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The most ancient ophiolite of the Central Asian fold belt: U–Pb and Pb–Pb zircon ages for the Dunzhugur Complex, Eastern Sayan, Siberia, and geodynamic implications

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Abstract

Ophiolitic rocks with a zircon age of ~1020 Ma occur in the Dunzhugur complex of East Sayan, Siberia, and are part of a Neoproterozoic to early Palaeozoic segment of the Central Asian fold belt. The most spectacular suite is exposed along the Oka and Bokson rivers, where a complete ophiolite sequence with mantle tectonites, a layered sequence composed of dunite, wehrlite, and pyroxenite, a gabbro section, a sheeted diabase dyke complex and basaltic pillow lavas are exposed. Petrologic and geochemical data suggest that all members of the ophiolite originally belonged to the same cogenetic mafic–ultramafic crustal section and support a supra-subduction zone setting in a fore-arc rifting environment for its origin. Two multigrain zircon size fractions from a plagiogranite are both slightly discordant but yielded a combined mean ^{207}Pb/^{206}Pb age of 1020 ± 10 Ma. Evaporation of three additional fractions of three to four grains each from the same sample produced a mean ^{207}Pb/^{207}Pb age of 1019.9 ± 0.7 Ma that we consider to most closely reflect the time of igneous crystallization of the plagiogranite. This is the oldest ophiolite so far dated from the Central Asian fold belt. The southern margin of the Siberian craton and the palaeo-Asian ocean were established at the end of the Mesoproterozoic, at least 1000 Ma ago. During the time interval 1000–570 Ma, one or several large ocean basins existed between Baltica, Siberia, Kazakhstan, Tarim and northern China, and these blocks are therefore unlikely to have been part of the supercontinent Rodinia. Rifting, initiation of subduction, and marginal basin formation began prior to 1000 Ma and continued through 570 Ma. The Dunzhugur ophiolite of Eastern Sayan provides evidence for the early opening of the palaeo-Asian ocean not later than 1000 Ma ago. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: ophiolite; zircon; absolute age; Siberia; Central Asian; fold belts; Rodinia

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1. Introduction

The southeastern part of the Eastern Sayan Range of southern Siberia (Fig. 1a) is critical to an understanding of the geological history of the entire Central Asian fold belt (CAFB), in Western literature also known as the Altaids [1]. The ophiolite belt exposed in Eastern Sayan is southern Siberia's largest and best preserved relict of the ancient oceanic crust of the palaeo-Asian Ocean [2–4]. The study of this ophiolite and associated allochthonous assemblages provides information on the timing of the inception and evolution of this ocean. The Dunzhugur ophiolite complex constitutes part of this large ophiolitic allochthon. In the course of geological mapping and specialized studies performed in the past (for references see [5]), the ultramafic Ilchir massif and the mafic Bokson gabbro massif were viewed as intrusive and extrusive bodies of separate assemblages of late Neoproterozoic (Vendian) to early Cambrian age: it was not until the early 1980s that Lyashenko [6,7], Dobretsov [8] and Dobretsov et al. [5] identified the ultramafic, gabbroic and associated volcano-sedimentary deposits as an ophiolite assemblage representing fragments of ancient oceanic crust. The age of this ophiolitic assemblage remained unconstrained, however, which led to the present study, which shows the Dunzhugur ophiolite to be the oldest oceanic relict with a precise age identified so far in the entire CAFB.

2. Tectonic setting of the ophiolite belt

Several tectonically dismembered ophiolite complexes are exposed along the margin of a large granite-metamorphic complex, in the Russian literature commonly referred to as the Gargan Block or Antiform (Fig. 1b). Presumably, the ophiolites once formed a continuous nappe overriding the entire Gargan Block [5]. In the present-day structure, the ophiolites make up an allochthon comprising the full spectrum of the ophiolitic lithologies; the allochthon is best preserved at the periclinal closures of the Gargan Antiform and is more fragmentary at its northern and southern flanks. Generally, the allochthon shows a tendency for increasingly shallower levels of the ophiolite suite to become exposed from east (where deep-seated ophiolitic lithologies are found) to west (where the volcano-sedimentary sequence is predominant), i.e., the level of erosion becomes deeper from west to east.

At the eastern closure of the Gargan Antiform, in the Ospino–Kitoi Range (Fig. 1a), the dunite–harzburgite assemblage is predominant, but there are also sporadic minor slices composed of fragments of the sheeted diabase dyke complex and basaltic lava sequence [9]. Furthermore, the geological setup is unique in that an ophiolitic serpentinite mélange is overlain, unconformably, by dolomites of the Gorlyk Formation of late Vendian–early Cambrian age, the contact between them being marked by ophicalcite [10]. This is the only stratigraphic evidence for a pre-Upper Vendian age for the ophiolite assemblage.

Southwest of the Ospino–Kitoi Range, on the southern limb of the Gargan Antiform, a layered magmatic sequence and isotropic gabbros appear in the ophiolite allochthon. Thus, in the area southwest of Lake Ilchir, the two lower allochthonous units make up a complete ophiolite succession, jointly constituting a single tectonic unit [5]. The lower unit displays a transition from pervasively serpentinized peridotites to a dunite–wehrlite–pyroxenite layered sequence; the upper unit comprises layered gabbroic rocks ranging in composition from pyroxenite to anorthosite. In the northeast part of the thrust sheet, equigranular and pegmatitic amphibole gabbro and gabbro–diorite are exposed, possibly corresponding to the isotropic gabbro of other ophiolite complexes [5]. The northern limb of the Gargan Antiform displays a sheeted dyke complex and isotropic gabbros, yet the dominant lithology is ultramafic (serpentinized dunite and harzburgite), in places occurring in stratigraphic continuity with the layered dunite–wehrlite–pyroxenite sequence [5,8].

