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GEOLOGY

The Sr, Nd, and Hf Isotopic Geochemistry of Rocks of the Gabbro–Diorite–Tonalite Association from the Eastern Segment of the Middle Urals as an Indicator of the Age of the Continental Crust in This Area

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Abstract—According to isotopic analysis of rocks of the Reft gabbro–diorite–tonalite complex (Middle Urals), gabbro and related diorite and dikes and vein-shaped bodies of plagiogranitoids, crosscutting gabbro, are similar to the depleted mantle substance in $\varepsilon_{Nd}(T)$ = 8.6–9.7 and $\varepsilon_{Hf}(T)$ = 15.9–17.9. Their model Hf ages are correlated with the time of crystallization. Here, the tonalites and quartz diorites constituting most of the Reft massif are characterized by lower values: $\varepsilon_{Nd}(T)$ = 3.7–6.0, $\varepsilon_{Hf}(T)$ = 11.1–12.7, and T_{DM} values significantly exceeding the age datings. This is evidence that Neoproterozoic crustal rocks were a source of parental magma for these rocks. The primary $^{87}Sr/^{86}Sr$ ratio in rocks of both groups is highly variable (0.70348–0.70495). The data obtained allow us to reach the conclusion that the Reft gabbro–diorite–tonalite complex was formed as a result of nearly synchronous processes occurring in the crust and the mantle within a limited area.

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Gabbro–diorite–tonalite complexes are represented by one of the most specific associations of igneous rocks within the Ural Mobile Belt (UMB) and the basement of the adjacent part of the West Siberian plate. The formation of such complexes is associated with the early stages of development of the Ural orogen, as evidenced by the spatial relationship of intrusive bodies, composed of these rocks, with volcanic sequences of similar composition lying at the base of the geological succession. The occurrence of associations of this type, as well as other gabbro–granitoid complexes, is traditionally considered by Ural geologists as a result of crystallization differentiation of basaltic melts. Except for single analyses of granitoids of this association [1], there are no data on the isotope composition of rocks of gabbro–diorite–tonalite complexes that could make it possible to clarify the problems of their genesis and to establish the sources of parental melts. This work presents the results of studying the Sr, Nd, and Hf isotope geochemistry of rocks of this type in terms of the Reft gabbro–diorite–tonalite complex exposed in the eastern segment of the Middle Urals. Research results have shown that the existing concepts of petrogenesis of these associations and features of the geological structure of the area studied require comprehensive revision.

The Reft gabbro–diorite–tonalite complex comprises a predominant part of the Reft gabbro–granitoid massif (Fig. 1), which is one of the largest igneous provinces of this type in the area studied. The massif is located within the eastern segment of the Middle Urals, which represents the zone made of Paleozoic volcanic and volcanic–sedimentary sequences, as well as comagmatic intrusive bodies that extend along the eastern edge of the open part of the Urals, plunging eastward beneath the cover of the West Siberian plate [2]. The complex consists of several tectonic blocks. The largest western block (60 × 15 km), occupying more than half of the massif, is composed of medium- to coarse-grained tonalites with a subordinate amount of quartz diorites. Two significantly smaller blocks (2 × 15 and 8 × 25 km), composed of hornblende-bearing gabbro and diorites in the eastern part of the massif, are separated from the western block of granitoids by the zone of ophiolitic rocks (Fig. 1). The gabbroids are complicated by numerous small dikes and

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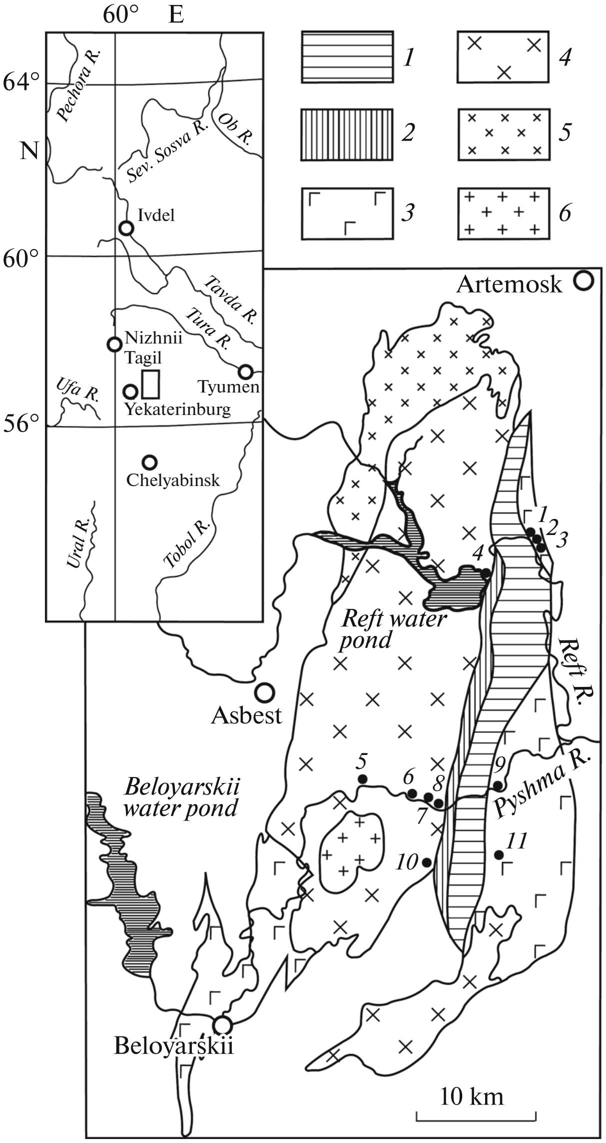

