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Geologic complexes of the southern marginal part of the Siberian Craton as indicators of the Neoproterozoic supercontinent evolution

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Abstract. The aim of this paper is to discuss the Late Precambrian rock complexes in the southern margin of the Siberian Craton, associated with the extension. The analysis of the data available suggests two episodes of intracontinental breakup which resulted in the opening of oceanic spaces (1300–900 and 850–550 million years). The time sequence of "volcanogenic terrigenous rocks of rifting origin → basic dike swarms → carbonate-terrigenous rock sequences → ophiolites and island-arc rocks" reflects the consecutive change of geodynamic environments in the marginal part of the craton. The stage of intracontinental rifting was replaced by the stage of advanced rifting, which preceded the continental breakup and the formation of the oceanic crust. Next followed two stages of oceanic crust evolution: the passive stage (sedimentary complexes of the passive margins) and the active stage (island arcs, backarc seas, and the like). Different versions are discussed for the manifestation of extension processes in the southwestern and southeastern segments of the Siberian Craton in connection with the breakup of the Rodinia supercontinent.

Introduction

The combination of continental blocks into large structures of planetary scale (supercontinents) is one of the most complex and interesting features in the Earth's evolution. It has been proved by the present time that supercontinents existed repeatedly beginning from the Early Precambrian [*Dalziel,* 1991; *Hoffman,* 1991; *Moores,* 1991; *Rogers,* 1996; etc.]. One of the most reliably documented supercontinents is Rodinia which originated in the Mesoproterozoic and broke up in the Neoproterozoic. During the last ten years a great number of papers were published by foreign geoscientists and, to a lesser extent, by Russian geologists, aimed at both the general reconstructions of the supercontinent [*Dalziel,* 1991; *Hoffman,* 1991; *M. McMenamin and D. McMenamin,* 1990; *Rogers,* 1996, to name but a few], and devoted to its individual cratonic blocks, including the Siberian one [*Condie and Rosen,* 1994; *Sklyarov et al.,* 2000, to name but a few]. These reconstructions, which are rather similar in many respects, suggest some ancient cratons which do not find their definite, exactly located places, like in a children mosaic. This stems, in many respects, from their poor knowledge and from the contradictory data obtained from their different parts. The Siberian Craton seems to have the largest number of the "degrees of freedom", which stems from the reasons, the most important of them being the poor knowledge of their metamorphic, magmatic, and sedimentary indicators, and also from the fact that many data are published mainly in local publications. For these reasons, the principal aim of this paper is the preliminary generalization of the indications imprinted in the structure of the southern segment of the Siberian Craton that can prove the Neoproterozoic breakup of the Rodinia Supercontinent.

The following rock complexes are usually used to prove the breakup of large cratonic blocks [*Rogers,* 1996]:

(1) basic dike series in the marginal parts of the cratons, which are the important indicators of the initial phases of the continental breakup processes. Actually, the very existence of these dike swarms does not necessarily record the initial phases of the continental breakup and the formation

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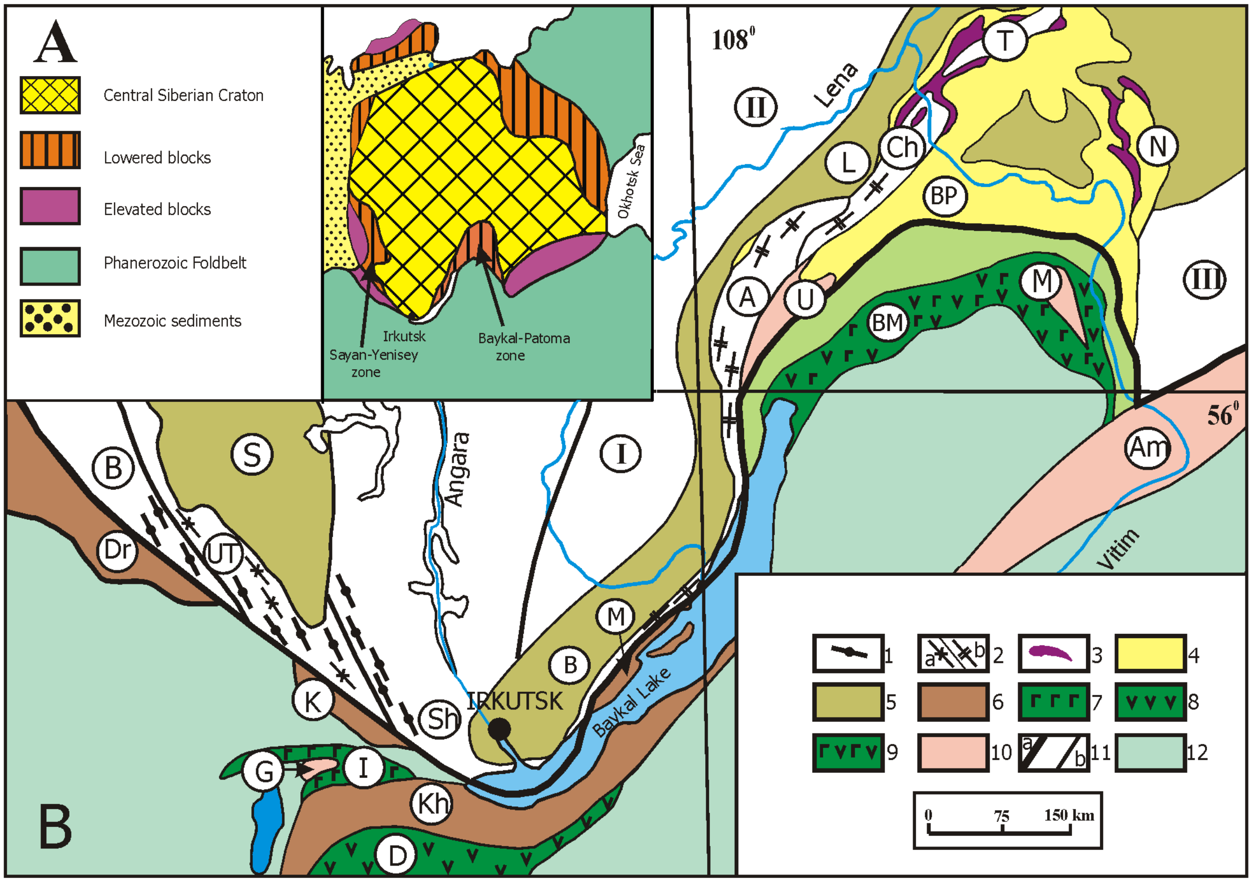

Figure 1. Location map of major structural elements in the south of the Siberian Craton and the distribution of the rock complexes associated with the evolution of the Neoproterozoic Supercontinent. (1) Late Riphean basic dike swarms (Nersa Complex); (2) Middle Riphean basic dike swarms: (a) Angaul Complex, (b) Chaya Complex; (3) basic volcanic rocks (Middle Riphean); (4) Carbonate-terrigenous deposits of the passive margin (Middle Riphean, Patoma Zone); (5) Late Riphean carbonate-terrigenous deposits of the passive margin and transitional to the rocks of collision origin (zones: (L) Lena zone, (BP) Baikal-Patoma zone, (B) Baikal zone, and (S) Sayan zone); (6) metamorphic rock complexes, inferred to be the rocks of the passive margin, which had been tectonically brought to contact the fragments of island-arc rocks (Kh – Khamardaban, K – Kitoika, and Dr – Derba complexes); (7–9) ophiolite belts: (7) Middle-Late Riphean (1.1–0.8 billion years) (I – Ilchira Belt); (8) Late Riphean-Vendian (0.7–0.55 billion years) (D – Dzhida Belt); (9) Middle-Late Riphean and late Riphean-Vendian (BM – Baikal-Muya Belt); (10) Early Precambrian terranes in the foldbelt (G – Gargan, M – Muya, Am – Amalat); (11a) the modern boundary of the Siberian Craton from geological and geophysical data, the craton is showed without its Phanerozoic sedimentary cover; (11b) various faults and boundaries between rock complexes; (12) Sayan-Baikal Foldbelt.
The letters denote the following major structural features of the Siberian Craton margin: A – Akitka volcanoplutonic belt; B – Biryusa Block; N – Nechera High; M – Maritime Zone; T – Tonod High; U – Ukuchikta Block; UT – Urik-Tumansheta Zone; Ch – Chuya High; Sh – Sharyzhalgai Protrusion; (I) Tungus, (II) Anabar, and (III) Aldan provinces. The black rectangles with numbers denote the areas of detailed surveys and the numbers of the figures referred to in the text.

of oceanic spaces, because rifting can result merely in the formation of intracontinental structures. The reliable substantiation of the origin of an oceanic basin calls for the age correlation of the processes of basic magmatism with the subsequent sedimentary and magmatic events;

(2) thick carbonate-terrigenous rock sequences in the marginal parts of the cratons, which are related to the sediments of a passive margin and can record the mature phase of the evolution of Atlantic-type oceans;

(3) the oldest ophiolites and the island-arc rocks associated with them in the fold areas adjacent to the cratons. Their age reflects the period of the active interaction between the oceanic and continental plates with the formation of island arcs and backarc basins.