At the western closure of the Gargan Antiform, where the Bokson River flows into the Oka River (Fig. 2), the ophiolite allochthon consists of virtually the entire ophiolite association with a predominance of a basaltic volcanic section and with flysch-type sedimentary sequences overlying the

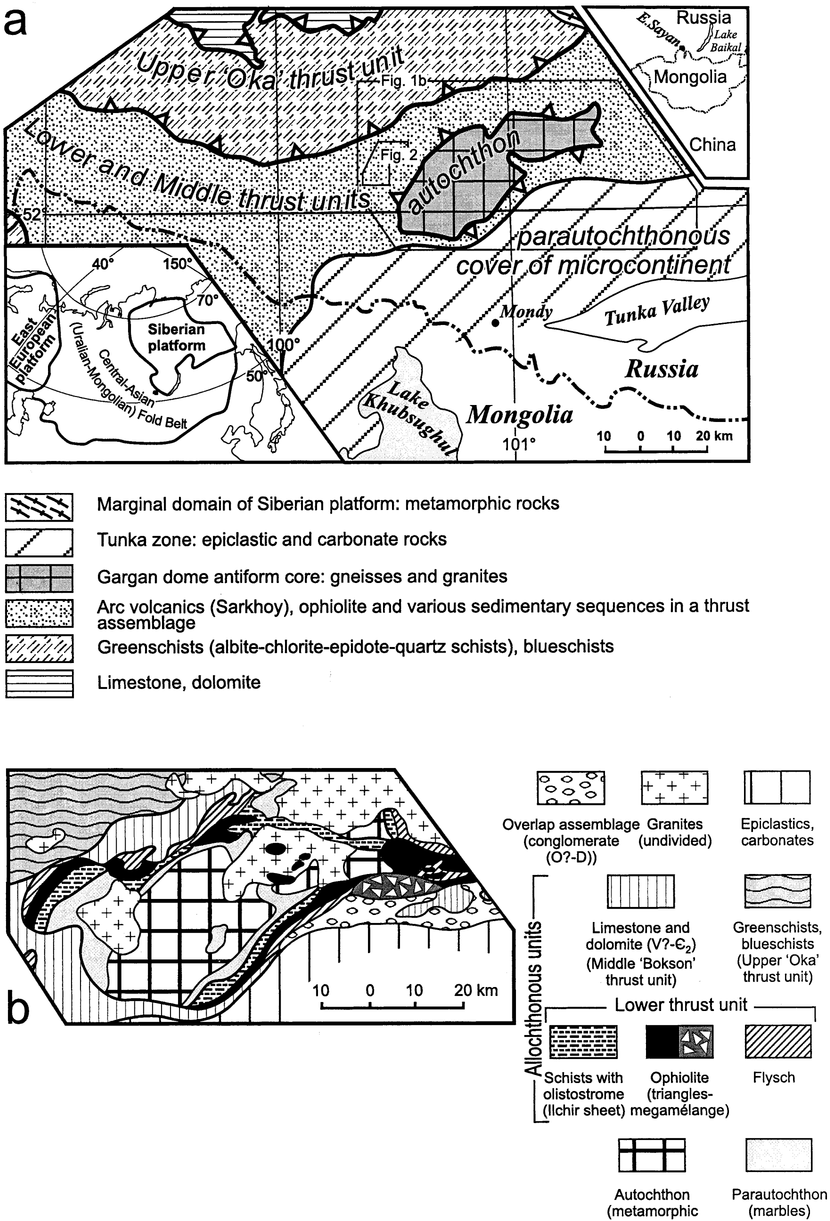

Fig. 1. Main geological units of the southern part of the East Sayan Range (a) and schematic map of the Gargan antiform (b). Inset shows location of East Sayan at the Russian/Mongolian border. Locations of Fig. 1b and 2 are outlined in Fig. 1a.

upper part of the ophiolite suite. The ultramafic section is significantly reduced here. The ophiolitic rocks of the western closure of the Gargan Antiform have been identified under the name Dunzhugur ophiolite [5] (Fig. 2).

The above data show that the Eastern Sayan ophiolite allochthon comprises a complete ophiolite succession: dunites and harzburgites at the base, followed upwards by a layered dunite–wehrlite–pyroxenite–gabbro sequence, then followed by isotropic gabbros, a sheeted diabase dyke complex and pillow lavas, associated with relatively