Fig. 1. Geological scheme of the Reft gabbro–granitoid massif with sampling points for isotopic analysis. *1*, Gabbroids of the ophiolite association; *2*, complex of parallel dolerite dikes; *3*, hornblende gabbro and diorites of the Reft complex; *4*, quartz diorites and tonalites of the Reft complex; *5*, Late Silurian trondhjemites of the Averinskii complex; *6*, rocks of the Devonian gabbro–granitoid association.

vein-shaped bodies of plagiogranitoids, varying in composition from quartz diorites to plagiogranites. All rock varieties of the Reft complex belong to the Na-alkaline series and are characterized by common petrochemical features. According to U–Pb and Sm–Nd isotopic analyses, the crystallization age of rocks, which differ from other tectonic blocks due to the basicity coefficient, is similar and limited to a fairly narrow age interval of 435–430 Ma [3]. For a long time, the spatial conjugation, the common features of the chemical composition, and the coevality of rocks of the complex have been explained by the differentiation of the parental basaltoid magma in an intermediate chamber and subsequent intrusion of the melts generated into the upper crustal horizons. The rocks of the Reft complex were intruded by granitoid and gabbro–granitoid plutons up to 10 km or more in diameter, as well as numerous dikes of Late Silurian and early Middle Devonian age. A more detailed description of the complex is given in several articles [3–5].

The Sm–Nd and Rb–Sr isotope systematics were examined in 12 rock samples of all the main rock varieties of the complex, collected in different parts of the Reft gabbro–granitoid massif (Fig. 1), using the ID-TIMS method at the Laboratory of Geochronology and Geochemistry of Isotopes of the Geological Institute, Komi Science Center, Russian Academy of Sciences (Apatity, Russia). An analysis of the Lu–Hf isotope systematics in zircons from four samples of the Reft rocks also varying in composition and geological position was performed at the Department of Geoscience of Johann Wolfgang Goethe University (Frankfurt-am-Main, Germany) using a Thermo Scientific Neptune MC-ICP-MS mass spectrometer equipped with a New Wave Research NWR UP-213 laser. The analytical procedures used for isotopic analysis are presented in [6–8].

We have established that the Reft gabbro–diorite–tonalite complex includes two groups of rock varieties distinctly different in the Nd and Hf isotopic compositions and the model ages calculated on the basis of the data obtained. This is evidence that there were two different sources of the magmatic melt, which is clearly observable on the correlation diagrams ε_{Sr}–ε_{Nd} and ε_{Nd}–ε_{Hf} (Figs. 2, 3), where the fields of rocks of these two groups do not overlap. Here, rocks of both groups are characteristic of a quite wide range in the initial $^{87}Sr/^{86}Sr$ ratio (0.70348–0.70634).

The rocks of the first group (fields *A*; Figs. 2, 3) are represented by gabbro and diorites, as well as dikes and vein-shaped bodies of plagiogranitoids, crosscutting gabbro, are similar to the depleted mantle substance in the following parameters: $^{143}Nd/^{144}Nd_i$ = 0.512518–0.512573, $\varepsilon_{Nd}(T)$ = 8.6–9.7, $^{176}Hf/^{177}Hf_i$ = 0.282961–0.283019, and $\varepsilon_{Hf}(T)$ = 16.2–17.5 (Fig. 4). This indicates that there was a unified mantle source for all these rocks. In view of the fact that according to the experimental data ([9], etc.) the genesis of granitic melts under mantle conditions is impossible, the appearance of moderately acid and acid melts with mantle isotope characteristics, which are parental for granitoids of vein-shaped bodies, should apparently have resulted from differentiation of the parental basic mantle in an intermediate chamber. The model ages of rocks of this group (T_{Nd}(DM) = 371–500 Ma and T_{Hf}(DM) = 362–443 Ma) within the accuracy of measurements correspond to their crystallization age. The second group of rocks (field *B*; Figs. 2, 3) is represented by tonalites and quartz diorites, composing a

