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GEOLOGY

Early Stages of the Paleoasian Ocean Formation: Results of Geochronological, Isotopic, and Geochemical Investigations of Late Riphean and Vendian–Cambrian Complexes in the Central Asian Foldbelt

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The term "Paleoasian Ocean" designates a system of different-age structures formed within the oceanic lithosphere. They were accreted to the Siberian Craton to form the Central Asian Foldbelt (CAFB) in the course of the Caledonian, Hercynian, and Indosinian epochs of tectogenesis. The appearance of the CAFB is related to the breakup of the Rodinia supercontinent [1, 2] and, in particular, to the breakup of its Laurasian segment into the Siberian and Laurentian cratons [3]. The early stages of development of the paleocean are represented by geological events occurring since the paleocean initiation until the Caledonian tectogenesis. Results of these processes are imprinted in the structure of the Caledonian fold zone. The fold zone is characterized by a mosaic structure related to the combination of large angular terranes of the Precambrian crust and Caledonian linear fold zones. The fold zones envelop the terranes to make up a joint framework of the fold zone (Fig. 1). Issues of the timing of the paleocean, the link of Precambrian terranes with the paleocean evolution, and the conditions of their accretion with the Caledonides remain controversial. In the present communication, these issues are discussed in connection with the problem of identification of the major temporal boundaries in the paleocean evolution based on the latest geochronological, isotopic, and geochemical investigations of magmatic, metamorphic, and sedimentary rocks in different structural zones of Caledonides of the CAFB.

Precambrian terranes commonly include rock complexes of different ages and tectonic styles. The subordinate Early Precambrian rocks make up the Gargan and Tarbagatai blocks and the Dzabkhan microcontinent (Fig. 1). The more widespread Riphean complexes are mainly composed of terrigenous–carbonate sequences that are metamorphosed to gneisses and marbles in some places [4]. Isotopic investigations of granites, which intrude into the Riphean sequences, showed that the dominating Nd model age T_{Nd}(DM-2st) of granitic melt sources ranges from 1.7 to 1.0 Ga [4]. This type of granite composition testifies to the limited participation of Early Precambrian sources in the crust of the majority of terranes. Hence, the origination of such a crust was primarily related to Riphean epochs of crust formation, including the Grenville, Early Baikalian, and Late Baikalian episodes.

Recently, Grenvillides have reliably been established in some sectors of the South Gobi microcontinent [5]. Early and Late Baikalides are more widespread. The early Baikalides are represented by fragments of the oceanic crust and island arcs in the Tuva–Mongol massif (Dunzhugur and Shishkhid zones) and the Baikal–Muya belt (Kicher and Param-Shaman zones). These structures began to appear at the beginning of the Late Riphean [6, 7]. The final stages of their evolution were marked by the folding and metamorphism 800 Ma ago and the postcollisional granitoid magmatism 785 Ma ago as a result of accretion with structures of Rodinia (table). Late Baikalian events are recorded by the continental-margin and island-arc associations formed 720–590 Ma ago (Sarkhoi and Oka zones of the Tuva–Mongol massif, Baikal–Muya belt, and Cis-Dvina and Isakov terranes of the Yenisei Ridge) [6–8].

The conditions and sites of the formation of Precambrian terranes are indicated by the isotopic composition of terrigenous rocks developed in the study region. They are characterized by a lower share of the ancient crustal material relative to coeval sediments at the Siberian Craton margin [7]. For example, cratonic rocks in the Baikal–Patom belt have lower $\varepsilon_{Nd}(T)$ values (from

