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GEOCHEMISTRY

Isotopic Provinces and Formation Stages of the Continental Crust in the Baikal–Muya Belt: Sm–Nd Isotopic Evidence for Granitic and Silicic Volcanic Rocks

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Recent geological, geochronological, geochemical, and isotopic data made it possible to establish the main stages of the formation and evolution of the oceanic and continental crusts of the Central Asian Foldbelt (CAFB), to outline isotopic provinces, and to elaborate geodynamic models of the crust formation related to the origin and breakdown of Rodinia and Gondwana supercontinents [1–3]. Nevertheless, many problems related to the earliest, Late Riphean–Vendian periods of the geological history remain a matter of debate [3, 4] due to the lack of isotopic geochronological and geochemical data. The Baikal fold region as a tectonotype of the Baikalides is the key domain for solving these problems. This communication is a synthesis of the original geochronological and Nd isotopic data on granitic rocks and silicic volcanics of the Baikal–Muya Belt (BMB) of the Baikal fold region. Isotopic provinces and formation stages of the crust are outlined on the basis of these data.

The BMB is a structural element of the eastern CAFB. The BMB borders with the Baikal–Patom Belt of the Riphean structures of the passive margin of the Siberian Craton in the north and with the Barguzin–Vitim Superterrane in the south (Fig. 1). The BMB includes several lithotectonic zones with different stratified sections, compositions, and sequences of igneous rocks. The structure of the BMB is a combination of linear and mosaic-block fold–nappe units of different ages formed at the site of paleotroughs (Kichera, Param–Shaman, and Karalon–Mamakan) and intertrough zones (Anamakit–Muya and Yana). The Late Baikalian structures of the extensional paleobasin of the Kater–Uakit zone occupy a special position in the southern part of the BMB.

The geological structure of the *Kichera zone* is controlled by a series of steeply dipping tectonic sheets composed of orthoamphibolites with stratal bodies and lenses of plagiorhyolite, garnet amphibolite, and granulite fragments [5]; schists and metasandstones with metabasaltic units; and lenses of calcareous marbles, plagiogneisses, and gneissic plagiogranites. These sheets are crosscut by pyroxenite–gabbronorite intrusions and Early Vendian plagiogranites of the Umolikit Complex [6].

The structure of the *Param–Shaman zone* is governed by migmatized amphibolites and overlying biotite and actinolite sheets with carbonaceous schist, metasandstone, dolomitic marble, high-Ti metabasalt, and metarhyolite interlayers. This sequence is not older than 1 Ga [7]. This zone includes massifs of the Param ultramafic rocks [8, 9] that correspond to the rocks of the Riphean continental lithospheric mantle in terms of geochemical and isotopic parameters.

The *Karalon–Mamakan zone* is composed of basic, intermediate, and silicic volcanic rocks. The rhyolite extrusions are dated at 665 ± 2 Ma. The volcanic rocks are crosscut by gabbro–diorite–plagiogranite and pyroxenite–gabbronorite intrusions. The Padra volcanoplutonic complex dated at 590 ± 5 Ma [11] is overlapped by the Upper Vendian sequence, which, in turn, is intruded by two-feldspar granites.

The *Anamakit–Muya intertrough zone* embraces the central part of the BMB and includes several subzones (Fig. 1). The basement of this zone is composed of metamorphic rocks overlain by the Riphean carbonate–terrigenous sequences with sporadic bodies of basic and silicic metavolcanics that underlie the Upper Riphean metavolcanic sequence [12]. Rocks of the Muya gabbro–diorite–plagiogranite complex, high-Ti gabbro

