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GEOLOGY

Isotopic Composition of the Hercynian Crust of Southern Mongolia: Substantiation of the Hercynian Juvenile Crust-Forming Event

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Geochronological and Nd isotopic studies of Phanerozoic granitoids of the Central Asian foldbelt (CAFB) [1–4], as well as Phanerozoic folded structures of the Cordilleras and Appalachians of North America and eastern Australia (see review in [5]), made it possible to distinguish the Phanerozoic stage in the formation of the juvenile continental crust [3]. Recognition of this stage essentially changed the notion on the evolution and growth rate of the continental crust in the geological history. In particular, this fact revealed the necessity to study stages, sources, and leading mechanisms of the juvenile crust formation in the Late Precambrian and Phanerozoic. For example, the results of our studies made it possible to distinguish the Riphean, Caledonian, Hercynian, and Indosinian cycles of crust formation in the Phanerozoic of the CAFB. These cycles were marked by the formation of the respective Nd isotopic crustal provinces [1–3]. Our conclusions were mainly based on the study of granitoids of Precambrian terranes and Caledonides. However, scanty data on Hercynides and Indosinides complicated the assessment of the scale and lithological specificity of the corresponding crust-forming epochs. This work summarizes new original data on rock complexes in South Mongolian Hercynides of the CAFB. Based on these results, we consider distinctive features of the Nd isotopic structure of the fold zone and mechanisms responsible for specific features of the Hercynian juvenile crust formation.

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GEOLOGICAL CHARACTERISTICS

Hercynides of southern Mongolia are represented by a system of EW-trending folded structures. In the south, they are bounded by terranes of the South Gobi microcontinent composed of Grenvillian and Caledonian rock complexes [6–8]. In the north, the field of Hercynides is bounded by Caledonides of the CAFB. The Edrenga and Transaltai zones are distinguished in the structure of Hercynides. In addition, the Hercynide structure also includes the Gobi Altai zone extending along the boundary with Caledonides (Fig. 1, inset a). According to [7, 8], the latter zone represents a marginal part of the Caledonian microcontinent, which was subjected to tectonic transformation in the Early and Middle Paleozoic. Therefore, we will consider the Gobi Altai zone as a part of the Caledonian megablock of the CAFB. We shall show below that this classification does not contradict isotopic–geochemical data on the composition and the model age of crust formation in the Gobi Altai zone. According to [7, 8], the northern part of the Edrenga zone, which borders with the Gobi Altai zone, is mainly composed of terrigenous and less common siliceous–volcanic complexes (S(?)–C_1). The southern part of the zone is composed of basalt–andesite–dacite associations (D_{2-3}) in the Edrenga-Nuru Range. According to our data, similar volcanic associations are also characteristic of the northern part of the zone (Fig. 1) represented by the Sumen-Khairkhan Range and the northern framing of the Adzh-Bogdo Range. The Transaltai zone is mainly composed of jaspers (S–D_1?), volcanic rocks (D_{1-2}), and terrigenous rocks (D_3–C_1), which are usually tectonically superposed with ultrabasic and melange formations [7, 8]. Hence, the Hercynides are commonly characterized by volcanogenic complexes and associated terrigenous–siliceous deposits and jaspers, which indicate the formation of Hercynides in large sea basins. Volcanic rocks of the Dzoilen Range are 421 ± 3 and 417 ± 2 Ma old ($^{206}Pb/^{238}U$ (SHRIMP-II) data [9]).