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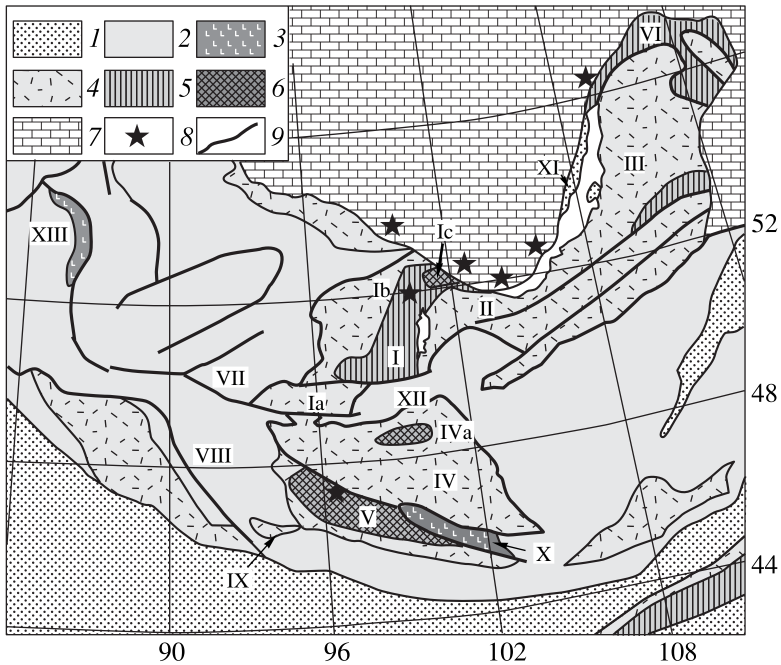

Fig. 1. Schematic structure of the Central Asian Foldbelt. Tectonic structures: (*1*) Hercynian and Indosinian; (*2–6*) Caledonian fold zone: (*2*) domains of Vendian–Cambrian ophiolitic and island-arc complexes, (*3*) domains of Late Riphean ophiolites (relicts of oceanic lava plateau), (*4–6*) terranes of the Precambrian crust: (*4*) undivided Riphean, (*5*) with the participation of the Grenvillian and Early Baikalian structures, (*6*) blocks of the Early Precambrian crust; (*7*) Siberian Craton; (*8*) magmatic complexes (indicators of riftogenic zones related to the breakup of Rodinia; (*9*) faults. (I–V) Precambrian terranes: (I) Tuva–Mongol: (Ia) Sangilen segment, (Ib) Oka–Shishkhid segment, (Ic) Gargan block; (II) Khamar-Daban and Slyudyanka; (III) Barguzin; (IV) Khangai: (IVa) Tarbagatai block; (V) Dzabkhan; (VI) Baikal–Muya belt; (VII–XIII) domains of ophiolites and island-arc complexes: (VII) Tannuola–Kaakhem, (VIII) Ozernaya (Khirgisnur), (IX) Ozernaya (Daribi), (X) Bayan-Khongor, (XI) Ol'khon, (XII) Dzhida, (XIII) Kuznetskii Alatau.

–17.8 to –5.7). Their Nd model age T_{Nd}(DM-2st) ranges from 3.0 to 2.0 Ga. In terrigenous rocks of terranes, ε_{Nd}(T) varies from –6 to +4.2, while T_{Nd}(DM-2st) = 1.9–1.0 Ga. In addition, geochemical characteristics of the Vendian–Cambrian carbonate cover in the studied terranes suggest the prevalence of island-arc rocks in the provenance [9, 10]. Thus, the data presented above indicate that sediments of terranes were primarily deposited in distal zones of ancient cratons. Initially, they were accumulated on the cratonic shelf zones. Beginning from the terminal Late Riphean, sediments also accumulated beyond the shelf zones, where their composition was largely governed by erosion products from island arcs and oceanic islands.

