## GEOLOGY

# Age, Composition, and Paleomagnetism of Dolerite−Gabbro Dolerite Intrusions of the Western Slope of the Anabar Massif: The Issue of Vendian Magmatism in the Region

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**Abstract**—The Kotuy intrusive complex was identified from the geological survey of the western slope of the Anabar Massif in the middle reaches of the Kotuy River. It is represented by dolerite−gabbrodolerite sills and dikes of Vendian age ($556 \pm 28$ Ma). A number of sills are characterized by 30−80 m thickness, and dikes often have a length of a few dozen kilometers. The distribution area of the complex is a few hundred square kilometers. However, the geodynamic evidence for the formation of extensive intrusive bodies in the northern part of Siberia in the Vendian is not clear. We present new geochronological, geochemical, and paleomagnetic data indicating that at least part of the Kotuy magmatic complex intrusions in the middle reaches of the Kotuy River should be attributed to the ~1500 Ma Kengede magmatic complex (Kuonamka large igneous province). In this light, the very existence of Vendian intrusive magmatism on the western slope of the Anabar massif appears questionable.

## INTRODUCTION

Our present knowledge of the evolution of the Siberian Platform in the Late Precambrian−Early Paleozoic is rather fragmentary. It is known that the Siberian craton separated from the adjacent continental blocks during the breakup of the supercontinent Rodinia in the Early Neoproterozoic and further resided in the tropical latitudes of the Southern Hemisphere [1]. Taimyr orogen was formed on the modern northern margin of the Siberian Platform during the Cryogenian−Ediacaran [2]. A large integrated sedimentary basin was formed immediately on the pericratonic part of northern Siberia, after a significant break in sedimentation from the Mesoproterozoic to the Ediacaran (~1400 to ~560 Ma) [3] and continued its evolution into the Paleozoic. Thus, after the completion of the formation of the Taimyr orogen, the last stage of which was marked by granitoid magmatism (~570 Ma) [2], a passive margin began to form in the northern part of the Siberian craton.

In this context, the identification of a rather large magmatic complex of basic composition of Ediacaran age (Kotuy complex, ~560 Ma) [4] on the western slope of the Anabar massif is a significant event, because, in general, there is practically no reliable information on occurrences of Vendian basite magmatism in the Siberian Platform supported by U−Pb isotope dating. The only other Ediacaran basite formation is the Vendian−Early Cambrian bimodal magmatic complex in the northeastern part of the platform and represented by dikes, small basalt beds, eruptive bodies, and rhyolites with an age of 546−525 Ma [5].

Thus, the Kotuy magmatic complex is a unique object for the Siberian Platform, because its existence requires a serious revision of our ideas about the conditions of the passive margin in the northern part of the platform ~560 Ma ago.

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## STUDY OBJECT

The Kotuy magmatic complex is located on the western and northwestern slope of the Anabar Massif in the northern part of the Siberian Platform [4]. The rocks of the complex are composed, typically, of gentle dip cutting bodies with an area of up to several tens to a few hundred square kilometers and a thickness of up to several dozen meters, as well as a limited amount of dikes of north-northeastern strike. Commonly, the intrusive bodies cut through Riphean sediments and only a few sills occur in between the Yusmastakh Formation of the Riphean and the Staraya Rechka Formation of the Vendian (Fig. 1) [4]. We studied one such sill [6] occurring within the rocks of the Yusmastakh Formation and overlain by carbonates of the Staraya Rechka Formation. The authors of the geological map claimed that there were "intrusive contacts of some bodies of the complex with sediments of the Staraya Rechka Formation" [4] to argue for the Vendian age of the complex, while the cold erosional contact of the sill roof with Vendian rocks, on the contrary, indicates that the intrusions were older than the Starorechensk Formation.

