Available online at www.sciencedirect.com
SCIENCE DIRECT®
Tectonophysics 375 (2003) 221–245
TECTONOPHYSICS
www.elsevier.com/locate/tecto

Siberia and Rodinia

S.A. Pisarevsky[a,*], L.M. Natapov[b]

[a] Tectonics Special Research Centre, Department of Geology and Geophysics, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[b] GEMOC ARC Key Centre, Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia

Received 28 March 2002; received in revised form 28 October 2002; accepted 5 June 2003

Abstract

An analysis of the Riphean sedimentary successions along the margins of the Siberian craton, together with recent geochronological and palaeomagnetic data from Siberia, require a revision of the hypothesis that Siberia was part of Rodinia. Some previously proposed Laurentia–Siberia reconstructions may be dismissed, whereas other models are permissible with minor modifications and conservative assumptions about recent geochronological data from Siberia. A comparison of Laurentian and Siberian apparent polar wander paths between 1050 and 1000 Ma shows a striking similarity. However, if Siberia was part of Rodinia, it was probably not contiguous with the Laurentian craton. In this scenario, northern and southern (Stanovoy block) margins of Siberia are possible candidates for conjunction with the rest of Rodinia. We propose a new reconstruction of Laurentia and Siberia at ca. 1050–1000 Ma.

Keywords: Siberia; Rodinia; Proterozoic; Plate tectonics; Sedimentary successions; Palaeomagnetism; Passive margin

1. Introduction

There is general agreement that most of Earth's continental crust was assembled in a supercontinent, Rodinia, which formed during collisional events in the late Mesoproterozoic and early Neoproterozoic (McMenamin and McMenamin, 1990; Hoffman, 1991). The position of Siberia in Rodinia is disputed, but it is generally shown as lying along either the northern or the western margin of Laurentia (all orientations in this paper are in present-day coordinates).

Sears and Price (1978) suggested a connection between northern and eastern Siberia with western Laurentia (Fig. 1a), based on apparent similarities between Precambrian crustal structures and tectonic boundaries on both cratons. This model was criticised by Condie and Rosen (1994), because "...the juvenile Early Proterozoic crustal belts in southwestern North America do not continue into Siberia, which is almost entirely Archean crust". Additionally, several researchers proposed alternative counterparts (Australia, Antarctica and/or South China) for the western Laurentian margin in Rodinia, including SWEAT (SW US–East Antarctica) (Moores, 1991), SWEAT with some modifications (Li et al., 1995), AUSWUS (Australia–SW US) (Brookfield, 1993; Karlstrom et al., 1999; Burrett and Berry, 2000) and recently AUS-

* Corresponding author. Tel.: +61-8-9380-7844; fax: +61-8-9380-1090.
E-mail address: spisarev@tsrc.uwa.edu.au (S.A. Pisarevsky).

0040-1951/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2003.06.001

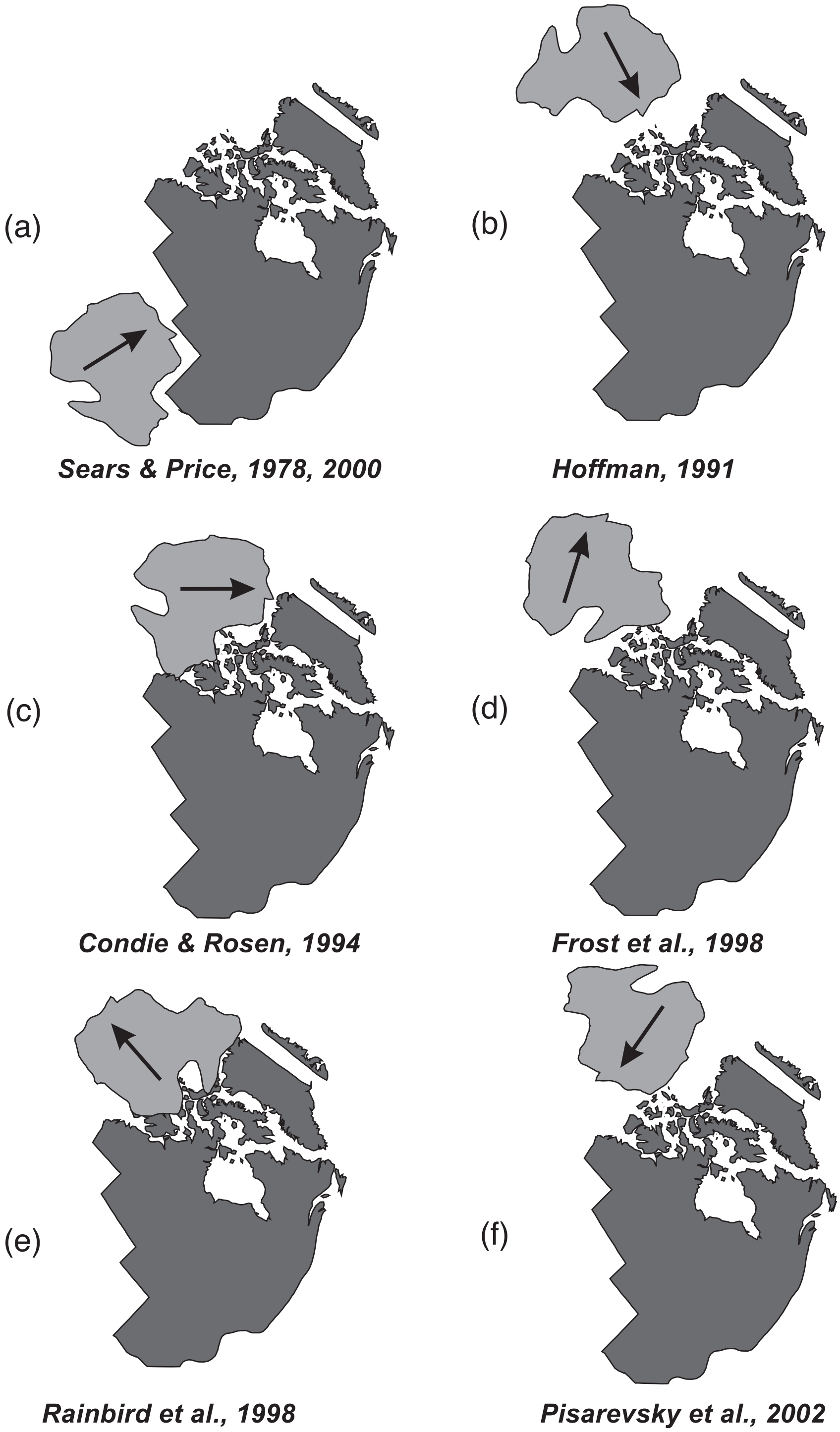

Fig. 1. Six published reconstructions of Laurentia with Siberia in present Laurentian coordinates. The arrow shows to the present Siberian north. Estimated (see text) Euler's rotation parameters (Siberia to Laurentia: latitude of the pole, longitude of the pole, angle in degrees): (a) 65.8, − 43.4, 86.7; (b) 0.0, − 171.9, − 22.2; (c) 63.3, 36.4, 58.2; (d) 76.4, 104.6, 129.0; (e) 78.1, 124.1, − 179.8; (f) 65.0, 159.3, − 69.6.

MEX (Australia–Mexico)(Wingate et al., 2002) configurations. The SWEAT model is used in most Rodinia reconstructions (e.g., Hoffman, 1991; Dalziel, 1997; Weil et al., 1998). Sears and Price (2000) argued in favour of their original model, employing a detailed comparison of the Precambrian provinces of Siberia and western Laurentia.

Other reconstructions of Siberia with northern Laurentia (Fig. 1b–f) are based primarily on the comparison of Archaean and Palaeoproterozoic crustal blocks that are assumed to have maintained their integrity since their amalgamation in the late Palaeoproterozoic. Hoffman's (1991) juxtaposition of northern Siberia and northern Laurentia (Fig. 1b) is based, in part, on some similarities in the metamorphic histories of the Anabar shield (Siberia) and the Thelon–Talson belt (Laurentia). Pelechaty (1996) supported this model with stratigraphic and palaeontological evidence, and also proposed that separation between Siberia and Laurentia did not occur until the early Cambrian, arguing that the 723 Ma Franklin igneous event resulted in a failed rift. This conclusion was criticised by Rainbird and de Freitas (1997) and Khudoley (1997), who argued in favour of Franklinian-age rifting rather than of early Cambrian one. Condie and Rosen (1994) proposed a slightly different fit (Fig. 1c), in which the Palaeoproterozoic Akitkan belt of Siberia is a continuation of the Thelon–Talson belt of Laurentia. Frost et al. (1998) juxtaposed southern Siberia and northern Laurentia (Fig. 1d). Their fit is based on the comparison of the Thelon magmatic belt with the Aldan block of the Aldan shield. Rainbird et al. (1998) juxtaposed southeastern Siberia and northern Greenland (Fig. 1e) to explain the presence of Grenville-age detrital zircons in Sette-Daban of eastern Siberia. Unfortunately, neither of the mentioned papers contains the rotation parameters for their reconstructions, so one may find some minor changes in our Fig. 1 in comparison with the original illustrations. Pisarevsky et al. (2003) proposed a new Siberia–Laurentia fit, based mainly on the available palaeomagnetic data (Fig. 1f).

Generally, all reconstructions in Fig. 1 are based on permissible, rather than conclusive arguments. As mentioned above, there are other possible counterparts for the western passive margin of Laurentia. An evidence for ca. 1.2 Ga rifting [the giant 1267 Ma Mackenzie Dyke Swarm (e.g., Ernst et al., 1996)] and ocean development along the northern Laurentian margin [a post-1.2 Ga "Poseidon" ocean northward (Frisch and Trettin, 1991 and references therein)] argues against reconstructions in Fig. 1b–d. These reconstructions are generally based on comparisons of Archaean and Palaeoproterozoic blocks, and if the mentioned Poseidon ocean existed, they are irrelevant at least for Rodinia times (ca. 1100–750 Ma). For the reconstruction in Fig. 1e (Rainbird et al., 1998), it is necessary to assume that collision between northern Greenland and southern Siberia (Stanovoy block) occurred after the intrusion of the Mackenzie dykes, but before the Grenville orogenesis. To our knowledge, there is no evidence for such collision.

However, the arguments above, in our view, are not conclusive to prove or disprove any of these reconstructions. In this paper, we analyse the Meso- to Neoproterozoic sedimentary sections of Siberia's palaeomargins and available coeval palaeomagnetic results from Laurentia and Siberia to determine a role of the Siberian craton in Rodinia reconstructions. We use the Russian stratigraphic scheme for the Proterozoic (Semikhatov, 1991), in which the Lower Riphean (1650–1350 Ma) and Middle Riphean (1350–1000 Ma) correspond approximately to the Mesoproterozoic of the International time scale (Harland et al., 1990), and the Upper Riphean (1000–650 Ma) corresponds to the Neoproterozoic, excluding the Vendian (650–545 Ma).

We carried out this research with full support of Professor Powell both as scientist and as a Director of TSRC. His outstanding knowledge gave a great contribution to understanding of the Proterozoic tectonics and to our study in particular.

2. Riphean margins of Siberia

The Siberian craton (Fig. 2) was assembled in the Palaeoproterozoic, mainly between 1.95 and 1.90 Ga, by the collision of several Archaean and Palaeoproterozoic crustal blocks (Rosen et al., 1994, 2000). Siberia is surrounded by Neoproterozoic (southwestern margin) and Phanerozoic sutures formed during the assembly of Laurussia and Pangaea (Zonenshain et al., 1990a,b). There are three major areas of exposed basement: the Aldan shield/Stanovoy block, the Anabar Shield and the Yenisey uplift. The remain-

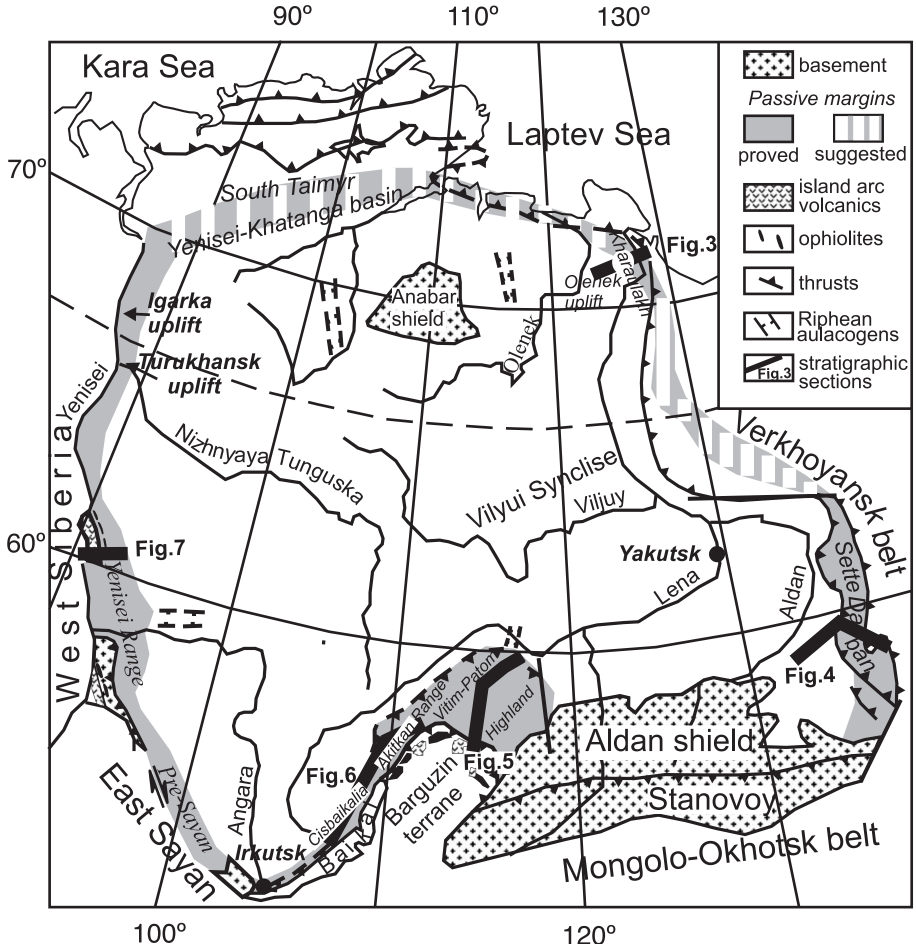

Fig. 2. Sketch map of the Siberian craton.

der of the craton is covered by Riphean, Vendian and Phanerozoic sedimentary successions. A common feature of the Riphean successions in the Siberian craton is their gradual thickening towards the cratonic boundaries (e.g., Khomentovsky et al., 1972; Khain, 1985), caused possibly by the development of passive continental margins during the Riphean. To analyse this hypothesis, we briefly describe the Riphean sections adjacent to the Siberian craton boundaries.