Also included into this list must be terrigenous rocks of volcanic origin, which are characteristic of the typical intracontinental rifts, because the breakup process begins with the formation of large intracontinental rifts. In the ideal case we can be sure in the breakup of a continental massif with the formation of an oceanic space in between only in the case of the following chronologically substantiated sequence: rift-related terrigenous and volcanic rocks, sometimes including the volcanic rocks of the continental margins involved in the destruction ⇒ basic dike swarms ⇒ the poorly deformed thick terrigenous-carbonate rock sequences of the newly formed oceanic basin. The evolution phases of this basin are recorded, in their turn, by the relicts of the spreading-zone ophiolites and by the ophiolites of the back-arc basins, associated with island-arc volcanogenic terrigenous and intrusive rocks. This sequence of the processes operating in cratonic blocks and in the adjacent areas of foldbelts reflects the succession of the following geodynamic environments: the formation and evolution of the intracontinental rift system ⇒ the advanced rifting stage expressed in the intrusion of large volumes of basalt magma into the upper crust and the beginning of a continental breakup ⇒ the initial formation of an oceanic space without any active interaction between the oceanic and continental plates ⇒ the mature stage of the oceanic evolution with an active interaction between the oceanic and continental plates. Here, we intentionally speak about *continental* breakup without using the term "supercontinent", because the substantiation of the latter calls for the correlation of geologic events in many modern cratonic blocks. In this paper we deal only with the southern part of the Siberian Craton (Figure 1).

This part of the Siberian Craton includes Neoproterozoic dikes and, locally, thick Riphean terrigenous-carbonate rocks underlain by the rocks of rift origin. The southwestern segment of the Central Asian foldbelt surrounding the Siberian Craton in the south includes Riphean ophiolites and associated island-arc volcanic and terrigenous rocks. Below follow the brief characteristics of the indicator-type lithologic complexes of the region, recording the evolution of the Rodinia Neoproterozoic supercontinent.

Terrigenous and Volcanic Rocks of Rift Origin

The traces of rifting-related processes can be most fully reconstructed in the Patoma Highland and can be traced using the formations of the Medvezhevskaya Formation, dated Middle Riphean, conventionally proceeding from the geological data available. The dating of the rocks is based on mainly geological relationships and is not supported by any correct geochronological data. The volcanogenic and terrigenous deposits of this formation are most completely represented on the northwestern slopes of the Chuya and Tonod highs, where they compose an intermittent band of the northeastern strike. Characteristic of this formation is the accumulation of thick facies-variable sequences of the sandstone-conglomerate composition, interbedded with subaqueous basic volcanics. The thickness of this formation varies from a few dozens to 2700 m [*Ivanov et al.,* 1995]. Based on their lithology, most of the sedimentary rocks are represented by mixtite. The local stagnant zones of the basin are marked by the accumulation of iron quartzite. Petrochemically, the volcanic rocks are close to basalt and andesite with an elevated alkali content. The flow of the volcanic material had been accompanied by the emplacement of basic dikes. The data available for the restored structural features of the Medvezhevskaya epoch suggest the existence of troughs separated by the projections with the Early Precambrian basement [*Ivanov et al.,* 1995]. These troughs had a submeridional orientation (in modern coordinates) during the early stages of their evolution and a northeastern one, at the final stages. The rearrangement of this kind had obviously been controlled by strike-slip deformations as a reaction to the processes of the oblique regional extension of the territory during the time period concerned. The rocks of this level had been widely distributed, as follows from their potential metamorphic analogs mapped along the southeastern flank of the Chuya Rise, and also in the area of the Nechera Rise and in the north of the Baikal-Muya Zone.

The next level of the rifting-related sedimentary and volcanic rocks has been recorded in the West Baikal region where these rocks are restricted to the lower levels of the Baikal rock series and to the Upper Riphean rocks underlying the rocks of this series (Figure 2) [*Mazukabzov et al.,* 2001]. Here, these rocks have local distribution and are represented by coarse clastic deposits with their clastic material consisting of the desintegrated granitoid and less frequent metamorphic rocks of the craton basement. The sedimentary rocks are associated with the volcanic rocks (tholeiites) of normal alkalinity.

The fragmentary distribution of the rifting-related rocks does not allow one to trace the zones of the Neoproterozoic rifting in the Sayan and Western Baikal regions, yet, they prove the formation of rifts in the southeastern margin of the Angara-Anabar block of the Siberian Craton.

To sum up, the southern marginal part of the Siberian Craton shows two distinct age levels of the rifting-related volcanic and sedimentary rocks, namely, the Mesoproterozoic and Neoproterozoic ones. No correct datings are available for the rift-related formations, yet, their geological relationships with the dated rocks suggest that these time intervals can be placed within the intervals of 1300–1100 and 850–750 million years.

Dike Swarms in the Marginal Part of the Craton

The marginal part of the craton basement discussed includes fairly widely distributed dikes, sills, and thin stocks of diabase and gabbro-diabase. There are several fields of intensive basic magmatism in the form of dike swarms. In the zones of poorly deformed and poorly metamorphosed rock sequences, the subvolcanic rocks are closely associated with sills and lava flows. In terms of their geography and