Some terranes probably began to form as independent structures as a result of the breakup of Rodinia, which is recorded by many events in the study region. The table presents structures corresponding to these events. At margins of the Siberian Craton, they are represented by dike belts (780–740 Ma), grabens with bimodal magmatism (e.g., Olokit graben, 727–673 Ma), and plutonic chains of ultrabasic alkaline rocks with carbonatites (655–630 Ma) [5]. These signatures of breakup are consistent with the manifestation of rifting in other sectors of Rodinia. For example, dike belts are synchronous with the second phase of rifting in the Yangtze and Australian cratons [11]. The formation of grabens and alkaline complexes corresponds to the timing of the Franklin magmatic belt [3]. Traces of the rifting episode mentioned above are also imprinted in Precambrian terranes of the CAFB (table). A chain of layered anorthosite–gabbro and harzburgite–pyroxenite–gabbro massifs appeared 735–723 Ma ago within the Baikal–Muya belt [7]. Approximately 760 Ma ago, the Oka accretionary prism of the Tuva–Mongol massif was intruded by sills of the N-MORB type under the influence of a mantle plume [6]. Our unpublished data indicate that the Dzabkhan trachyrhyolite–alkaline granite series appeared at the margin of the Dzabkhan microcontinent approximately 670 Ma ago. The temporal coincidence of rifting in cratons and CAFB terranes indicates that the formation of terranes is related to the breakup of the supercontinent.

Among the *Caledonian folded structures* (Fig. 1), the oldest structures are represented by ophiolites of the Bayan-Khongor and Kuznetskii Alatau zones [12, 13]. Rocks of these zones were formed simultaneously with rifting in southern Siberia 665 and 694 Ma ago, respectively (table). The ophiolites are mainly composed of high-Ti (TiO_2 > 1.8%, up to 3% in some places) basalts. Their geochemical characteristics are similar to those of oceanic plateau basalts of the Ontong–Java type [12]

Formation setting and timing (Ma) of magmatic and metamorphic complexes in Caledonides of the CAFB

Terranes, zones, and structures		Geodynamic setting									
		divergent boundaries and within-plate				convergent boundaries (island arcs and ACO)			accretionary and collisional		postaccretionary
		terranes and platform	MOR, oceanic plateau, and islands						including within-plate structures (shown in bold)		
		2	1	2	3	1	2	3	1	3	4
Siberian Craton											
Olokit graben		727–673									
Bodaibo trough								500–600			
Urik-Iisk graben		654–630									
Sharyzhalgai dikes		780–740									
Precambrian terranes											
Baikal–Muya belt	a)		~1000			1000–814	730–720		815–784		
	b)	735–723					665–604	590–550		580–525	470–430
Oka–Shishkhid fragment of the TMM	a)		~1000			1020–800			800		
	b)	750–736					720			**525**	490–460, **490–420**
Sangilen fragment of the TMM					V_1/V_2			536		510–489, **515**	489–460, **490**, **465**, **445**
Khamar-Daban										488	480–470, **474**, **460**
Dzabkhan		665						565–540		514, 470	
Ophiolite and island-arc zones											
Bayan-Khongor				670				570		500–>470	
Kuznetskii Alatau				694				>544			490–450, **510–452**
Shishkhid				>630						600–565	494
Tannuola–Kaakhem								569		510–490	457–450
Ozernaya					~570			545, 520		495, **530**	
Daribi								573		510, 490	464
Ol'khon					V–Є			585		505–485, **500**	461, **500**, **484**, **463**
Dzhida					V–Є			V–Є		508	480

Note: Terrane complexes are subdivided into (a) early and (b) late Baikalides according to [6, 7]. Columns 1–4 present groups of the following coeval events: (1) formation of Early Baikalian structures, (2) breakup of Rodinia and formation of Late Baikalides, (3) convergence and accretion within the paleocean, (4) postaccretionary magmatism. Based on [1–5, 7, 10, 12–15].

and plume sources of magmatism. The Nd isotopic composition $\varepsilon_{Nd}(T)$ in rocks of the Bayan-Khongor Complex ranges from +7.5 to +12.3. In contrast to volcanic rocks, $\varepsilon_{Nd}(T)$ in sediments of this complex varies from –3.5 to –2. These values correspond to a mixture of erosion products of rocks of lava plateaus and the ancient continental crust. Hence, the oceanic basin was small during the formation of the lava plateau, and the continental runoff had a significant influence on the composition of sediments.