2.1. Northeastern margin (Olenek uplift–Kharaulakh uplift)

The northeastern part of the Siberian craton formed in the late Palaeoproterozoic (2.0–1.8 Ga) as a result of accretion of Archaean and Palaeoproterozoic microcontinents (Rosen et al., 1994, 2000). The accumulation of the Riphean platform cover commenced around 1650 Ma, after about 150 my of erosion (Semikhatov, 1991, 1993; Rosen et al., 2000). The Riphean succession here consists of shallow-water marine carbonate and fluvial to shallow-water clastic sediments. The deep-water sediments were found in the easternmost exposures. The lowermost Riphean siliclastic Saginakhtakh Formation unconformably overlies Palaeoproterozoic rocks (Mokshanzev, 1979). This contact has so far been found only in the Olenek uplift (Fig. 3).

The thickness of the Riphean successions increases to the east (Fig. 3), from 1200 to >2200 m. Strati-

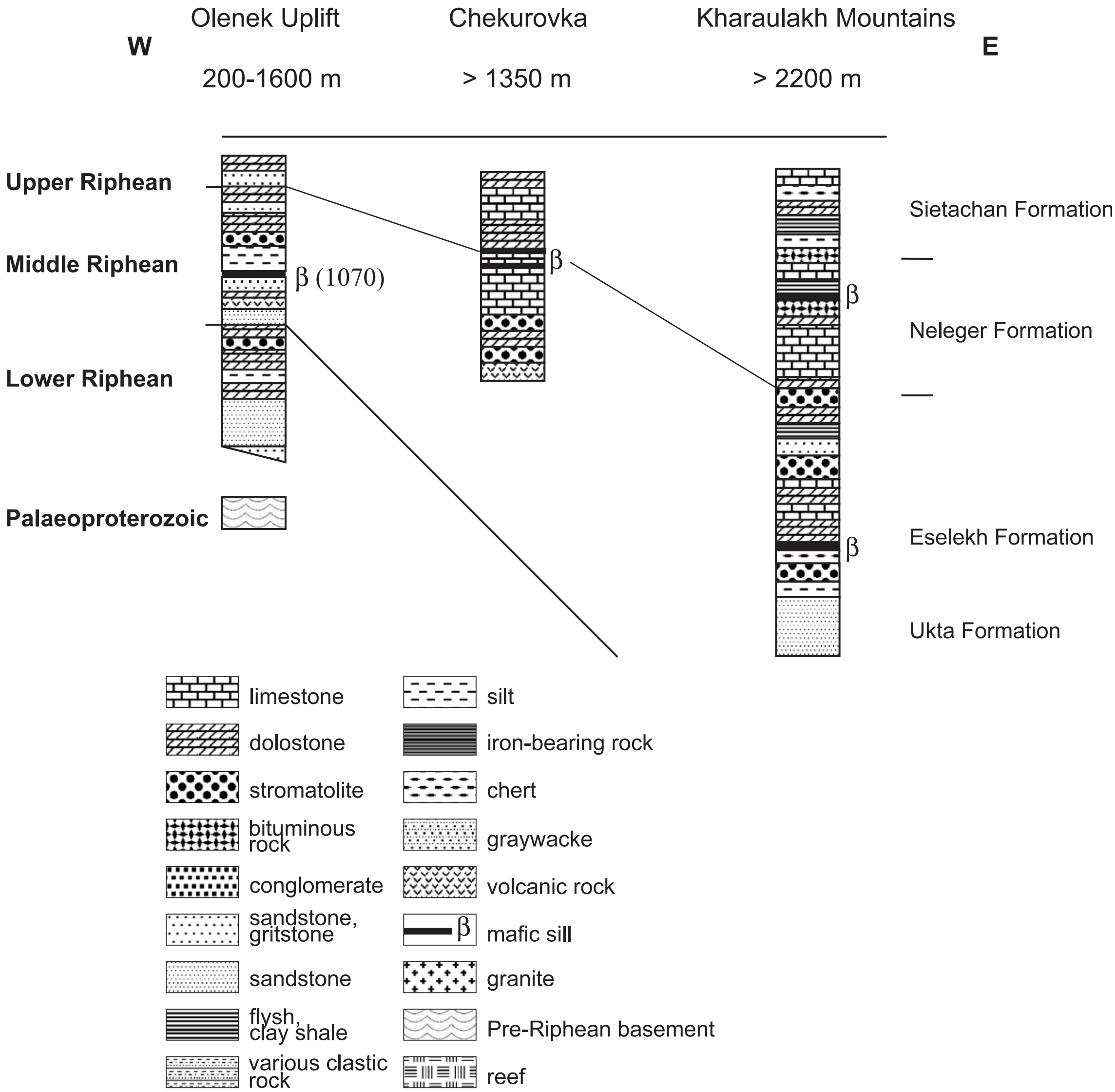

Fig. 3. Correlation chart of the Riphean successions at the northeastern margin of the Siberian craton.

graphic correlations (Fig. 3) are based on paleontological data (stromatolite and microphytolite complexes) and K–Ar dates on glauconite (e.g., Biterman and Gorshkova, 1962; Krasil'schikov and Biterman, 1970) and on stromatolites (Ponomarchuk et al., 1994). These ages range from 1480 to 850 Ma. Local disconformities at the base of some formations have been found, but no significant hiatuses occur in the Riphean successions, although they are present in rocks younger than ca. 850 Ma. Angular unconformities occur between Riphean sequence and Vendian sediments (Turkut Formation) (Leonov et al., 1965; Komar and Rabotnov, 1976; Mokshanzev, 1979; Sokolov and Fedonkin, 1985). The age of the lowermost Vendian rocks is about 650 Ma.

Subalkaline dolerite sills and dykes occur in the middle and upper parts of the Riphean succession (Fig. 3). A K–Ar age of 1070 Ma was obtained for a mafic sill intruded along the boundary between the Arimas and Debengda Formations (Olenek uplift)

(Chumakov and Semikhatov, 1981). Basaltic lavas and mafic volcaniclastic layers were found in the mid-Riphean Arimas and Ukta Formations and in the upper part of the upper Riphean Sietachan Formation (Malich et al., 1987).

The Riphean succession on the northeastern margin of the Siberian craton clearly represents a passive margin sequence. This is indicated by eastward thickening and shallow-to-deeper water facies variations. Ocean opening probably began between ca. 1600 and 1480 Ma. No significant igneous rocks have so far been found at the base of Riphean succession, although these rocks are not exposed in the eastern part of this area. A positive magnetic anomaly in this area (e.g., Zonenshain et al., 1990b) may indicate mafic rocks related to the rifting phase of the suggested continental breakup. Southeast and south of the described area the Neoproterozoic boundary of Siberia is concealed beneath the Mesozoic Verkhoyansk fold-and-thrust belt, hence the presence and stratigraphy of the Riphean sequences between 68°N and 64°N is unclear (Fig. 2).

2.2. Southeastern margin (Sette-Daban Ridge and adjoining areas)

The Riphean successions of this area (Fig. 4) were deformed during Cretaceous accretion of the Okhotsk massif (Parfenov, 1984; Natapov, 1988; Natapov and Stavsky, 1985; Zonenshain et al., 1990a,b; Nockleberg et al., 1998). These successions are preserved in asymmetric folds and west-vergent thrusts (Fig. 2). The combined Riphean section (up to 14 km thick) is probably the most complete one in Siberia (Khomentovsky et al., 1972; Nevolin et al., 1978; Semikhatov and Serebryakov, 1983; Shenfil, 1991; Khudoley et al., 2001). Its stratigraphic subdivision is based mainly on stromatolite and microphytolite assemblages, and transgressive clastic–carbonate cycles. Correlation of the four main zones on the SE cratonic margin is shown in Fig. 4.

The mainly fluvial to shallow water, clastic Uchur Group (Lower Riphean) unconformably overlies Archaean and Palaeoproterozoic basement rocks of the Aldan shield in the western part of the area (Uchur

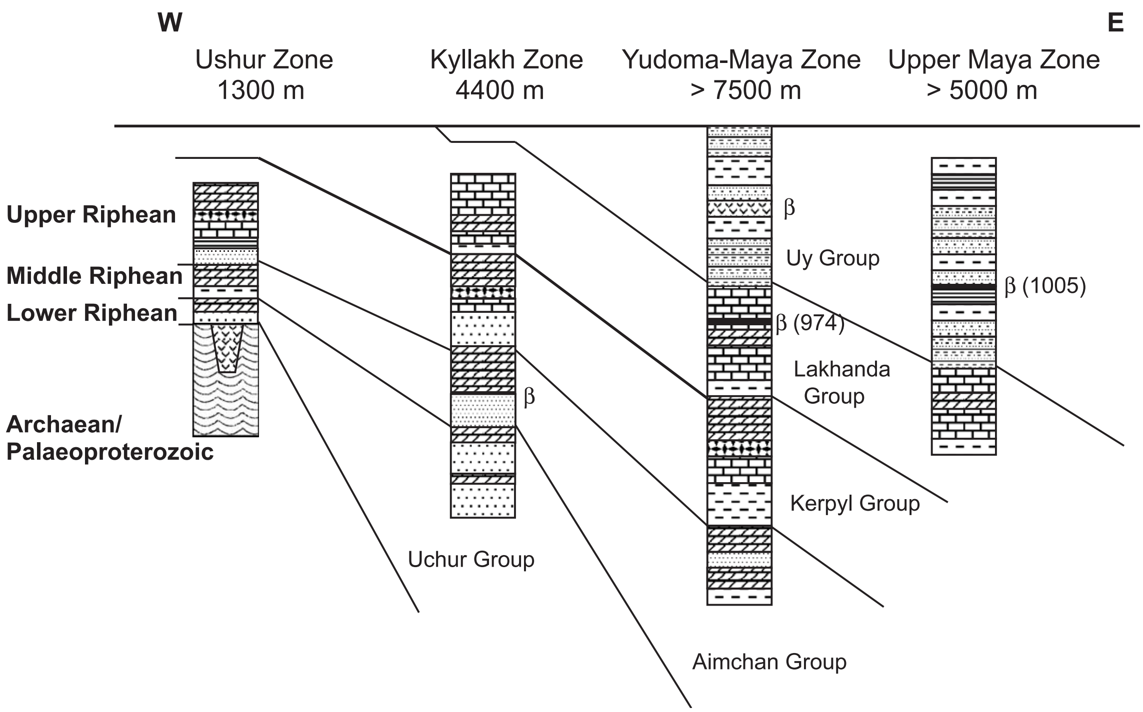

Fig. 4. Correlation chart of the Riphean successions at the southeastern margin of the Siberian craton. See Fig. 3 for legend.

Zone). Khudoley et al. (2001) reported about its eastward thickening and E or SE palaeotransport. They also mentioned that "...the lower Uchur Group shoals and coarsens westward from open-marine shales with limestone interbeds... to cross-bedded red sandstone of fluvial origin..." (Khudoley et al., 2001, p.135). The radiometric ages of glauconite sandstone in the lower part of the Uchur Group are between 1520 and 1450 Ma, and about 1360 Ma in the upper part of the group (Kazakov and Knorre, 1973; Semikhatov and Serebryakov, 1983). The youngest detrital zircons in the Uchur Group are about 1725 Ma (Khudoley et al., 2001).

The Aimchan Group unconformably overlies the Uchur Group and represents a transgressive cycle with lower clastic (peritidal) and upper carbonate (subtidal) components (Bartley et al., 2001). Thickness increases eastward (Semikhatov and Serebryakov, 1983), and westward coarsening of the sandstones and SE palaeocurrents were reported by Khudoley et al. (2001). K–Ar glauconite ages from the lower part of the Aimchan Group are 1210–1230 Ma (Chumakov and Semikhatov, 1981).

The Kerpyl Group unconformably overlies the Aimchan Group and forms the next transgressive cycle. Its thickness and limestone/dolostone ratio increase eastward (Nevolin et al., 1978; Semikhatov and Serebryakov, 1983), and the clastic rocks of the lower part of the group coarsen westwards (Khudoley et al., 2001). K–Ar glauconite ages of sandstones are between 1170 and 860 Ma (Garris et al., 1964; Kazakov and Knorre, 1973; Bartley et al., 2001). A new Pb–Pb date of 1043 ± 14 Ma on limestone from the middle part of the Kerpyl Group (Malgina Formation) was reported by Ovchinnikova et al. (2001).

The Lakhanda Group overlies the Kerpyl Group in the eastern part of the area (Fig. 4) with only local unconformities (Semikhatov and Serebryakov, 1983; Yan-Zhin-Shin, 1983; Khudoley et al., 2001). It is subdivided into a siliciclastic–carbonate lower part and carbonate upper part. The limestones and dolostones of the upper part accumulated in upper subtidal environments. The thickness, carbonate/shale, and limestone/dolostone ratios all increase eastward (Khudoley et al., 2001). K–Ar ages on glauconite are between 970 and 870 Ma (Chumakov and Semikhatov, 1981; Bartley et al., 2001). A Pb–Pb date of 1025 ± 40 Ma on limestone from the middle part of the Neryuen Formation (lower part of the Lakhanda Group) was reported recently (Semikhatov et al., 2000). Rainbird et al. (1998) reported a slightly discordant U–Pb baddeleyite age of 974 ± 7 Ma of a mafic sill intruded into the upper horizons of the Lakhanda Group, which is interpreted as a minimum age for Lakhanda Group deposition.

The upper Riphean Uy Group conformably overlies the Lakhanda Group, and is preserved only in the eastern part of the area. The group is predominantly clastic, and the percentage of siltstone and mudstone increases upward. The middle part of the Uy Group contains deep-water shales with evidence of deposition by gravity flows (Khudoley et al., 2001). Total thickness of the Uy Group increases eastward from 400 m to 4500 m. The ages of detrital zircons from the upper part of the Uy Group range from 1500 to 1050 Ma. A minimum age of deposition is provided by isotopic ages of 942 ± 19 Ma (Sm–Nd whole-rock, Pavlov et al., 2000) and 1005 ± 4 Ma (U–Pb on baddeleyite, Rainbird et al., 1998) for mafic sills that intrude the Uy Group. The presence of intrusion-related soft-sediment deformation structures (Khudoley et al., 2001), the occurrence of several basalt flows, and the presence of mafic pebbles in the upper part of the Kandyk Formation (lower part of the Uy Group) (Semikhatov and Serebryakov, 1983) suggest that the time of sill intrusion was close to the time of deposition of the host rock. The similarity in palaeomagnetic directions between sills and country rocks is consistent with this conclusion (Pavlov et al., 2002). The magmatic event was apparently minor in nature-sills (and some dykes) are typically meters to tens of meters thick. They are distributed mainly in the Yudoma–Maya Zone (Fig. 4), and most are intruded into the lower and middle Uy Group. The close similarity between palaeomagnetic poles of the lower (Kandyk Formation) and upper (Ust–Kirba Formation) suggests that the entire Uy Group accumulated over a short time interval (see Section 3). The Uy Group is also intruded by the 640–660 Ma ultramafic-alkaline Ingili intrusion (El'yanov and Moralev, 1975). The younger K–Ar dates of ~760 Ma from the lower part of the Uy Group (Yan-Zhin-Shin, 1983; Semikhatov and Serebryakov, 1983 and references therein; Sukhorukov, 1986) disagree with the ages mentioned above.

The upper part of the Uy Group is overlain by the Yudoma (Vendian) Group along a pronounced angular unconformity, which cuts progressively westward across older Riphean units (Khomentovsky et al., 1972; Semikhatov and Serebryakov, 1983; Khudoley et al., 2001). The base of the Yudoma Group is dated at about 645 Ma (Sokolov and Fedonkin, 1985).

