paleopacific that separated the Siberian margin of Eurasia and the Paleozoic terrane collage of the territories of Mongolia and China. The geological consequences of such tectonics are in accordance with the views presented in (Bazhenov and Mossakovsky, 1986; Natal'in and Sengör, 2005; Van der Voo et al., 2006; Voronov, 1997). Strike-slip movements of the Siberian domain with its clockwise rotation and in virtue of the configuration of the main structural boundaries conditioned a stable compression regime within the Central Asian province (southwestern framing of the Siberian craton) and in contrast—an extension setting in the northernmost parts of the West Siberian province. At the same time the movements were intermittent, which is reflected in the reconstructed multiple stages of the main orogeny epochs (Buslov et al., 2008; De Grave et al., 2007), in the association of strike-slips and other structural forms, disturbing the initial wholeness of the Mesozoic sedimentary complex of West Siberia, at specific time boundaries (Belyakov et al., 2000; Filippovich, 2001; Koronovsky et al., 2009).

## Discussion and conclusions

The tectonic evolution of Siberia in the Neoproterozoic, Paleozoic and Mesozoic can globally be compared with the processes of buildup and breakup of two supercontinents: Rodinia and Pangea. The transformation of one tectonic event at the margins of Siberia into another was often determined by the intensity and scales of strike-slip dislocations.

In the beginning of the Neoproterozoic the Siberian craton, while in the structure of Rodinia, continued the North American craton to the north so that its western margin (geographic coordinates) was a prolongation of the western margin of Laurentia. At this time Siberia was located in equatorial latitudes. At the margins of Siberia sedimentation processes took place mostly in the environments of continental shelf. The craton was a giant peninsula.

By the beginning of the Cryogenian the craton, while still in the structure of Rodinia, moved southward in subtropical latitudes. At the same time along the southern margin of Siberia rifting processes dominated, controlled by the counter clockwise rotation of the craton, that is to say, by transform strike-slips. The separation of Siberian and Laurentian continental masses and the opening of an oceanic basin along the southern margin (geographic coordinates) of Siberia took place gradually from east to west as a result of a strike-slip. The retraction of the craton caused by spreading on the southeast was complemented by subduction processes on the opposite northwestern circumference. At the same time the volcanic belts related to the subduction were separated from the craton by wide continental margin basins.

We consider the Middle Cryogenian boundary (about 750 Ma) as the time of complete detachment of Siberia from

Laurentian continental masses. The paleogeography of the Siberian paleocontinent is again that of equatorial latitudes. The formation of the Central Asian orogenic belt was also an important event of this period. However the main stage of accretion of the "early" island arcs with the development of the Central Taimyr and Yenisei belts on the northern and western circumference of the Siberian continent was on the Cryogenian–Ediacaran boundary.

During the Ediacaran period the Siberian continent, surrounded by oceans, was in a subequatorial region of the Southern hemisphere and was turned in such a way that its western margin (geographic coordinates) had a sublatitudinal strike and northwards orientation.

By the beginning of the Paleozoic along this margin in the equatorial region of the Northern hemisphere a long island arc system was formed. The transformation of the structure of the active margin during the Ordovician accretion is related to the breakup of the crust and dragging of its fragments during its movements along a system of sinistral strike-slip dislocations against the backdrop of the clockwise rotation of the Siberian plate. The paleogeography of the continent in the Late Cambrian–Ordovician still corresponded to a subequatorial belt of the Southern hemisphere. However its spatial orientation changed so that the western margin (geographic coordinates) that grew bigger through addition of the Altai–Baikal orogen was directed eastward with a sublongitudinal strike.

By the middle of the Paleozoic the Siberian paleocontinent, interacting with Baltica through a system of transoceanic transforms that connected their northern margins (geographic coordinates), was displaced in tropical latitudes of the Northern hemisphere. These large-amplitude strike-slip systems that formed much earlier, probably as early as the beginning of the Paleozoic, led to the drift of the Kara microcontinent towards Siberia. The geodynamics of the southwestern margin (geographic coordinates) at this time was related to the active closure phase of the paleoocean during its approach with the continental masses of the Kazakhstan superterrane and Baltica.

The Paleozoic–Mesozoic boundary during the formation of Pangaea is related to the amalgamation of Siberia with surrounding continental masses. The paleogeographic position of Siberia was that of temperate latitudes of the Northern hemisphere, its western margin (geographic coordinates) again had a sublatitudinal strike but was oriented southward, where the main continental masses of Pangaea were located. Within Pangaea the Siberian craton had a peripheral position as was the case in the structure of Rodinia. The Verkhoyansk area of the continent remained open to the ocean. The structural arrangement of Central Asia, which sutured the Siberian craton to the Eurasian part of Pangaea, took place in conditions of strike-slip tectonics. In particular, the development of the fold-and-thrust structure of the Taimyr part of the orogenic belt was conditioned by the "soft" interaction between the Kara microcontinent and Siberia as a result of their oblique convergence and collision with the interacting plates rotating in opposite directions.

The main event in the evolution of the Siberian continental plate in the Early Mesozoic was trap magmatism due to the effect of the large Siberian plume. We assume that the intracontinental rifting on the Permian–Triassic boundary, which accompanied the plume magmatism in West Siberia, was controlled by strike-slip faults. It associates with Late Paleozoic sutures, which were reactivated as a result of the ongoing clockwise rotation of the Siberian continental plate from the Paleozoic.

The structure of Central Asia remained unstable up until the end of the Mesozoic. According to paleomagnetic data the intraplate sinistral strike-slip movements caused by the rotation of the Siberian part of the Eurasian plate continued until the Late Cretaceous. Among others the gradual west-to-east closure of the Mongol–Okhotsk gulf of the Paleopacific took place in a strike-slip environment, which determined the current structure of this part of the Central Asian orogenic belt. The Siberian craton in the structure of the Eurasian plate was located by the end of the Mesozoic at high latitudes of the Northern hemisphere, close to the present day ones. In order to reach its present day position a clockwise rotation was needed. This allows us to assume that the strike-slip component inherited from the Mesozoic tectonics endured into the Cenozoic, although the strike-slip scale was significantly smaller.

In summary, strike-slip tectonic processes occurred everywhere throughout all the intervals of the Siberian plate's geological history. They determined the tectonic style of the evolution of the Siberian region structures on early stages during the development of oceans as well as during active subduction of the generated oceanic crust, and, no doubt, on the accretionary–collisional and the latest plate stages of development. It is a characteristic feature that the reconstructed strike-slip zones have a huge length and, usually, are associated to borders of large tectonic elements, that is to say they indicate a process of a regional, and more often—a global scale.

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