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The Siberian Craton and its evolution in terms of the Rodinia hypothesis

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Recent geochronological studies in southern Siberia support a Siberian assembly between 2.1 and 1.8 Ga. This broadly coincides with major orogenic events in most other Precambrian continents including Laurentia. In the Mesoproterozoic, Siberia was mainly an area of stable platform sedimentation whereas Laurentia underwent a continental growth from southeast. Lack of traces of the Grenville orogeny in Siberia suggests its peripheral position in Rodinia. The eastern (Uchur–Maya area) and western (Yenisei area) Siberian margins probably faced oceans during the Meso- and Neoproterozoic. Recent geological, geochronological, geochemical, and paleomagnetic data suggest integrity of Siberia and Laurentia in the Meso- and early Neoproterozoic with the Siberian southern margin close to the northern margin of Laurentia. However, some ‘intervening’ continental blocks were probably located between these two cratons. The 750–720 Ma igneous event was probably related to the rifting between Siberia and Laurentia and the opening of the Paleo-Asian Ocean, causing the development of a passive margin sedimentary succession in southern Siberia.

Introduction

It is generally assumed that the Siberian craton was part of the Meso-Neoproterozoic supercontinent Rodinia (e.g., Hoffman, 1991; Rogers, 1996; Dalziel, 1997; Pisarevsky et al., 2003; Pisarevsky and Natapov, 2003). However, its exact position and the time of its separation from Rodinia are still under debate (see, for example, Pisarevsky and Natapov, 2003 and references therein). Most Rodinian reconstructions place Siberia close to Laurentia, suggesting that both cratons are remnants of a single proto-craton that was assembled during the late Paleoproterozoic. Here we present a brief overview of the geological evolution of the Siberian craton between the late Paleoproterozoic and the Neoproterozoic. We present some geological similarities between Siberia and Laurentia that are useful in evaluating the hypothesis about their common origin. We use the Russian stratigraphic scheme for the Proterozoic (Semikhatov, 1991), according to which the Lower (1650–1350 Ma) and Middle (1350–1000 Ma) Riphean correspond roughly to the Mesoproterozoic of the International Time Scale (Gradstein et al., 2004), and the Upper Riphean corresponds to the Tonian and Cryogenian systems of the Neoproterozoic (1000–630 Ma). The Vendian is an equivalent of the Ediacaran (630–542 Ma).

Siberia assembly

Major tectonic and metamorphic events caused by the assembly of the Siberian craton occurred at ~2.1–1.8 Ga (Rosen et al., 1994; Rosen, 2003). The Laurentian protocraton was assembled roughly at the same time—between 2.00 and 1.80 Ga (Hoffman, 1989). This time interval broadly coincides with important orogenic events on nearly every continent (Zhao et al., 2002), which is possibly related to an assembly of the putative older Paleoproterozoic supercontinent (Condie, 2002; Zhao et al., 2002).

Most Siberian building blocks are Archean (Rosen et al., 1994; Rosen, 2003). As an important exception there are the Hapchan and Berekte blocks (Figure 1), where no Archean ages have been found (Rosen et al., 2000). Building blocks of the craton are welded by ~2.1–1.8 Ga orogenic belts and suture zones (Figure 1). They are characterized by high-grade metamorphic complexes, and collisional and post-collisional granites (Aftalion et al., 1991; Rosen et al., 1994; Mints et al., 2000; Gladkochub et al., 2005; Poller et al., 2004, 2005; Kotov et al., 2004). The ages of the post-collisional granites in the southern Siberian craton are mainly between 1.88 and 1.84 Ga (Donskaya et al., 2002, 2003; Larin et al., 2003; Poller et al., 2004, 2005). A late Paleoproterozoic metamorphic event has reworked the Archean crust in some building blocks (for example, Central Aldan, East Aldan blocks, see Figure 1). Paleoproterozoic juvenile crust has been reported for the Akitkan orogenic belt (Rosen et al., 1994; Condie and Rosen, 1994; Neymark et al., 1998) and the Angara orogenic belt (Gladkochub et al., 2001a). However, an Archean crust, strongly deformed in the late Paleoproterozoic, prevails within these belts.