Eastward thickening of the Riphean successions (Fig. 4) and apparent progradation of the ancient sedimentary prism suggest that the southeast edge of the Siberian continent represents a Riphean passive margin (e.g., Parfenov, 1984; Natapov, 1988). This margin existed from 1600–1500 Ma until at least 1000–900 Ma. It is difficult to reconstruct the palaeogeography for the rest of the late Riphean due to the Pre-Vendian hiatus and denudation. However, there is no evidence of any collisional event in the Neoproterozoic. Moreover, the Vendian and Palaeozoic successions of this area also probably represent a passive margin section.

Evidence of a rifting event that led to development of a passive margin is present in the southwestern part of this area, where Palaeoproterozoic volcano-sedimentary successions of the Ulkan graben underlie sediments of the Uchur Group (Gur'yanov et al., 2000). The Ulkan succession consists of quartz sandstone of the Toropkinsk Formation (200 m), trachybasalt and minor sandstone of the Ulkachan Formation (750 m), and liparite and dacite with some trachybasalt, conglomerate and sandstone of the uppermost El'geteisk Formation (2140 m) (Gur'yanov and Karsakov, 1990). The volcanic and sedimentary rocks are intruded by subalkaline and alkaline gabbro and granite. Ages of volcanic and intrusive rocks (U–Pb, Sm–Nd, Rb–Sr) are between 1726 and 1676 Ma (Neymark et al., 1992; Larin et al., 1997; Gur'yanov et al., 2000). The tectonic structure, bimodal alkaline magmatism, and coarse sediments in this area are attributed to Palaeoproterozoic rifting.

Khudoley et al. (2001) proposed another tectonic model for this segment of the Siberian margin in the Mesoproterozoic based mainly on a reconnaissance provenance study in the Sette-Daban area. According to this model, Riphean sediments accumulated in an epicontinental basin until about 1000 Ma (Uy Group time), when rifting occurred and subsequent opening of a deep-water basin began. Their arguments are based primarily on the supposed tectonic coherence of the Okhotsk massif with the Siberian craton. Khudoley et al. (2001), using the palaeomagnetic data of Pavlov et al. (1991), claimed that the relative positions of the Siberian platform and Okhotsk massif were similar to today. The study of Pavlov et al. (1991), however, indicates several degrees of latitudinal difference and 30–50° of rotation between these two blocks. In addition, the claimed lithostratigraphic similarity between the Riphean successions in Sette-Daban and the Okhotsk massif is not conclusive. In particular, the Doribin Formation of the Okhotsk massif is supposed to correspond to the Malgina Formation (Kerpyl Group). Indeed, both contain stromatolite *Malginella malgica Kom. Et Semikh.*, but Malgina Formation does not contain groups *Baicalica*, *Inzeria*, *Conaphyton*, *Gymnosolen* or *Paramites*, which are characteristic for the Doribin Formation. Malgina Formation is bituminous, whereas the Doribin Formation is not. Also, the lithological correlations are not rigorous, because the Riphean successions in the Okhotsk massif are incomplete (Rabotnov, 1977; Natapov and Surmilova, 1995). The middle and upper Riphean successions of the Omolon massif, which was probably tectonically coherent with the Okhotsk massif (e.g., Zonenshain et al., 1990a,b), consist of chlorite- and quartz-muscovite schist, quartzite, quartz sandstone, siltstone and carbonate rocks of a total thickness of about 1000 m. They are different from the Sette-Daban successions. Moreover, the Phanerozoic sections of these two massifs are completely different from those of the Siberian craton (Zonenshain et al., 1990a,b), and probably Sette-Daban itself is evidence for Cretaceous collision of the Okhotsk massif and the Siberian craton. In the reconstructions of Khudoley et al. (2001, Fig. 12) the Okhotsk massif is not shown as a potential source area. We suggest that the results of the provenance study of Khudoley et al. (2001) may be explained by other models, with the presence of an open ocean basin eastward of Sette-Daban, assuming more complicated sedimentary pathways, which can have greater importance than proximity in provenance studies (Sircombe, 2001).

We conclude that a passive margin probably existed along the entire eastern boundary of the Siberian craton from the early Riphean until at least 1000–900 Ma. Significant parts of the Neoproterozoic successions were destroyed during the Pre-Vendian hiatus and denudation. Vendian and Phanerozoic successions were also interpreted as passive margin deposits (e.g., Parfenov, 1984; Ilyin, 1990; Zonenshain et al., 1990a,b; Khudoley et al., 2001). Such conclusions place some limitations on the reconstructions of Sears and Price (2000), and of Condie and Rosen (1994) (Fig. 1a,c). If such configurations existed, the breakup between Siberia and Laurentia probably occurred in the late Palaeoproterozoic or the early Mesoproterozoic at the latest, hence these two fits could not have existed after 1000 Ma, during Rodinia time.

2.3. Southern margin (Aldan–Stanovoy block)

This block consists of two Archaean sub-provinces: Aldan and Stanovoy (Fig. 2), which have different tectonic histories prior to their collision at ca. 1.93 Ga along the present Kalar shear zone (e.g., Bibikova et al., 1989; Nutman et al., 1992; Rosen et al., 1994; Larin et al., 2000; Kovach et al., 2001). These two sub-blocks were separated by an ocean in the Palaeoproterozoic, and sedimentary rocks of the ca. 2.2 Ga Udokan Group (Rosen et al., 1994) in the westernmost Olekma terrane of the Aldan sub-province may represent a passive margin of this ocean (Zonenshain et al., 1990a,b). Since that time, the Aldan–Stanovoy block was a positive structure, and Riphean sediments were subsequently eroded. They are preserved only on its northern slope. The southern margin, including the Stanovoy sub-province, was tectonically reworked during Mesozoic collisions related to the assembly of Asia (Parfenov, 1984; Zonenshain et al., 1990a,b). As the tectonic overprint destroyed all evidence of the Riphean palaeogeography in this Siberian margin, and connections with other cratons, including Laurentia, are possible. This leaves the possibility that one of the reconstructions shown in Fig. 1d and e (Frost et al., 1998; Rainbird et al., 1998) are correct. However, the presence of the Stanovoy sub-province (Fig. 2), which contains distinct structures generally perpendicular to those of the Aldan block and is separated from this block by the Palaeoproterozoic oceanic suture, undermines at least part of the evidence for these fits—the tracing of Archaean and Palaeoproterozoic crustal blocks and orogenic belts from Laurentia into Siberia. Another possibility for south Siberia–north Laurentia reconstructions is that the Stanovoy block was originally a part of northern Laurentia, and that the late Palaeoproterozoic collision actually occurred between Laurentia and Siberia. To prove this, the similarities between the time of crust-forming and tectono-thermal events in Laurentian crustal elements—Slave and Rae provinces, and/or northern Greenland, should be found. So far, there are more differences than similarities in the corresponding geochronological data (Hoffman, 1989; Frisch and Trettin, 1991; Larin et al., 2000; Kovach et al., 2001), although these data are too sparse to be conclusive.

2.4. Southern margin (Vitim–Patom Highland and Cisbaikalia)

The Riphean successions of the Vitim–Patom Highland (Fig. 2) were deformed during the Baikalian (789–730 Ma) and Caledonian (545–350 Ma) events (Zonenshain et al., 1990a,b; Sryvtsev et al., 1992; Rosen et al., 1994; Parfenov et al., 1995; Rytsk et al., 1999). These events were related to the collision of Siberian craton and Barguzin composite terrane, which contains ophiolites and Riphean island arc fragments in its frontal part (e.g., Zonenshain et al., 1990a,b; Konnikov et al., 1994; Gusev and Khain, 1996; Khain et al., 1997; Kazakov and Velikoslavinsky, 1999; Sklyarov et al., 2001). This Siberian margin contains an embayment (Fig. 2) with the Akitkan volcanic belt to the west and the Zhuya dextral fault to the east. Despite the deformation, the Riphean successions are well preserved and contain an almost complete and continuous section (Sklyarov et al., 2001).

The lower Riphean Teptogora Group contains metamorphosed clastic sediments, and includes iron-bearing rocks and mafic volcanic rocks. This succession is intruded by gabbro and diorite dykes and sills, which are absent in the younger successions (Sklyarov et al., 2001). A Pb–Pb isochron age for the lower part of this group is 1602–1542 Ma (Sharov et al., 1991). The Teptogora Group possibly accumulated during the rifting stage of passive margin development (Sklyarov et al., 2001).

The middle and upper Riphean successions of the Vitim–Patom Highland consist of several formations (Fig. 5), representing large transgressive sedimentation cycles with coarse sediments at the bottom and carbonate rocks at the upper part of each formation

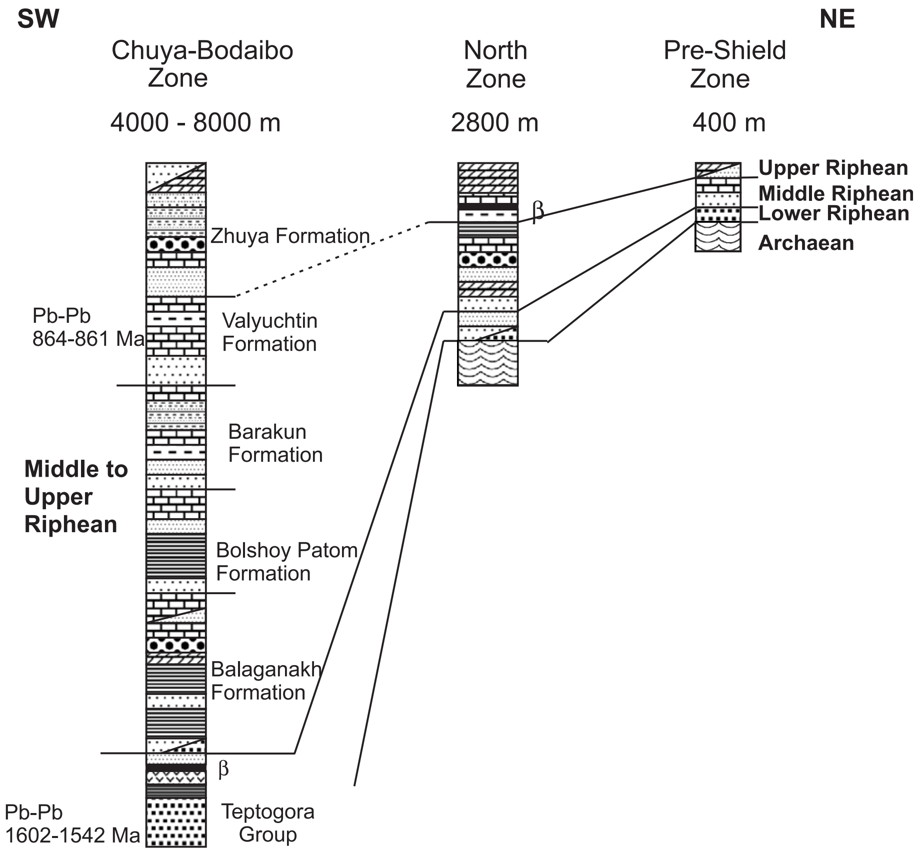

Fig. 5. Correlation chart of the Riphean successions in the Patom Highland. See Fig. 3 for legend.

(Khomentovsky et al., 1972; Mironyuk, 1987; Zapol'nov, 1988). This subdivision is based mainly on stromatolite and microphytolite assemblages. The Pb–Pb age of limestones in the upper part of the Valyuchtin Formation (Fig. 5) is 864–861 Ma (Fefelov et al., 2000). The thicknesses of the sections increase to the south and southwest (Fig. 5).

Two belts of Riphean sediments, separated by the Palaeoproterozoic Akitkan volcanic belt, are exposed in the southwest of the Vitim–Patom Highland and continue into Cisbaikalia. Here the Riphean successions are preserved in a narrow (about 30 km) and long (500 km) belt, which is overthrust, to the west, by Palaeoproterozoic metamorphic schists and granitoids (Fedorovsky, 1985; Turchenko and Sokolov, 1988). Thrusting probably occurred during the final stages of collision with the Barguzin terrane in the latest Neoproterozoic and early Palaeozoic. The Riphean sediments (Goloustnaya Formation) overlie Palaeoproterozoic basement and, in some localities, contain mafic volcanic rocks in the lower part of the succession (Maslov and Kichko, 1985). The thickness of the Riphean succession increases eastward (Fig. 6). The eastern sections (Olokit Zone, Fig. 6) contain metavolcanics and metasediments of the Teptogora Group, consisting of thick low and middle Riphean turbidites with minor carbonates and the volcanic upper Riphean Synnyr Formation (Fig. 6). The middle Riphean sediments represent the continental slope environments.

The entire Riphean succession of the Vitim–Patom Highland and Cisbaikalia probably represents a Meso- to Neoproterozoic passive margin of the Siberian craton. This point of view generally supports the conclusions of other researchers (e.g., Kazakov and Velikoslavinsky, 1999; Rytsk et al., 1999; Sovetov et

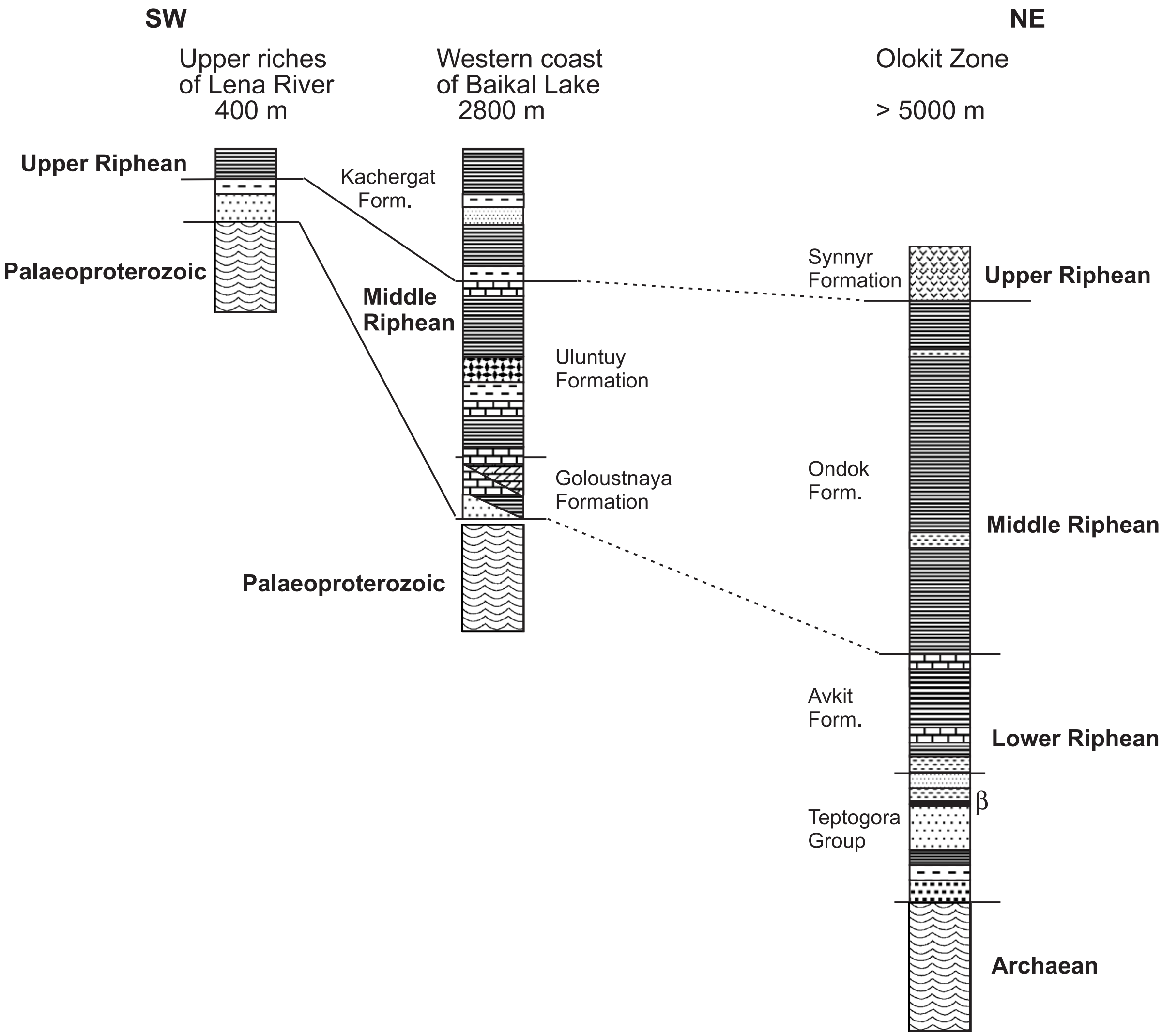

Fig. 6. Correlation chart of the Riphean successions in the Cisbaikalia. See Fig. 3 for legend.

al., 1999; Sklyarov et al., 2001). It is also supported by a deep seismic profile across Cisbaikalia (Mandel'baum and Smirnova, 2000). Some studies suggest that this passive margin was transformed into an active margin in the mid-Neoproterozoic (e.g., Gusev and Khain, 1996; Rytsk et al., 1999; Kuzmichev et al., 2001). However, in either case, this edge of Siberia was bordered by an ocean basin during Rodinia time (1000–750 Ma), and this contradicts reconstructions of north Laurentia with south Siberia (Frost et al., 1998; Rainbird et al., 1998), shown in Fig. 1d and e.