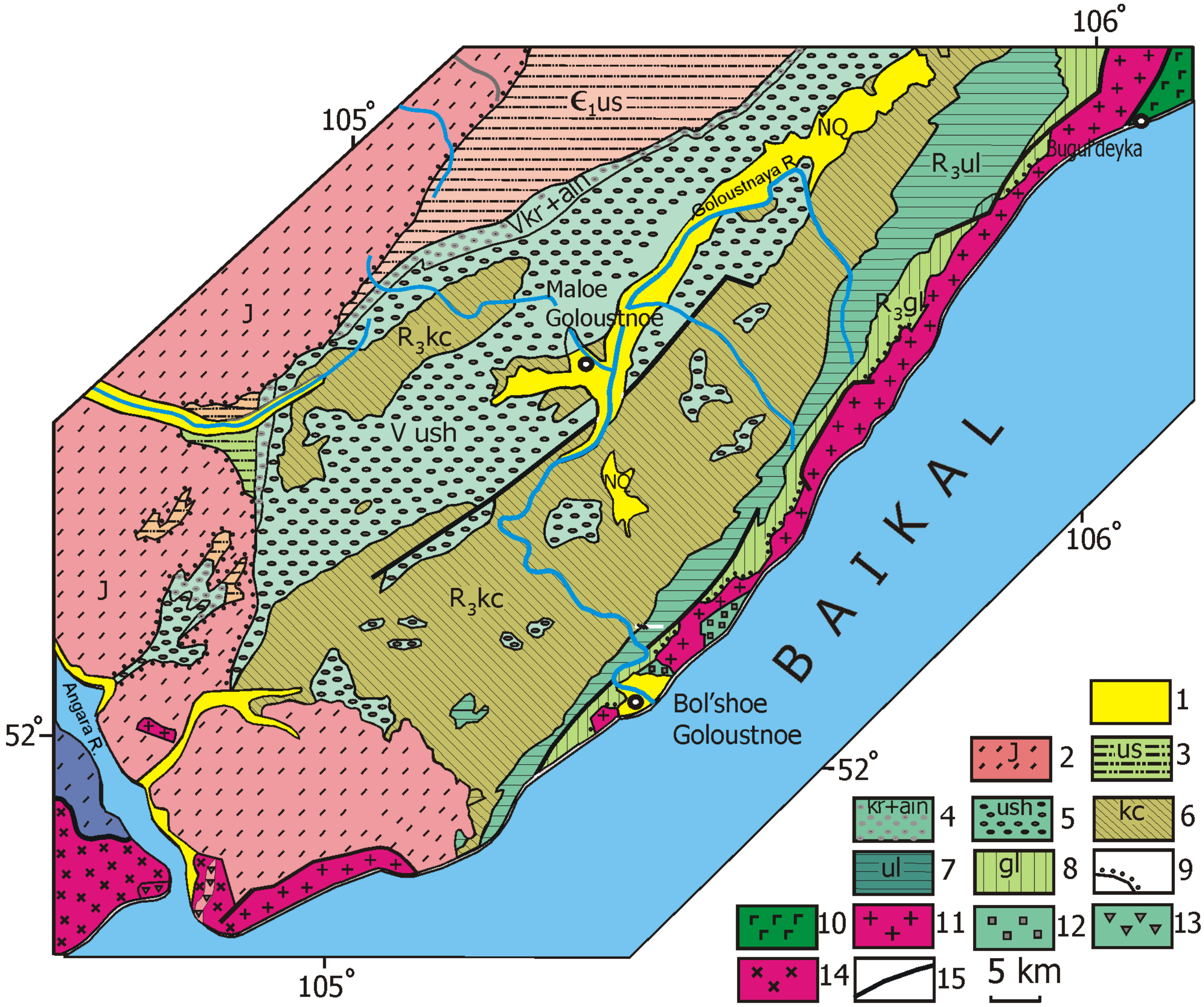

Figure 2. Schematic geological map of the Western Baikal region – a stratotype locality of the Neoproterozoic sedimentary deposits of the Baikal Group.
(1) Cenozoic sediments; (2) Jurassic sediments, undifferentiated; (3) the rocks of the Usol Formation (Early Cambrian); (4) the rocks of the Kurtun and Ayanka formations (Vendian); (5) deposits of the Ushakov Formation (Vendian); (6–8) Late Riphean deposits of the Baikal Group: (6) Kachergat Formation, (7) Uluntui Formation, (8) Golousta Formation; (9) stratigraphic unconformity; (10) basic volcanics and gabbroids; (11) Early Proterozoic granites of the Primorskii Complex; (12) gneiss, amphibolite, and migmatite (Archean-Early Proterozoic); (13) orthoamphibolite and metagabbro of the Listvyanka Complex (Proterozoic); (14) gneiss, crystalline schist, amphibolite, migmatite, and marble of the Sharyzhalgai Series (Archean); (15) main fault zones.

associations with certain geological structures, the following fields of the Proterozoic dike swarms have been mapped in the southern flank of the Siberian Craton (Figure 1): the North Baikal field and the Sayan field, the latter including the Sharyshalgai basement protrusion.

The North Baikal Field. A great number of gabbro-diabase dikes and less frequent sills are widely developed in the Akitka and Baikal ranges, which coincide spatially with the North Baikal volcanoplutonic belt. They are distributed discretely and are often grouped into zones and belts. Usually, these are single dikes with distinct salbands, though some large bodies have somewhat diffused contacts with the granites. Some of the dikes have a complex dike-in-dike structure (in the upper reaches of the Savkina River, Akitka Range). The dikes are 5–8 km long and have a maximum width of 50 m. They are emplaced in the granitoids of the Irel and Primorskii complexes, in the volcanogenic sediments of the Akitka Group, and also in the Paleo- and Meso-Proterozoic metamorphic rocks. The degree of the secondary alterations of the gabbro-diabase is highly variable. High secondary alterations are characteristic of the dikes in the

Baikal Range. The gabbro-diabase of the Akitka Range in its segment close to the platform is almost unaltered and has a fresh appearance, yet eastward, closer to the large faults, shows a variable degree of dynamometamorphic transformation up to amphibole schists. In terms of their composition, the dikes correspond to subalkalic basalt or tholeiite. The dike swarm has been traced southward as far as the area of the Onguren Settlement (Figure 3).

The facts that the dikes cut the volcanogenic and terrigenous deposits of the North Baikal Belt, and that they are overlain by the carbonate-terrigenous deposits of the Baikal Group restrict the time of the dike emplacement to the age interval of 1900–850 million years. The high alteration of the diabase, often resulting in the complete absence of magmatic mineral associations, impedes the more exact dating of the dikes.

Sayan Dike Field and the Sharyzhalgai Protrusion. The southern flank of the craton includes several areas of Riphean dike swarms (Figures 4 and 5). Most of the dikes are steeply dipping, have a NW strike, coinciding with the main fault system of the region, and range from 20–30 cm to 3–5 m in width. In places the dikes have a gentle to subhorizontal dip caused by their adjustment to the flat elements of the large folds. In areas of good exposure, some of the dikes can be traced over the distances of 1–10 km. The results of the aeromagnetic surveys suggest that some dikes are as long as >15 km [*Sklyarov et al.,* 2000]. Based on the degree of the metamorphic transformation of the basic rocks composing the dikes, and taking into account some geochronological data, the dikes of the region have been classified into three groups of different ages (from the older to the younger), corresponding to the Arban, Angaul, and Nersa complexes, respectively [*Sklyarov et al.,* 2000]. The Arban dike complex, dated pre-Riphean from the geological data and showing the highest degree of metamorphism, is not discussed here.

The Angaul dike complex was found in the Iya-Urik structure and is represented by diabase and gabbro-diabase dike and sill bodies, and also by more scarce picrite porphyry, for which individual K-Ar and Rb-Sr datings are available:

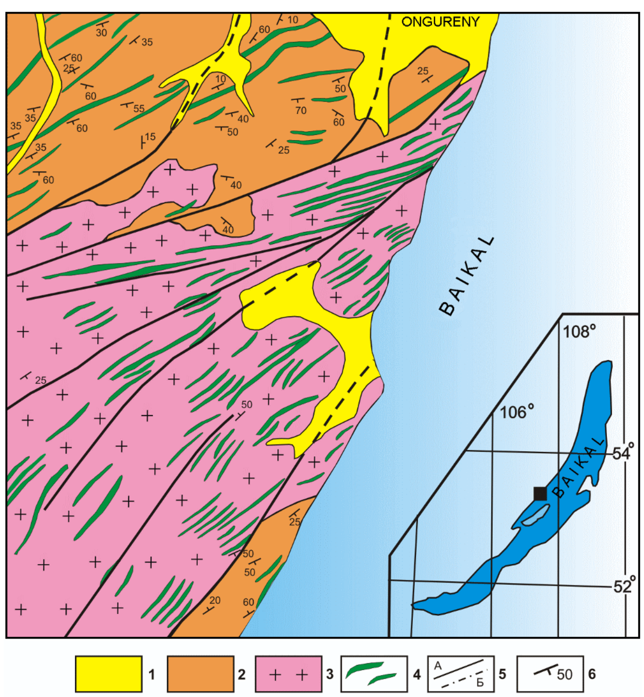

Figure 3. Schematic geological map of the Kocherikov area of the Baikal Zone.
(1) Quaternary deposits; (2) terrigenous deposits of the Sarma Group (PR_1); (3) granitoids of the Primorskii Group (PR_1); (4) diabase and gabbro-diabase dikes; (5) mapped (a) and inferred (b) faults; (6) dip and strike. The inset map shows the location of this site.