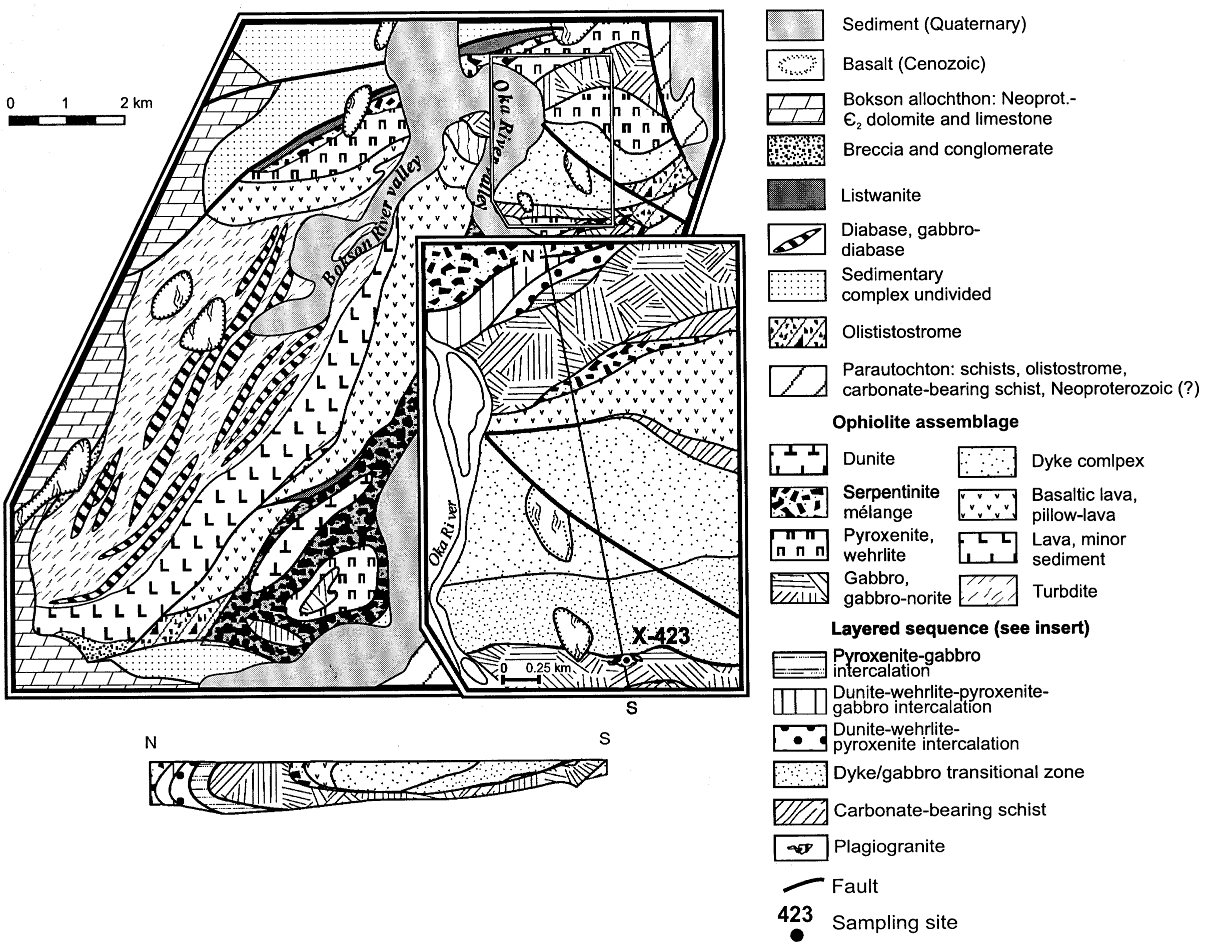

Fig. 2. Generalized map of the Dunzhugur ophiolite area. Inset shows schematic map and cross-section (below map frame) of the northeastern synformal part of the Dunzhugur ophiolite (eastern side of Oka River) with ophiolitic assemblage and sample localities.

deep-water sedimentary rocks (typical flysch), i.e., the Eastern Sayan ophiolites are typical relicts of oceanic crust.

Indirect evidence suggests either an early Neoproterozoic (Riphean) or early to middle Palaeozoic age for the ophiolite suite (Vendian–early Cambrian dolomites with ophicalcites at their contact). However, the timing of the tectonic emplacement of the ophiolite allochthon into a thrust pile consisting of dismembered ophiolitic rocks, island arc volcanics, and various sedimentary sequences along the continental margin of the Gargan Block remains open to discussion [11–14].

In order to elucidate the igneous formation age of the ophiolites, we undertook a radiometric study focusing on the Dunzhugur ophiolite complex. To identify the allochthon's setting and to time its emplacement into the thrust pile, the structure of the entire allochthonous domain in the southeastern part of Eastern Sayan had to be unravelled [13,15].

3. Structure of the Dunzhugur ophiolite

The Dunzhugur ophiolite (Fig. 2, inset) is made up of two parts, each with a distinctive structure.

Its southwestern part consists of two thrust sheets whose lower tectonic contacts dip west and northwest away from the Gargan Block. The lower thrust sheet is composed of a serpentinite mélange containing large blocks that display virtually the entire lithologic spectrum of the ophiolite assemblage. The upper thrust sheet consists of a slice made up of extrusive rocks and a fragment of a coherent section with extrusives in its lower portion, conformably overlain by a dark colored flysch sequence with slump breccias containing ophiolitic clasts and gabbroic sills with mid-ocean ridge basalt (MORB) affinity in its middle portion and varicolored flysch-like siltstones in its upper portion. The sedimentary sequence is referred to as the Dunzhugur Formation.

The northeastern part of the Dunzhugur ophiolite is represented by a dislocated synform (Fig. 2, inset) with its axial plane dipping northwards, away from the Gargan Block (see section at bottom of Fig. 2). The synform is well developed in its eastern part, along the right side of the Oka River. Here, it incorporates two thrust sheets, the lower one made up of a serpentinite mélange and the upper consisting of a wehrlite–pyroxenite–gabbro assemblage and sheeted dykes.

On the northern limb of the synform, the rocks of the upper thrust sheet are represented by rhythmically alternating dunites, wehrlites, pyroxenites and gabbros. Away from the synform's core, the proportion of wehrlites and pyroxenites increases, dunites appear, and the gabbros virtually disappear, in keeping with the overturned attitude of the northern limb (Fig. 2, inset). Among the rocks of the layered sequence there occur intrusive bodies of coarsely and very coarsely crystalline pyroxenites, wehrlites, and gabbros. These bodies have intricately branching shapes; in places they are sill-like and extend along the magmatic layering, locally merging together to become volumetrically predominant over the enclosing layered rocks.

On the southern limb of the synform, the following description was given [16]: "... over a length of 500 m in the gabbro, one can observe how first sparse diabase dykes, 1–3 m wide, appear which gradually become increasingly abundant, and at the end of the section a dyke swarm occurs with sporadic gabbroic screens." In places, the virtually continuous 'section' is tectonically dismembered into tectonic slices; thus, on the synform's northern limb, at the contact between gabbro and sheeted dykes, small tectonic lenses of serpentinite and tectonized carbonate-bearing schists are observed (Fig. 2, inset). The sheeted dyke complex in the upper thrust sheet makes up the core of the synform. It includes two generations of dykes; the first generation is represented by subparallel diabase and microgabbro half dykes with chilled margins striking 310–360°, whereas the second generation dykes have no preferred strike.

The Eastern Sayan ophiolites experienced a complex history, involving: (1) formation of an incipient island arc above a nascent subduction zone in an ancient oceanic basin, (2) detachment from their basement and convergence with the margin of the microcontinent, (3) incorporation into an accretionary prism, (4) burial beneath shelf deposits and, finally, (5) obduction of all the rock complexes onto the microcontinental margin. After ophiolite obduction, the area experienced a dramatic uplift: the carbonate deposits were eroded, and the ophiolites were exposed on the present surface [13,15].

4. Original setting of the Dunzhugur ophiolite

The origin of the ophiolitic assemblage is most conclusively elucidated by the geochemical affinities of the upper part of the ophiolite suite. The sheeted dykes and pillow lavas are most fully developed in the Dunzhugur complex [5,16,17], and two dyke generations were identified. One generation is represented by amphibole diabase, gabbro diabase, and microgabbro, corresponding geochemically to the basalt–andesitic basalt high-Mg, low-Ti tholeiitic series and showing marked Fe enrichment with increasing differentiation index. The other dyke generation is represented by Opx-phyric rocks geochemically matching the high-Mg member of the boninite series [5,16,17].

