Features of the Riphean-Early Paleozoic magmatism of the southeast of the Siberian platform

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Abstract. Geochemical study of mafic dikes and sills of the Riphean (Ulakhanbam) and Ordovician (Suordakh) ages in the area of the Sette-Daban ridge allowed to establish differences between these complexes. For the Ulakhanbam magmatic rocks, the mantle source was basically similar in characteristics to E-MORB. Despite the possible sediment contamination, wide range of εNd(T) values is most likely due to the specific composition of the mantle source, which likely had an admixture of OIB material. The Ordovician reservoir had OIB characteristics, whereas the MORB material had a subordinate significance.

1. Introduction
The Verkhoyansk fold-and-thrust belt is located along the eastern margin of the Siberian platform and extends for 2500 km from the coast of the Laptev Sea in the north and almost to Udskaya Bay of the Sea of Okhotsk in the south. According to variation in structural style, the fold-and-thrust is divided into the foreland and the hinterland zones [1].

The foreland zone is divided (from north to south) into the Olenek, West Verkhoyansk and South Verkhoyansk sectors. The study area is the South Verkhoyansk sectors that will be discussed in more detail.

The South Verkhoyansk sector is subdivided into three zones (from west to east): the Maya-Kyllakh, Sette-Daban and South Verkhoyansk zones (figure 1), each of which contains several subzones. They are composed of rocks of different ages and are characterized by different structural styles [1], [2].

The westernmost Maya-Kyllakh zone is located along the border with the platform and is composed of Riphean, Vendian, Cambrian and Ordovician terrigenous and carbonate rocks. In the central and southern parts of the zone, these strata are unconformably overlapped by carbonate sediments of the Lower Carboniferous and terrigenous rocks of the Lower Permian and Lower Jurassic. The total thickness of all strata does not exceed 8-10 km. The structure of the Maya-Kyllakh zone is dominated by imbricate thrusts fan [1], [2].
Figure 1. Tectonic map of the South Verkhoyansk and neighboring regions [1], [2]. Legend: 1 - Archean-Paleoproterozoic crystalline basement of the Siberian platform and the Okhotsk massif, 2 - Intrusive, volcanic and volcanic-sedimentary complexes of the Mesozoic active margin of the Asian continent, 3-5 - South Verkhoyansk sector: 3 - South Verkhoyansk zone, 4 - Sette-Daban zone, 5 - Maya-Kyllakh zone, 6 - main faults, 7 - boundaries of the area of the Ordovician igneous rocks of the mafic composition distribution, 8 - the area of Riphean igneous rocks distribution.

The Sette-Daban zone is located east of the Maya-Kyllakh and occupies an axial portion of the South-Verkhoyansk sector. Due to the pinching out of the Maya-Kyllakh zone in the north, the Sette-Daban zone borders along the frontal thrust with the Siberian platform and the Priverkhoyansk foreland basin. The zone is composed of intensely deformed Vendian, Lower and Middle Paleozoic rocks with a total thickness of about 14 km. Massive carbonates predominate in the upper part of the section, and shale and limestone dominate in the lower part with an increase of clay material to the east. Basically, these rocks belong to rift and passive margin complexes. The Sette-Daban zone has a "palm tree" structure pointing to its formation during transpression, superimposed on earlier thrusts [2], [3].

The South Verkhoyansk zone is the easternmost zone of the South Verkhoyansk sector and is composed of the Lower Carboniferous - Middle Jurassic terrigenous rocks. In the western part of it, mudstones and siltstones predominate, while in the central and eastern parts there are massive sandstones. The total thickness of the strata is about 18 km [2].