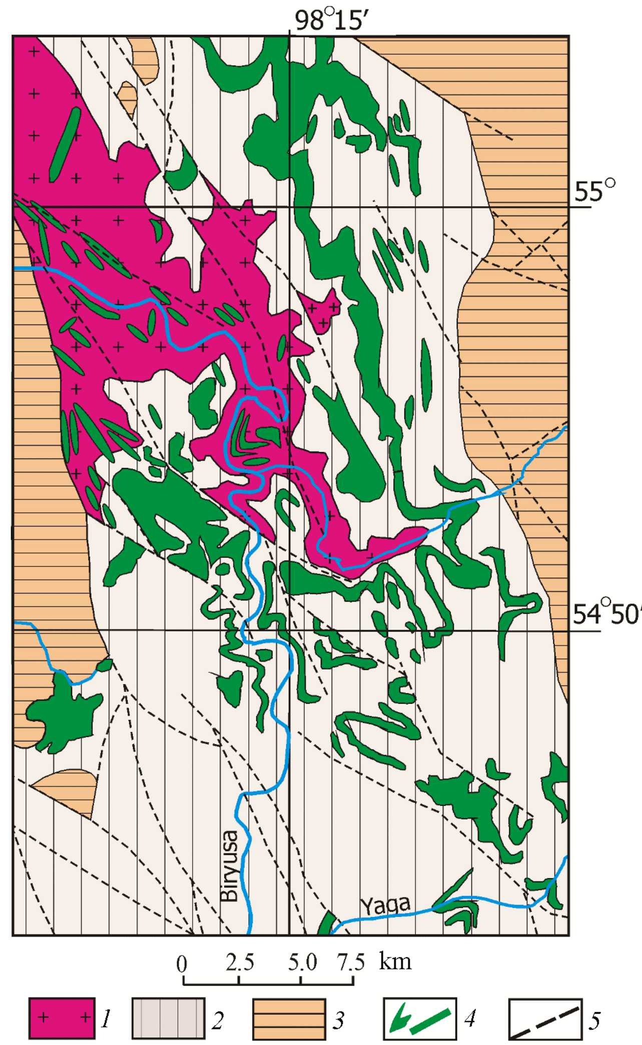

Figure 4. Schematic geological map for the area of the middle course of the Biryusa River (compiled using the data of G. A. Belozerov and T. V. Gorbovskaya).
(1) Early Proterozoic granitoids of the Sayan Complex; (2–3) Late Riphean Karagas Group: (2) Shangulezh and Tagul Formations (bottom of the sequence); (3) Uda Formation; (4) Nersa dolerite complex (sills and dikes) of Early Riphean age; (5) fault.

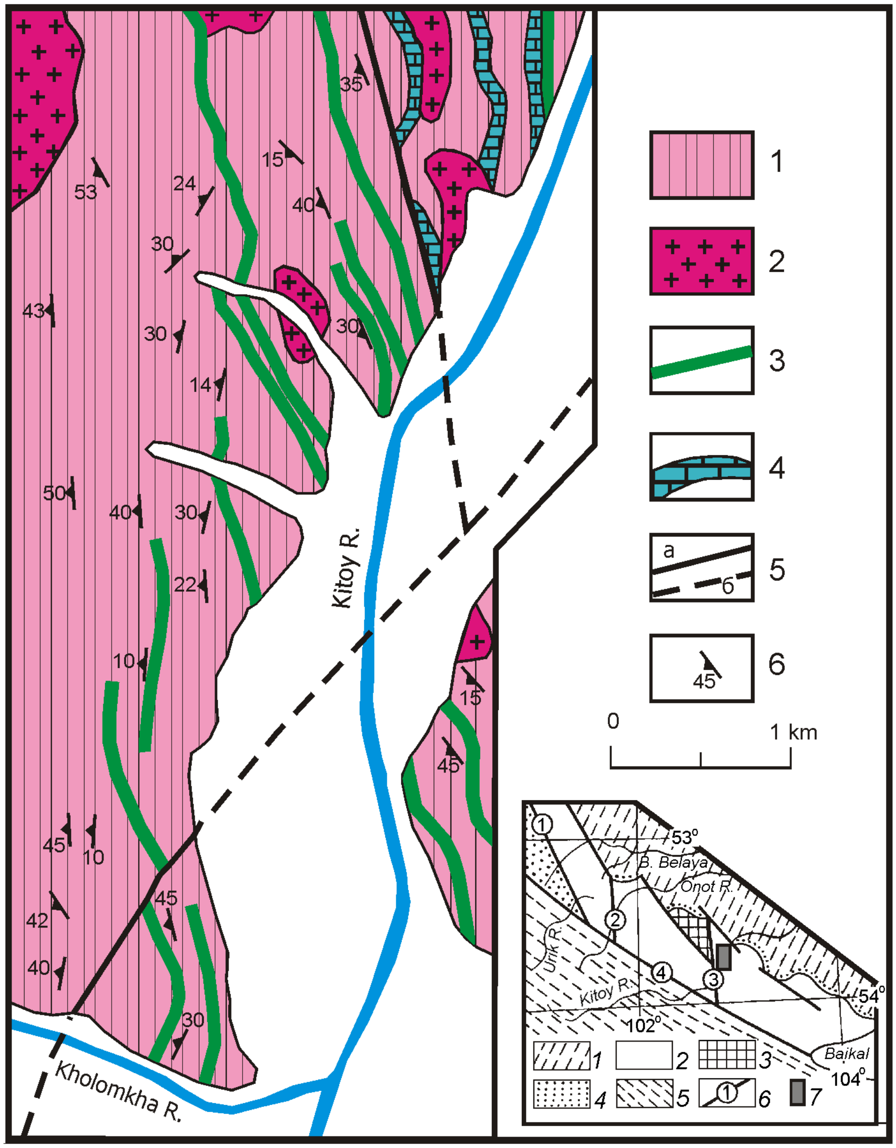

Figure 5. Neoproterozoic gabbro-dolerite dikes in the area of the Kitoi River middle course.
(1) Early Precambrian metamorphic rocks; (2) Proterozoic granitoids; (3) Neoproterozoic gabbro-dolerite dikes; (4) marble layers; (5) faults: (A) observed, (B) inferred; (6) dip and strike.
The inset shows the tectonic map of the southern flank of the Siberian Craton and adjacent folded areas: (1) platform sediments, (2) Sharyzhalgai Protrusion, (3) Onot Graben, (4) Urik-Iya Graben, (5) Sayan-Baikal Foldbelt, (6) faults: (1) Tagninskii, (2) Onot, (3) Kitoi, (4) Main Sayan; (5) study area.

1550–1650 and 1100–1300 Ma [*Domyshev,* 1976; *Sekerin et al.,* 1999]. The diabase had experienced fairly high secondary alteration, often with the complete replacement of the magmatic minerals. The basic rocks are transitional between the tholeiite and subalkalic series. A group of basic igneous rocks, distinguished as an individual series, was found to occur locally, including lamproite [*Sekerin et al.,* 1995], and to be close to the time of the emplacement of the above-mentioned basic rocks. Based on one Rb-Sr isochrone for the bulk of the rocks with high secondary alterations, these subvolcanic rocks were dated 1268±12 Ma [*Sekerin et al.,* 1995].

The dike swarms of the younger Nersa Complex, often closely associated with the sills, occur mainly in the area underlain by the deposits of the Karagas Group of the Sayan Trough, and also in the Sharyzhalgai Protrusion, where they occur as sills, dikes, and small stocks of irregular form. The sills separate the stacks of lithologically different rocks, amount to 100 m in thickness, and extend for distances of >75 km. There are occasional multistage sills [*Domyshev,* 1976]. Most of the dikes trend NW (330–340°), yet in some areas this trend is replaced by a northeastern one. The dike mapped vary in length from a few hundred meters to a few kilometers, their widths varying from a few to a hundred meters. The largest of them often show a differentiated structure [*Domyshev,* 1976]: their margins are composed of microdiabase, and their central parts, of gabbro grading to diabase.

Most of the dikes show steep dips, except for some localities where they have gentle dips and are conformable with the gneissosity of the enclosing rocks.