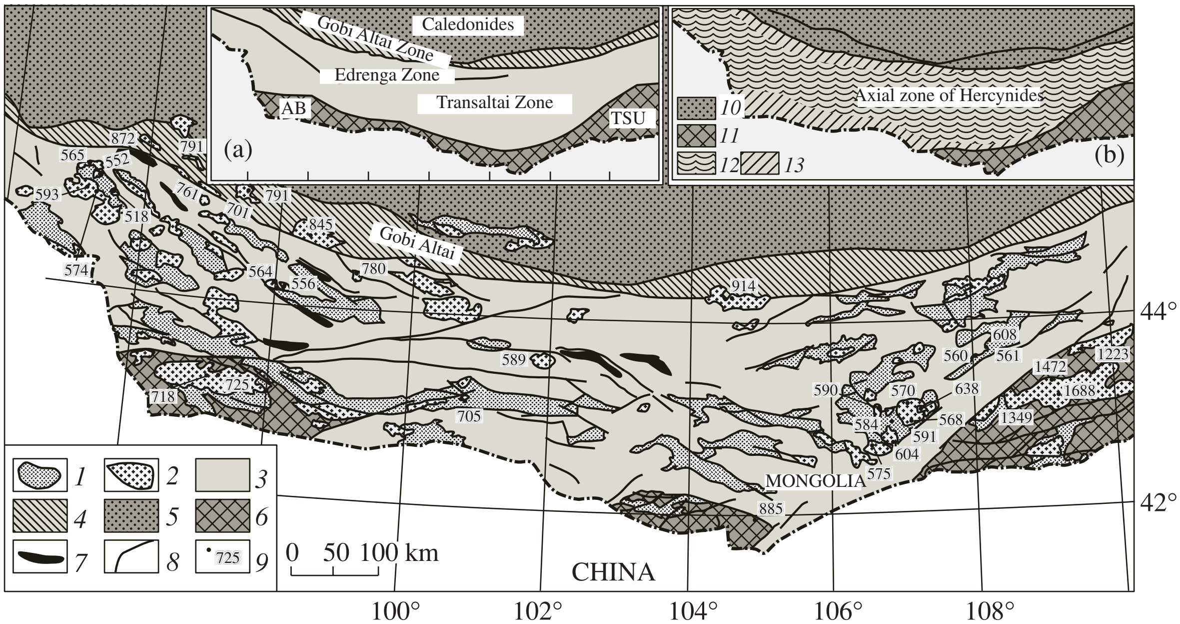

Fig. 1. Geological structure of southern Mongolia and location of granitoid sampling sites and volcanic fields. (*1*) Volcanic fields of the marginal magmatic belt ($C–P_1$); (*2*) granitoids of different ages; (*3–6*) tectonic structures: (*3*) Hercynides, (*4*) Gobi Altai zone, (*5*) Caledonides, (*6*) blocks of the South Gobi microcontinent; (*7*) exposures of island-arc complexes; (*8*) faults; (*9*) location of sampling sites for granitoids and felsic volcanics and the model $T_{\rm Nd}$(DM) age of rocks (Ma). (*10–13*) isotopic provinces of the crust: (*10*) Caledonian, (*11*) pre-Caledonian (Grenvillian?), (*12*) Hercynian (juvenile province of the Hercynian axial zone), (*13*) junctions of Hercynides with older continental blocks. Insets: (a) scheme of the structural zonation of the territory, blocks of the South Gobi microcontinent: (AB) Atas–Bogdo, (TSU) Totoshan–Ulanul; (b) scheme of the isotopic structure (isotopic zonation) of the crust in southern Mongolia.

Accretion of Hercynian structures to the southern edge of the North Asian paleocontinent terminated at the beginning of the Early Carboniferous. This process was accompanied by folding and thrusting. The newly formed edge of the continent evolved as an active continental margin until the beginning of the Permian [10, 11]. This region included a marginal belt composed of basalt–andesite–dacite–rhyolite associations of volcanic rocks with the participation of granitoid massifs. The South Mongolian Hercynides were reworked in the late Mesozoic by intraplate processes. Owing to such multistage activity, magmatic rocks of a wide age interval were formed in the region.