The boundary of ~570 Ma was an essential landmark in the history of Caledonides (table). This boundary can be considered the starting point of paleocean formation based on the timing of the following rock complexes of ophiolite zones (Ma): Tannuola (569), Daribi (573), Khan-Taishiri (570), Ozernaya (>545), Kuznetskii Alatau (>544), and Dzhida and Ol'khon (Vendian–Lower Cambrian [10]). However, the rock associations usually include andesites and low-Ti basalts (TiO_2 <1.5%, Ta–Nb minimum), which are typical of subduction zones. This age boundary also includes several oceanic islands, where high-Ti basalts make up allochthonous packages tectonically juxtaposed with island-arc complexes (Ozernaya, Tannuola, Dzhida, and Kuznetskii Alatau zones). Sedimentary rocks associated with both groups of volcanic complexes are characterized by $\varepsilon_{Nd}(T)$ values ranging from +5.6 to +8.6. These values are similar to those in volcanic rocks (from +6.4 to +9.9) related to mantle (juvenile) sources [4, 10]. The influence of external provenances, in particular ancient continents, was insignificant. Hence, the rock associations discussed in this paper formed in offshore zones located away from ancient continents.

The age interval mentioned above includes the formation of rock complexes of active margins at boundaries of the Dzabkhan microcontinent (562 and 546 Ma) [14] and Baikal–Muya belt (590–550 Ma) [7]. Folding and metamorphism took place along the eastern boundary of the Tuva–Mongol massif in the Early–Late Vendian time (i.e., approximately 580–570 Ma ago) [6] and in the Bodaibo trough at the margin of the Siberian Craton (600–500 Ma) [7, 15] (table). Thus, convergent boundaries began to form everywhere in the Paleoasian Ocean ~570 Ma ago.

The Caledonian fold zone ceased to evolve ~500–480 Ma ago owing to the early Caledonian accretion. Consequently, the previously isolated lithotectonic structures of the Paleoasian Ocean merged into a single continental block [10]. The accretion was accompanied by folding, metamorphism, and magmatism in both fold zones and Precambrian terranes (table). These processes were characterized by a large-scale within-plate magmatism that produced picrites, layered gabbro, alkaline and nepheline syenites, as well as alkaline and Li–F granites [10]. Igneous rocks of the respective compositions formed during all accretionary events (table). Such a combination of accretionary and within-plate activity indicates that the Caledonian fold zone was produced by the collision (accretion) of island arcs and Precambrian terranes of the Paleoasian Ocean with a system of oceanic islands (hot spots) [10]. Later stages of the Paleoasian Ocean development were related to the formation of Hercynides and Indosinides.

Model of early stages of the Paleoasian Ocean evolution. The data presented above suggests the following model of the formation of structures in the Caledonian foldbelt in the course of the Paleoasian Ocean evolution (Fig. 2).

(1) Early Baikalian stage (1000–780 Ma). The Grenvillian orogeny, which completed the formation of Rodinia, was related to the compensation of processes of oceanic crust growth (spreading) at the framing of the supercontinent (Fig. 2a). After the completion of Grenvillides, the growth of the oceanic lithosphere was compensated in subduction zones at margins of the supercontinent, including its shelf zone. These processes initiated the early Baikalian crust formation (Fig. 2b). Such subduction zones are represented by the Kicher zone in the Baikal–Muya belt [7], as well as the Dunzhugur and Shishkhid zones in the Tuva–Mongol massif [6]. Their formation was terminated by a collision with rigid blocks (~815–785 Ma ago). In general, events of this stage were provoked by stresses upon the supercontinent from Panthalassa. They complicated the shelf structures of Rodinia and predated the Paleoasian Ocean formation.

(2) At the interval of 750–630 Ma, the impact of a superplume upon Rodinia resulted in the breakup of the Laurasian segment into the Siberian and Laurentian continents with the formation of an oceanic lithosphere between them (Figs. 2c, 2d). The newly formed marine basin remained a narrow structure like the Red Sea until ~630 Ma ago. Therefore, monotype ultrabasic alkaline massifs with carbonatites could form along the borders of Siberia and Laurentia (Fig. 2d).