The extrusive rocks also fall into two rock suites (Table 1). One is composed of Cpx–Pl andesitic basalts and andesites (aphyric, less fre-

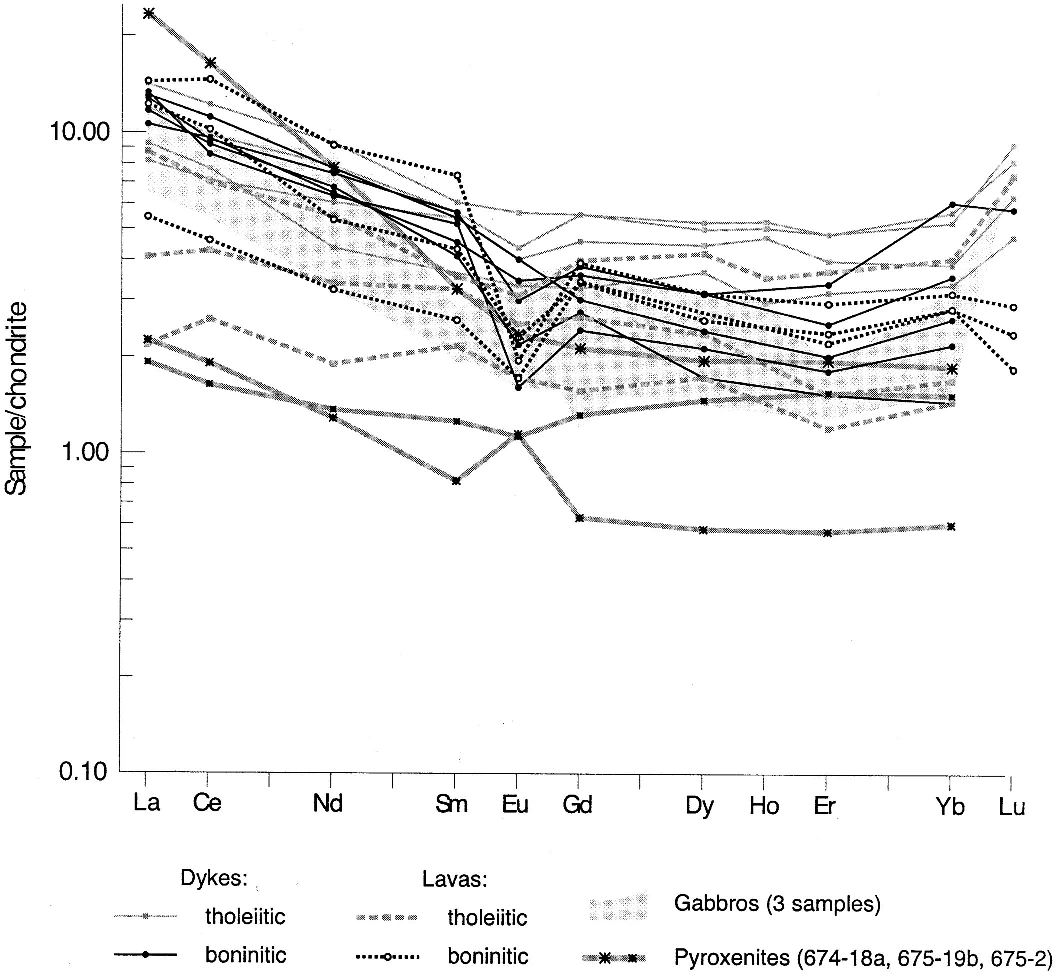

Fig. 3. Chondrite-normalized REE patterns for Dunzhugur ophiolite rocks (data from [16,17] and Table 1). Chondrite composition from [43]. Analyses by neutron activation and isotopic dilution.

quently porphyritic). Geochemically, these rocks resemble the first-generation diabase dykes. The second generation corresponds to the much less common lavas of high-Mg boninite affinity. The high-Mg lavas make up the uppermost part of the section. The rare earth element (REE) spectra for the gabbros, pyroxenites and some dykes and lavas show typical U-shaped boninitic patterns, whereas the remaining dykes and lavas display flat to LREE-enriched patterns typical of T-MORB and arc tholeiites (Fig. 3).

The dunite–harzburgite composition of the metamorphic peridotites suggests that they are Alpine-type restites after high degrees of partial melting of a lherzolite mantle [18]. Precisely this restite type is complementary to the low-Ti and boninitic Dunzhugur volcanic rocks in the context of a petrogenetic model that accounts for the petrographic composition of the peridotites, layered sequence, and gabbros, combined with the volcanic chemistry [19]. This implies that all members of the Dunzhugur ophiolite originally belonged to the same cogenetic mafic–ultramafic crustal section. The lavas and dykes are compatible with the low-Ti ophiolite type, whose formation is attributed to the primitive stages of intra-

Table 1
Major, trace and rare earth elements for rocks of the Dunzhugur ophiolite[a]