CHARACTERISTICS OF THE STUDIED MATERIAL

In [2, 3, 5], methods for distinguishing stages of the formation of the continental crust and isotopic provinces based on the Nd isotopic composition of granitoids and felsic volcanic rocks, which are products of anatectic crustal melts, are given. In the present work, the data mentioned above are supplemented with data on the composition of volcanic and associated sedimentary rocks of paleoceanic complexes corresponding to the initial stages of juvenile crust formation [12]. The geological age of rocks for calculating the $\varepsilon_{\rm Nd}(T)$ and $T_{\rm Nd}$(DM) values was established from paleontological data on stratified rocks and our numerous geochronological data on plutonic and volcanic rocks. We also used data from [9], which mainly characterize volcanic rocks of Hercynian folded complexes.

Volcanic rocks of folded complexes are represented by basalts and less common andesites. They were studied at the southern foothills of the Gobi Altai Range; in the Sumen-Khairkhan, Edrenga-Nuru, and Dzoilen ranges; and in the Transaltai Gobi (Fig. 1). Taking into account data from [9], we may infer that these rocks are commonly depleted in Ti (TiO_2 <1%). They are characterized by the fractionation of incompatible microelements; moderate enrichment in LREE ($(La/Yb)_N$ = 2.6–8.0); and negative anomalies of Nb, Ta ($(La_N/Nb_N$ = 1.7–5.6), Zr, Hf, and Ti. They associate with marine sediments, suggesting their formation in island- or back-arc basins. Medium- and high-Ti basalts with geochemical characteristics of MORB and OIB are less developed. The Nd isotopic composition of lavas in all these paleoceanic (or ophiolite) complexes is variable: $\varepsilon_{\rm Nd}(0.42)$ from +5.9 to +9.8 and $T_{\rm Nd}$(DM) from 0.71 to 0.54 Ga. The highest $\varepsilon_{\rm Nd}(0.42)$ value of +9.8 [9], which coincides with the depleted mantle (DM) composition, is typical of MORB-type basalt. However, most of the studied rocks are represented by island-arc lavas and their isotopic composition corresponds to the $\varepsilon_{\rm Nd}(0.42)$ interval ranging from +6.1 to +7.7. Their magmas could form in the subduction zone at a certain contribution of