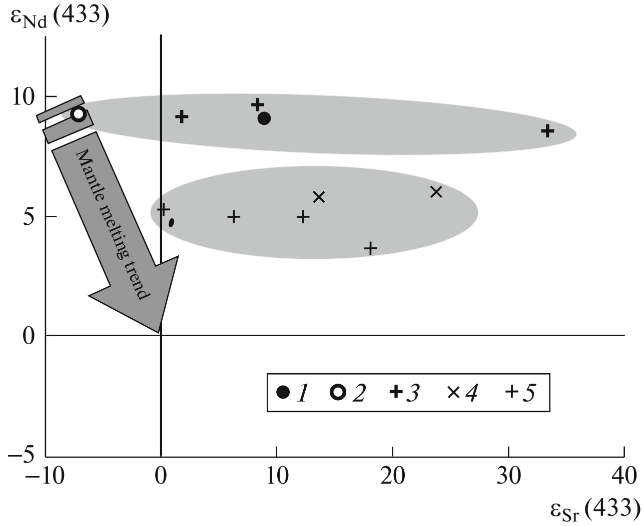

Fig. 2. The ε_{Sr}–ε_{Nd} correlation diagram for rocks of the Reft gabbro–diorite–tonalite complex. *1*, Gabbro; *2*, diorite; *3*, plagiogranites from veins bodies enclosed in gabbro; *4*, quartz diorites; *5*, tonalite from a large body (the western part of the massif).

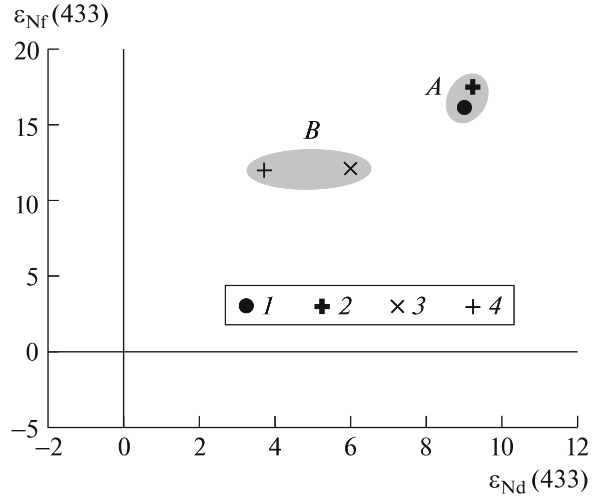

Fig. 3. The ε_{Nd}–ε_{Hf} correlation diagram for the Reft gabbro–diorite–tonalite complex. *1*, Gabbro; *2*, plagiogranite from a vein body enclosed in gabbro; *3*, quartz diorite; *4*, tonalite from a large body (the western part of the massif). Average ε_{Hf} values for a sample were used for constructing the diagram.

large body in the western part of the massif. The granitoids of this group are characterized by lower values of $^{143}Nd/^{144}Nd_i$ = 0.512265–0.512388, $\varepsilon_{Nd}(433)$ = 3.7–6.0, $^{176}Hf/^{177}Hf_i$ = 0.282826–0.282870, and $\varepsilon_{Hf}(T)$ = 11.1–12.7. The model ages of these rocks, calculated on the basis of the results of study of the Sm–Nd and Lu–Hf isotope systems, are markedly different: 690–889 Ma and 578–644 Ma, respectively. Here, there is an important common feature: they are much older than the time of rock crystallization. A significant difference between the model age values and the time of crystallization means that the source of melts parental for rocks of this group contained a substance, most likely dominant, which after separation from the mantle occurred in the crust for a long time.

According to the calculation data, the age of this crust is Neoproterozoic. Previously it was shown that the Middle Urals segment of the eastern zone of the Urals is most probably a fragment of the same Paleozoic structure as the Tagil island arc located to the west [10]. Therefore, we consider Neoproterozoic metamorphic rocks of the Belogorsk complex (Fig. 4), developed in the framework of massifs of the Ural Platinum Belt, as a possible source for granitoids of this group because of the similarity in the Nd isotope composition. In the eyes of some researchers, these rocks represent an exhumed fragment of the ancient basement of the Tagil paleo-island arc [11].