	Ophiolite dykes									Ophiolite lavas						Ultramafic rocks		
Sample:	3552v	3552j	3553e	3556g	3051	3059	3122b	3554a	3554b	2567v	2567d	2577a	6089v	6093d	6096	674-18a	675-19b	675-2
Rock type:	tholeiitic				boninitic					tholeiitic			boninitic			pyroxenite		
SiO_2	52.44	52.46	56.16	55.3	53.28	53.64	51.68	52.74	59.78	52.38	56.24	52.94	54.7	51.28	56.88			
TiO_2	0.26	0.34	0.46	0.37	0.18	0.23	0.23	0.21	0.24	0.36	0.4	0.35	0.21	0.14	0.14			
Al_2O_3	14.85	16.03	14.84	14.66	10.1	8.83	11	8.06	11.34	15.09	15.92	15.06	14.6	9.52	11.32			
Fe_2O_3	0.79	1.32	3.67	0.56	2.04	1.36	1.21	1.48	1.51	3.35	2.12	2.36	1.69	4.01	1.88			
FeO	6.39	6.56	6.05	8.34	6.19	7.02	7.36	6.18	4.98	4.9	5.39	5.18	3.64	4.61	5.58			
MnO	0.14	0.17	0.1	0.12	0.15	0.18	0.16	0.14	0.11	0.2	0.11	0.15	0.1	0.12	0.13			
MgO	8.12	7.27	4.11	5.77	14.65	15.9	13.68	17.9	10.14	7.14	5.66	6.11	11.39	13.6	12.37			
CaO	8.15	7.09	7.62	6.32	4.5	5.81	6.93	5.95	4.05	5.48	4.11	7.1	3.79	6.72	3.45			
Na_2O	2.83	3.55	2.51	3.7	1.64	1.57	2	0.19	3.35	3.72	4.09	4.01	4.23	3.01	3.26			
K_2O	1.62	1.34	0.14	0.32	0.28	0.06	0.1	0.05	0.15	0.54	0.63	0.72	0.2	0.65	0.65			
P_2O_5	0.04	0.04	0.05	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.01	0.02	0.02	0.02	0.02			
LOI*	3.75	3.71	3.81	3.99	6.55	5.38	5.48	6.65	3.95	6.22	4.69	5.29	5.5	5.97	4.58			
Total	99.38	99.88	99.52	99.49	99.6	100.01	99.86	99.59	99.64	99.41	99.37	99.29	100.07	99.65	100.26			
Sr	65	57	16	160	49	32	27	19	68	170	200	200	65	57	32			
Cr	230	170	270	430	1100	650	910	1300	430	82	70	82	190	650	860			
Co	31	44	31	35	44	40	31	31	31	40	34	35	32	49	40			
Ni	74	68	40	57	300	200	110	320	110	51	37	58	72	590	220			
V	64	82	25	82	25	25	25	25	100	84	77	63	150	130	130			
La	3.4	3	5.2	4.4	4.9	4.8	3.9	4.7	4.3	1.5	0.8	3.2	2	5.3	4.5	8.57	0.825	0.706
Ce	7.4	6.8	11.7	9.4	8.2	10.7	9.2	9.1	8.8	4.1	2.5	6.7	4.4	14	9.8	15.7	1.83	1.57
Nd	3.1	4.3	6.6	5.6	4.5	5.5	4.6	5.3	4.8	2.4	1.35	3.9	2.3	6.5	3.8	5.53	0.918	0.971
Sm	tr	1.25	1.4	1.3	1.2	1.25	1.05	1.3	0.95	0.75	0.5	0.82	0.6	1.7	1	0.752	0.190	0.290
Eu	0.29	0.35	0.49	0.38	0.14	0.35	0.3	0.26	0.19	0.22	0.15	0.27	0.15	0.17	0.2	0.205	0.100	0
.0977																		
Gd	1	1.4	1.7	1.7	0.74	0.92	1.1	1.17	0.84	0.81	0.48	1.22	1.05	1.2	1.04	0.652	0.194	0.405
Dy	1.4	1.7	2	1.9	0.81	0.92	1.2	1.2	0.66	0.9	0.66	1.6		1.2	0.99	0.742	0.222	0.560
Ho	0.25	0.4	0.45	0.43								0.3						
Er	0.79	0.99	1.2	1.2	0.45	0.5	0.63	0.84	0.38	0.38	0.3	0.92	0.55	0.73	0.59	0.484	0.142	0.386
Yb	0.83	0.96	1.3	1.4	0.54	0.65	0.88	1.5	0.36	0.42	0.36	1	0.7	0.78	0.7	0.461	0.148	0.378
Lu	0.18	0.24	0.35	0.31				0.22				0.28	0.07	0.11	0.09			
Y	7.6	9.6	11.8	11.5	4.5	4.4	6.1	7.9	3.2	3.5	2.9	9.9	4.2	7.5	7			

[a] Major and trace elements by X-Ray fluorescence spectrometry [17]. REE of pyroxenites by isotope dilution at IGEM, Moscow. *LOI = loss on ignition.

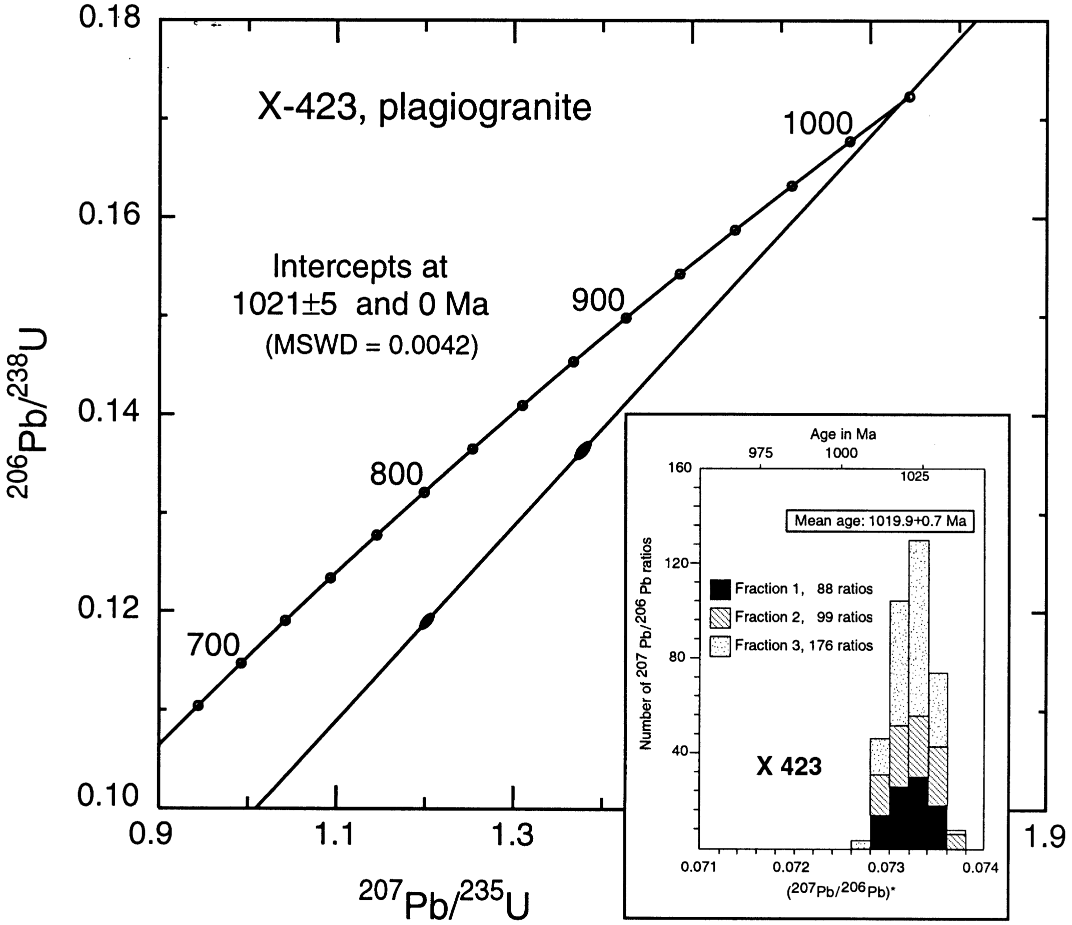

Fig. 4. Concordia diagram for multigrain zircon fractions of plagiogranite sample X-423, Dunzhugur ophiolite, East Sayan, Siberia. Inset shows histogram with distribution of radiogenic lead isotope ratios derived from the evaporation of three small zircon fractions of three to four grains each from same sample.

oceanic island arc, fore-arc and back-arc basin formation [19–21,58]. The major element trends for the diabase dykes (Table 1) are similar to the Tonga primitive arc volcanic rocks [22]. The isotropic gabbros are also classified with the low-Ti ophiolitic gabbro of the Serri and the Saitta [23]. The lithologic spectrum of the layered sequence, including the boninitic rocks, and the crystallization sequence observed in it are typical of supra-subduction zone ophiolites, where aqueous fluids played an important role in magma genesis [24]. Therefore, the available petrologic and geochemical data lend further support to the supra-subduction zone affinity of the Dunzhugur ophiolite [5]. The characteristics of the flysch/slump deposits overlying the volcanic rocks, similar to the Great Valley Series in the Coast Ranges fore-arc ophiolite of California [58] may indicate that the upper part of the ophiolite suite formed near the submarine slope of a volcanic arc.