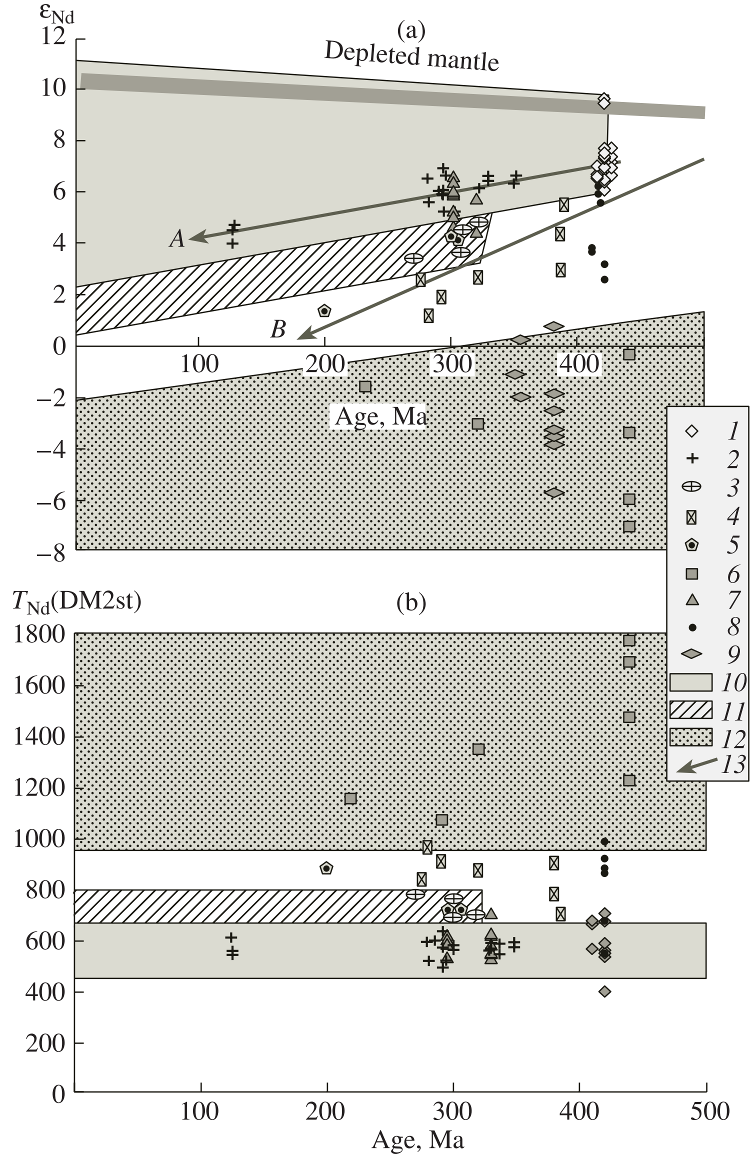

Fig. 2. Diagrams (a) ε_{Nd} vs. age and (b) T_{Nd}(DM) vs. age for rocks of different structural zones of southern Mongolia. (*1*) Basalts and andesites of island-arc complexes; (*2–9*) granitoids of different structural zones: (*2*) axial zone of Hercynides, (*3*) boundary areas of Hercynides, (*4*) Gobi Altai zone, (*5*) Atas-Bogdo block of the South Gobi microcontinent, (*6*) Totoshan-Ulanul block of the South Gobi microcontinent, (*7*) rhyolites and dacites of the marginal volcanic belt (C–P_1), (*8*) sedimentary rocks associated with rocks of island-arc complexes, (*9*) metamorphic rocks of the Gobi Altai zone [13]; (*10–12*) fields of evolution of the Nd isotopic composition: (*10*) rocks of ophiolite complexes and granitoids of Hercynides in southern Mongolia, (*11*) granitoids of marginal areas of Hercynides, (*12*) granitoids of the Totoshan-Ulanul block of the South Gobi microcontinent; (*13*) evolution trends of the Nd isotopic composition: (*A*) intermediate composition of the crust, (*B*) granitoids of Caledonides of the Ozernaya [14] and Mongol–Altai zone in the CAFB.

an old crustal sedimentary component. Parent melts of medium- and high-Ti basalts were probably derived from a DM source with participation of an enriched plume component.

Sedimentary rocks in Hercynian folded complexes are represented by a wide spectrum of rocks ranging from conglomerates and gritstones to clayey and siliceous siltstones and jaspers. Clayey and siliceous varieties, which correspond to the averaged composition of provenances, were studied by isotopic–geochemical methods. In island-arc associations of the Dzoilen and Gurvan-Saikhan ranges, siliceous siltstones and volcaniclastic rocks [9] exhibit isotopic–geochemical values characteristic of volcanic rocks: $\varepsilon_{Nd}(0.42)$ from +6.3 to +7.4 and T_{Nd}(DM) = 0.71–0.54 Ga. This fact indicates the accumulation of sediments mainly due to the erosion of juvenile island-arc complexes beyond the area of the remarkable influence of ancient continental provenances. Similar siltstones from volcanic associations of the Sumen-Khairkhan, Edrenga-Nuru, and Transaltai Gobi ranges differ from volcanic rocks in lower $\varepsilon_{Nd}(0.42)$ values ranging from +3.1 to +3.9 (T_{Nd}(DM) ~0.92–0.85 Ga). This fact indicates their participation in the formation of ancient crustal provenances. Metamorphic complexes of the Caledonian Gobi Altai zone [13] and rocks of the Totoshan-Ulanul block of the South Gobi microcontinent, which bound the Hercynides in the north and south, respectively, could serve as such provenances (Fig. 1). The $\varepsilon_{Nd}(T)$ value in these rocks varies from +3.0 to –7.1.