2.5. Western margin (Pre-Sayan area)

The western Siberian margin is separated by a large dextral strike-slip fault from the East Sayan fold belt. Riphean successions are exposed in narrow (10–50 km) northeasterly trending belt (Fig. 2), and consist of the lower Karagas Group and upper Oselkovaya Group. The latter is unconformably overlain by the Vendian Moty Formation. The basal part of the Karagas Group unconformably overlies Archaean and Palaeoproterozoic basement, and was accumulated mainly in continental and shallow marine environments (Sklyarov et al., 2001). The age of these sediments is middle or late Riphean (based on microphytolite complex). The middle part (Lower and Upper Tagul Formations) contains more carbonate sediments (dolostones) with late Riphean microphytolites (Khomentovsky et al., 1972). The upper part contains turbidites and silicic and carbonate sediments (Sklyarov et al., 2001). The Karagas Group is intruded by dolerite sills and dykes of the Nersinsk Complex, which have a preliminary Ar–Ar (plagioclase) age of 890–860 Ma (Sklyarov et al., 2001). The Oselkovaya Group consists mainly of clastic marine sediments with carbonates and turbidites in its upper part. The thickness of the Riphean successions increases to the southwest.

The Riphean successions in the Pre-Sayan area represent a Meso- to Neoproterozoic passive margin, and this is in agreement with the conclusions of previous studies (e.g., Sklyarov et al., 2001 and references therein) and is supported by a deep seismic profile across the Pre-Sayan (Mandel'baum and Smirnova, 2000). The passive margin may have been transformed into an active margin in the late Neoproterozoic (e.g., Kozakov et al., 2001; Kuzmichev et al., 2001). Therefore, this southwestern margin of Siberia probably also faced ocean at least at ca. 1000–600 Ma. This contradicts the reconstruction of Rainbird et al. (1998) shown in Fig. 1e, at least for Rodinia time.

2.6. Western margin (Yenisei Range)

The Riphean successions of the Yenisei Range were deformed and intruded by granites during one or several collisions with island arcs and possibly other terranes in late Riphean to Vendian times (e.g., Zonenshain et al., 1990a,b; Volobuev, 1994; Khain et al., 1997; Vernikovsky et al., 1999; Sovetov and Romashko, 1999). The lower Riphean Korda Formation unconformably overlies Palaeoproterozoic granite-gneiss (Fig. 7); the upper boundary is unclear. The thickness of the Korda Formation increases westwards.

The remainder of the Riphean succession is subdivided into three groups (Fig. 7). The Sukhoi Pit Group was deposited in a marine environment with shelf clastic and carbonate sediments in its eastern part and deeper-water facies in its western part. Thickness generally increases to the west. Some volcanic rocks and mafic sills and dykes are present, which yielded K–Ar (whole rock) ages of 980–990 Ma (Semikhatov and Serebryakov, 1983). The K–Ar age (glauconite) for sandstones of the middle part of the Sukhoi Pit Group is 1140 Ma (Rundquist and Mitrofanov, 1993). Another set of K–Ar (whole rock) dates of 1180–1080 Ma obtained from clay-rich sediments of the Sukhoi Pit Group (Semikhatov and Serebryakov, 1983). The Tungusik Group unconformably overlies the Sukhoi Pit Group. The age of its lower part is about 1000 Ma (Khabarov et al., 1999). Thickness increases to the west, where deep-water environments prevail. Westward progradation of the palaeoshelf can also be traced by the reefs (Ruchkin and Konkin, 1998). The uppermost Oslyanka Group generally demonstrates similar indications of passive margin palaeoenvironment (Fig. 7).

K–Ar ages (Semikhatov and Serebryakov, 1983; Khabarov et al., 1999) suggest that deposition of the Sukhoi Pit, Tungusik and Oslyanka Groups occurred between 1350 and 850 Ma. After ~850 Ma the passive margin in this area was transformed into an active margin (e.g., Volobuev, 1994). This is indicated by 880–860 Ma syn-collisional and 760–720 Ma post-collisional granites (Vernikovskaya et al., 2002; Vernikovsky et al., 2003), and by obduction of late Riphean to Vendian ophiolites (Volobuev, 1994; Khain et al., 1997; Vernikovsky et al., 1999, 2003).

During the suggested existence of the Rodinia supercontinent (1000–750 Ma), therefore, this part of the Siberian craton faced an oceanic domain (or domains).

2.7. Western margin (Turukhansk and Igarka uplifts)

In the Turukhansk uplift, Riphean siliciclastic and carbonate rocks up to 4.5 km thick are exposed in three east-vergent overthrust blocks (Bartley et al., 2001 and references therein). The lower part of the succession commences with the mainly siliciclastic Bezymyannyi Formation. The thickness of this formation is 800–1000 m and it accumulated within an open marine basin near storm wave base (Bartley et al., 2001 and references therein). It is overlain conformably by shallow-water limestones of the Linok

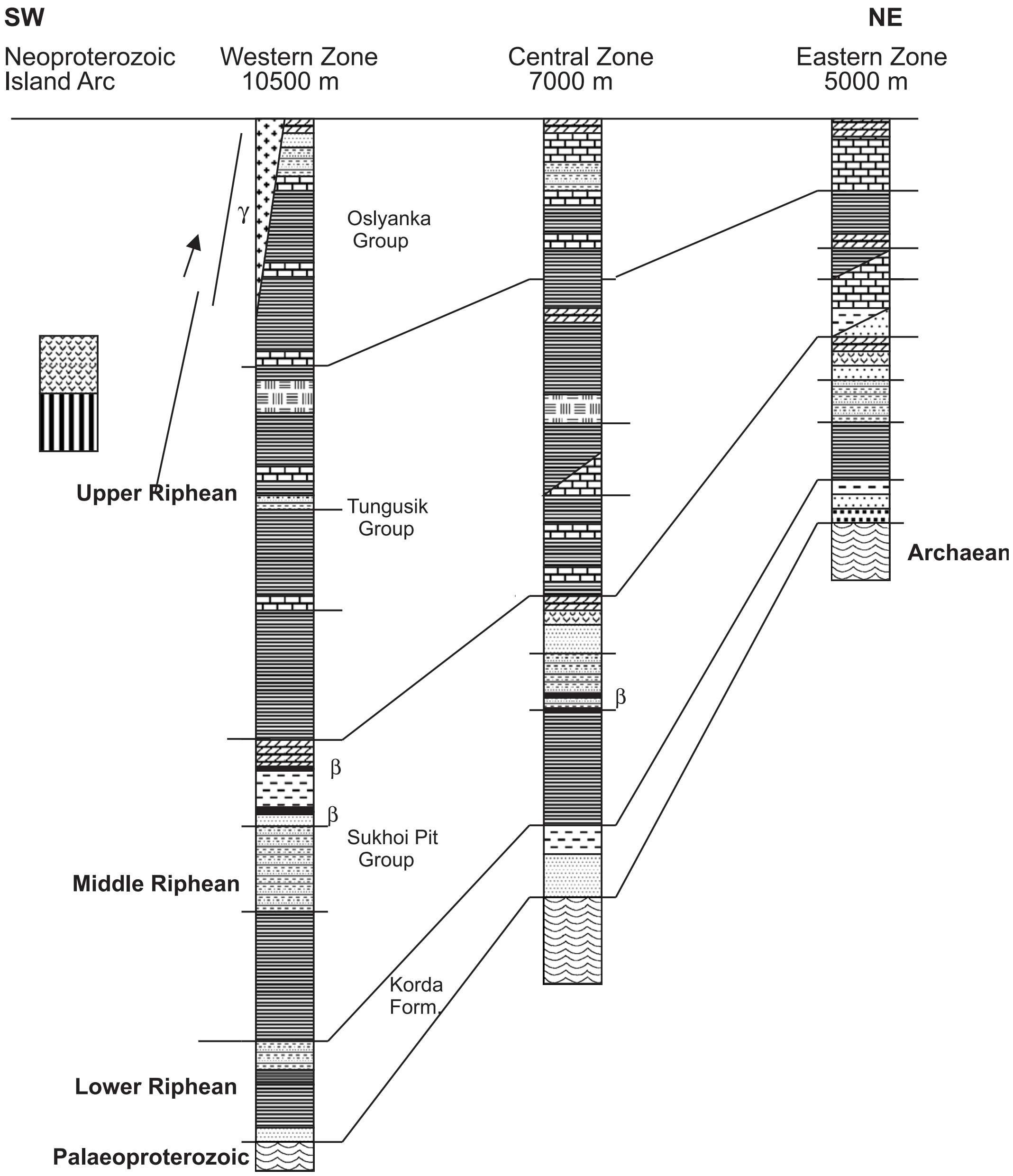

Fig. 7. Correlation chart of the Riphean successions in Yenisei Range. See Fig. 3 for legend.

Formation, which have a thickness of about 140 m in the eastern part of the area, and up to 380 m in the western part. According to Petrov (1993), Veis and Petrov (1994), and Bartley et al. (2001), the Linok Formation was deposited below and near the storm wave base along an extensive carbonate platform. It is overlain by carbonates of the Sukhaya Tunguska Formation, which accumulated in upper subtidal to intertidal settings (Sergeev et al., 1997; Bartley et al., 2001). The thickness of this formation also increases westward from 560 to 680 m (Malich et al., 1987). These three formations are middle Riphean in age according to stromatolite and microphytolite assemblages (Bartley et al., 2001). A Pb–Pb age for carbonates of the middle part of the Sukhaya Tunguska Formation is 1035 ± 60 Ma (Ovchinnikova et al., 1995).

The upper Riphean deposits (dated using stromatolites) are separated from the middle Riphean succession by a regional erosional surface. They are subdivided into five formations (Derevnya, Burovaya, Shorikha, Miroedikha and Turukhansk), all of which accumulated in shelf environments (Petrov and Veis, 1995; Petrov and Semikhatov, 2001; Sergeev et al., 1997; Bartley et al., 2001). K–Ar determinations on globular glauconite give ages of 800–860 Ma for the Derevnya Formation, and 830–895 Ma for the Burovaya Formation (Bartley et al., 2001). However, these ages may reflect resetting of the K–Ar system at 850–900 Ma by meteoric diagenesis during uplift and unroofing (Petrov and Semikhatov, 2001 and references therein). Palaeontological and chemostratigraphic data (Petrov and Semikhatov, 2001) suggest that the Burovaya and Derevnya Formations correlate with the lower Lakhanda Group of the Uchur–Maya region (see Section 2.2), which is cut by mafic sills of ca. 1000 Ma (Rainbird et al., 1998) and has a Pb–Pb age of 1025 ± 40 Ma (Semikhatov et al., 2000). Vendian sediments overlie the Riphean succession along an angular unconformity. They are subhorizontal, indicating that deformation of the Riphean successions occurred before the Vendian.

About 90 km to the north, in the Igarka Uplift, the only Riphean sediments present belong to the Chernaya Rechka Formation (correlative to the Turukhansk Formation in the Turukhansk Uplift). Vendian sediments here overlie either this formation, or the folded volcano-sedimentary rocks of Palaeoproterozoic (Kovrigina, 1996) or Riphean (Bogdanov et al., 1998) age. Bogdanov et al. (1998) suggested that these rocks represent a palaeorift.

We conclude that the Riphean succession along the northern part of the western Siberian boundary was deposited on a passive margin, as recognised also by other authors (e.g., Bogdanov et al., 1998). Collision with an unknown continental block occurred in the late Riphean (before the Vendian) and resulted in folding and thrusting of the Riphean successions. The passive margin can also be traced in seismic profiles that show depression of the crustal basement down to 12–15 km westward and uplift of the Moho (Kuznetsov and Titarenko, 1988). We conclude that during Rodinia time (ca. 1000–750 Ma) the entire western margin of the Siberian craton probably faced an ocean.

2.8. Northern margin

This area is dominated by thick Phanerozoic sediments of the South Taimyr and Yenisei–Khatanga basin. Riphean successions are exposed only along the northern slope of the Anabar massif (Fig. 2), dipping to the north, under Mesozoic cover of the Yenisei–Khatanga depression, and may continue under it, although this is yet to be proven. Farther to the north, South Taimyr is covered by folded Palaeozoic sediments, and it is unclear whether these sediments are underlain by older sediments. The folding probably occurred during collision of the Siberian craton with the Kara plate and/or Central Taimyr accretionary belt. The time of this collision is disputed and may be as young as Cretaceous (Zonenshain et al., 1990a,b; Uflyand et al., 1991), or as old Vendian (Vernikovsky and Vernikovskaya, 2001). In any case, the Riphean history of this margin is unclear.