5. Geochronological study

We selected a plagiogranite from a small intrusive body at the contact between gabbro and sheeted dykes (Fig. 2, inset) for radiometric study, using the U–Pb and Pb–Pb systems for zircon dating.

Zircons were separated from a ca. 100 kg plagiogranite sample (no. X-423, for location see Fig. 2, inset) and are represented by small, stubby (below 90 μm), semi-transparent or opaque, short-prismatic grains; transparent grains were rare. Two-grain-size zircon separates were analyzed by the conventional U/Pb multigrain technique, using a Cameca TSN 206A mass spectrometer at the Vernadsky Institute in Moscow (Table 2). Analytical methods followed [25]. U and Pb concentrations were measured by isotope dilution using a mixed ^{208}Pb–^{235}U tracer. The total blank was 0.1 ng Pb.

The 75 μm grain-size fraction was pre-treated with nitric acid, which often enhances the degree of concordance. However, discordant ages were obtained for both fractions (Table 2). When plotted on a discordia line in a Concordia diagram that is forced through the origin (MSWD = 0.0042), the intercept age is 1021 ± 5 Ma (Fig. 4) [41]. More conservatively, the mean age calculated from the ^{207}Pb/^{206}Pb ratios of both fractions is 1022 ± 10 Ma. The large error is due to the high common Pb correction. Because the zircons showed no cores under the microscope, and since cores are rarely found in zircon grains so small, the date of ~1021 Ma is considered to reflect the minimum age of plagiogranite intrusion.

To verify the above zircon age, three small zircon fractions of three to four grains each from the same sample were analyzed by evaporation [26] at the Max-Planck-Institut für Chemie in Mainz. For analytical details see [27]. The combined mean age resulting from 363 measured ^{207}Pb/^{206}Pb ratios is 1019.9 ± 0.7 Ma (Table 3, Fig. 4, inset, error is $2\sigma_{mean}$). This age is identical to, but more precise than, the conventional age and provides a reliable constraint for the igneous crystallization of the plagiogranite. The uppermost Middle Riphean age (the boundary between Middle and Upper Riphean is ca. 1000 Ma) for the Dunzhugur ophiolite is the oldest so far determined for any ophiolite in the CAFB.

Table 2
U–Pb isotopic data for two zircon fractions from plagiogranite sample X-423

Number	Size fraction (μm)	Weight (g)	U (ppm)	Pb (ppm)	^{206}Pb/^{204}Pb^{m}	^{207}Pb/^{206}Pb^{c}	^{206}Pb/^{238}U^{c}	^{207}Pb/^{235}U^{c}	^{206}Pb/^{238}U age and error	^{207}Pb/^{235}U age and error	^{207}Pb/^{206}Pb age and error	Corr. coeff.
1	+75	0.0008	471.7	77.08	372.5 ± 3.5	0.07328 ± 70	0.1364 ± 3	1.378 ± 2	824 ± 2	880 ± 10	1022 ± 33	0.63
2	−75	0.0042	63.32	8.47	560 ± 6	0.07333 ± 50	0.1190 ± 3	1.202 ± 1	725 ± 2	802 ± 8	1023 ± 22	0.55

m = measured ratio; c = ratio corrected for common lead at 1000 Ma [42], spike, fractionation and blank. All errors are 2σ.

6. Discussion and conclusions

The age and tectonic emplacement history of the Dunzhugur ophiolite allochthon is especially important for unraveling the evolution of the eastern segment of the CAFB. For this purpose, it is critical to consider the setting of the Dunzhugur ophiolite in the general fold-and-thrust stratigraphy of Eastern Sayan and to discuss the available data obtained from areas adjacent to the Siberian craton (Fig. 5).

In the present-day East Sayan structural setting, the allochthonous complex forms limbs of an antiform. In its core, or the autochthon, the Mesoproterozoic basement is exposed that was remobilized in Ordovician time [51]. The parautochthon is represented by shelf carbonate platform deposits of Neoproterozoic age. Within the Sayan allochthon, three nappe assemblages were identified (Fig. 1a).

The lower nappe assemblage comprises three thrust sheets: Ilchir, Ophiolitic, and Sarkhoy, as shown in Fig. 1a. The Ilchir thrust sheet incorporates schistose basalts, andesites and volcano-sedimentary and sedimentary deposits. Locally, olistostromes with ophiolitic and carbonate olistoliths are found. The ophiolitic thrust sheet comprises rocks typical of the ophiolite assemblage and flysch sequences of Neoproterozoic and early Palaeozoic age. The Dunzhugur complex is a segment of an ophiolite belt. The Sarkhoy thrust sheet is composed of a volcano-sedimentary arc-like rock association. The age of the volcanic rocks is ~700 Ma [35], the volcanomictic strata being of likely younger age. The middle thrust assemblage incorporates carbonate deposits of the Bokson Group and related sequences of late Vendian–early Cambrian age. The upper (Oka) thrust assemblage contains tectonically juxtaposed lithologically and temporally contrasting units: Neoproterozoic volcanics and sediments and Ordovician–Silurian sediments.

Based on the rock composition of the parautochthon and thrust sheets, one may reconstruct the following settings: (i) a continental shelf and slope, (ii) an incipient island arc and contiguous basins, (iii) an accretionary prism, (iv) an evolved island arc and (v) an obduction zone.

The above data elucidate a complex scenario for the emplacement of the ophiolites and associated rock assemblages of Eastern Sayan. Conceivably, by the end of the Mesoproterozoic, at about 1000 Ma, an incipient volcanic arc was initiated on the pre-existing oceanic crust (most likely of the palaeo-Asian Ocean) above a nascent subduction zone.