Postaccretion magmatic rocks are represented by formations of different ages developed in the folded structure of the Hercynides and the surrounding Caledonian and Grenvillian terranes. They are dominated by rocks related to the formation of the late Paleozoic marginal belt [10]. Products of magmatism related to Mesozoic pulses of tectonomagmatic activity also occur [11]. Precarboniferous granitoids were established in Caledonides of the Gobi Altai zone and Grenvillides of the South Gobi microcontinent.

Regardless of the composition and age, postaccretion rocks within the Hercynides are characterized by positive $\varepsilon_{Nd}(T)$ values ranging from +4.3 to +7.0 and a relatively narrow range of T_{Nd}(DM) variation (0.78–0.5 Ga).

Granitoids of the Gobi Altai zone are also characterized by positive $\varepsilon_{Nd}(T)$ values ranging from +1.2 to +2.7. However, as compared to coeval rocks of the Edrenga and Transaltai zones, these values are systematically lower, indicating their older crustal source (T_{Nd}(DM) = 0.91–0.87 Ga). Granitoids of the Totoshan-Ulanul block of the South Gobi microcontinent are noted for negative $\varepsilon_{Nd}(T)$ values ranging from 0.0 to –7.1 and the oldest Nd model age (T_{Nd}(DM) = 1.8–1.1 Ga). In contrast, granites of the Atas-Bogdo block of the microcontinent (Fig. 1) exhibit isotopic compositions similar to granites of the Gobi Altai. They are characterized by positive $\varepsilon_{Nd}(T)$ values ranging from +1.4 to +4.4 (T_{Nd}(DM) = 0.88–0.72 Ga).

DISCUSSION

Figure 1 demonstrates T_{Nd}(DM) values of granitoids and felsic volcanic rocks, as well as their distribution in southern Mongolia. The positions of rocks with different values of the isotopic model age show a certain zonation. The lowest values (0.64–0.50 Ga) are typical of felsic magmatic rocks, which are absent in boundary areas but are developed in virtually the entire inner part of the Hercynides (axial zone). Granitoids in the boundary areas of the Hercynides are characterized by $\varepsilon_{Nd}(T)$ values systematically lower than in granites of the axial zone and older model ages: T_{Nd}(DM) = 0.78–0.70 and 0.71 Ga, respectively, for the northern and southern boundary areas of the Hercynides (Figs. 1, 2).

Granitoids in the Hercynide framing (Gobi Altai zone and South Gobi microcontinent) have distinctive isotopic characteristics. Granitoids of the Totoshan-Ulanul block (South Gobi microcontinent) of Grenvillian structures have negative $\varepsilon_{Nd}(T)$ values and the oldest T_{Nd}(DM) values (1.8–1.1 Ga) [6]. In the Gobi Altai zone located between the Hercynides and the Caledonides, granitoids are characterized by Nd model ages varying within 0.91–0.87 Ga. These values correspond to model ages established previously for the Caledonian crust of the CAFB [1–3] and, hence, confirm geological ideas about affiliation of the Gobi Altai zone with the Caledonian block of the CAFB [7]. A close range of model ages (0.88–0.72 Ga) is typical for granitoids of the Atas-Bogdo block (South Gobi microcontinent), which is assigned to Caledonian structures [7].

The diagram in Fig. 2 demonstrates the isotopic parameters of different (in composition and age) rocks in the Hercynides and their framing. It is apparent that data points of rocks are distributed in accordance with their location in certain structures of the study area. The field of the Hercynian juvenile crust is prominent. Its boundaries are defined by evolution trends of isotopic compositions of volcanic rocks in paleoceanic complexes specified on the basis of respective $^{147}Sm/^{144}Nd$ values. The field of juvenile crust formation includes sediments of rock associations of certain areas (e.g., the Dzoilen Range), which formed beyond the domain of ancient crust provenances, as well as granitoids and felsic volcanic rocks of the axial zone of the Hercynides. Their data points are grouped in the lower part of the field and arranged in accordance with the evolution trend for the isotopic composition of the middle continental crust ($^{147}Sm/^{144}Nd = 0.11$). Hence, the composition of the Hercynian continental crust defined by the isotopic composition of granitoids is identical to the composition of the juvenile crust of paleoceanic complexes. In the T_{Nd}(DM) versus age diagram (Fig. 2b), data points of granitoids of the Hercynian axial zone lie in the field restricted by age boundaries from 420 Ma (geochronological and model age of rocks of ophiolite complexes identical in the isotopic composition to the DM) to 640 Ma. We believe that these boundaries of model ages are characteristic of the Hercynian juvenile crust.