The rocks of the Kotuy complex are defined as dolerites or gabbro-dolerites of normal alkaline series, depleted in alkalis and enriched in silica [7]. Their age was constraint by isotopic dates of $587 \pm 30$, $639 \pm 30$, $748 \pm 35$, $805 \pm 40$, $870 \pm 45$, $883 \pm 45$, and $1007 \pm 50$ Ma obtained mostly by the K–Ar method implemented for whole-rock samples. The authors of the report [7], however, pointed out that K–Ar dating can be reset by alteration and that the least altered rock sample has the oldest date. Most recent interpretations, however, assume the age of the rocks of the complex to be between 587 and 639 Ma [4], which is supported by the date of $556 \pm 28$ Ma (Sm–Nd, Pl-Ol-Cpx-WR isochron) obtained from a dike in the interfluve of the Vyurbyur and Kotuykan rivers.

The U–Pb date of $1503 \pm 2$ Ma [8] was obtained for baddeleyite from the typical intrusion of the complex, the Orevun sill, after the publication of the geological map [4]. A number of U–Pb dates in the range of 1490–1503 Ma were obtained for seam-shaped bodies of the Kotuykan River similar in composition [8]. Intrusive bodies with similar ages occurring within the territory of the Anabar Massif were attributed to the Kengede complex [4] known in the international community as the Kuonamka Large Igneous Province (LIP) [8].

In general, the rocks of the Kotuy Complex are characterized by similar geochemical and petrographic characteristics, but the known age constraints for them directly contradict each other.

## METHODS

We collected samples from 15 remote sites (outcrops) of nine sills belonging to the Kotuy complex and four Triassic dikes during field work on the Kotuy River (Figs. 1a, 1b). The best studied intrusion of the complex is considered to be the Orevun sill, exposed along the Kotuy River from the Khatyska River to the Ortoku River (Fig. 1). Since we cannot exclude the possibility that this body may represent a set of intrusions of various ages without a clearly visible contact, we have collected geochemical and geochronological samples at various sites.

At each sampling point 5–10 oriented samples were taken. Twelve samples were selected for geochemical analysis. The geochronological sample was collected in the area of the southern end of the Orevun Sill (70°8′58.80″ N, 103°21′34.90″ E) (Fig. 1a) at a distance of ~30 km south of the sampling site of Ernst [8]. All the rocks studied are represented by fine- to medium-grained dolerites with characteristic ophitic and poikilitic–ophytic structure. The degree of secondary alteration of the rocks is estimated as low, with manifestations of propylitization.

Paleomagnetic and geochemical analysis was designed to compare the age and nature of individual intrusions of the Kotuy complex indirectly without dating each individual body directly. Obtaining new geochronological data, in turn, will help to clarify the age of the rocks of the complex.

Paleomagnetic analyses were carried out in the Laboratory of the Main Geomagnetic Field and Petromagnetism, Institute of Physics of the Earth, Russian Academy of Sciences (IPE RAS), and the Center for Collective Use, Petrophysics, Geomechanics. and Paleomagnetism, IPE RAS.

The concentrations of major oxides were measured by the XRF method using an S8 TIGER X-ray fluorescence spectrometer; the concentrations of rare and trace elements were measured by the ICP-MS method using an Agilent 7900 quadrupole mass spectrometer in the Geodynamics and Geochronology Center for Collective Use, Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences [10].