Most of the dikes are composed of medium- and fine-grained rocks. These are typical diabase and gabbro-diabase with the varying proportions of the main rock-forming minerals, the leading of the latter being clinopyroxene and plagioclase. Less common are olivine and pigeonite. The typical accessory mineral is titanomagnetite, chromite being found occasionally in the form of fine inclusions in olivine.

Most of the dikes have a composition of tholeiite [*Gladkochub et al.,* 2001a] and correspond to the N-MORB type or to the type transitional to E-MORB. Less common are subalkalic dikes. The geochemical characteristics of the studied gabbro-diabase samples suggest that the formation of the initial melts for the subvolcanic rocks of the tholeiite and subalkalic rock series had taken place in an enriched lithospheric chamber.

The age of the dikes was determined using an Ar-Ar method (plagioclase) and found to be 850–890 Ma [*Gladkochub et al.,* 2000]. Later a date of 750 Ma was found for the same dikes using a Sm-Nd isochrone. The considerable difference between these values can be explained as follows. The configuration of the Ar spectra having a U-shaped form may indicate the presence of excessive radiogenic argon. In this case the values obtained can be treated as the lowest limit of the dike age (not older than 850 Ma). Therefore the most realistic age is 750 Ma.

Thus, there seem to be two generations of the post-Paleoproterozoic dikes, the time periods of their emplacement being 1100–1300 Ma (Angaul Complex) and 750–850 Ma (Nersa Complex), the former date being more uncertain.

Poorly Deformed Terrigenous-Carbonate Rocks

The preserved fragments of the sedimentary terrigenous-carbonate rock sequences reflect, but to a certain extent, the potential orientation of the sedimentation regions associated with the formation of the passive continental margins in the south of the Siberian Craton. The relations of the rocks discussed with the deeper structural forms vary from marginal unconformities to cryptically conformable ones, this being controlled by the extension factor. In terms of the sedimentation character and the spatial positions in the segment concerned, there are three structural-facies zones: the Patoma, Baikal, and Sayan ones. Some tectonic relicts of the sedimentary sequences can be traced in the Baikal-Muya zone.

In the Patoma Zone the Middle-Late Riphean rocks of the Ballaganakh Sequence (as thick as 7 km) rest conformably on the rocks of the Medvezhevo Formation in the grabens and with eroded intervals beyond them, where they rest of the Early Proterozoic rocks. This suggests the expansion of sedimentation over a significantly larger territory, at least, in the limits of the Baikal-Patoma Highland, where the accumulation of the lower elements of the sequence was irregular and was controlled by the zones of large faults with the formation of clinoforms. A distinctive feature of the deposits is the combination of immature and poorly differentiated terrigenous sediments (polymictic to oligomictic) and occasional conglomerates and carbonaceous shales with interbeds of high-alumina shale [*Nemerov and Stanevich,* 2001]. The formation of this deep and extensive sedimentary basin seems to have been caused by not only the extension but also by the thermal relaxation of the lithosphere after the high thermal effect of the preceding stage. The rocks of this level are overlain by the rocks of the Nygra and Dalnyaya Taiga series, as thick as 3600 m, varying from terrigenous to carbonate deposits with the elements of a flyschoid structure. The type of their facies changes suggests that they had accumulated in a marginal basin under shallow to deep-water conditions. The clastic material had been transported from the adjacent areas of the craton and, possibly, from the initiating Baikal-Muya island-arc system. The rhythmical sequences of the rocks suggest the still continuing slow tectonic subsidence of the territory with the undercompensation conditions originating in the central parts of the basin. These phenomena in the evolution of the pericratonic basin seem to have been caused by its rearrangement [*Stanevich and Perelyaev,* 1997] which, in its turn, might have been associated with a change in the dynamic conditions in the Baikal-Muya island arc system [*Nemerov and Stanevich,* 2001].

The subsequent evolution history of the region reflected the transformation of the peripheral basin to a foreland basin with collision events during the closing stage of the Baikalian cycle.

The propagation of the terrigenous-carbonate deposits of this age farther south and southwest is an interesting and debatable problem. The thick (5–12 km) terrigenous-carbonate rock sequences developed along the southern and southwestern boundaries of the craton in the foldbelt (Figure 1) seem to mark the environments of the continental slope and its foot. These metasediments, known as the Olkhon, Slyudyanka and Kitoi Groups, are metamorphozed in a zonal pattern (up to the granulite facies), and, based on the high grades of their metamorphism, were treated by most of the geologists as the Early Proterozoic or even Late Archean formations. The studies of the last years [*Bibikova et al.,* 1990; *Donskaya et al.,* 2000; *Salnikova et al.,* 1998] proved the Early Paleozoic age of the high-grade metamorphism (460–480 Ma). The problem of the protolith age remained unsolved. However, the rhythmic structure and lateral consistency of the carbonate and terrigenous-carbonate rock sequences, similar to that of the rocks of the Ballaganakh Group, as well as the analysis of the geological situation, suggest them to be the sediments of the Riphean passive margin. It should be emphasized that apart from their high metamorphic grade there are no indications of their

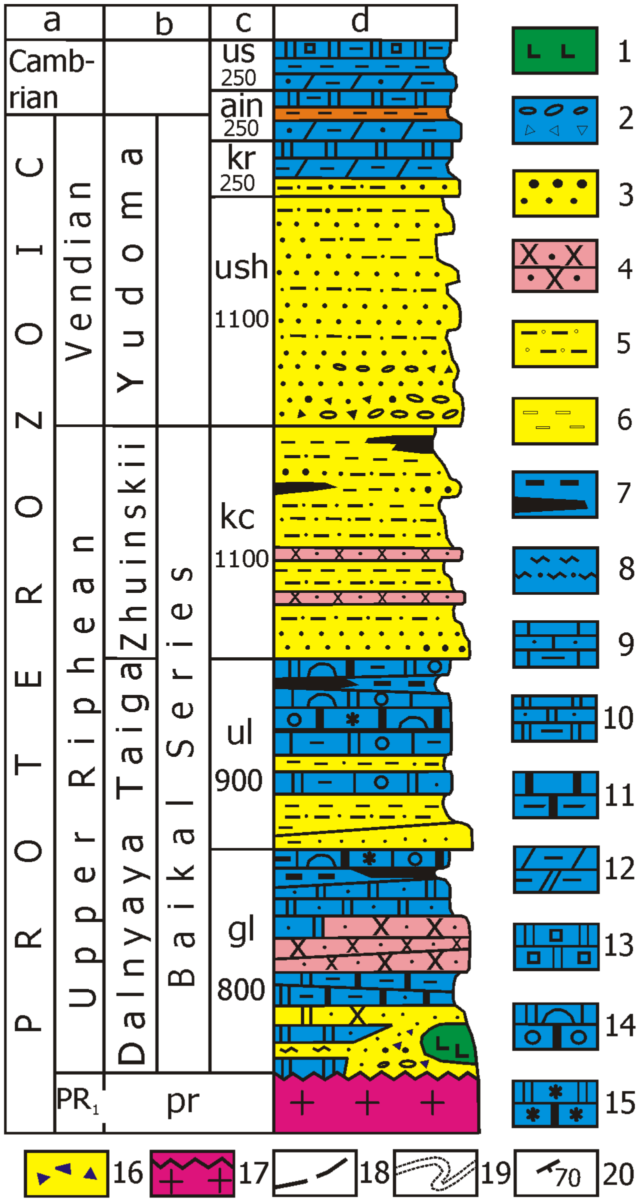

Figure 6. Stratigraphic column of the Neoproterozoic-Early Cambrian deposits.
(1) basic volcanic rocks; (2) conglomerate and conglobreccia; (3) polimictic arcose-graywacke gravelite and sandstone; (4) quartz sandstone; (5) siltstone; (6) argillite and silty argillite; (7) carbon-bearing argillite and silty argillite; (8) pelitic and aleuropelitic shale; (9) limestone, including its sandy varieties; interbedded dolomites and aleuroargillites; (10) dolomite, including sandy varieties and interbedded with silty argillites; (11) dolomitic limestone, including calcareous and silty argillitic dolomites; (12) calcareous and dolomitic marl; (13) salt-bearing carbonate; (14) stromatolites and microphytolites; (15) silicification; (16) synsedimentation breccia; (17) erosion; (18) fault zone; (19) structural style; (20) typical stratification measurement (in degrees).
Stratigraphic column: (a) general scale, (b) regional horizons and series, (c) formations with average thicknesses given in meters, (d) lithology, (pr) granitoids of the Primorskii complex.

more older age. And since the metamorphism had been associated with the processes of the Early Paleozoic collision, it can be inferred that the fragments of the marginal part of the craton, overlain by thick sediments, had been involved in the zone of the maximum collision effect.