2.9. Summary

We conclude that the Siberian craton was almost completely surrounded by ocean basins in the late Mesoproterozoic and early Neoproterozoic. However, we cannot exclude the possibility of a connection with some other craton (Laurentia?) along Siberia's northern margin and/or along the eastern part of its southern margin (Stanovoy block). The latter is less likely, because in this case we must assume that the Stanovoy block was originally part of another craton, and there is very little evidence for this, at least if we suppose that it was part of Laurentia. Moreover, no reliable evidence for Neoproterozoic or early Palaeozoic rifting along this margin of Siberia has so far been found. Pelechaty (1996) reported evidence for early Cambrian rifting along the northern margin of Siberia, which coincides with sedimentation in the latest Proterozoic to early Palaeozoic Franklinian Basin (Surlyk, 1991; Higgins et al., 1991) north of Laurentia (present coordinates). Rainbird and de Freitas (1997), and Khudoley (1997), however, criticised this hypothesis arguing in favour of 727–721 Ma Franklinian rifting (Ernst et al., 1996) rather than of early Cambrian one.

3. Palaeomagnetic data

The majority of reliable [with $Q \geq 4$ (Van der Voo, 1990)] late Mesoproterozoic to Neoproterozoic palaeomagnetic data are from Laurentia (Table 1). The Laurentian Apparent Polar Wander Path (APWP) can be traced within the ca. 1140–1020 Ma time interval, but younger poles are sparse. The poles between 1020 and 720 Ma define a "Grenville Loop" of poles in the Pacific Ocean (Fig. 8), although the shape and "direction" of this loop is debated (e.g., Park and Aitken, 1986; Hyodo and Dunlop, 1993; Weil et al., 1998; Alvarez and Dunlop, 1998; McElhinny and McFadden, 2000). Alvarez and Dunlop (1998) analysed palaeopoles from the Grenville Province, which were obtained from rocks remagnetised during post-Grenvillian exhumation between 1000 and 900 Ma. Some of these overprints are calibrated by $^{40}Ar-^{39}Ar$ ages that support a clockwise Grenville Loop (Fig. 8). Following a similar approach, McElhinny and McFadden (2000, Table 7.4) also constructed a clockwise loop. However, their mean poles between 940 and 800 Ma are poorly dated, so we have simplified this part of the loop in Fig. 9 by interpolating between reliable poles listed in Table 1.

The majority of late Mesoproterozoic and early Neoproterozoic palaeomagnetic data for Siberia were

Table 1
Late Mesoproterozoic-Early Neoproterozoic palaeomagnetic poles

Object	Age (Ma)	Pole (°N)	Pole (°E)	A_{95} (°)	Q	Reference
Laurentia						
Franklin dykes	723 + 4/ – 2	5	163	5	II-IIII 6	Heaman et al., 1992; Park, 1994
Natkusiak Formation	723 + 4/ – 2	6	159	6	III-III 6	Palmer et al., 1983; Heaman et al., 1992
Tsezotene sills and dykes	779 ± 2	2	138	5	III-I-I 5	Park et al., 1989; LeCheminant and Heaman, 1994
Wyoming dykes	782 ± 8 785 ± 8	13	131	4	III-I-I 5	Harlan et al., 1997
Haliburton Intrusions A	980 ± 10	– 36	143	10	III-I 4	Buchan and Dunlop, 1976
Chequamegon sandstone	ca. 1020[a]	– 12	178	5	-II-I-I 4	McCabe and Van der Voo, 1983
Jacobsville sandstone J (A + B)	ca. 1020[a]	– 9	183	4	-II-I-I 4	Roy and Robertson, 1978
Freda sandstone	1050 ± 30	2	179	4	-IIII-I 5	Henry et al., 1977; Wingate et al., 2002
Nonesuch shale	1050 ± 30	8	178	4	-IIII-I 5	Henry et al., 1977; Wingate et al., 2002
Lake Shore Traps	1087 ± 2	22	181	5	IIIII-I 6	Diehl and Haig, 1994; Davis and Paces, 1990
Portage Lake volcanics	1095 ± 2	27	181	2	II-I-I 4	Halls and Pesonen, 1982; Davis and Paces, 1990
Upper North Shore volcanics	1097 ± 2	32	184	5	II-III 5	Halls and Pesonen, 1982; Davis and Green, 1997
Logan sills R	1109 + 4/ – 2	49	220	4	II-IIII 6	Halls and Pesonen, 1982; Davis and Sutcliffe, 1985
Siberia						
Ust–Kirba Formation, U–K mafic sills included (Uy Group)	< K	– 8	183	10	-II-I-I 4	Pavlov et al., 2002
Kandyk Formation, K (Uy Group)	ca. 1000[b]	– 3	177	4	III-I-I 5	Pavlov et al., 2002; Rainbird et al., 1998
Ignikan Formation, I (Lakhanda Group)	>K, < N	– 16	201	4	I-I-I-I 4	Pavlov et al., 2000
Nelkan Formation, N (Lakhanda Group)	>I, < M	– 14	219	6	I-I-I-I 4	Pavlov et al., 2000
Milkon Formation, M (Lakhanda Group)	ca. 1025[b]	– 6	196	4	III-I-I 5	Pavlov et al., 2000
Kumahinsk Formation, Ku (Lakhanda Group)	>M, < MAL	– 14	201	7	I-I-I-I 4	Pavlov et al., 2000
Malgina Formation, MAL 1	1043 ± 14	– 22	226	7	II-III 5	Osipova in Smethurst et al., 1998; Ovchinnikova et al., 2001
Malgina Formation, MAL 2	1043 ± 14	– 25	231	3	IIIIIII 7	Gallet et al., 2000; Ovchinnikova et al., 2001
Linok Formation, L	ca. 975-1100	– 15	256	8	-II-III 5	Gallet et al., 2000

[a] Age based on APWP interpolation.
[b] Age based on new indirect data, see text.

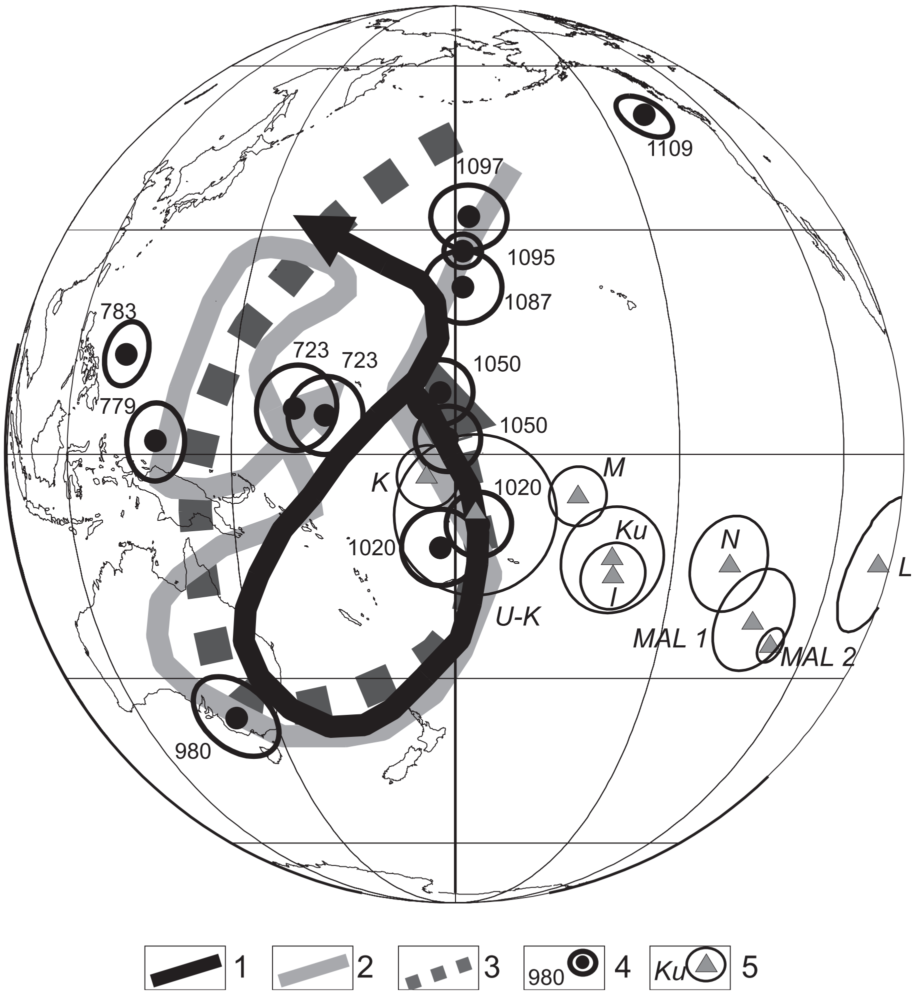

Fig. 8. Laurentian Meso- to Neoproterozoic APWPs: 1 = after Hyodo and Dunlop (1993); 2 = after McElhinny and McFadden (2000); 3 = after Weil et al. (1998); 4 = Laurentian palaeopoles with ages (see Table 1); 5 = Siberian palaeopoles with abbreviations (see Table 1).

obtained from the Uchur–Maya area (Table 1). Most of these results (from preliminary publications) were summarised by Smethurst et al. (1998). Based on these data, Smethurst et al. (1998) suggested that Siberia was not connected to Laurentia at 750 Ma. However, more recent geochronological data (see Section 2.2) require reconsideration of the ages of the studied formations. For example, palaeopoles from the Kandyk, Ignican, Nelkan and Milkon Formations were originally assigned ages of 730, 840, 865 and 900 Ma, respectively, based on K–Ar results (Pavlov, in Smethurst et al., 1998). New data (see Section 2.2) suggest that these rocks are between 1100 and 1000 Ma in age (Pavlov et al., 2000, 2002). If so, frequency of magnetic reversals recorded in these sections would seem more realistic. From top to bottom, the Ust–Kirba and Kandyk Formations are of "reverse" polarity, and the Ignican, Nelkan, Milkon and Kumaha Formations are of "normal" polarity; frequent reversals are recorded in the Malgina Formation (Gallet et al., 2000; Pavlov et al., 2000, 2002). The previous age scheme, based on K–Ar data, suggests the presence of two very long consecutive polarity superchrons, much longer than the longest known example—the Kiaman superchron (316–262 Ma, McElhinny and McFadden, 2000, p.

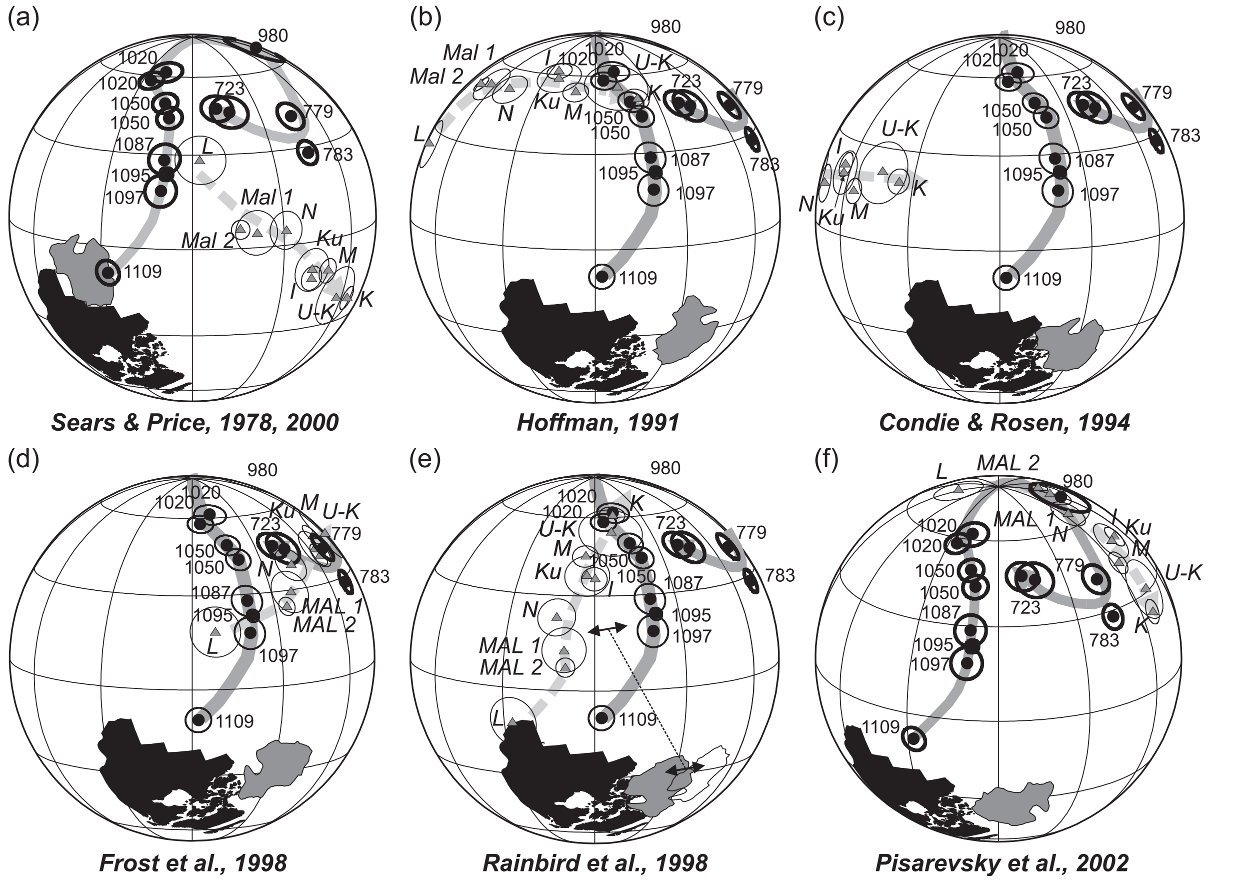

Fig. 9. Laurentia–Siberia fits and palaeomagnetic data for ~ 1000 Ma.

162). Nevertheless, the paucity of absolute dates precludes any final conclusion, and we try to review all potential models.

The Siberian poles define an almost straight line (Fig. 9), which, owing to the high quality of the palaeomagnetic studies (Gallet et al., 2000; Pavlov et al., 2000, 2002) and the well-defined stratigraphy and magnetostratigraphy of the studied rocks, probably represents a reliable segment of the Siberian APWP. The time constraints are still disputed (see above), but the most likely age range is from 1050 to 1040 Ma for the Malgina Formation (Ovchinnikova et al., 2001) to 1000–950 Ma for Kandyk and Ust–Kirba Formations (Rainbird et al., 1998; Pavlov et al., 2002).

The age of pole L (Linok Formation, Table 1) is poorly determined, but Gallet et al. (2000) suggest that the Linok Formation in the Turukhansk area is correlative with the Malgina Formation. They suggest that the difference in pole positions for the two formations is caused either by local tectonics in the Turukhansk area, or by Palaeozoic opening of the Viluyi rift (Gallet et al., 2000 and references therein). The latter seems unlikely, because it was probably just a failed rift (or aulacogen), which did not break up the Siberian craton (Fig. 28 of Khain, 1985; Zonenshain et al., 1990a,b). Deep seismic profiles show 35–42 km of continental crust and about 250 km of continental lithosphere under the Vilyui Syneclise (Egorkin et al., 1987). It is also possible that the difference in pole position between these two formations could reflect a difference in age.