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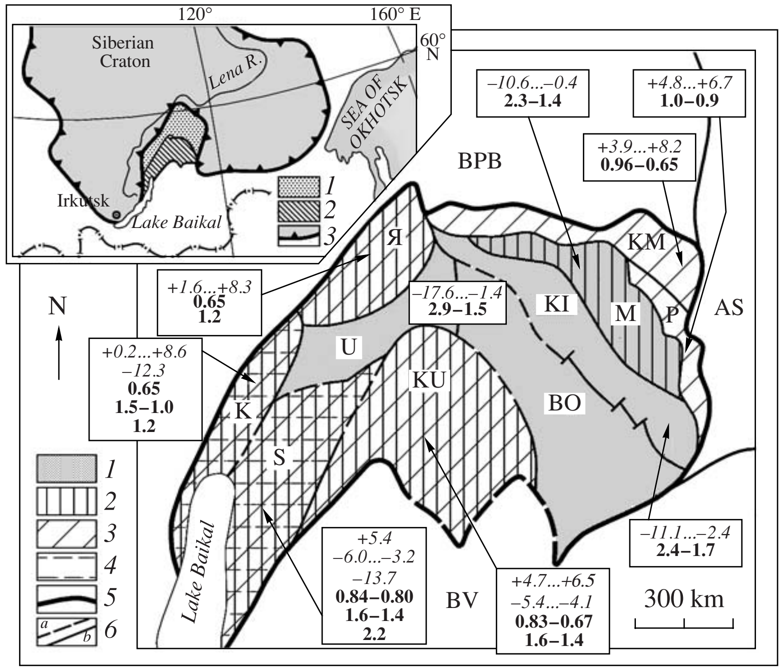

Fig. 1. The model Nd age, Ga (bold) and $\varepsilon_{Nd}(T)$ values (italics) in silicic igneous rocks of the Baikal–Muya Belt. Isotopic provinces: (*1*) Early Precambrian, (*2*) Early and Middle Riphean, (*3*) Late Riphean; (*4*) domains of Hercynian granitoids with Early Precambrian model Nd ages; (*5*) tectonic boundaries of the BMB, (*6*) faults: (*a*) inferred, (*b*) proved.

Structural zones of the BMB: (K, P, KM) Kichera, Param–Shaman, and Karalon–Mamakan paleotroughs, respectively; (Ya) Yana and Anamakit–Muya paleotroughs; subzones: (BO) Bambuika–Olinda, (KI) Kelyan–Irakinda, (M) Muya, (U) Ugdokit, (S) Svetlins; (KU) Kater–Uakit extensional basin; (AS) Aldan–Stanovoi Shield; (BPB) Baikal–Patom Belt; (BV) Barguzin–Vitim Superterrane. Isotopic provinces: (1) Early Precambrian, (2) Early–Middle Riphean, (3) Late Riphean; (4) domains of Hercynian granitoids with Early Precambrian Nd model ages; (5) tectonic boundaries of the BMB; (6) faults: (a) inferred, (b) proved. Inset shows location of the Baikal fold region: (*1*) outer Baikal–Patom Foldbelt, (*2*) inner Baikal–Muya Foldbelt, (*3*) tectonic boundaries of the Siberian Craton.

massifs, and sporadic dunite–troctolite–gabbro plutons are associated with volcanic rocks. Metamorphism and deformation of these rocks were accompanied by emplacement of gneissic granites dated at 785 Ma [12]. The superimposed depressions with trachyrhyolites of the Zhanok Formation (723 ± 4 Ma), hypabyssal potassic granitic rocks, and layered anorthosite–gabbro and harzburgite–pyroxenite–gabbro plutons were formed at the orogenic stage.

The *Yana intertrough zone* is characterized by a combination of Late Riphean domes and Early Vendian linear structures. They are composed of metasandstones, schists, and metagraywackes overlapped by metabasalts with metasandstones and schist interlayers. Gneissic plagiogranites developed here have an age of 636 ± 5 Ma.

The *Kater–Uakit zone* is dominated by complexly folded assemblages of turbidites, graywacke flyschoids, carbonate rocks, and carbonaceous–siliceous schists. Silicic and basic volcanics no older than 0.7 Ga occur only in the lower part of the section.

According to the available geochronological data, the geological history of the BMB includes the Early Baikalian (1000 ± 100 to 720 ± 20 Ma) and Late Baikalian (700 ± 10 to 590 ± 5 Ma) tectonic cycles complicated by epochs of folding, metamorphism, and emplacement of granitic plutons 0.80–0.78 and 0.62–0.59 Ga ago [13]. The Late Vendian–Early Cambrian terrigenous–carbonate sedimentary rocks in the superimposed basins overlap the Baikalian fold complexes with angular unconformity and basal conglomerates. All these rocks, in turn, are intruded by Paleozoic granitic rocks (470–280 Ma).

Figure 1 shows the spatial distribution of model Nd ages T_{Nd}(DM) and $\varepsilon_{Nd}(T)$ values in granitic and silicic volcanic rocks. Figure 2 shows the dependence of $\varepsilon_{Nd}(T)$ and T_{Nd}(DM) on the age of rocks.