The baddeleyite for isotopic analysis was separated after crushing with an electric pulse on the Selfrag unit (US Geological Survey, Denver) using a modified Wilfley table [11] (Lund University, Sweden). Isotopic analyses were performed on a Micromass Sector 54 thermal ionization mass spectrometer at the University of Wyoming in the single-collector mode using a Daly detector for all isotopes. A mixed $^{205}Pb/^{233}U/^{235}U$ (ET 535) isotopic tracer was used for isotope dilution analyses. Blank concentrations ranged from 0.8 to 1.2 pg for Pb and did not exceed 0.01 pg for U. The experimental data were processed using the PBMac-DAT and ISOPLOT packages [12, 13]. All errors represent $2\sigma$ variance.
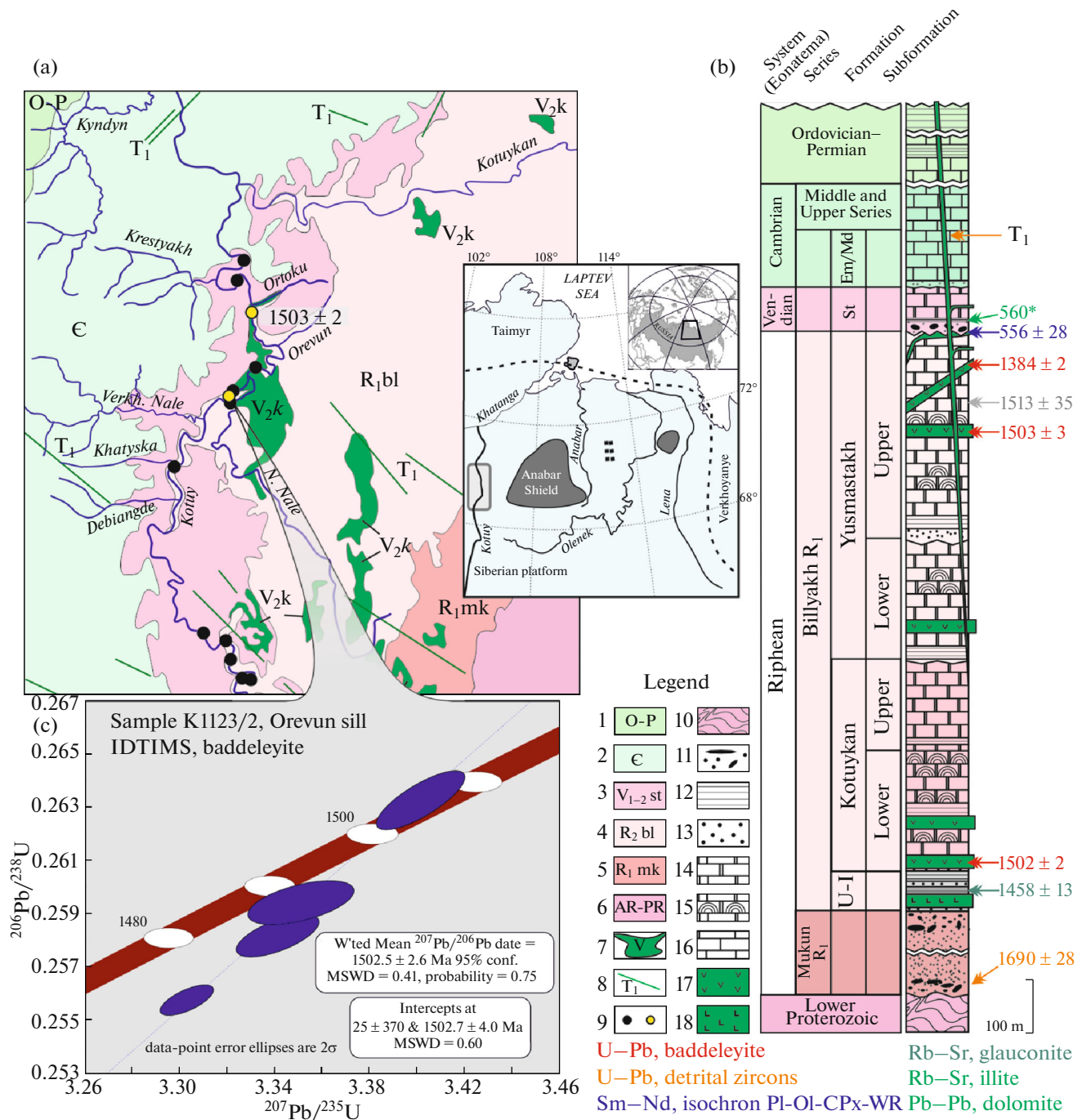
**Fig. 1.** (a) Geological map of the western slope of the Anabar massif [6]; (b) stratigraphic column of the western slope of the Anabar massif; (c) ID TIMS concordia obtained for four Orevun Sill baddeleyite data points. (1) Ordovician—Silurian; (2) Cambrian; (3) Staraya Rechka Formation of the Vendian; (4) Billyakh Series; (5) Mukun Series; (6) Archean—Proterozoic basement formations; (7) intrusive bodies of the Kotuy magmatic complex; (8) intrusive bodies of the Early Triassic magmatic complex; (9) paleomagnetic (black) and geochronological (yellow) sampling points; (10) basement rocks; (11) conglomerates, gravelites; (12) siltstones, mudstones, (13) sandstones; (14) dolomites; (15) stromatolitic limestones, dolomites; (16) limestones; (17) intrusive rocks of basic composition; (18) effusive rocks of basic composition. * Review of isotopic dates (see [9]).