Despite many years of research, correlation of the magmatic formations of the South Verkhoyansk is still controversial. Thus, the Suordakh hypabyssal trachydolerite complex was identified relatively
recently, during the State Geological Mapping at 1:200 000 scale Program (GDP-200) in the central part of the Sette-Daban zone, when its U-Pb isotopic age was established [4]. Previously, these bodies belonged to the Belorechensk complex, whose Early or Middle Paleozoic age was determined by K-Ar dating [5] and could not be considered as reliable. The latest studies [6] allowed us to give a general characteristic to the Suordakh bodies, but so far the amount of data obtained on this complex remains insignificant.

Thus, the purpose of this paper is to characterize the Suordakh hypabyssal complex, and also compare it with the better studied Riphean Ulakhanbam complex, in order to examine the evolution of the magmatism of the southeastern margin of the Siberian platform in the Riphean - Early Paleozoic.

2. Geological and petrographic features of magmatic complexes

2.1 Riphean intrusions

Intrusions of the Ulakhanbam complex are mainly represented by sills with minor dikes of dolerite and rare dikes of mafic tuffisites. Sills are composed of dolerites and olivine dolerites. They have a length from hundreds of meters to the first tens of kilometers and thickness varying from 1-2 m to 120-170 m. The contacts of mafic sills with host Riphean sediments are usually straight and concordant.

The rock-forming minerals of the Ulakhanbam complex dolerites (figure 2) are the intermediate and basic plagioclase - 27–45%, augite - 28–42%, micropegmatite accretions of quartz and potassium feldspar –3–16%, hypersthene - 3-8%, biotite - 1-7%, quartz - up to 4%; accessory minerals: apatite - single grains; ore minerals: ilmenite, magnetite - 5-14% [7].

Figure 2. Ulakhanbam dolerite microphotographs. Micropegmatite structure (A), ophitic, gabbroophitic structure (B); doleritic structure (C) with analyzer and doleritic structure without analyzer (D).
The Late Riphean age of the complex was established by geological observations [5] and confirmed by geochronological dating. In the central part of the Maya-Kyllakh zone, just north of the Allakh-Yun river (figure 1), Vendian sediments unconformably overlap sills. For dolerites of this complex, several isotopic ages were obtained: 974 ± 7 Ma and 1005 ± 4.3 Ma, according to the U-Pb baddeleyite method [8], 981 ± 69, 946 ± 37, 932 ± 46, and also 942 ± 18 Ma by the Sm – Nd isochronous rock – plagioclase – pyroxene method [9], [10]. Thus, the formation of dolerites of the Ulakhanbam complex took place at the beginning of the late Riphean, in the time interval from 1000 to 930 Ma.

2.2 Ordovician intrusions
The sills of the Suordakh complex have a thickness varying from 2 to 15 m, locally reaching 25-30 m, with a length up to 10 km. Contacts with host rocks are straight and abrupt. Carbonate rocks are recrystallized, sometimes with the formation of marbles, terrigenous rocks are corneal. The thickness of contact metamorphism zones is up to 2-3 m. Trachydolerites and dolerites are composed of basic plagioclase (40-60%), augite, titanium-augite (25-45%), quartz (up to 3%), titanomagnetite, olivine (up to 15%), ilmenite. Accessory minerals - apatite, zircon, sphen. Secondary minerals are represented by chlorite, epidote, sericite, carbonate, sometimes amphibole, biotite. The structure varies from pegmatoid, ophitic to tholeiitic (figure 3).

Figure 3. Suordakh dolerite microphotographs. Dolerite-ophitic structure (A), poikilite structure (B), poikilophitic structure (C) with analyzer and poikilophitic structure without analyzer (D).

The age of sills of the Suordakh complex was determined by the U-Pb baddeleyite method as 450 ± 24 and 444 ± 22 Ma [6]. The Ordovician age is also found in the vertical N-trending dyke, which cuts the Riphean sedimentary rock on the west limb of the Gornostah anticline — 457 ± 34 Ma [6]. This indicates that the distribution area of the Suordakh complex may be larger than distribution of sills.
3. Geochemical features of magmatic complexes
Chemical composition of 52 samples (including [6], [11]) was identified by XRF and ICP-MS methods. The following figures (figures 4-8) show the difference in composition of mafic intrusions of the Ulakhanbam and Suordakh complexes.