Paleotrough zones. The Early Baikalian (850–815 Ma) granitic and silicic volcanic rocks of the Kichera zone largely have Middle Riphean model Nd ages (T_{Nd}(DM) = 1.4–1.1 Ga), while $\varepsilon_{Nd}(T)$ values vary from +0.2 to +2.8 Ga (Figs. 1, 2). Late Baikalian (650–610 Ma) granitic rocks are distinguished by high positive $\varepsilon_{Nd}(T)$ values ranging from +3.5 to +8.6 Ga and T_{Nd}(DM) of ~1 Ga. The $\varepsilon_{Nd}(0.65)$ value of +8.6 in plagiogranites coincides with the DM composition, testifying to manifestation of the Late Baikalian stage of juvenile crust formation in the Kichera zone.

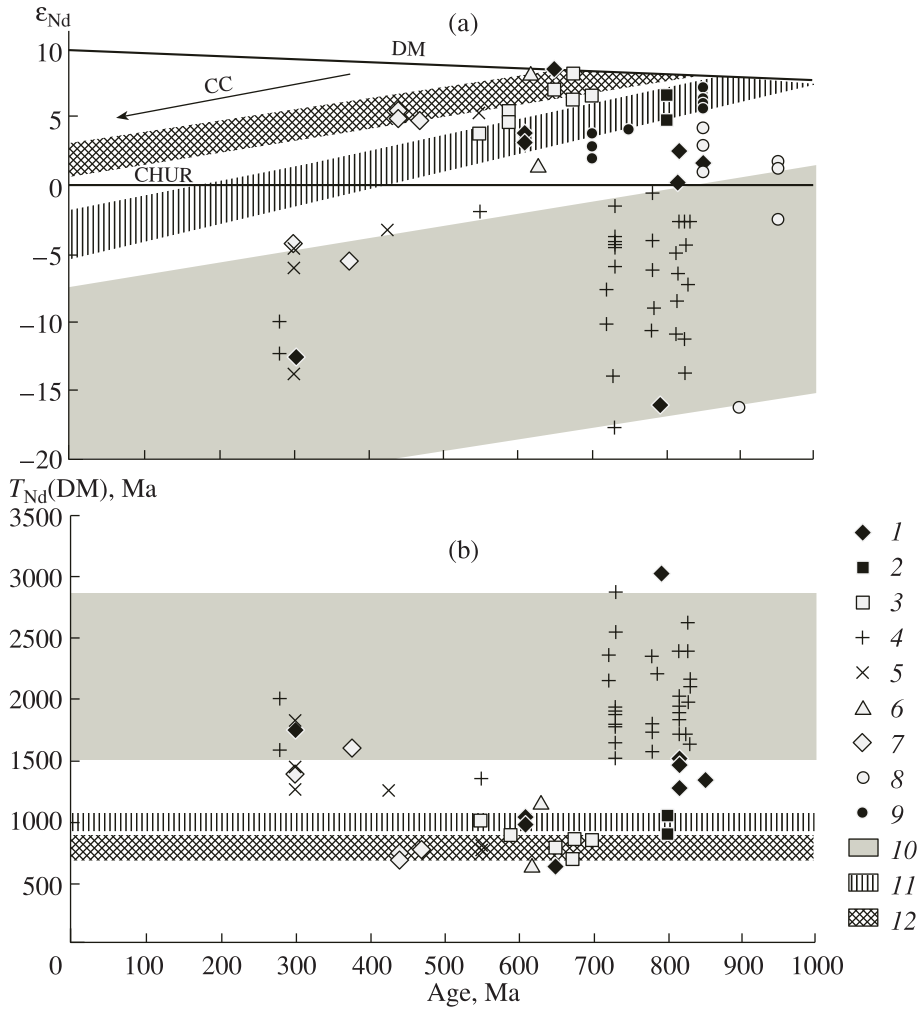

Fig. 2. Diagrams: (a) ε_{Nd} vs. age and (b) T_{Nd}(DM) vs. age for rocks of the Baikal–Muya Belt. (*1–7*) Granitic and silicic volcanic rocks of the structural zones and subzones: (*1–4, 6, 7*) structural zones: (*1*) Kichera, (*2*) Param–Shaman, (*3*) Karalon–Mamakan, (*4*) Anamakit–Muya, (*6*) Yana, (*7*) Kater–Uakit; (*5*) Svetlin subzone of the Anamakit–Muya zone; (*8, 9*) sedimentary rocks: (*8*) Anamakit–Muya zone, (*9*) other zones; (*10–12*) evolution fields of Nd isotopic compositions: (*10*) Early Baikalian granitic and silicic volcanic rocks of the Anamakit–Muya zone (except the Svetlin subzone), (*11, 12*) Early Baikalian and Late Baikalian juvenile continental crust, respectively. The evolutionary trend of Nd isotopic composition in the continental crust (CC) with $^{147}Sm/^{144}Nd = 0.12$ is shown for comparison.