At least 800 Ma ago, in the marginal part of the basin and on the shelf and slope of the Khamardaban–Gargan microcontinent, sedimentary sequences accumulated that are preserved in the present-day structure of southern Eastern Sayan, in the Ilchir thrust sheet, and in the parautochthon. The basement and cover of the microcontinent, at ca. 800 Ma, in a supra-subduction zone setting, were intruded by tonalites and trondhjemites of the Samsunur Complex [55], pointing to

Table 3
Isotopic data and ages from evaporation of three small zircon fractions of plagiogranite sample X-423

Sample number	Zircon color and morphology	Grain number[a]	Mass scans[b]	Evaporation temperature (°C)	Mean ^{207}/Pb/^{206}Pb ratio[c] and 2σ error[d]	^{207}Pb/^{206}Pb age and 2σ error
X-423	clear to yellow-brown, long and short prismatic	1	88	1590	0.073203 ± 46	1019.6 ± 1.3
		2	99	1587	0.073224 ± 51	1020.6 ± 1.4
		3	176	1594	0.073218 ± 27	1020.0 ± 0.7
Mean of three grain fractions		1–3	363		0.073213 ± 22	**1019.9 ± 0.7**

[a] Each fraction consisted of three to four grains ~20–25 μm in length.

[b] Number of ^{207}Pb/^{206}Pb ratios evaluated for age assessment.

[c] Observed mean ratio corrected for non-radiogenic Pb.

[d] Errors based on uncertainties in counting statistics and at the 2σ (mean) level, i.e., $2\times$S.D./$\sqrt{n}-1$.

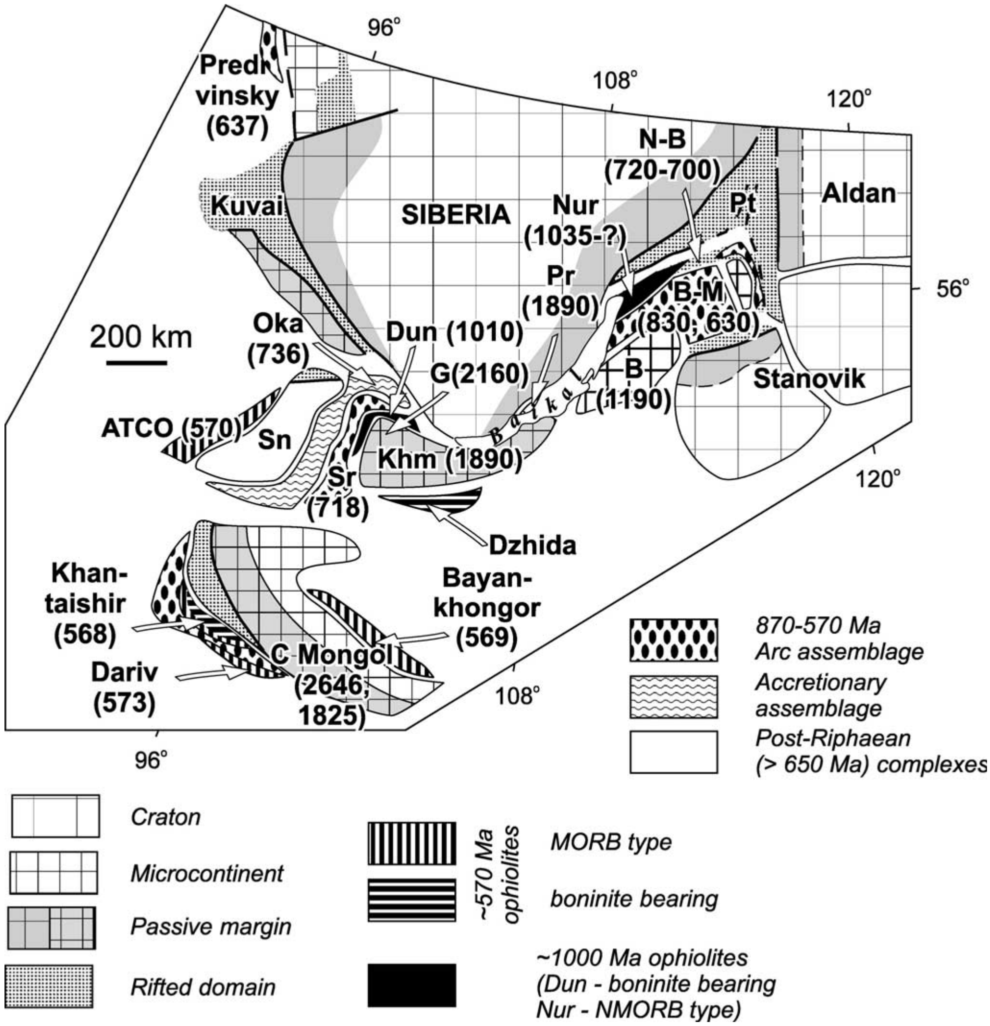

Fig. 5. Main tectonic units of the palaeo-Asian ocean (present reference frame) at 1000–570 Ma. For the period 670–570 Ma, ophiolite complexes alone are shown. Compiled by A.S. Gibsher and E.V. Khain. ATCO = Agardagh-Tes Chem ophiolite [39], B = Barguzin (U–Pb method on zircons [44]), B-M = Baikal–Muya (Nd–Pb–Sr data, U–Pb method on zircons, [32,45,46]), Bayankhongor [36], C Mongol = Central Mongolian (U–Pb method on zircons and Sm–Nd data, [47–49]), Dariv (U–Pb method on zircons, Sm–Nd data [37,50]), Dun = Dunzhugur (this study), G = Gargan (U–Pb method on zircons and Pb–Pb data on minerals and WR [51,52]), Khantaishir (U–Pb method on zircons, [38]), Khm = Khamar-Daban (Pb–Pb data [53]), N-B = North-Baikalian (U–Pb method on zircons, Nd–Sr–Pb data [33,54]), Nur = Nurundukan suite [31], Oka [55], Sn = Sangilen, Sr = Sarkhoy [35], Predivinsky [56], Pr = Priolkhon'e [57], Pt = Patom. Numbers indicate radiometric age in Ma.

the inception of a subduction zone that was inclined beneath the margin of the microcontinent. This gave rise to an accretionary wedge. During the first part of the late Riphean, the deformed assemblages of the incipient Dunzhugur volcanic arc were probably accreted onto this zone.