The zone bordering the Baikal Lake still preserves the fragments of sedimentary rocks that had accumulated in the proximal part of the basin reflecting the evolution of the passive margin (Figure 6). The time of their deposition is dated by the sediments of the Golousta Formation of the Baikal Group and by the underlying deposits of the Nuga and Khota formations of Late Riphean age. The duration of the passive margin development seems to have been limited there by the basal layers of the Kachergat Formation. The bulk of the clastic material was supplied during the pre-Kachergat time from the side of the Siberian Craton, sufficient for the deposition of sediments as thick as 2.5 km. The sediments of the Kachergat Formation suggest the conditions of a foreland basin, this being proved by the early supply of clastic material from the perioceanic region.

The Sayan branch of the passive continental margin of late Riphean time had been located in the territory of the craton, which had been subject to extension not resulting in the formation of rifts. Under these conditions a sedimentary basin had been formed (Sayan Trough), where the sediments of the Karagas Group, ranging from 1100 to 3700 m in thickness, had deposited. The base of this group sequence includes the basal layers that had accumulated in the continental and lagoonal conditions and are represented by red conglomerates, cross-bedded sandstones and siltstones with less common sandy dolomites. Above follow carbonate-terrigenous and carbonate rocks. The sequence is terminated by terrigenous flyschoid and siliceous and carbonate sediments enriched in phosphate. The process of sedimentation was accompanied by the intrusion of the sheets and cross-cutting bodies of the Nersa diabase. This distinguishes the Sayan branch of the passive continental margin from the Patoma and Baikal ones. On this basis it can be classified as a passive margin with the volcanic type of its development.

The Karagas Group is overlain by the Oselkovaya Group of Vendian rocks. The rocks of the latter rest transgressively on the different horizons of the Karagas rocks and in terms of their structure and mode of formation correspond to the rocks of the foreland trough which terminated the evolution of the Baikal cycle [*Sovetov,* 2001].

To sum up, like in the case of the rift-related rocks, there are two distinct levels of terrigenous-carbonate deposits which are interpreted as the sediments of the passive margin or reflecting the stage of the transition from the passive to the active margin. In the Patoma Zone, these deposits are associated, both in space and time, with the rift-related volcanic and terrigenous rocks of the Medvezhevo Formation. In the Baikal and Sayan zones, coarse clastic deposits and volcanic rocks also occur at the bases of the Baikal and Karagas Groups, respectively. Like in the case of the volcanic and terrigenous rocks of rift origin, no correct isotope datings are available for these rocks.

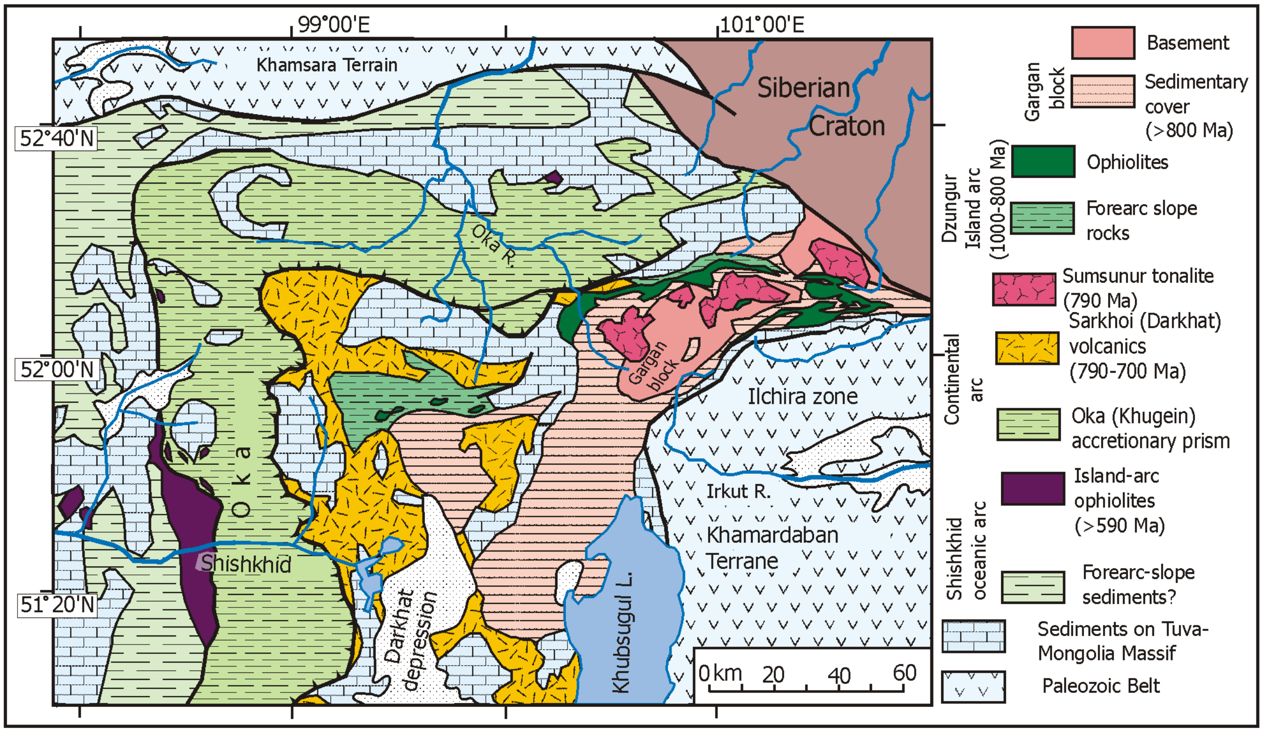

Figure 7. Tectonic map of the Tuva-Mongolian Superterrane (compiled by A. B. Kuzmichev). Note. The map does not show Paleozoic granites and Cenozoic sediments and basalts (except for those in large depressions).

Ophiolites and Island-Arc Rocks

Ophiolites and the island-arc rocks associated with them are widespread in the Central Asian Foldbelt bordering the Siberian Craton in the south. They have been described extensively in the literature [*Khain et al.,* 1997, 2001; *Sklyarov et al.,* 1992, to name but a few.] However, no ophiolite sequences, typical of the early evolution of oceanic basins, namely, of the stages of oceanic basin opening, have been found. The ages of the individual belts and massifs are still the matter of debate, which can be explained by the difficulty of their correct dating. Nevertheless, the critical analysis of the data available, along with the recent correct datings [*Khain et al.,* 2001; *Rytsk et al.,* 2001], allow us to substantiate two age levels for the ophiolites and island-arc rocks.

The oldest ophiolites that had originated roughly 1000 million years ago occupy now the closest position relative to the Siberian Craton (Figure 1). These are the fragments of the ophiolites of the Baikal-Muya Belt in the North Transbaikal region [*Rytsk et al.,* 2001], the ophiolites of the Ilchir Belt in the Southeastern Sayan region (Figures 7 and 8) [*Khain et al.,* 2001], and the fragments of basic and ultrabasic rock bodies of the Arzybei Block in the Southeastern Sayan Mountains [*Nozhkin and Turkina,* 2001], whose ophiolite or island-arc origin have been substantiated. These rock complexes have been dated 1035–1042 million years. The most reliable date was obtained for the plagiogranites (U-Pb, zircon) from the Ilchira ophiolite belt [*Khain et al.,* 2002] which is characterized by a complete and poorly disturbed rock sequence.