Similarities in ages between the Paleoproterozoic orogenic belts of Siberia and Laurentia cratons suggest that they could have originated from the same proto-craton. A variety of suggested ‘piercing points’ (e.g. Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998) have led to a variety of Siberia–Laurentia reconstructions (Pisarevsky and Natapov, 2003). Unfortunately, the only quantitative method for paleogeographic reconstructions—paleomagnetism—is hardly applicable for the Paleoproterozoic due to the insufficient number of reliable Archean and Paleoproterozoic paleomagnetic data from most of the Laurentian and Siberian building blocks (Pisarevsky, 2005).

Riphean and Vendian sedimentation

The Archean terranes and Paleoproterozoic basement complexes of the Siberian craton are shown in Figure 1. Most of the craton is covered by Riphean and Phanerozoic sediments and the basement is only exposed in four areas: (1) the Anabar shield and the Olenek uplift (north); (2) the Aldan shield and the Stanovoy block (south-east); (3) the Goloustnaya, Baikal, and Sharizalgai uplifts and the Birusa block (south); (4) the Yenisey and Kann uplifts (southwest).

Figure 1 Geological scheme of the Siberian craton and distribution of Meso-Neoproterozoic passive continental margin sedimentary sequences (compiled with using Rosen et al., 1994)

Building blocks: I—Tungus; II—Magan; IIIa—West Daldyn; IIIb—East Daldyn; IV—Markha; V—Hapchan; VI—Birekte; VII—XII—

Aldan—Stanovoy province: VII—Olekma, VIII—Central Aldan, IX—East Aldan, X—Batonga, XI—Magocha, XII—Tynda.

Archean-Paleoproterozoic basement uplifts: A—Anabar shield; Ald—Aldan shield; B—Birusa block; Bk—Baikal uplift; G—Goloustnaya uplift; K—Kann uplift; O—Olenek uplift; S—Sharizhlagay uplift; St—Stanovoy block; Y—Yenisey uplift.

Paleoproterozoic intracratonic rift zones: ub—Ulkano—Billikcan; ui—Urik—Iya.

Riphean sedimentary succession areas: bp—Baikal-Patom; cb—Cisbaikalia; i—Igarka; ps—Pre-Sayan; t—Turukhansk; um—Uchur-Maya; yn—Yenisei.

After the final stabilization of the Siberian basement at 1.9–1.8 Ga, a series of extensional events produced several intracratonic sedimentary basins (Figure 1). The oldest one formed at ~1.73–1.68 Ga in the Ulkano–Billikchan graben (rift zone) with volcano-plutonic fill (Larin et al., 1997) and in the Urik–Iya graben (Figure 1) with volcano-sedimentary fill intruded by 1.53 Ga anorogenic granites (Gladkochub et al., 2002). The Riphean sedimentary successions accumulated in intracratonic basins and along cratonic margins. They gradually thicken toward the cratonic boundaries (e.g., Khomentovskiy et al., 1972; Khain, 1985). Most Riphean sediments are overlain by thick Phanerozoic cover and are only exposed in the

internal areas of Siberia around the Anabar shield and on the Olenek uplift (Figure 1). Consequently, they are mostly known from drill holes and seismic profiles. As a result, some aspects of their stratigraphic correlation are still under debate (Rundqvist and Mitrofanov, 1993; Surkov and Grishin, 1997). The thicknesses of Riphean sedimentary successions in intracratonic basins range from 1 to 4 km (Surkov et al., 1991), but they increase up to 10–14 km near the cratonic margins (Pisarevsky and Natapov, 2003). Most researchers (Khain, 1985; Zonenshain et al., 1990; Surkov and Grishin, 1997; Kuznetsov, 1997; Rosen, 2002) suggest that the accumulation of the Riphean platform cover commenced at ~1.6 Ga, after almost 200 Ma

of erosion, but the lack of precise geochronological information makes this suggestion somewhat problematic.