The Early Baikalian (800 Ma) plagiogranites of the Param–Shaman zone, as well as the Late Baikalian and Early Caledonian (700–550 Ma) granitic and volcanic rocks of the Karal–Mamakan and Yana (intertrough) zones are characterized by Late Riphean T_{Nd}(DM) values of 1.1–0.7 Ga and $\varepsilon_{Nd}(T)$ values of +8.3 to +1.6 Ga. Close parameters (T_{Nd}(DM) from +0.77 to +0.68 Ga and $\varepsilon_{Nd}(T)$ from +5.5 to + 4.7) were determined for the Late Riphean rhyolite (675 Ma) and Early Paleozoic (470–440 Ma) granites from the Kater–Uakit zone. The occurrence of granitic rocks with high positive $\varepsilon_{Nd}(T)$ values indicates manifestation of the Late Baikalian stage of crust formation in these zones.

The *Anamakit–Muya intertrough zone*. Irrespective of the rock age (830–815 and 730–720 Ma), the Early Baikalian igneous rocks of the Bambuika–Olinda subzone are characterized by a continuous range of model Nd ages varying from the Late Archean to the Early Riphean (2.9–1.5 Ga) and $\varepsilon(t)$ ranging from –17.6 to –1.4 (Figs. 1, 2). The close Nd isotopic parameters are typical of the Early Baikalian and the Late Vendian granitic rocks and silicic volcanics from the Kelyan–Irakinda and Muya subzones: T_{Nd}(DM) varies from 2.4–1.7 to 2.6–1.3 Ga; $\varepsilon_{Nd}(T)$, from –11.1 to –2.4 and –10.6 to –0.4, respectively. In contrast to these values, the Late Vendian (550 Ma) granitic rocks of the Svetlin subzone have the Late Riphean model Nd age (0.80–0.78 Ga) and positive $\varepsilon_{Nd}(T)$ value of +5.4.

Irrespective of the spatial location, the Late Paleozoic granitoids of the BMB are characterized by Early Proterozoic–Middle Riphean geochemical parameters (T_{Nd}(DM) = 2.2–1.4 Ga, $\varepsilon_{Nd}(T)$ varies from –13.7 to

–3.2 Ga) (Figs. 1, 2), indicating the formation of melts of these granites due to the melting of both Early Precambrian and Riphean crustal sources.

The variation of Nd isotopic characteristics of granitic and silicic volcanic rocks in the BMB, as well as associated clastic sediments as a function of their age (Fig. 2), suggests different styles of crust-forming processes in (i) various structural zones of the BMB and (ii) at the early and late stages of the Baikalian tectogenesis divided by a boundary at ~700 Ma.

Rocks of the Anamakit–Muya zone are marked by a distinct vertical trend with T_{Nd}(DM) varying from 2.9 to 1.4 Ga and $\varepsilon_{Nd}(T)$ varying from –17.6 to –1.4, indicating that silicic igneous rocks of this zone are products of partial melting of a long-lived (Archean–Early Proterozoic) crustal source and the Early Baikalian juvenile mantle material.

Except for one case, the predominance of the juvenile material and the subordinate role of Early Precambrian crustal sources are recorded in the Nd isotopic composition of the Early Baikalian (850–790 Ma) granitoids and rhyolites from the Kichera and Param–Shaman zones (T_{Nd}(DM) varies from +1.5 to +0.93 Ga; $\varepsilon_{Nd}(T)$, from +0.2 to +6.7). The evolution field of the Nd isotopic composition of silicic igneous rocks of these zones may be regarded as the compositional field of the Early Baikalian continental crust (Fig. 2).