The island-arc, mainly intrusive, rocks, for which isotope age values are available, vary widely, yet the significant number of the valid datings fall within the interval of 800-950 million years [*Nozhkin and Turkina,* 2001; *Rytsk et al.,* 2001, to name but a few]. Naturally, there are other younger age values, which will be discussed below.

In any case, we can be sure that the oldest ophiolites are of Mesoproterozoic age. It should be noted that in this paper we do not discuss the Paleoproterozoic ophiolites from the Sharyzhalgai Ridge, where they are included in the structure of the metamorphic basement [*Gladkochub et al.,* 2001b; *Sklyarov et al.,* 1998]. The geochemistry of the ophiolites described above suggests them to be of supersubduction origin, that is, to correspond to the geodynamic environment of the active continental margin.

The ophiolites of the second group (Figure 1) are much more abundant in the fold belt. The age range of the ophiolites proper and of the island-arc volcanic and intrusive rocks associated with them is 700–500 Ma [*Khain et al.,* 2001]. As to the area discussed (Figure 1), this group includes the fragments of the ophiolites and associated island arcs of the Baikal-Muya Belt, the Eravna island-arc belt, and the ophiolites and island-arc rocks of the Dzhida Belt. The rocks of this age are also widespread farther westward in the Altai-Sayan region, and southward in Mongolia.

To sum up, there are two groups of rocks that had origi-

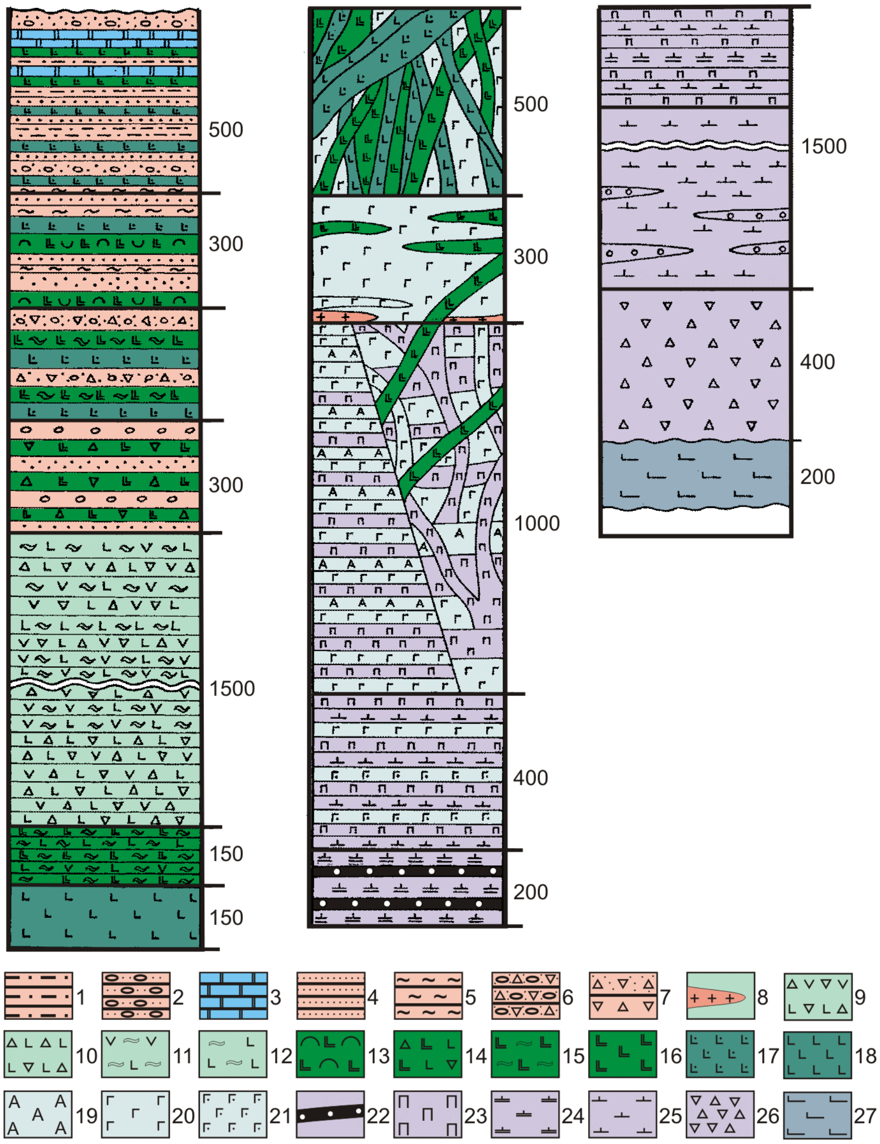

Figure 8. Combined sequence of the ophiolite association rocks in the Southeast Sayan Area. (1) siliceous sediments; (2) siltstone and conglomerate; (3) dolomite; (4) sandstone; (5) shale; (6) siltstone with tuff; (7) sandstone with tuff; (8) plagiogranite dike; (9) brecciated basaltic andesite lava; (10) brecciated basalt lava; (11) basaltic andesite lava; (12) basaltic pillow lava; (13) boninite tuff; (14) brecciated boninite lava; (15) boninite lava; (16) boninite dike; (17) gabbro diabase; (18) massive diabase; (19) anorthosite; (20) gabbro; (21) olivine gabbro; (22) chromite lens; (23) orthopyroxinite; (24) dunite; (25) peridotite; (26) melange zone; (27) amphibolite

nated in the geodynamic environment of active continental margins: 1100–800 and 700–500 Ma. In spite of some intermediate, often doubtful age values, the subdivision of the ophiolite and island-arc rocks of this segment of the Central Asian Orogenic Belt of Siberia into the two age groups mentioned above seems to be valid.

One of the most disputable items is the problem of the positions of the ophiolites and the older island-arc rocks associated with them relative to the Siberian Craton with which these rock complexes are in direct contact now. The first point to be emphasized is the fact that the rock complexes concerned are the constituents of the composite terranes (superterranes), the positions of which relative to the Siberian Craton are problematic for the time of the amalgamation of the subterranes into one Central Asian Orogenic Belt of Siberia. At least spatially, the ophiolite and island-arc rock complexes gravitate to two Precambrian blocks: the Gargan Block (Tuva-Mongolia Microcontinent) and the Muya Block (Barguzin Microcontinent). Some geologists [*Didenko et al.,* 1994; *Mossakovskii et al.,* 1993] suggest that the development of island arcs and back-arc basins, where the ophiolites and island-arc rocks accumulated, took place under the conditions of the active interaction of the oceanic plate with the blocks of the continental crust of the old Gargan and Muya blocks which were situated fairly far from the Siberian Craton. As follows from the palinspastic reconstructions offered in these papers, the ophiolites and island-arc terrigenous and volcanic rocks had accumulated in the marginal part of the East Gondwana, where the Tuva-Mongolia Microcontinent and, possibly, the Muya Block had been located. Yet, it is possible that the latter had been closer to the Siberian Craton which had been a constituent of the Rodinia Supercontinent 1000 million years ago [Gladkochub et al., 2000, 2001a, 2001b; *Sklyarov et al.,* 2000; *Yarmolyuk and Kovalenko,* 2001]. The accretion of the Muya Block to the southern flank of the Siberian Craton has been dated 570 million years ago [*Rytsk et al.,* 1999]. The connection of the Tuva-Mongolia Microcontinent with the southern flank of the Siberian Craton took place in the course of the Ordovician collision marked by the Baikal collision belt [*Donskaya et al.,* 2000]. Hence, it can be inferred that the Meso-Neoproterozoic ophiolites and the associated island-arc rocks of the Central Asian Foldbelt are not spatially connected with the marginal part of the Siberian Craton, but have their own different geologic history.