The Laurentian protocraton (or Hudsonian craton after Van Schmus et al., 1993) also stabilized after ~1.8 Ga (Hoffman, 1989), with continental growth from the SSE (in present coordinates) followed by the Grenville collision after 1.2 Ga along its southeastern margin. Importantly, no traces of the Grenville-age orogeny have turned up so far in Siberia. Hence, if Siberia and Laurentia were parts of a single continent after ~1.8 Ga, it is likely that the Siberian part was located close to present-day north or northwest Laurentia.

The best studied Riphean sedimentary successions crop out along the SE Siberian margin, in the Uchur–Maya area (Figure 1). Its combined thickness is about 14 km, and it constitutes the most complete Riphean–Vendian section in Siberia (e.g. Khomentovsky et al., 1972; Semikhatov and Serebryakov, 1983; Khudoley and Guriev, 2003; Pisarevsky and Natapov, 2003). Riphean sediments in the Uchur–Maya area represent several transgressive cycles (Bartley et al., 2001; Khudoley et al., 2001; Pisarevsky and Natapov, 2003). The eastward thickening and apparent progradation of the ancient sedimentary prism suggests that this succession was accumulated at the Meso- to Neoproterozoic passive margin of Siberia (e.g., Parfenov, 1984; Pisarevsky and Natapov, 2003). The radiometric ages of glauconite sandstone in the lower part of the succession range from 1520 to 1000 Ma (Kazakov and Knorre, 1973; Semikhatov and Serebryakov, 1983). The middle part of the succession is intruded by mafic sills with U–Pb baddeleyite ages of 974 ± 7 Ma and 1005 ± 4 Ma (Rainbird et al., 1998) and a Sm–Nd whole-rock age of 942 ± 9 Ma (Pavlov et al., 2000). Vendian sediments overlie the Riphean succession along a pronounced angular unconformity, which progressively cuts westward across older Riphean units (Khomentovsky et al., 1972; Semikhatov and Serebryakov, 1983; Khudoley et al., 2001).

The southern part of the Siberian craton consists of three distinct parts: the Aldan–Stanovoy province, the Baikal–Patom area and the Cisbaikalia area. The eastern part comprises the Aldan–Stanovoy province (Figure 1). This province was a positive area during the Riphean, and intracratonic sediments are preserved only on its northern slope. The southern margin including the Magocha and Tynda blocks was tectonically reworked during Mesozoic collisions related to the assembly of Asia. The tectonic overprint destroyed all evidence of the Riphean paleogeography along this Siberian margin. It is not clear whether this region was a continental margin or a part of a larger continental block.

Further to the west, in the Baikal–Patom area (Figure 1) the lower part of the Riphean succession comprises fluvial terrigenous sediments with subordinate volcanic material. This volcanic–sedimentary sequence is covered by Middle and Upper Riphean sediments, representing large stratigraphic cycles. Some of the strata in the lower part of the Middle Riphean succession were deposited in a deep-water continental shelf. In this area there are also continental slope and continental rise facies. Geochronological data are sparse and not reliable, and the stratigraphic subdivision is based mainly on stromatolite and microphytolite assemblages. There are 1602–1542 Ma Pb–Pb isochron ages for the lower part of the Riphean succession (Sharov et al., 1991) and 864–861 Ma Pb–Pb ages on limestones of the upper part (Fefelov et al., 2000). The sediment thickness increases from 2800 m up to 8000 m to the south, suggesting that it was deposited at the Siberian passive margin (Pisarevsky and Natapov, 2003). Neoproterozoic ophiolite and arc-related rocks (Figure 1) may be caused by mid-Neoproterozoic conversion of this margin from passive to active type (e.g., Gusev and Khain, 1996; Rytisk et al., 1999). The succession was deformed during the collision of the Siberian craton and some terranes of the Central Asian orogenic belt in the Vendian–Early Paleozoic (Pisarevsky and Natapov, 2003 and references therein).