For the next stage (the second half of the late Riphean), based on data from Eastern Sayan, one may reconstruct the evolved Sarkhoi ensimatic volcanic arc and related basins. At the end of Neoproterozoic time, formation of carbonate deposits of the Bokson Group began on the shelf of the microcontinent, and the ophiolites and related assemblages of the accretionary prism were buried beneath the shelf deposits. The Ordovician structural rearrangement was accompanied by ophiolite obduction, voluminous granitic intrusions, and remobilization of the margin of the Khamardaban–Gargan microcontinent [51]. Finally, deformation continued into Carboniferous time.

In summary, the Eastern Sayan ophiolites experienced a complex history, involving: (1) formation of incipient arc in an ancient oceanic basin, (2) detachment from their basement and convergence with the margin of the microcontinent, (3) incorporation into an accretionary prism, (4) burial beneath shelf deposits and, finally, (5) obduction of all rock complexes onto the microcontinental margin, probably due to ephemeral ridge subduction and slab break-off. After ophiolite obduction, the area experienced a dramatic event of metamorphism, granite magmatism, and uplift as a result of slab breakoff: the carbonate deposits were eroded, and the ophiolites were uplifted and exposed on the present surface. The stratigraphic succession and the early stages of development of the East Sayan ophiolites are remarkably similar to the Coast Range ophiolite of California [58], but the East Sayan ophiolites seem to have experienced a rather more protracted history.

It is critical to define the role of the Eastern Sayan ophiolites in the regional structure of the CAFB and the tectonic history of this area. There is accumulating evidence that the Siberian Craton, with its Archaean and palaeoproterozoic basement, is surrounded in the north, west, southwest and southeast by Neoproterozoic and possibly Mesoproterozoic belts of ophiolites and subduction related complexes, extending from the Taimyr Peninsula through the Yenisey Range and Eastern Sayan to the Baikal–Muya fold belt and the Amur River basin (Fig. 5) [10]. This conclusion is of importance because it shows that the ancient nucleus of Siberia was already isolated in Neoproterozoic time, and the palaeo-Asian ocean had opened. The outcrops of this Circum-Siberian belt are discontinuous, forming segments separated by areas covered by much younger platform deposits. The Dunzhugur ophiolite complex constitutes the southern segment of this belt. It is possible that the Eastern Sayan ophiolite belt extended eastwards through a triple junction and farther through the Olkhon region of the Lake Baikal basin where it joined the Baikal–Vitim (Muya) zone (B-M in Fig. 5). In this region Neoproterozoic successions with passive and active margin attributes of the palaeo-Asian ocean have been described [29,30].

During the Neoproterozoic, the rifted passive margins along the Siberian Craton and the microcontinents were transformed, at different times and in different places, into active margins with the formation of volcanic arcs as well as back-arc and intra-arc basins. A Riphean full ophiolite sequence including mantle tectonites is only exposed in Eastern Sayan, whereas the other segments of the Neoproterozoic Circum-Siberian belt only contain fragments of serpentinized peridotite, gabbro and pyroxenite, as well as fragments of sheeted dykes and pillow lavas. The oldest ages (besides the Dunzhungur ophiolite) have been obtained from the Nurundukan suite in the Kicherskaya zone of the Baikal–Muya fold belt (Fig. 5). Four bulk metabasalt samples with N-MORB geochemical affinities correspond to a Sm–Nd age of 1035 ± 92 Ma with $\varepsilon_{\mathrm{Nd(t)}} = 7.1$ [31]. A U–Pb zircon age of 790 ± 5 Ma was obtained for a trondjhemite intruding the metabasalts (E.Yu. Rytsk, personal communication, 2000). However, no ophiolite assemblage has so far been identified in the Kicherskaya zone.

There are more abundant data for the interval between 850 and 600 Ma, obtained mostly from subduction-related complexes. At that time the margins of the palaeo-ocean became sites of new large island arc systems and back-arc basins. In the northern Baikal area, Sm–Nd isochron ages of 830–850 Ma were obtained from subduction-related gabbros [32]. Younger stages of subduction zone magmatism in this area are marked by a layered peridotite–pyroxenite–gabbro massif with Sm–Nd isochron ages of 735 ± 26 Ma and 704 ± 40 Ma respectively [33], and 630–620 Ma [32,34]. In Eastern Sayan and northern Mongolia, felsic volcanics of the Sarkhoy–Darkhat volcanic arc yielded a Rb–Sr age of 720 Ma [35].

The time around 570 Ma is characterized by several well documented full ophiolite sequences in the southern part of the belt in western Mongolia (Fig. 5). The ages of the ophiolite complexes at Bayankhongor [36], the Khantaishir Range [37,38], the Dariv Range [37] and the Agardag zone in southern Tuva [39] are all 570 ± 5 Ma, based on the Sm–Nd whole-rock method and the U–Pb and Pb–Pb methods on zircons. New paleomagnetic data for southern Siberia and western Mongolia [40] suggest that the Mongolian terranes were already adjacent to Siberia by the late Vendian and early Cambrian and that this period marks the end of the closure of this part of the palaeo-Asian ocean and could account for the occurrence of late Vendian to early Cambrian ophiolites in the region than were thrust over the passive margins of adjacent microcontinents.

All the data listed above lead to the conclusion that the margins of the Siberian continent and the palaeo-Asian ocean were established not later than the beginning of the Neoproterozoic, and possibly somewhat earlier, towards the end of Mesoproterozoic, more than 1000 Ma ago. Data from the Timan–Pechora region, the Polar Urals and Central Kazakhstan belonging to the opposite, western, side of the ocean (in modern coordinates) confirm this conclusion [37]. During the time interval 570–1000 Ma one or several large ocean basins existed between Baltica, Siberia, Kazakhstan, Tarim, and Northern China. Therefore, these blocks were isolated, and no continuous Rodinia supercontinent can be reconstructed at that time, in line with recent paleomagnetic evidence as summarized in [59]. The existence of at least one of these ocean basins is documented by the late Mesoproterozoic–late Neoproterozoic Circum-Siberian belt of ophiolites and subduction-related complexes. Rifting, ocean opening, initiation of subduction and marginal basin formation began more than 1000 Ma ago and continued through 570 Ma. The Duzungur ophiolite of Eastern Sayan provides evidence for the early opening of the palaeo-Asian ocean at least 1000 Ma ago.

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