The Nd isotopic characteristics of the Late Baikalian and Caledonian silicic igneous rocks of the Kichera, Karalon–Mamakan, Yana, and Kater–Uakit zones (T_{Nd}(DM) varies from +1.2 to +0.65 Ga; $\varepsilon_{Nd}(T)$, from +1.6 to +8.6) testify to the predominance of the Late Baikalian juvenile material in their sources. In Fig. 2, the data points of these rocks make up a field that corresponds to the evolutionary trend of the average continental crust of Late Baikalian age. Thus, each cycle of the Baikalian tectogenesis in the geological history of the BMB is characterized by a special crust-forming event in the time intervals of approximately 1.0–0.8 and 0.70–0.62 Ga.

Analysis of the spatial distribution of $\varepsilon_{Nd}(T)$ and T_{Nd}(DM) values shows that the Early Baikalian crust-forming processes developed mainly in relatively narrow and separate Kichera and Param–Shaman paleotroughs of the BMB (Fig. 1), whereas processes of the formation of the Late Baikalian continental crust were pivotal in the Karalon–Mamakan, Yana, and Kater–Uakit zones (Fig. 3). It should be noted that the Nd isotopic composition of sediments in these zones (T_{Nd}(DM) = 1.2–0.94 Ga) also bears indications of a newly formed crust (Fig. 2), suggesting the accumulation of sediments beyond the domain of ancient provenances and, hence, far from the Siberian continent [14].

In contrast to the zones considered above, the isotopic composition of granites from the Anamakit–Muya zone indicates their formation as a result of the impact of early Baikalian crust-forming processes upon the Early Precambrian continental crust. This conclusion is consistent with the Nd isotopic composition of sedimentary rocks in this zone, which include erosion products in both the Middle Riphean (T_{Nd}(DM) = 1.5–1.2 Ga) and the Early Precambrian (T_{Nd}(DM) = 2.9–1.9 Ga) sources (Fig. 2). The reworking of the Riphean continental crust is documented only in the Svetlin subzone (Fig. 3).

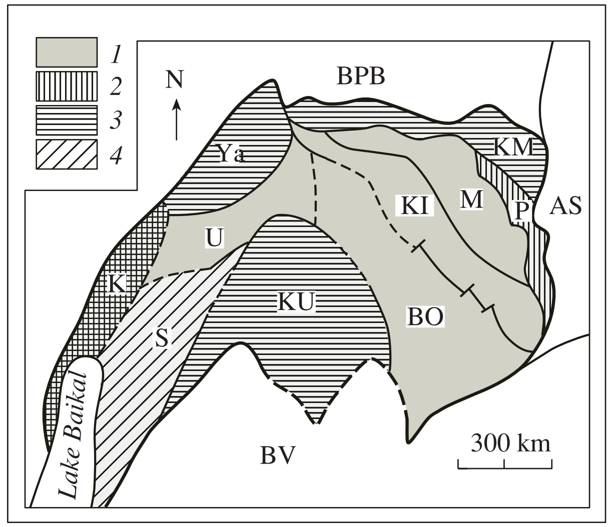

Fig. 3. Manifestation of crust-forming processes in the Baikal–Muya Belt. (*1*) Areas of the reworked Early Precambrian continental crust, (*2*) area of the Early Baikalian crust-forming processes, (*3*) area of the Late Baikalian crust-forming processes, (*4*) area of the reworked Late Riphean crust. See Fig. 1 for other designations.

CONCLUSIONS

Thus, the BMB structure is characterized by isotopic heterogeneity expressed in the juxtaposition of terranes related to the crust-forming events of different ages (Fig. 3). The Early Baikalian crust-forming events are manifested in the Kichera and Param–Shaman zones; the Late Baikalian events, in the Karalon–Mamakan, Yana, and Kater–Uakit zones. The remobilization of the Early Precambrian continental crust and the subordinate contribution of the Late Riphean juvenile sources are typical of most of the Anamakit–Muya zone. New isotope data presented above allowed us to outline the Early and Late Baikalian epochs of the juvenile crust formation, in addition to the epochs established previously [1, 2]. At present, it is difficult to estimate the initial dimensions of the respective blocks of the juvenile crust. They can be indirectly estimated based on sedimentary rocks of the trough zones. As was mentioned above, they were formed in distal zones of ancient cratons. The thickness of sedimentary sequences and their complex structure suggest large dimensions of the crustal blocks.

The final events in the formation of the BMB were probably related to the accretion of all terranes into a common block together with the Barguzin terrane. These events were likely completed in the Late Caledonian epoch of tectogenesis in the CAFB. The latter important event was responsible for the compositional averaging of the BMB crust owing to the juxtaposition (tectonic delamination) of crustal elements of different ages. Such a mechanism of crust transformation in the study region is indicated by the Late Paleozoic granitoids, whose Nd isotopic composition does not depend on their localization in the BMB.