In the southernmost part of the Siberian craton, the Riphean succession is located in the Cisbaikalia area (Figure 1) (Mazukabzov et al., 2001). This succession unconformably overlies the basement rocks of the Goloustnaya and Baikal uplifts. The lower part of the succession is composed of dolomites, arkoses, greywackes and conglomerates and includes layers of mafic volcanites (Maslov and

Kichko, 1985). The stratigraphic relations (Chumakov and Semikhatov, 1981; Postnikov, 2001) suggest that this sequence is younger than the lower part of Middle Riphean succession in the nearby Baikal–Patom area and it probably is Upper Riphean in age. The entire Riphean succession in the Cisbaikalia area is up to 3000 m thick and deposited in shelf and continental slope environments.

The southwestern Siberian margin in the Pre-Sayan area (Figure 1) is separated by a large dextral strike-slip fault from terranes of the Central Asian orogenic belt with Neoproterozoic ophiolites and island arc complexes (Figure 1) (Khain et al., 2003). Here basement rocks of the Birusa block are overlain by the ~3700 m thick upper Riphean succession which has been interpreted to have been formed at a passive continental margin (Sklyarov et al., 2001). The lower and middle parts of this succession contain coarse sandstone, arkose, and conglomerate intercalated with volcanic rocks, and may represent the rift stage of continental breakup. This part of the succession is also intruded by mafic dykes and sills, some of which have recently been dated by ^{40}Ar – ^{39}Ar method at 741 ± 4 Ma (Gladkochub et al., 2006). Some intrusions exhibit evidence of emplacement into wet, unconsolidated sediment (Domyshev, 1976). The upper part of this succession contains turbidites and silicic and carbonate sediments (Sklyarov et al., 2001). Thicknesses of the Upper Riphean succession increase to the southwest, broadly consistent with the existence of a Neoproterozoic passive margin along the southwestern Siberian boundary (Sklyarov et al., 2001; Pisarevsky and Natapov, 2003). However, this passive margin sedimentation probably commenced later—in the Neoproterozoic. Passive margin related sediments along northern Laurentia have been studied in northern Greenland and in the Ellesmere Island, and they are significantly younger — of Vendian age (Dewing et al., 2004). This contradicts reconstructions that place Siberia close to north of Laurentia (e.g. Frost et al., 1998). However, if some ‘buffering’ of continental blocks between Siberia and Laurentia was involved (Pisarevsky and Natapov, 2003; Gladkochub et al., 2006), the traces of Laurentian Neoproterozoic passive margin could be concealed in northern Alaska and the Chukchi Peninsula, which drifted away from North America in the Tertiary (Embry, 1998).

In the southern part of the western Siberian margin the Lower Riphean successions are located within the Yenisei area (Figure 1) and unconformably overlie the Paleoproterozoic granite–gneiss of the Kan and Yenisei uplifts. These sediments were deformed in late Riphean and Vendian times, combining a complex fold and thrust belt. This makes it difficult to reconstruct the paleogeographic environment. However, the general thickening of the Riphean successions to the west and the presence of deep-water facies in the western part suggest the presence of a passive margin here in the Mesoproterozoic and early Neoproterozoic (Pisarevsky and Natapov, 2003; Vernikovskiy et al., 2004). This suggestion is supported by the westward progradation of the paleoshelf, which can be traced by paleoreefs (Ruchkin and Konkin, 1998). After ~900 Ma the passive margin in this area was transformed into an active margin (e.g. Volobuev, 1993; Vernikovskiy et al., 2004). This is indicated by 880 and 760 Ma collisional granites and late Riphean–Vendian ophiolites that occur to the west from the Yenisei uplift (Figure 1) (Volobuev, 1993; Khain et al., 1997; Vernikovskiy et al., 2004 and references therein). Eastward from the Yenisei uplift, Riphean sediments of the passive margin are unconformably overlain by late Riphean molasse and Vendian–Cambrian carbonates (Vernikovskiy et al., 2004 and references therein).