Fig. 9a–f shows the previous reconstructions of Siberia and Laurentia at 1000 Ma as in Fig. 1, together with palaeomagnetic data. In each case, the continents are rotated together with their corresponding APWP segments. In a correct reconstruction of Siberia and Laurentia, the APWP segments should coincide. The configurations in Fig. 9a and c (Sears and Price, 1978, 2000; Condie and Rosen, 1994) contradict the palaeomagnetic data in any possible interpretation of the ages of the Siberian poles. The reconstruction of Hoffman (1991) is possible (Fig. 9b), if a collision occurred between the two cratons at 1050–1000 Ma. However, to our knowledge, there is no evidence for such a collision from either continent. The configuration of Frost et al. (1998), shown in Fig. 9d, could exist only before 1100–1080 Ma, but would suggest that the Pb–Pb date of 1043 ± 14 Ma for the limestone of the Malgina Formation is 30–40 my too young. The reconstruction of Rainbird et al. (1998), shown in Fig. 9e, may be considered after some changes: two APWPs will coincide if Siberia was situated farther to the east, and, as in the previous case, the age of the Malgina Formation is older than 1043 Ma. This modification, shown schematically in Fig. 9e, however, contradicts the suggestion of Rainbird et al. (1998) that East Greenland was the source of detrital zircons of "Grenvillian" age in Sette-Daban. Fig. 9f shows the reconstruction of Pisarevsky et al. (2003) which was proposed assuming that the age of the Malgina Formation was 1000–980 Ma—close to its younger age limit proposed by Gallet et al. (2000). This reconstruction is possible only if all Pb–Pb ages for Sette-Daban and Turukhansk limestones and U–Pb ages of sills are wrong, and the K–Ar dates are correct (see Section 2.2).

4. Discussion

We now test the published reconstructions of Laurentia and Siberia shown in Figs. 1 and 9 using both palaeomagnetic and geological arguments.

Palaeomagnetic data and the evidence for a Meso- to Neoproterozoic passive margin in northeastern Siberia do not support the reconstruction of Sears and Price (1978, 2000), (Figs. 1a and 9a). Additionally, there is a mismatch of crustal age domains. Southwestern North America is dominated by juvenile early Proterozoic belts, whereas the Aldan Shield of Siberia is Archaean (e.g., Condie and Rosen, 1994). Sears and Price (2000), citing Nd isotopic data from Ramo and Calzia (1998), argued for the presence of a substantial Archaean source component in the Death Valley area of Mojavia. However, Ramo and Calzia (1998) concluded that this Archaean component was introduced as sedimentary detritus and was probably subducted and mixed with juvenile material at a convergent zone, either at the present western margin of the Wyoming craton or elsewhere. Sears and Price (2000) also correlated a 1740 Ma U–Pb zircon crystallization age from the Okhotsk massif in Siberia with similar-aged magmatic events from the Mojave, Yavapai and Mazatzal provinces (Van Schmus and Bickford, 1993). This 1740 Ma date (Table 1 in Kuzmin et al., 1995; see also Khudoley et al., 2001) is the youngest in a series of 21 age determinations ranging mainly between 3350 and 1830 Ma. These dates are much older than dates from the Mojave, Yavapai and Mazatzal provinces (Van Schmus and Bickford, 1993). Sears and Price (2000) juxtaposed the Palaeoproterozoic (maximum 2.4–2.5 Ga, Rosen et al., 2000) Birekte block of Siberia (or Olenek block, following the determination of Condie and Rosen, 1994), against the Archaean Hearne Province/Medicine Hat block (Hoffman, 1989). Sears and Price (2000) attempted to correlate the North Alberta Palaeoproterozoic continental and oceanic arc terranes with the predominantly metasedimentary Hapshan Orogenic Belt which underwent granulite-facies metamorphism at 2080–1970 Ma (Rosen et al., 2000). The North Alberta arcs experienced granulite-facies metamorphism during accretion to the Hearne Province, approximately 200 my later, at ca. 1850–1800 Ma (Ross et al., 2000).

The reconstruction of Hoffman (1991) may be supported by the palaeomagnetic data only if an ~ 1000 Ma collision occurred between north Siberia and north Laurentia (Fig. 9b). However, no evidence for such a collision has been found. The presence of a Meso- to Neoproterozoic passive margin in north Siberia is possible, but not proven, so we cannot dismiss Hoffman's (1991) reconstruction on this basis.

Palaeomagnetic data contradict the reconstruction of Condie and Rosen (1994) in any interpretation of the ages of the Siberian palaeopoles (Fig. 9c). The presence of a Meso- to Neoproterozoic passive margin

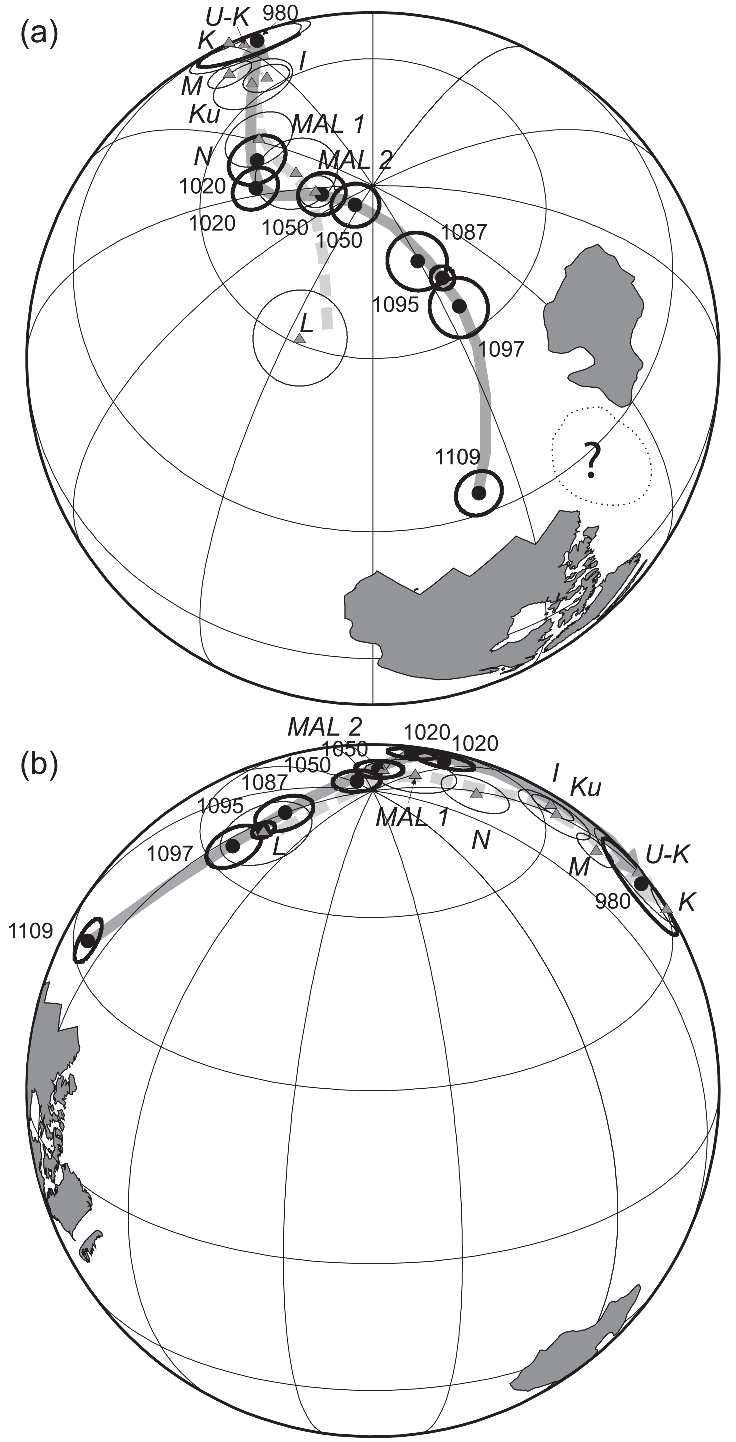

Fig. 10. The best fit of Laurentian and Siberian Meso- to Neoproterozoic APWPs and palaeoreconstructions of Laurentia and Siberia for ~ 1045 Ma in two magnetic polarity options (a and b, correspondingly). Euler's rotation parameters: Laurentia the absolute framework (39.8, − 139.1, − 113.3); Siberia to Laurentia: (a) 65.0, 144.0, 141.8; (b) 38.5, 5.3, − 95.0.

in eastern Siberia also contradicts this model. In addition, a key argument used by Condie and Rosen (1994), namely that the Thelon belt of Laurentia continued into the Akitkan belt of Siberia, was criticised by Kovach et al. (2001), who claimed that "opposite to 2.02–1.91 Ga granitoids of the Thelon–Talson zone with Archaean Nd model ages (3.0–2.6 Ga), the volcanic rocks of the Akitkan belt yield 1.87–1.82 Ga ages and have Palaeoproterozoic Nd model ages (2.5–2.3 Ga)."

Palaeomagnetic data also contradict the reconstruction (Fig. 9d) of Frost et al. (1998). These authors juxtaposed the Stanovoy block of Siberia with northern Laurentia. Although, there is no evidence for a Riphean passive margin in this part of Siberia (see Section 2.3), an argument against this fit is the presence of the Stanovoy province (Fig. 2), which contains structures which are generally perpendicular to those of the Aldan block. Some collision-related magmatic and metamorphic events along the northern margin of Stanovoy block (Gusev and Khain, 1996) provide evidence for collision of the Stanovoy and Aldan blocks at 1.8–2.0 Ga (Rosen et al., 1994 and references therein).

The reconstruction of Rainbird et al. (1998) may fit the palaeomagnetic data after some adjustment shown in Fig. 9e. It also requires wider age range for the Siberian palaeopoles than provided by recent U–Pb and Pb–Pb dating (Rainbird et al., 1998; Ovchinnikova et al., 2001). In this case, however, Siberia was situated at some distance from East Greenland, which was proposed by Rainbird et al. (1998) to be a source for the "Grenville"-age detrital zircons in Sette-Daban. In addition, Kalsbeek et al. (2000) did not find any conclusive evidence for metamorphism and granitic activity related to Grenvillian plate collision in East Greenland. The high-grade metamorphism of the Krummendal sequence (East Greenland) and associated anatectic granite formation took place at 920–950 Ma (Kalsbeek et al., 2000), which is ~ 100 my younger than the "Grenville"-age detrital zircons in southeastern Siberia (Rainbird et al., 1998). The presence of Riphean passive and active margin palaeoenvironments in Baikal–Patom, Cisbaikalia, Pre-Sayan, and Yenisei Range (see Sections 2.4–2.7) contradicts the reconstruction of Rainbird et al. (1998) in its original form (Fig. 2e), but may be explained in the adjusted configuration (Fig. 9e). This reconstruction, however, requires at least a narrow ocean between Laurentia and Siberia in Rodinia time, and, consequently, implies that Siberia was not part of Rodinia. The model of Rainbird et al. (1998) faces the same problem with the Stanovoy block as the model of Frost et al. (1998).

The reconstruction of Pisarevsky et al. (2003) may fit the palaeomagnetic data (Fig. 9f) if recent U–Pb and Pb–Pb geochronology from the Sette-Daban area (Rainbird et al., 1998; Ovchinnikova et al., 2001) are wrong (Section 2.2). This model, however, suggests minor rotation and displacement of Siberia with respect to Laurentia during the early Neoproterozoic, so in this case Siberia was not a part of Rodinia in a strict sense.

If the new geochronological data from Sette-Daban are correct, the apparent similarity between the Laurentian and Siberian APWPs suggests that both continents could have been parts of the Rodinia supercontinent. Fig. 10 shows two possible best fits of the ca. 1100–980 Ma Laurentian and Siberian APWPs for two polarity options. Both reconstructions are made for ~ 1045 Ma. Fig. 10a indicates that Siberia and Laurentia could be parts of Rodinia, although not in direct contact, as all of the discussed models suggest. In this case, some unknown continental block (question mark in Fig. 10a) could have been located between them. The apparent absence of the continuation of the giant ca. 1267 Ma Mackenzie Dyke Swarm (e.g., Ernst et al., 1996) in Siberia supports this idea. The involvement of Siberia in Rodinia is unlikely for the other polarity option (Fig. 10b).

We conclude that the new reconstruction shown in Fig. 10a provides better explanation for the palaeomagnetic, geochronological and geological data from Siberia and Laurentia than any of other existing reconstructions. A similarity of APWPs for two continents between 1050 and 980 Ma suggests that they were probably the parts of Rodinia supercontinent. However, it is possible that some unknown continental block was located between them.

Acknowledgements

This research was supported by the Australian Research Council (ARC) through its Research Centres program. Pisarevsky acknowledges a University of Western Australia Gledden Senior Fellowship. Reconstructions were made using PLATES software from the University of Texas at Austin and GMT software of Wessel and Smith. We are very grateful to A.N. Khramov and J.B. Murphy for their helpful reviews. We also thank M.T.D. Wingate and A. Kröner for their informal reviews. This is Tectonics Special Research Centre publication no. 205, ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents publication no. 304, and a contribution to International Geological Correlation Project 440.

References

Alvarez, V.C., Dunlop, D.J., 1998. A regional paleomagnetic study of lithotectonic domains in the Central Gneiss Belt, Grenville Province, Ontario. Earth Planet. Sci. Lett. 157, 89–103.

Bartley, J.K., Semikhatov, M.A., Kaufman, A.J., Knoll, A.H., Pope, M.C., Jacobsen, S.B., 2001. Global events across the Mesoproterozoic–Neoproterozoic boundary: C and Sr isotopic evidence from Siberia. Precambrian Res. 111, 165–202.

Bibikova, E.V., Gavrikova, S.N., Kirnozova, T.V., Fedchuk, V.I., 1989. Early Proterozoic granites in the southern Aldan Shield; Isotopes and isotopic ages. Isotopes in Nature. GDR Academia of Sciences, Centr. Inst. of Isotope and Radiation Res., Leipzig, pp. 13–14.

Biterman, I.M., Gorshkova, E.R., 1962. New data about Sinian stratigraphy of Olenek and Kuoika–Daldyn Uplifts. Later Precambrian Stratigraphy of Siberia and Far East (Abstracts). Novosibirsk Press, Novosibirsk, pp. 11–12.

Bogdanov, N.A., Khain, V.Y., Rosen, O.M., Shipilov, E.V., Vernikovsky, V.A., Drachev, S.S., Kostyuchenko, S.L., Kuzmichev, A.B., Sekretov, S.B., 1998. Explonatory Notes for the Tectonic Map of the Kara and Laptev Seas and Northern Siberia (Scale 1:2,500,000). Institute of the Lithosphere of Marginal Seas, Russian Academy of Sciences, Moskow. 116 pp.

Brookfield, M.E., 1993. Neoproterozoic Laurentia–Australia fit. Geology 21, 683–686.

Buchan, K.L., Dunlop, D.J., 1976. Paleomagnetism of the Haliburton Intrusions: superimposed magnetisations, metamorphism, and tectonics in the late Precambrian. J. Geophys. Res. 81, 2951–2966.

Burrett, C., Berry, R., 2000. Proterozoic Australia–Western United States (AUSWUS) fit between Laurentia and Australia. Geology 28, 103–106.

Chumakov, N.M., Semikhatov, M.A., 1981. Riphean and Vendian of the USSR. Precambrian Res. 15, 229–253.

Condie, K.C., Rosen, O.M., 1994. Laurentia–Siberia connection revisited. Geology 22, 168–170.

Dalziel, I.W.D., 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol. Soc. Amer. Bull. 109, 16–42.