The new geological, geochronological, and isotopic data allow us to propose two models of the geodynamic evolution of the Baikalian fold complexes. The first (autochthonous) model considers the BMB a constituent of the common Baikalian Megablock of the ancient crust that served as the eastern (in present-day coordinates) continental margin of the Paleoasian Ocean. The Late Precambrian evolution of this margin was controlled by rifting and collision. The crust-forming processes in this scenario corresponded to the formation of the suboceanic crust in rifts of the Red Sea type and the subsequent reworking in the course of collision-related squeezing of paleorifts and intertrough basins.

The second (allochthonous) model implies the formation of fragments of the BMB at the shelf of the Rodinia supercontinent. The development of subduction zones along the BMB boundaries and the involvement of sedimentary complexes of the Rodinia shelf in subduction processes promoted the formation of the Early Baikalian igneous complexes with isotopic marks indicating different proportions of the juvenile and ancient crustal sources. The breakdown of Rodinia about 750–700 Ma ago initiated the appearance of the Paleoasian Ocean and the consequent formation of Late Baikalian island-arc and marginal continental complexes of the BMB that are characterized by juvenile Nd isotopic composition. Fragments of the BMB were amalgamated into the Caledonian Siberian Superterrane of the CAFB approximately 500–460 Ma ago as a result of accretion of heterogeneous lithotectonic complexes of the Paleoasian Ocean.

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REFERENCES

1. V. I. Kovalenko, V. V. Yarmolyuk, V. P. Kovach, et al., Geotectonics **33** (3), 191 (1999) [Geotektonika **33** (3), 21 (1999)].
2. V. I. Kovalenko, V. V. Yarmolyuk, V. P. Kovach, et al., Geochem. Int. **34**, 628 (1996) [Geokhimiya **34**, 699 (1996)].
3. V. I. Kovalenko, V. V. Yarmolyuk, V. P. Kovach, et al., J. Asian Earth Sci. **23**, 605 (2004).
4. E. V. Khain, E. V. Bibikova, E. B. Salnikova, et al., Precambrian Res. **229**, 1 (2002).
5. Yu. V. Amelin, E. Yu. Rytsk, R. Sh. Krymsky, et al., Dokl. Earth Sci. **371A**, 455 (2000) [Dokl. Akad. Nauk **371**, 652 (2000)].
6. Yu. V. Amelin, E. Yu. Rytsk, and L. A. Neymark, Earth Planet. Sci. Lett. **148**, 299 (1997).
7. E. Yu. Rytsk, V. P. Kovach, R. Sh. Krymsky, and Yu. A. Kleimenov, in *Proceedings of the 3rd All-Russia Conference on Subdivision of the Precambrian* (Kol. Nauch. Tsentr, Apatity, 2000), pp. 243–245 [in Russian].
8. V. S. Gladkikh, G. S. Gusev, A. I. Peskov, et al., Sov. Geol., No. 5, 89 (1988).
9. G. S. Gusev, A. I. Peskov, and S. K. Sokolov, Geotectonika **26** (2), 72 (1992).
10. E. Yu. Rytsk, B. V. Belyatsky, and V. S. Shalaev, in *Isotopic Dating of Geological Processes: New Methods and Results* (GEOKhI, Moscow, 2000), pp. 313–315 [in Russian].
11. E. Yu. Rytsk, A. F. Makeev, V. A. Glebovitsky, and A. M. Fedoseenko, Dokl. Earth Sci. **397A**, 765 (2004) [Dokl. Akad. Nauk **397**, 1 (2004)].
12. E. Yu. Rytsk, Yu. V. Amelin, N. G. Rizvanova, et al., Stratigr. Geol. Correlation **9**, 315 (2001) [Stratigr. Geol. Korrel. **9** (4), 3 (2001)].
13. E. Yu. Rytsk, and V. P. Kovach, in *Proceedings of Conference on Geodynamic Evolution of the Lithosphere of the Central Asian Mobile Belt* (Irkutsk, 2005), Issue 3, Vol. 3, pp. 85–88 [in Russian].
14. V. P. Kovach, A. B. Kotov, A. P. Smelov, et al., Petrology **8**, 353 (2000) [Petrologiya **8**, 394 (2000)].