The northern part of the western Siberian margin is studied in the Turukhansk and Igarka areas (Figure 1). Recent ~1035–1025 Ma Pb–Pb ages for carbonates (Semikhatov et al., 2000; Ovchinnikova et al., 1995) and correlations with Uchur–Maya area on the stromatolite and microphytolite assemblages (e.g. Bartley et al., 2001) suggest that Mesoproterozoic sedimentation commenced here in the Middle Riphean. Volcanic rocks in the bottom part of Riphean succession in the Igarka area may indicate a rifting stage. The age of these volcanics is unclear (Kovrigina, 1996; Bogdanov et al., 1998). The thicknesses here are smaller than in the southern sections. However, the thickness increases to the west, and the sedimentological

Figure 2 Laurentian and Siberian palaeo-positions for ~1100–980 Ma (see Table 1 in Pisarevsky and Natapov, 2003) and new Laurentia–Siberia fit (revised after Gladkochub et al., 2006). Reconstructions were made with the PLATES software of the University of Texas at Austin and with utilities of the Visual Paleomagnetic database of Pisarevsky and McElhinny (2003).

characteristics fit the suggestion about there being a Riphean passive margin here (Bogdanov et al., 1998; Pisarevsky and Natapov, 2003). Collision with some unidentified continental block occurred in the late Riphean (pre-Vendian), and resulted in folding and thrusting of the Riphean successions.

The sedimentary successions along the northern Siberian margin (present-day coordinates) have lesser thicknesses and poor age constraints. They cannot be unequivocally recognized as indicators of Mesoproterozoic passive margins, but such an interpretation is possible (Pisarevsky and Natapov, 2003). The Riphean sediments north of the Anabar shield are concealed under the thick younger cover so their depositional environments are unclear.

Neoproterozoic magmatism

Extensive tectonic and magmatic activities and rapid sedimentation processes were characteristic for the late Riphean and Vendian stages of the Siberian evolution. They could be related to the Neoproterozoic Rodinia breakup and opening of the Paleo-Asian Ocean (Zonenshain et al., 1990; Berzin and Dobretsov, 1993). Neoproterozoic mafic dyke swarms are widespread over the southeastern and southern parts of the Siberian craton. These mafic dykes swarms are known in the Uchur–Maya area, Baikal and Sharizhlagay uplifts and within Pre-Sayan area (Gladkochub et al., 2000, 2001b; Pavlov et al., 2000).

Recent geochronological studies have revealed ^{40}Ar – ^{39}Ar plagioclase ages of mafic dyke swarms of the southern Siberian craton close to 780–740 Ma (Sklyarov et al., 2003; Gladkochub et al., 2006). The youngest intrusions are slightly older than the ~723 Ma Franklin intrusions of northern Laurentia (Heaman et al., 1992). However, the ^{40}Ar – ^{39}Ar ages of the the Siberian intrusions are probably less robust than the Franklin U–Pb age, so knowledge of the U–Pb geochronology of the Siberian intrusions would facilitate a more meaningful comparison. The age difference could be also explained by a progressive opening of the basin between Siberia and Laurentia at 780–720 Ma from east to west (in present-day coordinates). Geochemical studies of south Siberian Neoproterozoic dykes and North American Franklin dykes suggest that they could have originated from the same mantle plume (Gladkochub et al., 2006).