**Figure 4.** A plutonic TAS diagram (after [12], adapted by [13]). Suordakh - a field of igneous rocks of the Suordakh complex. Ulakhanbam - a field of igneous rocks of the Ulakhanbam complex. The solid line subdivides the alkaline from subalkaline rocks.

For the rocks of the Ulakhanbam complex, a low Nb/Y ratio values is typical, with average values varying from 0.1 to 0.3, while for the Suordakh complex Nb/Y ratio values range from 0.45 to 0.7. In comparison to Ulakhanbam complex, Suordakh dolerites have an increased content of TiO$_2$, P$_2$O$_5$, light rare-earth elements, and also Rb, Zr, and Nb.

On the spidergrams (figure 5), mafic rocks of the Ulakhanbam complex occupy an intermediate position between the compositions of the OIB and E-MORB. They are characterized by a flat distribution of REE and heavy REE enrichment. There are negative anomalies on Ta, Nb, K, as well as on Sr, P and Ti.

**Figure 5.** Elements spidergrammes. Normalized (A) - to chondrite, (B) - to the primitive mantle (according to [14]).
Samples of the Suordakh complex follow OIB distribution, but are also enriched with heavy REE. Compared to Ulakhanbam rocks, higher values are noted for Nb-Ta and P-Nd, as well as for light REE. Two large negative anomalies are fixed on K and Sr.

According to the discrimination diagrams (figure 6-7), samples from Riphean bodies fall into the zone of mid-oceanic basalts, while the Lower Paleozoic rocks occupy fields of intraplate basalts, as well as basalts of oceanic islands. Most clearly groups stood out on the diagrams with Ti, V, Sm, Sc and Zr. Diagrams with alkaline (K, Na) elements and Fe gave ambiguous results for some samples, likely resulting from hydrothermal alteration of rocks.

**Figure 6.** Discrimination diagrams. (A) V-Ti/50-5*Sc, (B) 50*Sm-Ti/50-V (by [15]) Legend: OIB - oceanic islands basalt, IAB - island-arc basalt, MORB - mid-ocean ridges basalt

**Figure 7.** Discrimination chart. Zr-Ti/100-Y*3 (A, by [16]) and Zr/Y and Zr (B, by [17]). Legend: A and B - island-arc tholeiitic basalt, B - ocean-floor basalt, B and C - calc-alkaline basalt, D - within-plate basalt (WPB), VAB – volcanic arc basalt, MORB - mid-ocean ridges basalt
The results of Sm-Nd isotopic studies are shown in the figure 8. Wide range of εNd(T) values is typical for both complexes, but for Riphean rocks it is much wider and varies from +2.3 to +7.5.

![Fig.8 Values of εNd(T) (according to [6], [10], [11])]  

4. Discussion and conclusion
The εNd(T) values varying from +3.6 to +6.5 for the Suordakh mafic intrusions may indicate both the interaction between the depleted and enriched mantle sources and the contamination of sedimentary rocks by magma. Similar conclusions can be made for rocks of the Riphean age.

For the Ulakhanbam intrusions, the mantle source was similar in characteristics to E-MORB. Negative anomalies in Ta, Nb, Sr, P and Ti may be interpreted as a result of contamination, and this makes interpretation of discrimination diagrams quite ambiguous. However, positive εNd(T) values for the Ulakhanbam sills are likely related to the specific composition of the mantle source, which probably had an admixture of OIB material.

The situation with Ordovician rocks was probably the opposite. Distribution of rare earth and minor elements on the spidergram follow that of OIB, and with reference to positive εNd(T) values, it implies that mantle source was close to OIB, whereas the MORB material was subordinate. Possible degree of influence of contamination has not yet been evaluated.

Interpretation of the data was carried out with the support of the grant of the RSF 18-17-00240.

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