## RESULTS

### Paleomagnetism

The stepwise magnetic demagnetization of the selected samples showed that the geological bodies studied were characterized by varying quality of the paleomagnetic record, nevertheless, allowing the characteristic remanent magnetization to be identified reliably (Fig. 2a). The characteristic remanent magnetization (ChRM) is distinguished over a wide spec-

trum of demagnetizing temperatures 300−600°C and is characterized by moderate and gentle negative inclinations and southwestern declination (Fig. 2b). The main carrier minerals of natural remanent magnetization (NRM) in various geological bodies may be titanomagnetite (Fig. 2d, sample no. 182), magnetite (Fig. 2d, sample no. 32), or oxidized magnetite. The presence of high-temperature oxidation structures of titanomagnetite crystals in the rock samples (Fig. 2c), the Hopkinson peak (Fig. 2d) on the temperature dependence curves of magnetic susceptibility, and the distribution of points on the Day−Dunlop diagram (Fig. 2f) indicate that the main magnetization carrier mineral in the rocks studied is predominantly in the single- or pseudosingle-domain state and can carry ancient stable magnetization.

The ChRM directions in the sills of the Kotuy intrusive complex are consistent with the directions identified earlier in the sills and dikes of the Kuonam LIP (Fig. 2e), within the Anabar massif and the Udzhinskii and Olenyokskii uplifts [15]. The expected directions for the Ediacaran of the western slope of Anabar were recalculated from the paleomagnetic directions obtained earlier for rocks of the Ushakov, Moshakov, and Chistyakov formations, as well as for the Madagascar group of Siberian paleomagnetic poles (Fig. 2e) [14]. Note that the paleomagnetic directions we obtained for the Mesoproterozoic of the Anabar Massif and the expected Ediacaran directions are practically indistinguishable. Accordingly, intrusive bodies of such age are difficult to distinguish unambiguously solely on the basis of paleomagnetic data.

### Geochronology and geochemical characteristics of rocks

Four analyses of baddeleyite grains from sample K1132 plot along a discordia line with an upper intercept with concordia at 1502.5 ± 2.6 Ma, which we interpret as the magmatic age of the Orevun sill. The lower concordia intercept overlaps the origin within uncertainty, reflecting modern lead loss (Fig. 1c).

The abundances of petrogenic and rare elements were obtained for the dated Orevun sill and for eight undated intrusions. The samples studied are characterized by moderate $SiO_2$ content (46.3 to 50.3 wt %) and low MgO content (5.0 to 7.3 wt %) and have sum of $K_2O + Na_2O$ from 2.3 to 4.3 wt %. The $TiO_2$ content varies from 1.5 to 5.1 wt %.

The rare and trace elements patterns of rocks of the Kotuy complex presented in Fig. 3c show homogeneous REE characteristics and small variations in highly incompatible elements. The shapes of pattern and the slope of the REE spectra correspond to oceanic plateau basalts (OIB). The data points in Th/Yb−Nb/Yb diagram [17] (Fig. 3d) lie above the mantle array between the E-MORB [18] and OIB [16] fields,

indicating insignificant involvement of the crustal component in the source or metasomatic alteration of the lithospheric mantle. Similar geochemical characteristics have been established for intrusions of the Kuonamka LIP [8], widely manifested in the northern part of Siberia, indicating the similarity of the mantle source and melting conditions.