Davis, D.W., Green, J.C., 1997. Geochronology of the North American Midcontinent rift in western Lake Superior and implications for its geodynamic evolution. Can. J. Earth Sci. 34, 476–488.

Davis, D.W., Paces, J.B., 1990. Time resolution of geologic events on the Keweenaw Peninsula and applications for development of the Midcontinent Rift system. Earth Planet. Sci. Lett. 97, 54–64.

Davis, D.W., Sutcliffe, R.H., 1985. U–Pb ages from the Nipigon plate and northern Lake Superior. Geol. Soc. Amer. Bull. 96, 1572–1579.

Diehl, J.F., Haig, T.D., 1994. A paleomagnetic study of the lava flows within the Copper Harbour Conglomerate, Michigan: new results and implications. Can. J. Earth Sci. 31, 369–380.

Egorkin, A.W., Zyuganov, S.K., Pavlenkova, N.A., Chernushev, N.M., 1987. Results of investigations of the lithosphere studies from long-range profiles in Siberia. Tectonophysics 140, 29–47.

El'yanov, A.A., Moralev, V.M., 1975. The faults and the distribution of ultramafic-alkaline massifs of Aldan and South-Verkhoyansk provinces. Geol. Geophys. 1, 32–41 (in Russian).

Ernst, R.E., Buchan, K.L., West, T.D., Palmer, H.C., 1996. Diabase (dolerite) dyke swarms of the world: first edition. Geol. Surv. Can. Open File 3241.

Fedorovsky, V.S., 1985. Lower Proterozoic of the Baikal Mountains: Geology and the Crust Forming in the Early Precambrian. Nauka Press, Moscow. 200 pp. (in Russian).

Fefelov, N.N., Sharov, V.N., Yablonovskii, B.V., 2000. Pb–Pb age of metamorphosed carbonate deposits of the Imnyakh Formation (Bodaibo Synclinorium). Geol. Geophys. 41, 48–56 (in Russian).

Frisch, T., Trettin, H.P., 1991. Precambrian successions in the northernmost part of the Canadian Shield. In: Trettin, H.P. (Ed.), Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland. Geol. Surv. Can., Geology of Canada, vol. 3, pp. 103–108.

Frost, B.R., Avchenko, O.V., Chamberlain, K.R., Frost, C.D., 1998. Evidence for extensive Proterozoic remobilization of the Aldan Shield and implications for Proterozoic plate tectonic reconstructions of Siberia and Laurentia. Precambrian Res. 89, 1–23.

Gallet, Y., Pavlov, V.E., Semikhatov, M.A., Petrov, P.Yu., 2000. Late Mesoproterozoic magnetostratigraphic results from Siberia: paleogeographic implications and magnetic field behaviour. J. Geophys. Res. 105, 16481–16499.

Garris, M.A., Kazakov, G.A., Keller, B.M., 1964. Upper Precambrian geochronological scale (Riphean and Vendian). Radiometric Age of Geological Successions. Nauka Press, Moscow, pp. 431–455 (in Russian).

Gur'yanov, V.A., Karsakov, L.P., 1990. The Lower Precambrian stratigraphy of south-eastern part of Siberian platform. The Lower Precambrian stratigraphy of Far East. Far East Branch of Russian Acad. Sci., Vladyvostok, pp. 18–30 (in Russian).

Gur'yanov, V.A., Karsakov, L.P., Goroshko, M.V., 2000. Early Proterozoic sedimentary–volcanogenic Ulkan through in the South-East of Siberian platform: magmatism peculiarity and structure position. The Materials of XXXIII Tectonic Meeting. Main Tectonic Problems. Tectonics of Russia. GEOS, Moscow, pp. 150–152 (in Russian).

Gusev, G.S., Khain, V.E., 1996. On relationships between Baikal–Vitim, Aldan–Stanovoy and Mongolo–Okhotsk Terranes. Geotectonics 29, 422–436.

Halls, H.C., Pesonen, L.J., 1982. Paleomagnetism of Keweenawan rocks. Geol. Soc. Am. Mem. 156, 173–201.

Harlan, S.S., Geissman, J.W., Snee, L.W., 1997. Paleomagnetic and 40Ar/39Ar geochronologic data from late Proterozoic mafic dykes and sills, Montana and Wyoming. USGS Prof. Pap. 1580 (16 pp.).

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1990. A Geological Time Scale 1989. Cambridge Univ. Press, Cambridge. 263 pp.

Heaman, L.M., LeCheminant, A.N., Rainbird, R.H., 1992. Nature and timing of Franklin igneous event, Canada: implications for a Late Proterozoic mantle plume and the break-up of Laurentia. Earth Planet. Sci. Lett. 109, 117–131.

Henry, S.G., Mauk, F.J., Van der Voo, R., 1977. Paleomagnetism of the upper Keweenawan sediments: the Nonesuch Shale and Freda Sandstone. Can. J. Earth Sci. 14, 1128–1138.

Higgins, A.K., Ineson, J.R., Peel, J.S., Surlyk, F., Sønderholm, M., 1991. Cambrian to Silurian basin development and sedimentation, North Greenland. In: Trettin, H.P. (Ed.), The Innuitian Orogen and Arctic Platform of Canada and Greenland. Geological Society of Canada, Geology of Canada, vol. 3, pp. 111–162.

Hoffman, P.F., 1989. Precambrian geology and tectonic history of North America. In: Bally, A.W., Palmer, A.R. (Eds.), The Geology of North America—An Overview. The Geology of North America A. Geological Society of America, Boulder, CO, pp. 447–512.

Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwana inside out? Science 252, 1409–1412.

Hyodo, H., Dunlop, D.J., 1993. Effect of anisotropy on the paleomagnetic contact test for a Grenvillian dike. J. Geophys. Res. 98, 7997–8017.

Ilyin, A.V., 1990. Proterozoic supercontinent, its latest Precambrian rifting, breakup, dispersal into smaller continents, and subsidence of their margins: evidence from Asia. Geology 18, 1231–1234.

Kalsbeek, F., Thrane, K., Nutman, A.P., Jepsen, H.F., 2000. Late Mesoproterozoic to early Neoproterozoic history of the East Greenland Caledonides: evidence for Grenvillian orogenesis? J. Geol. Soc. (Lond.) 157, 1215–1225.

Karlstrom, K.E., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., Ahall, K.-I., 1999. Refining Rodinia: geologic evidence for the Australia–Western U.S. connection in the Proterozoic. GSA Today 9 (10), 1–7.

Kazakov, G.A., Knorre, K.G., 1973. Upper Precambrian geochronology of Uchur–Maya district of Siberian platform. Geological-Radiometric Interpretation of Discordant Age Data. Nauka Press, Moscow, pp. 192–205 (in Russian).

Kazakov, A.N., Velikoslavinsky, S.D., 1999. Baikal–Vitim late Riphean–early Vendian palaeoceanic basin. Geological Development of the Proterozoic Peri-Cratonic and Palaeooceanic Structures of the Northern Eurasia. Tema, St. Petersburg, pp. 41–43 (in Russian).

Khabarov, E.M., Ponomarchuk, V.A., Morozova, I.P., Travin, A.N., 1999. Carbon isotopes in Riphean. Carbonates from the Yenisey Range. Stratigr. Geol. Correl. 7, 537–556.

Khain, V.E., 1985. Geology of the USSR, First Part: Old Cratons and Paleozoic Fold Belts. Gebrüder Borntraeger, Berlin. 272 pp.

Khain, V.E., Gusev, G.S., Khain, E.V., Vernikovsky, V.A., Volobuev, M.I., 1997. Circum-Siberian Neoproterozoic ophiolite belt. Ophioliti 22, 195–200.

Khomentovsky, V.V., Shenfil, V.Yu., Yakshin, M.S., Butakov, E.P., 1972. Base section of Upper Precambrian and Lower Cambrian deposits of Siberian Platform. Nauka Press, Moscow. 355 pp. (in Russian).

Khudoley, A.K., 1997. Stratigraphic evidence for the Siberia–Laurentia connection and Early Cambrian rifting: comment. Geology 25, 570.

Khudoley, A.K., Rainbird, R.H., Stern, R.A., Kropachev, A.P., Heaman, L.M., Zanin, A.M., Podkovyrov, V.N., Belova, V.N., Sukhorukov, V.I., 2001. Sedimentary evolution of the Riphean–Vendian basin of southeastern Siberia. Precambrian Res. 111, 129–163.

Komar, V.A., Rabotnov, V.T., 1976. Upper Precambrian of North-East Russia. Izv. Akad. Nauk SSSR, Ser. Geol. 8, 5–16 (in Russian).

Konnikov, E.G., Gibsher, A.S., Isokh, A.E., Sklyarov, E.V., Khain, E.V., 1994. Late Proterozoic evolution of the northern segment of Paleoasian Ocean: new radiological and geochemical data. Geol. Geophys. 7–8, 152–168 (in Russian).

Kovach, V.P., Smelov, A.P., Kotov, A.B., Larin, A.M., Salnikova, E.B., Kozakov, I.K., 2001. Laurentia–Siberia connection revisited again: an overview of U–Pb zircon geochronology and Nd isotopes for the Siberian craton. Gondwana Res. 4, 667–668.

Kovrigina, E.K., 1996. The state geological map of USSR, scale 1:1,000,000. Sheet Q-44,45 (Igarka). VSEGEI Cartographic Press, Leningrad.

Kozakov, I.K., Kotov, A.B., Salnikova, E.B., Kovach, V.P., Natman, A., Bibikova, E.V., Kirnozova, T.I., Todt, V., Krener, A., Yakovleva, S.Z., Lebedev, V.I., Sugorakova, A.M., 2001. Age marks of the structural development of the metamorphic complexes of the Tuva–Mongolia massif. Geotectonics 3, 22–43 (in Russian).

Krasil'schikov, A.A., Biterman, I.M., 1970. Olenek uplift. Geology of USSR, Vol. 18, Part 1. Nedra Press, Moscow, pp. 91–100 (in Russian).

Kuzmichev, A.V., Bibikova, E.V., Zhuravlev, D.Z., 2001. Neoproterozoic (~ 800 Ma) orogeny in the Tuva–Mongolia massif (Siberia): island arc–continent collision at the northeast Rodinia margin. Precambrian Res. 110, 109–126.

Kuzmin, V.V., Chuchonin, A.P., Shulezhko, I.K., 1995. Stages of metamorphic evolution of rocks of crystalline basement of the Kukhtui Uplift (Okhotsk Massif). Dokl. Russ. Akad. Sci. 342, 789–791 (in Russian).

Kuznetsov, V.L., Titarenko, V.V., 1988. Seismic models for consolidated crust of the western Siberian platform and the joint zone with Western Siberia plate. Geol. Geophys. 5, 128–135 (in Russian).

Larin, A.M., Amelin, Yu.V., Neymark, L.A., Krimsky, R.Sh., 1997. The origin of the 1.68–1.73 Ga. Anorogenic Ulkan Volcano-Plutonic Complex, Siberian Platform, Russia: inferences from geochronological, geochemical and Nb–Sr–Pb isotopic data. An. Acad. Bras. Cienc. 69, 295–312.

Larin, A.M., Kotov, A.B., Kovach, V.P., Salnikova, E.B., Ivanov, V.E., 2000. U–Pb geochronology and Sm–Nd isotope systematics of the magmatic complexes of the Dzhugdzhur–Stanovoy folded area: geodynamic cosequences. Isotpopic Dating of the Geological Processes: New Methods and Results: 1. Russian Conference. GEOS, Moscow, pp. 214–216.

LeCheminant, A.N., Heaman, L.M., 1994. 779 Ma mafic magmatism in the northwestern Canadian Shield and northern Cordillera: a new regional time-marker. 8th International Conference. Geochronology, Cosmochronology and Isotope Geology, Program Abstracts (Berkeley, California). US Geol. Surv. Circ., vol. 1107, p. 197.

Leonov, B.N., Biterman, I.M., Natapov, L.M., 1965. Tectonic evolution of Olenek Uplift in the Later Precambrian. Dokl. RAN 161, 1137–1140 (in Russian).

Li, Z.X., Zhang, L., Powell, C.McA., 1995. South China in Rodinia: part of the missing link between Australia–East Antarctica and Laurentia? Geology 23, 407–410.

Malich, N.S., Masaitis, V.L., Surkov, V.S., 1987. Geological Structure of USSR and Pattern of Distributions of Minerals. Siberian Platform, vol. 4. Nedra Press, Leningrad. 448 pp. (in Russian).

Mandel'baum, M.M., Smirnova, T.G., 2000. Marginal zones of South part of Siberian Platform on the seismic sensing data: Pre-Baikal and Pre-Sayan. Reg. Geol. Metallog. 10, 136–142 (in Russian).

Maslov, V.K., Kichko, A.I., 1985. Zonal development of mineralisation in the Middle–Upper Riphean deposits of West and North-West Pre-Baikal zone. Lithol. Miner. Resour. 6, 83–96 (in Russian).

McCabe, C., Van der Voo, R., 1983. Paleomagnetic results from the upper Keweenawan Chequamegon Sandstone: implications for red bed diagenesis and Late Precambrian apparent polar wander of North America. Can. J. Earth Sci. 20, 105–112.

McElhinny, M.W., McFadden, P.L., 2000. Paleomagnetism: Continents and Oceans. Academic Press, San Diego. 386 pp.

McMenamin, M.A.S., McMenamin, D.L., 1990. The Emergence of Animals: The Cambrian Breakthrough. Columbia Univ. Press, New York. 217 pp.

Mironyuk, E.P., 1987. Riphean. Patom area. Geological Structure of USSR and Pattern of Distributions of Minerals. Siberian Platform, vol. 4. Nedra Press, Leningrad, pp. 134–135 (in Russian).

Mokshanzev, K.B., 1979. Proterozoic of North-East Outskirts of Siberian Platform. Nauka Press, Siberian branch, Novosibirsk. 214 pp. (in Russian).

Moores, E.M., 1991. Southwest US–East Antarctic (SWEAT) connection: a hypothesis. Geology 19, 425–428.

Natapov, L.M., 1988. History of accretionary structure of Siberian continent, north-eastern surroundings. Geology of Seas and Oceans. Reports of Soviet Geologists to 28 IGC. Nauka Press, Leningrad, pp. 171–186 (in Russian).

Natapov, L.M., Stavsky, A.P., 1985. Geodynamic model of the north-east of USSR and its application to metallogenic analysis. Sov. Geol. 8, 70–78 (in Russian).

Natapov, L.M., Surmilova, E.P., 1995. Position and nature of the Okhotsk massif. Otečestv. Geol. 2, 49–53 (in Russian).

Nevolin, B.S., Potapov, S.V., Stavzev, A.L., 1978. Upper Proterozoic (Riphean) and Lower Cambrian of the South-East margin of Siberian platform. Yudomo–Maya depression and Okhotsk massif. In: Khomentovsky, V.V. (Ed.), New Data on Stratigraphy and Paleontology of Late Precambrian of the East and North Regions of Siberia. IGG Press, Novosibirsk, pp. 21–63 (in Russian).

Neymark, L.A., Larin, A.M., Yakovleva, S.A., Gorochovsky, B.M., 1992. Uranium–lead age of igneous rocks in the Ulkan grabenin the south-eastern part of the Aldan Shield. Trans. Russ. Acad. Sci. Earth Sci. 324, 92–96.