Paleogeographic implications

Recent latest Mesoproterozoic–earliest Neoproterozoic paleomagnetic data (Gallet et al., 2000; Pavlov et al., 2001) suggest that Siberia and Laurentia–Greenland could be parts of some larger continent aged between ~1.05 and ~0.95 Ga. Using these data, Pisarevsky and Natapov (2003) proposed a new Siberia–Laurentia fit. The southern Siberian margin in their reconstruction faces the north-

ern Laurentian margin. A similar fit has been proposed by Frost et al. (1998) (Figure 2), but the main difference is the gap between Siberia and Laurentia, which leaves room for other crustal blocks (e.g., northern Alaska, Chukchi Peninsula and others) that were juxtaposed against northern Laurentia prior to the ~125 Ma opening of the Canadian basin (e.g., Zonenshain et al., 1990; Embry, 1998; Natal'in, 2004; Drachev, 2004). Gladkochub et al. (2006) have slightly modified this reconstruction using comparisons of mafic igneous complexes in the two cratons (Figure 2). Unfortunately, older reliable Siberian (Ernst et al., 2000; Didenko et al., 2003) and Laurentian (summarized in Pesonen et al., 2003) paleopoles are too sparse, and sometimes too controversial, to trace the Laurentia–Siberia reconstruction back in time. However, main geological arguments for direct Laurentia–Siberia connection (e.g., Frost et al., 1998; Gallet et al., 2000; Pavlov et al., 2001), or indirect (Pisarevsky and Natapov, 2003; Gladkochub et al., 2006) connection, include similarities between Archean and Paleoproterozoic continental blocks and orogenic belts. Hence, if Laurentia and Siberia were connected at the end of the Mesoproterozoic, this connection should have been in existence since ~1.8 Ga — the supposed time of assemblage of these cratons.

Conclusions

In summary, the main characteristics of the late Paleoproterozoic to Neoproterozoic evolution of the Siberian craton are:

1. Siberia was assembled between 2.1 and 1.8 Ga by the collision of several Archean and early Paleoproterozoic building blocks. This broadly coincides with the assembly of most Precambrian cratons. These events could be related to the assemblage of the Paleoproterozoic supercontinent.
2. Some minor extensional events in Siberia occurred in the early Mesoproterozoic, causing the appearance of intra-continental basins. Stable platform sedimentation commenced after ~1.8 Ga. Laurentia also was stable from ~1.8 Ga, with continental growth from the SSE. Hence, if Siberia and Laurentia were parts of a single continent after ~1.8 Ga, it is likely that the Siberian part was located close to northern Laurentia.
3. No traces of the Grenville-age orogeny have been found in Siberia, implying that this craton was on the periphery of Rodinia.
4. The southern parts of the eastern (Uchur–Maya area) and western (Yenisei area) cratonic boundaries have probably faced the ocean since the Early Mesoproterozoic. Evidence for Mesoproterozoic passive margins in the northern part of Siberia is less convincing.
5. Passive margin developed along the southwestern Siberian boundary later, in the Neoproterozoic. It could be caused by the breakup of Rodinia and opening of the Paleo-Asian Ocean. The Franklin igneous event could have been a trigger for this breakup. Traces of the coeval Laurentian passive margin are yet to be found in northern Alaska and/or the Chukchi Peninsula.
6. Paleomagnetic data support a unity of Siberia and Laurentia between 1100 and 950 Ma, but not direct connection (Figure 2). Other continental blocks (northern Alaska, the Chukchi Peninsula) probably were located between them.

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Eugene Sklyarov, Arkadiy Stanevich, Sergei Pisarevsky, Dmitry Gladkochub, Lev Natapov, Tatiana Donskaya, Anatoliy Mazukabzov (from left) share a great interest in the Precambrian tectonic evolution, the metamorphic and igneous activity of the Siberian craton and the assembly/breakup of Rodinia.

E.S., D.G. and T.D. focused specifically on metamorphic and igneous petrology. A.S. busied himself with Precambrian microfossils and stratigraphic correlations, S.P. was responsible for paleomag reconstructions as well as involved in wide-scale paleomagnetic correlation in the frame of Rodinia. L.N. and A.M. concentrated mainly on the regional tectonics.