### DISCUSSION AND CONCLUSIONS

The U−Pb date obtained for baddeleyite from the southern part of the Orevun sill (1502.5 ± 2.6 Ma) and the date obtained for its northern end (1503±2 Ma) are in good agreement, indicating that this large sill is still a single body that can be related to the Kuonamka LIP. The palaeomagnetic and geochemical data obtained for other intrusive bodies attributed to the Kotuy complex indicates that they most likely originated from the same source as the Orevun sill and were formed at the same time (~1503 Ma ago). At present, however, we do not have unambiguous criteria for separating the Kengede (~1503 Ma) and Kotuy (~560 Ma) complexes on the basis of geochemical and palaeomagnetic features. The latter are unsuitable for reliably distinguishing these complexes because the expected palaeomagnetic directions for the Mesoproterozoic and Vendian are quite close to each other (Fig. 2e). Geochemical data are simply not available for reliably dated Vendian intrusions of the Kotuy complex and therefore insufficient to make a reliable comparison. Only one dyke in the interfluve of the Vyurbyur and Kotuykan rivers with Sm−Nd age determination by the mineral isochron (Pl-Ol-Cpx-WR) can be considered as a relatively reliably dated body of the Kotuy complex [4]. Intrusions that cut through the rocks of the Staraya Rechka Formation and overlap with Early Cambrian sediments could have been reliable indicators of Vendian magmatism, but no such bodies were found. Nevertheless, the present knowledge of the Kotuy complex cannot exclude that we are dealing with a set of intrusive bodies of different ages with similar petrochemical composition and palaeomagnetic directions.

Another large dyke swarm with U−Pb baddeleyite dates of 1496 ± 7, 1494 ± 3, and 1494 ± 5 Ma was recently identified in the southern part of the Anabar massif [19], which was attributed to the manifestation of Kengede magmatism. Previously, the ages of some of these bodies were estimated at 1426 ± 40 and 1412 ± 4 Ma [4]. Accordingly, there is more and more data indicating a wide distribution area of basites with an age of ~1500 Ma, while there is still neither geological nor solid geochronological evidence for the existence of Vendian intrusive magmatism.