Data points of granitoids of the Gobi Altai zone do not fall into the field of the Hercynian juvenile crust. Their positions in Fig. 2 are consistent with the evolution trend for the isotopic composition of granitoids from the Ozernaya zone in the Caledonides of the CAFB [14], and the model age of these granitoids (T_{Nd}(DM) = 0.91–0.87 Ga) corresponds in general to model ages of granitoids in the Caledonides of the CAFB [2, 3]. These facts testify to the similarity of the composition of the Caledonian crust and the Gobi Altai zone.

Against the background of granitoids formed in the Hercynian fold zone, we can see granitoids developed at the contact with Caledonides of the Gobi Altai zone and blocks of the South Gobi microcontinent. Their data points fall into the field located between the evolution trend for compositions of Caledonian granitoids, on the one hand, and compositions of granitoids of the Hercynian axial zone, on the other hand. Correlation of regions with the manifestation of such granites (e.g., the Sumen-Khairkhan Range) with regions of the Hercynian axial zone (e.g., the Edrenga-Nuru or Transaltai Gobi region) reveals no principle differences in the composition of ophiolite complexes and associated sedimentary rocks. Therefore, we believe that the specificity of the isotopic composition of such granitoids is related to processes of tectonic layering in interaction zones of the Caledonian and Hercynian terranes. Owing to the tectonic layering, the crust of these zones acquired compositional characteristics transitional between the Hercynian and Caledonian crusts. It is likely that the same process was responsible for the composition of granites formed in the interaction zone of Hercynides and structures of the South Gobi microcontinent (Fig. 1).

CONCLUSIONS

The geological, geochronological, geochemical, and Nd isotope data presented in our work confirm our previous inference based on a limited amount of data about the Hercynian stage of the juvenile crust formation in the CAFB [1–3]. These data allow us to specify the extent of crust-forming processes, define the boundaries of a new isotopic province of the crust, and assess its isotopic characteristics. The Hercynian juvenile crust governed the structure of the major part (more than 1000×200 km) of the South Mongolian segment of Hercynides in the CAFB. The crust began forming in the Silurian–Devonian (~420 Ma ago) under conditions of ensimatic island arcs, back-arc basins, and oceanic plateau and islands. According to data on the composition of sediments, these areas were located in distal zones of the continental provenances. Sources of island-arc complexes were related to convergent boundaries with the probable involvement of long-lived crustal material as sediments into subduction zones. Structures of the Hercynian Paleoasian ocean, which also included terranes of the South Gobi microcontinent, were transformed into a continental block in the Late Devonian–Early Carboniferous owing to accretion, folding, metamorphism, and tectonic layering along the boundaries of heterogeneous structural zones. The crust was reworked by magmatic processes 350–120 Ma ago due activation of the continental margin in the Carboniferous–Early Permian and intraplate rifting in the late Mesozoic. The compositions of felsic rocks formed in this time interval as products of anatectic magma fall into the isotopic evolution field of a relatively homogeneous continental crust, which should be regarded as the Hercynian juvenile crust. Its parameters are defined by values of the model Nd isotopic age within 420–640 Ma.

Thus, the results obtained allow us to infer about the epoch of large-scale Early–Middle Paleozoic ("Hercynian") formation of the juvenile continental crust in the CAFB and to distinguish a corresponding isotopic province.

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