Processes of rifting also provoked the breakup of the Rodinia shelf and independent motion of its fragments. These processes were responsible for the formation of oceanic lava plateaus of the Bayan-Khongor and Kuznetskii Alatau zones ~700–665 Ma ago. They produced rock complexes of active margins and island arcs (Baikal–Muya belt and the Shishkhid and Sarkhoi zones of the Tuva–Mongol massif [6]) above subduction zones around the expanding marine basin. The oceanic lithosphere, which formed along fracture zones in this period, served as a basis for the Paleoasian Ocean (Fig. 2c). The fracture zones affected both the supercontinent and the adjacent sectors of Panthalassa.

(3) Approximately 630 Ma ago, the paleocean began to surpass the superplume in dimension and the within-plate magmatic activity terminated, at least, along the southern margin of Siberia. The share of ancient crustal material was minimized as a result of changes in the character of marine sediments in the cover of the Pre-

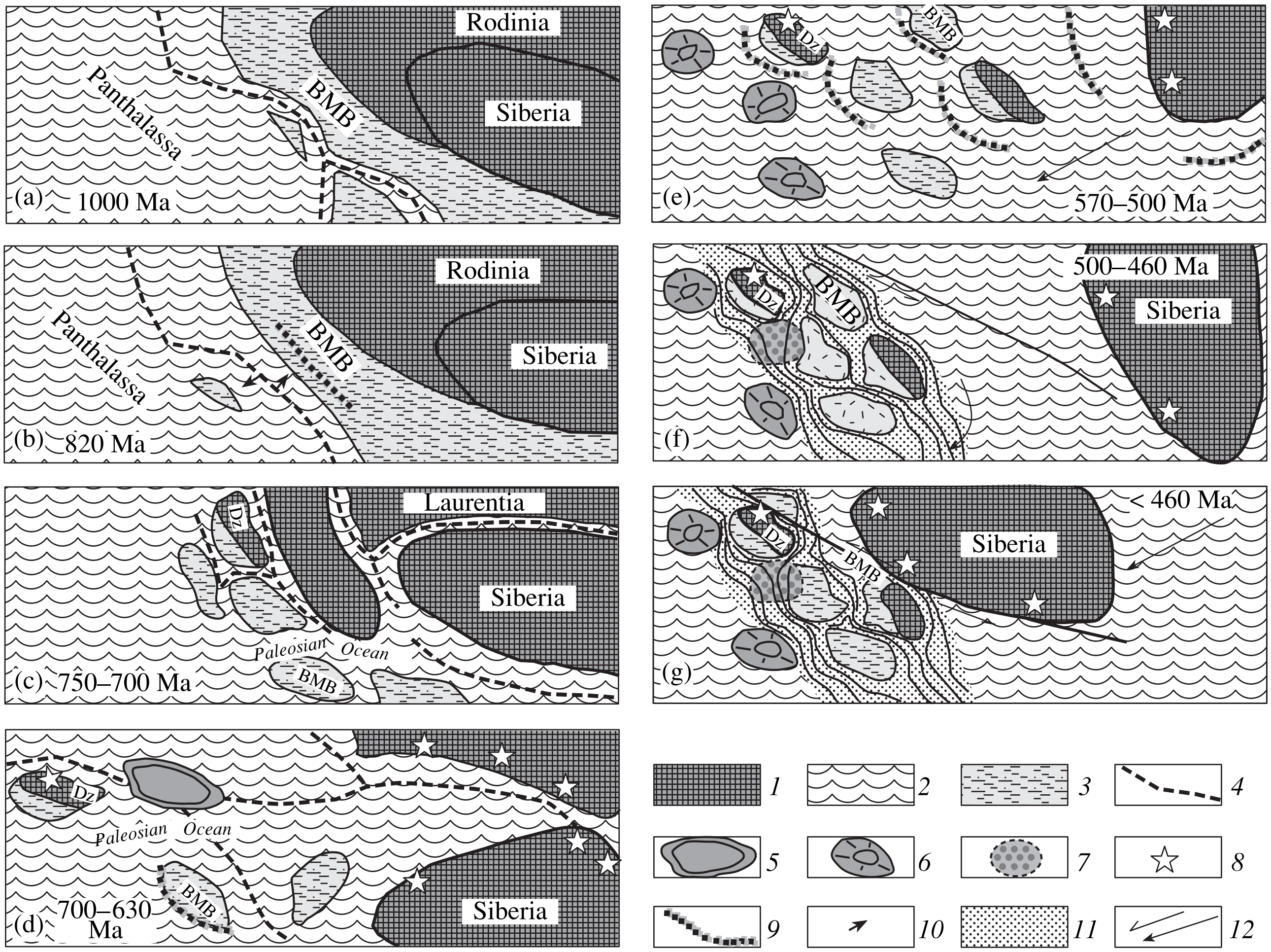

Fig. 2. Model of the formation of Caledonides of the CAFB due to the collision of island arcs and microcontinents of the Paleoasian Ocean with the oceanic island system. Principle positions of the studied complexes at different stages of the formation of Caledonides of the CAFB based on the study of the Dzabkhan terrane (Dz) and the Baikal–Muya belt (BMB). (*1*) Rodinia supercontinent; (*2*) oceanic basins; (*3*) Rodinia shelf; (*4*) spreading and rifting zones; (*5*) oceanic plateau; (*6*) oceanic islands (mantle hot spots); (*7*) magmatic areas above hot spots; (*8*) complexes (indicators of rifting) (ultrabasic alkaline rocks, layered gabbro, and alkaline granites); (*9*) subduction zones; (*10*) vectors of motion of the oceanic lithosphere; (*11*) Caledonian superterrane; (*12*) direction of the motion of lithospheric blocks.

cambrian terranes. This is suggested by the location of terranes beyond the domain of continents.

(4) Approximately 570 Ma ago, the paleocean underwent a basically new phase of evolution owing to the universal manifestation of processes of convergence and the consequent formation of numerous intraoceanic (young) island arcs. These processes fostered folding and metamorphism of rocks in active boundary zones of Precambrian terranes (Fig. 2e) and several sectors of the Siberian Craton margin.