Discussion

The controversy and often ambiguity of dating some of the geologic complexes developed at the southern flank of the Siberian Craton and in the adjacent areas of the foldbelt, as well as the ambiguity of their geodynamic interpretation, caused by the high tectonic reworking, resulted in the proposition of different scenarios for the geological evolution of the region during the Late Precambrian. Even the authors of this paper disagree with one another in many aspects. The discussion of only most probable versions would have enlarged the limited volume of this paper. Therefore we will restrict ourselves to two potential scenarios based on the two age sequences of the rocks, which seem to imprint the processes of the intracontinental breakup and the subsequent opening and evolution of the oceanic basin.

The first group of the rocks corresponds to the age interval of 1300-850 million years. It includes

(a) the rift-related volcanic and terrigenous rocks of the Medvezhevo Formation and the dike swarms of the Chai (partially) and Angaul complexes (1300–1100 Ma), which had been emplaced under the conditions of the initial and advanced stage of intracontinental rifting;

(b) the facially consistent terrigenous and carbonate deposits of the Ballaganakh Group in the Patoma Zone and the rocks of the Baikal-Muya Zone (1100–900 Ma), correlating with the former, both being interpreted as the fragments of the passive continental margin. Taking into account the most probable fact that the metamorphosed sediments of the Olkhon, Slyudyanka, and Kitoi groups belong to this level, it can be supposed that this rock complex, found throughout the southern flank of the craton, is the main stratigraphic indicator of the oceanic space opening;

(c) the ophiolites and island-arc volcaniclastic and intrusive rocks of the East Sayan (Ilchir) and Baikal-Muya belts, developed in the fold area adjacent to the craton (1100–850 Ma). In contrast to the former two complexes developed mainly in the craton itself, these rocks belong to the terranes of the adjacent foldbelt and might have formed at a significant distance from the craton.

The second age group of the rocks (850–500 Ma) seems to reflect the different trends in the craton and perioceanic block movements. This is expressed in the fairly chaotic relations between the rift-, island-arc-, and collision-related rocks. They include

(a) the obviously rift-related rocks. These are the dike swarms and dike-sill rocks of the Nersa Complex, widespread in the Sayan Zone and in the Sharyshalgai Ridge (800–750 Ma). Also included into this group can be the volcanic rocks the Khota Suite, having the characteristics of typical basalts from destructive continental margins, which underlie the sediments of the basal rocks of the Baikal Group;

(b) the terrigenous carbonate deposits of the Karagas Group of the Sayan Zone, the basal beds of the Baikal Group (Baikal Zone), and their analogs in the Patoma Zone (850–650 Ma);

(c) the ophiolites and the associated island-arc rocks of the Central Asian foldbelt (the Dzhida branch and, partially, the Baikal-Muya zone), dated 700–500 Ma.

It should be emphasized that (1) some of the rock complexes discussed have not been dated reliably and still are the objects of discussion; (2) the rift-related volcanic and terrigenous rocks, as well as some dike swarms, might have been associated with intracontinental rifting without any subsequent break of the continent. There are many examples of this situation in the geological history of the Earth. It is only in the case of the known sequence of geological events that we can infer the transformation of intracontinental extension to a continent breakup with the formation of an oceanic space. Yet, if in spite of the argued assumptions this sequence of events did exist, then two major episodes of large-scale intracontinental extension can be inferred, the events which could result in the opening of the oceans. The size and role of each stage can be treated as diametrically opposed.

One scenario suggests the rifting, opening, and evolution of an oceanic basin in the time interval of 1300-900 million years. The thick terrigenous-carbonate rock sequences, the fragments of which can be traced along the entire southern flank of the craton, recorded the “Atlantic” phase of the ocean opening. These rock sequences are closely associated with the rifting-related rocks preceding them. The ophiolites and associated island-arc formations in the adjacent regions of the foldbelt with an age of 1100–800 million years correspond to the “mature” stage of the paleoocean evolution. The collision events, corresponding to the closure of the paleobasin or to the large-scale processes of the collision of the terranes with the paleocontinent are recorded, in particular, by the granite gneisses of the Muya Block with the age of 825–790 Ma [*Rytsk et al.,* 2001], by the tonalites of the Tuva-Mongolia microcontinent (812–790 Ma) [*Kuzmichev et al.,* 2001], and also by the collision granites in the northwestern part of the East Sayan, dated 870–860 Ma [*Nozhkin and Turkina,* 2001].

The processes of the second stage (800–500 million years) had different trends in the middle of the Neoproterozoic in the southwestern (East Sayan) and southeastern (Baikal-Patoma) segments of the southern flank of the craton. The Baikal-Patoma segment was dominated by the development of a large back-arc basin, bounded in the south by the volcanic arcs wedging in the SW direction. Characteristic of the East Sayan segment was a wide development of dike swarms and associated rift-related rocks (Karagas Group), recording the processes of a large-scale rifting activity. As follows from the reconstructions for other cratons [*Hoffman,* 1991], this period of time corresponded to the breakup of Rodinia. The Vendian-Early Paleozoic ophiolites and island-arc rocks, abundant in the Central Asia Foldbelt, marked the "mature" evolution stage of the Paleoasian ocean, the final closure of which took place in the Ordovician.

According to the second scenario the first rifting event was not accompanied by the opening of any significant newly formed basin. In this case the ophiolites and associated island-arc rock complexes, as well as the collision-related rocks of the respective age, which occur only in the Central Asian Foldbelt, can be classified as exotic terranes which had been accreted to the Siberian Craton later. The craton itself is believed [Gladkochub et al., 2000, 2001a, 2001b; *Sklyarov et al.,* 2000; *Yarmolyuk and Kovalenko,* 2001] to have been a part of the Rodinia Supercontinent at that time. Whereas the ophiolites and island-arc rock complexes seem to have been formed away from the margin of the Siberian Craton, namely, in the East Gondwana group of terranes, and were associated with the processes of the formation and evolution of the active continental margins in the Precambrian continental massifs, such as the Tuva-Mongolia Microcontinent.

The opening and evolution of the oceanic basin (Paleoasian Ocean), recorded in the structural features of the southern flank of the Siberian Craton, can be placed into the interval of 850–650 million years. The Neoproterozoic dike swarms of the Nersa Complex were intruded into the rocks of Sharyshalgai Ridge during the early extension phases against the background of the growth of a dome-shaped rise of complex morphology, caused by the rising asthenospheric mantle and the thinning of the lithosphere. Because of the cooling of the asthenolith or the relaxation of the extension stresses, the growth of the domal uplift did not result in the formation of an axial rift basin in its central part.

The breakup of the Rodinia Continent and the opening of the Paleoasian Ocean were caused by the development of extension along the two branches of the paleorift. In the East Sayan branch, the Neoproterozoic dike swarms and sills were intruded into the sedimentary deposits of the Karagas Group and into the protrusions of the metamorphic basement.

In the Baikal-Patoma paleorift branch the volcanic activity is recorded by the extrusive rocks of the Khota Formation in the Golousta High, resting as the basal beds in the sedimentary rock sequences of the Baikal Group. The metavolcanics are the relicts of the rifting-related rocks corresponding to the environments preceding the formation of basins in the oceanic (Paleoasian ocean) margin [*Sklyarov et al.,* 2001]. In spite of some differences between these scenarios, they look similar as follows from the data available for the sequences of the Lower Vendian rocks. The characteristics of the latter reflect the environments of the accretion-collision events which took place during the inferred opening and evolution of the Paleoasian Ocean.

The scenarios proposed here for the geological evolution of the southern margin of the Siberian Craton can be treated in a different way in the light of the breakup of the Rodinia Supercontinent. The first of them suggests that the origin of the oceanic basin recorded by the geological rocks of the region concerned took place during the "assembling" of the supercontinent, the events of its breakup being recorded only in the southwestern segment of the cratons's southern flank. This interpretation agrees with the numerous palinspastic maps (for example, the map proposed by *Rogers* [1996]), in accordance with which the segment concerned had been the marginal part of the continent from the very beginning. The second scenario does not reject the rifting processes with the formation of oceanic crust, yet infers them to be local and incomparable in size with the events of the second half of the Neoproterozoic, corresponding to the global breakup of Rodinia.

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