As an alternative explanation of the Neoproterozoic model ages of the rocks examined, a model according to which the primary melt source for these rocks represented the mixing of the basic oceanic crust and pelitic sediments in the subduction zone can be considered ([12, 13], etc.). The latter are considered to be a product of erosion of the ancient crust of an adjacent plate. However, the hypothesis of the generation of melts, parental for tonalites and granodiorites, seems less likely because the pelitic material should have originated from a much more ancient substance

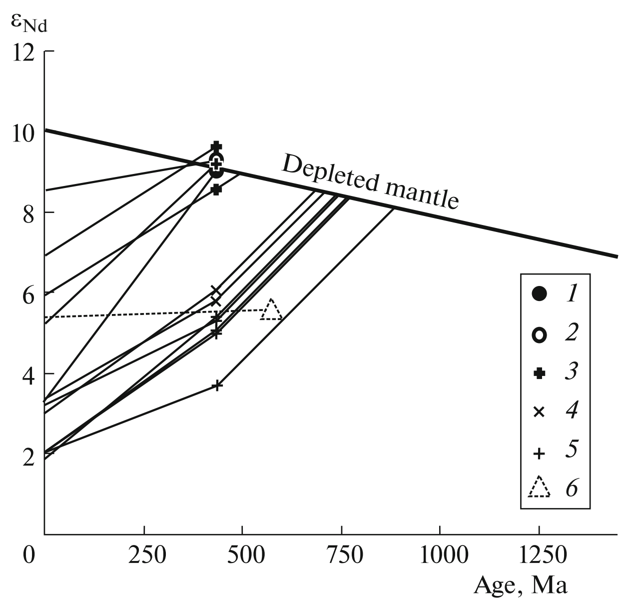

Fig. 4. Evolution of the Sm–Nd isotopic system in rocks of the Reft gabbro–diorite–tonalite complex. *1*, Gabbro; *2*, diorite; *3*, plagiogranitoids from vein bodies enclosed in gabbro; *4*, quartz diorites; *5*, tonalites from a large body (the western part of the massif); *6*, Ep–Gr–Mu–Amf plagiogneisses of the Belogorsk metamorphic complex.

in order to provide average Neoproterozoic model ages. However, rocks that could have been a source for this material are unknown within the eastern segment of the Middle Urals and the adjacent part of West Siberian plate. Finds of single, most probably restitic, zircons with no rhythmic zoning, characteristic of magmatic zircons, and more ancient Neoproterozoic ages of 787 ± 4 and 581 ± 1 Ma [3] in comparison with the time of rock formation testify in favor of the fact that the Neoproterozoic metamorphic rocks served as a source of melts for rocks of the second group.

At fairly stable Nd and Hf isotopic compositions of rocks of both groups, the Sr isotope ratio varies greatly. The minimum primary $^{87}Sr/^{86}Sr$ ratio value (0.70348) that is common for rocks that originated from a mantle source was measured in rocks of the first group (field *A*, Fig. 2). Most of the samples are characterized by a higher proportion of radiogenic Sr ($^{87}Sr/^{86}Sr_i$ = 0.70411–0.70634) compared to mantle-derived rocks. As a result, measurement points of these rocks lie on the ε_{Sr}–ε_{Nd} correlation diagram to the right of the mantle trend line. Similar features of the isotopic composition established in the rocks of ophiolite complexes and ocean-floor basalts are usually explained by their interaction with seawater [14, 15]. In our case, the direct interaction of rocks of the Reft complex with seawater during the crystallization process was impossible, but one can assume with a high probability an influence on the isotopic composition of the fluid formed due to plunging of water-saturated oceanic sediments into the subduction zone. According to the data available, during the Llandoverian–Wenlockian, when the formation of the Reft complex occurred, the eastern segment of the Middle Urals contained a marginal sea [10]. The formation of basaltic melts, which was parental for rocks of the second group, occurred with partial melting of the suprasubduction mantle wedge probably with the active participation of an aqueous fluid with a high $^{87}Sr/^{86}Sr$ ratio resulting from slab dehydration in the subduction zone. Significant variations in the $^{87}Sr/^{86}Sr_i$ ratio revealed in the rocks studied can only be explained by the uneven saturation of the generated melt with this fluid. Along with the influence of a fluid, variations in the Sr isotope composition in rocks of the second group (field *B*, Fig. 2) can also be explained by heterogeneity of the crustal source of granitoid melts.

Thus, the data obtained clearly testify to the presence in the area studied of a continental crust with an age not younger than the Neoproterozoic. The formation of the Reft gabbro–diorite–tonalite complex was formed as a result of nearly synchronous processes occurring in the crust and the mantle within a limited area. Here, the differentiation of the mantle-derived basic magma played an insignificant role during the formation of these rocks.

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