(5) The early history of paleocean formation terminated 500–480 Ma ago with the collision (accretion) of the newly formed island arcs, backarc basins, and fragments of the Rodinia shelf (Precambrian terranes) with a system of oceanic islands. The accretion was accompanied by regional metamorphism, as well as intense crustal (granitic) and within-plate (basic and alkaline) magmatism. Finally, the fold zone (or superterrane) with a juvenile continental crust was formed (Fig. 2f). The subsequent convergence of the Caledonian superterrane with the Siberian Craton (probably under conditions of oblique collision without metamorphism) terminated in the Devonian (Fig. 2g).

Thus, the early stages of the Paleoasian Ocean evolution were characterized by the prevalence of juvenile crust formation. This feature is defined as a specific (Central Asian) type of continental crust characterized by the accretion of lithotectonic complexes of the ocean floor (island arcs, backarc basins, and oceanic islands) and microcontinents into a single superterrane with the juvenile continental crust. The initial stage of the Paleoasian Ocean formation was related to the breakup of Laurentia approximately 750–630 Ma ago and the formation of separate terranes (fragments of the supercontinent shelf, as well as oceanic islands and lava plateaus) within the newly formed oceanic lithosphere. Therefore, the newly formed Paleoasian Ocean can be defined as a late Baikalian oceanic–continental lithospheric region that encompasses not only the Siberia–Laurentia interface, but also the adjacent sectors of the shelf and Panthalassa. The late Baikalian terranes migrated to central parts of the paleocean that were involved in the formation of convergent boundaries approximately 570 Ma ago. Consequently, several ensimatic island arcs and active margins appeared at the margins of some terranes. Approximately 510–490 Ma ago, the entire rock complex of the newly formed early Caledonian crust (island arcs, backarc basins, and oceanic islands) accreted with terranes of the Precambrian crust, resulting in the formation of a juvenile (in terms of sources) crust of the Caledonian fold zone.

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