Nockleberg, W.J., West, T.D., Dawson, K.M., 1998. Summary terrane, mineral deposits, and metallogenic belt maps of the Russian Far East, Alaska, and the Canadian Cordillera. US Geological Survey, Open File Report 98-136.

Nutman, A.P., Gavrikova, S.N., Chernyshev, I.V., 1992. Late Archean crust formation and mid-Proterozoic reworking in the Stanovik block of Aldan Shield, USSR. In: Glover, J.E., Ho, S.E. (Eds.), The Archean: Terranes, Processes and Metallogeny. UWA Publ., vol. 22, pp. 89–92.

Ovchinnikova, G.V., Semikhatov, M.A., Gorokhov, I.M., Belyatskii, B.V., Vasil'eva, I.M., Levskii, L.K., 1995. U–Pb systematics of Precambrian carbonates: the Riphean Sukhaya Tunguska Formation in the Turukhansk Uplift, Siberia. Lithology Min. Resour. 30, 525–536.

Ovchinnikova, G.V., Semikhatov, M.A., Vasil'eva, I.M., Gorokhov, I.M., Kaurova, O.K., Podkovyrov, V.N., Gorokhovskii, B.M., 2001. Pb–Pb age of limestones of the middle Riphean Malgina Formation, the Uchur–Maya region of East Siberia. Stratigr. Geol. Correl. 9, 490–502.

Palmer, H.C., Baragar, W.R.A., Fortier, M., Foster, J.H., 1983. Paleomagnetism of Late Proterozoic rocks, Victoria Island, Northwest Territories, Canada. Can. J. Earth Sci. 20, 1456–1469.

Parfenov, L.M., 1984. Continental Margins and Islands Arcs of Mesozoides of the North-East Asia. Nauka Press, Novosibirsk. 192 pp.

Parfenov, L.M., Bulgatov, A.N., Gordienko, I.V., 1995. Terranes and accretionary history of the Transbaikal orogenic belts. Int. Geol. Rev. 37, 736–751.

Park, J.K., 1994. Palaeomagnetic constraints on the position of Laurentia from middle Neoproterozoic to Early Cambrian times. Precambrian Res. 69, 95–112.

Park, J.K., Aitken, J.D., 1986. Paleomagnetism of the Katherine Group in the Mackenzie Mountains: implications for post-Grenville (Hadrynian) apparent polar wander. Can. J. Earth Sci. 23, 308–323.

Park, J.K., Norris, D.K., Larochelle, A., 1989. Paleomagnetism and the origin of the Mackenzie Arc of northwestern Canada. Can. J. Earth Sci. 26, 2194–2203.

Pavlov, V.E., Manukyan, A.M., Sharkovsky, M.B., Levashova, N.M., 1991. First data on the Riphean paleomagnetism of the Okhotsk massif. Dokl. Russ. Acad. Sci. 317, 688–692.

Pavlov, V.E., Gallet, Y., Shatsillo, A.V., 2000. Palaeomagnetism of the upper Riphean Lakhanda Group of the Uchur–Maya area and the hypothesis of the late Proterozoic supercontinent. Fiz. Zemli 8, 23–34 (in Russian).

Pavlov, V.E., Gallet, Y., Petrov, P.Yu., Zhuravlev, D.Z., Shatsillo, A.V., 2002. Uy series and late Riphean sills of the Uchur–Maya area: isotopic and palaeomagnetic data and the problem of the Rodinia supercontinent. Geotectonics 36, 278–292.

Pelechaty, S.M., 1996. Stratigraphic evidence for the Siberia–Laurentia connection and Early Cambrian rifting. Geology 24, 719–722.

Petrov, P.Y., 1993. Depositional environments of the lower formations of the Riphean sequence, northern part of the Turukhansk Uplift, Siberia. Stratigr. Geol. Correl. 1, 181–191.

Petrov, P.Y., Semikhatov, M.A., 2001. Sequence organization and growth patterns of late Mesoproterozoic stromatolite reefs: an example from the Burovaya Formation, Turukhansk Uplift, Siberia. Precambrian Res. 111, 257–281.

Petrov, P.Y., Veis, A.F., 1995. Facial–ecological structure of the Derevnya Formation microbiota: Upper Riphean, Turukhansk Uplift, Siberia. Stratigr. Geol. Correl. 3, 435–460.

Pisarevsky, S.A., Wingate, M.T.D., Powell, C.McA., Johnson, S., Evans, D.A.D., 2003. Models of Rodinia assembly and fragmentation. In: Yoshida, M., Windley, B., Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Geol. Soc. London Spec. Publ. 206, 35–55.

Ponomarchuk, V.A., Shenfil, V.Yu., Yakshin, M.S., Lebedev, Yu.N., Kuzmin, D.S., Morozova, I.P., 1994. The direct K–Ar dating of stromatolite of Olenek Uplift. Dokl. RAN 339, 378–381 (in Russian).

Rabotnov, V.T., 1977. Upper Precambrian stratigraphy of the Okhotsk block. Dokl. Akad. Nauk SSSR 234, 148–151 (in Russian).

Rainbird, R.H., de Freitas, T.A., 1997. Stratigraphic evidence for the Siberia–Laurentia connection and Early Cambrian rifting: comment. Geology 25, 569–570.

Rainbird, R.H., Stern, R.A., Khudoley, A.K., Kropachev, A.P., Heaman, L.M., Sukhorukov, V.I., 1998. U–Pb geochronology of Riphean sandstone and gabbro from southeast Siberia and its bearing on the Laurentia–Siberia connection. Earth Planet. Sci. Lett. 164, 409–420.

Ramo, O.T., Calzia, J.P., 1998. Nd isotopic composition of cratonic rocks in the southern Death Valley region: evidence for a substantial Archean source component in Mojavia. Geology 26, 891–894.

Rosen, O.M., Condie, K.C., Natapov, L.M., Nozhkin, A.D., 1994. Archean and Early Proterozoic evolution of the Siberian craton: a preliminary assessment. In: Condie, K.C. (Ed.), Archean Crustal Evolution. Elsevier, Amsterdam, pp. 411–459.

Rosen, O.M., Zhuravlev, D.Z., Sukhanov, M.K., Bibikova, E.B., Zlobin, V.L., 2000. Early Proterozoic terranes, collosion zones, and associated anorthosites in the northeast of the Siberian craton: isotope geochemistry and age characteristics. Geol. Geophys. 41, 163–180 (in Russian).

Ross, G.M., Eaton, D.W., Boerner, D.E., Miles, W., 2000. Tectonic entrapment and its role in the evolution of continental lithosphere: an example from the Precambrian of western Canada. Tectonics 19, 116–134.

Roy, J.L., Robertson, W.A., 1978. Paleomagnetism of the Jacobsville Formation and the apparent polar path for the interval ~ 1100 to ~ 670 m.y. for North America. J. Geophys. Res. 83, 1289–1304.

Ruchkin, G.B., Konkin, V.D., 1998. Minerageny of Sedimentary Basins of Continents and their Margins. Yenisey Range, Baikal–Vitim Fold Belt. VSEGEI Cartographic Press, Moscow, pp. 320–402 (in Russian).

Rundquist, D.V., Mitrofanov, F.P., 1993. Precambrian Geology of the USSR. Elsevier, Amsterdam. 528 pp.

Rytsk, E.Yu., Shalaev, V.S., Krymsky, R.S., 1999. Baikal–Muya fold belt: the fragment of the late Precambrian continental margin. Geological Development of the Proterozoic Peri-Cratonic and Palaeooceanic Structures of the Northern Eurasia. Tema, St. Petersburg, pp. 136–138 (in Russian).

Sears, J.W., Price, R.A., 1978. The Siberian connection: a case for Precambrian separation of the North American and Siberian cratons. Geology 6, 267–270.

Sears, J.W., Price, R.A., 2000. New look at the Siberian connection: no SWEAT. Geology 28, 423–426.

Semikhatov, M.A., 1991. General problems of Proterozoic stratigraphy in the USSR. Soviet Scientific Rev., Section B, Geology Reviews. Harwood Acad. Publ., New York. 189 pp.

Semikhatov, M.A., 1993. New common stratigraphic scales of Precambrian: a comparison. Stratigr. Geol. Correl. 1, 6–20 (in Russian).

Semikhatov, M.A., Serebryakov, S.N., 1983. Siberian Hypostratotype of Riphean. Nauka Press, Moscow. 356 pp. (in Russian).

Semikhatov, M.A., Ovchinnikova, G.V., Gorokhov, I.M., Kuznetsov, A.B., Vasil'eva, I.M., Gorokhovskii, B.M., Podkovyrov, V.V., 2000. Isotopic age of Middle–Upper Riphean boundary: Pb–Pb geochronology of Lakhanda Group carbonates, Eastern Siberia. Trans. Russ. Acad. Sci. Earth Sci. 372, 216–221.

Sergeev, V.N., Knoll, A.H., Petrov, P.Y., 1997. Paleobiology of the Mesoproterozoic–Neoproterozoic transition: the Sukhaya Tunguska Formation, Turukhansk Uplift, Siberia. Precambrian Res. 85, 201–239.

Sharov, V.N., Fefelov, N.I., Zarudnova, N.V., Rusakova, V.A., Brandt, S.B., 1991. Pb–Pb dating of the Mama synclinorium schists: Patom highland. Dokl. Akad. Nauk SSSR 319, 209–212 (in Russian).

Shenfil, V.Y., 1991. Upper Precambrian of the Siberian Platform. Nauka Press, Novosibirsk. 206 pp. (in Russian).

Sircombe, K.N., 2001. Promise and peril: microanalysis, provenance and reconstruction in Rodinia and beyond. Geol. Soc. Austr. Abstr. 65, 101–104.

Sklyarov, E.V., Gladkochub, D.P., Mazukabzov, A.M., Stankevich, M.A., Donskaya, T.V., Konstantinov, K.M., Sinzov, A.V., 2001. Indicator complexes of supercontinent Rodinia break up. Geological excursion guide of workshop "Supercontinents and geological evolution of Precambrian". Institute of Earth Crust, Irkutsk, p. 75 (in Russian).

Smethurst, M.A., Khramov, A.N., Torsvik, T.H., 1998. The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian Platform: from Rodinia to Pangea. Earth-Sci. Rev. 43, 1–24.

Sokolov, B.S., Fedonkin, M.A., 1985. Vendian System, vol. 2. Nauka Press, Moscow. 237 pp. (in Russian).

Sovetov, Yu.K., Romashko, A.I., 1999. Late Riphean residual basin related to the collision of terrane and Siberian craton (Yenisei Range). Geological Development of the Proterozoic Peri-Cratonic and Palaeooceanic Structures of the Northern Eurasia. Tema, St. Petersburg, pp. 163–165 (in Russian).

Sovetov, Yu.K., Khabarov, E.M., Blagovidov, V.V., Saraev, S.V., 1999. Riphean divergent continental margin of the Siberian craton (Patom Highland): the evolution of sedimentary systems and basins. Geological development of the Proterozoic peri-cratonic and palaeooceanic structures of the Northern Eurasia. Tema, St. Petersburg, pp. 159–162 (in Russian).

Sryvtsev, N.A., Khalilov, V.A., Buldygerov, V.V., Perelyayev, V.P., 1992. Geochronology of the Baykal–Muya belt granitoids. Geol. Geophys. 9, 72–78 (in Russian).

Sukhorukov, V.I., 1986. The Upper Riphean type sections of the Ulakhan Bam ridge. In: Khomentovsky, V.V. (Ed.), Late Precambrian and Early Paleozoic of Siberia. Siberian Platform and Outer Part of the Altay–Sayan Fold Belt IGG, Novosibirsk, pp. 23–64 (in Russian).

Surlyk, F., 1991. Tectonostratigraphy of North Greenland. Bull. - Grønl. Geol. Unders. 160, 25–47.

Turchenko, S.I., Sokolov, Yu.M., 1988. Baikal–Patom Belt. Precambrian Geology of USSR. Nauka Press, Leningrad, pp. 321–330 (in Russian).

Uflyand, A.K., Natapov, L.M., Lopatin, V.M., Chernov, D.V., 1991. The tectonic nature of the Taimyr Peninsula. Geotectonics 25, 512–523.

Van der Voo, R., 1990. The reliability of paleomagnetic data. Tectonophysics 184, 1–9.

Van Schmus, W.R., Bickford, M.E., 1993. Transcontinental Proterozoic provinces. In: Reed, J.C., et al. (Eds.), Precambrian: Continental US. Geology of North America, vol. C-2. Geological Society of America, Boulder, CO, pp. 171–334.

Veis, A.F., Petrov, P.Y., 1994. The main pecularities of the environmental distribution of microfossils in the Riphean basins of Siberia. Stratigr. Geol. Correl. 2, 97–129.

Vernikovskaya, A.E., Vernikovsky, V.A., Sal'nikova, E.B., Datsenko, V.M., Kotov, A.V., Kovach, V.P., Travin, A.V., Yakovleva, S.Z., 2002. Yeruda and Chirimba granitoids (Yenisei Ridge) as indicators of late Proterozoic collisions. Russian Geol. Geophys. 43, 259–272.

Vernikovsky, V.A., Vernikovskaya, A.E., 2001. Central Taimyr accretionary belt (Arctic Asia): Meso-Neoproterozoic tectonic evolution and Rodinia breakup. Precambrian Res. 110, 127–141.

Vernikovsky, V.A., Vernikovskaya, A.V., Sal'nikova, E.B., Kotov, A.B., Chernykh, A.I., Kovach, V.P., Berezhnaya, N.G., Yakovleva, S.Z., 1999. New U–Pb data on the formation of the Predivinsk paleoisland–arc terrane. Russ. Geol. Geophys. 40, 256–261.

Vernikovsky, V.A., Vernikovskaya, A.E., Kotov, A.B., Sal'nikova, E.B., Kovach, V.P., Yakovleva, S.Z., 2003. Neoproterozoic accretionary and collisional events on the western margin of the Siberian craton: new geological and geochronological evidence from the Yenisey Ridge. Tectonophysics 375, 147–168 (this issue).

Volobuev, M.I., 1994. Riphean ophiolite complex of Yenisey Range. Geotectonics 27, 524–528.

Weil, A.B., Van der Voo, R., Mac Niocaill, C., Meert, J.G., 1998. The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstruction for 1100 to 800 Ma. Earth Planet. Sci. Lett. 154, 13–24.

Wingate, M.T.D., Pisarevsky, S.A., Evans, D.A.D., 2002. Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? Terra Nova 14, 121–128.

Yan-Zhin-Shin, V.A., 1983. Tectonics of the Sette-Daban Horst Anticlinorium. Soviet Acad. Sci. Press, Yakutsk. 133 pp. (in Russian).

Zapol'nov, A.K., 1988. Precambrian cover. Precambrian Geology of USSR. Nauka Press, Leningrad, pp. 330–342 (in Russian).

Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1990a. Geology of the USSR: a plate tectonic synthesis. Geodynamics Series, vol. 21. American Geophysics Union, Washington, DC. 242 pp.

Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1990b. Tectonics of Lithospheric Plates of the USSR. Nedra Press, Moscow, vol. 1, 327 pp., vol. 2, 334 pp. (in Russian).