It is most likely, nevertheless, that bodies of Mesoproterozoic age are exposed in the middle reaches of the Kotuy River on the western slope of the Anabar Massif, which means that not only is the scale of Kotuy magmatism significantly less than was previously believed, but its very existence in general is ques-
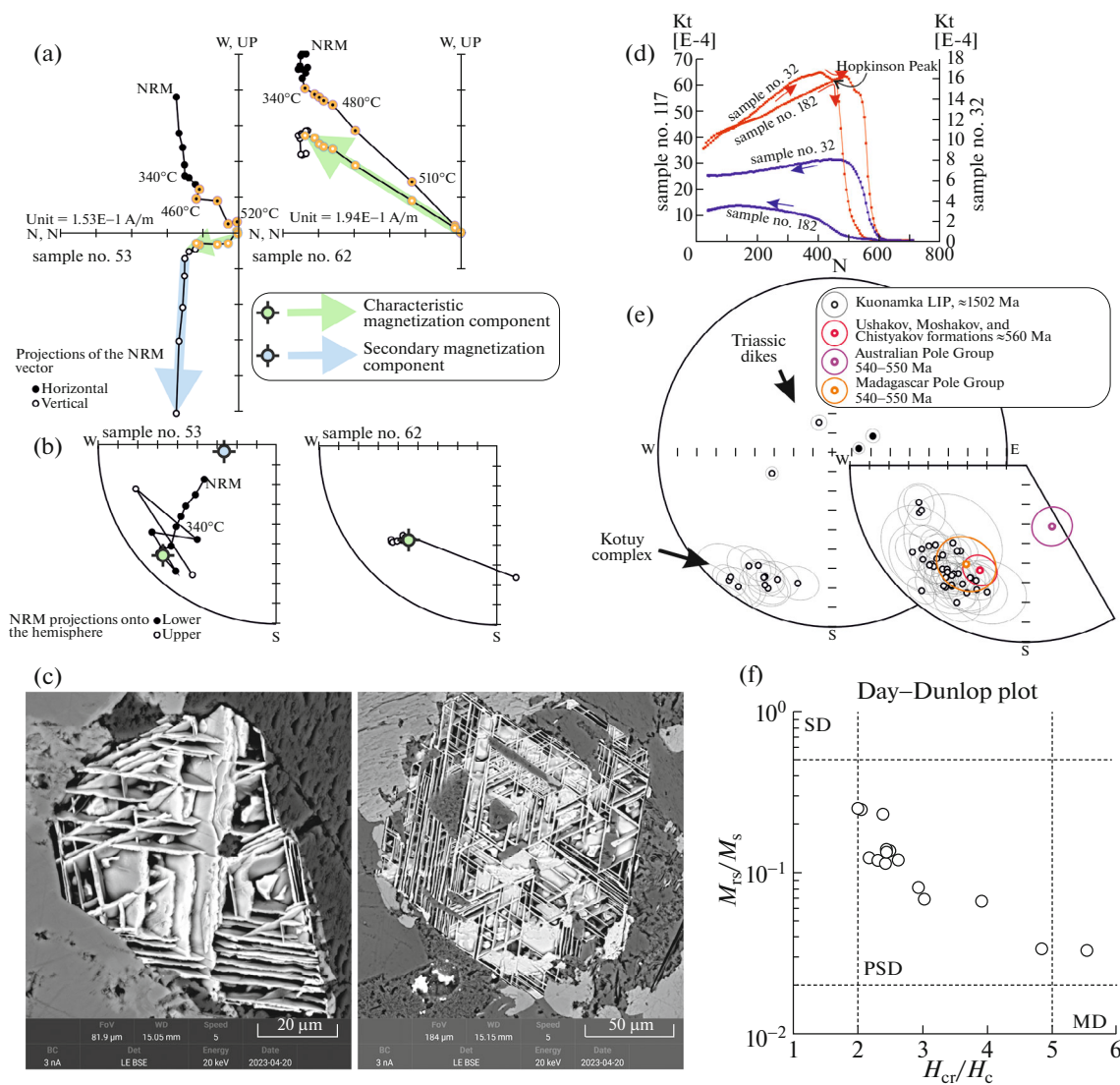
**Fig. 2.** Petromagnetic and palaeomagnetic results obtained for intrusive bodies of the Kotuy complex. Results of stepwise temperature demagnetization: (a) Zijderveld diagrams, (b) stereograms of the NRM vector. (c) SEM microphotographs of high-temperature decay structures of titanomagnetite crystals; (d) dependence of magnetic susceptibility on temperature; (e) stereograms of magnetization directions for bodies of the Kotuy complex, Kuonam LIP, and Vendian rocks of the Siberian Platform [14]; (f) Day–Dunlop diagram.
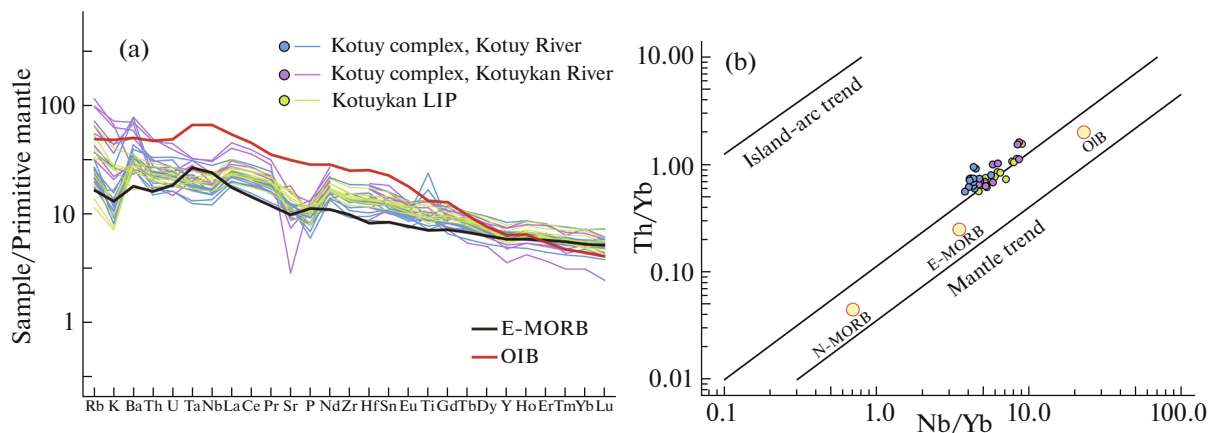


**Fig. 3.** Geochemical characteristics of rocks of the Kotuy complex (Kotuy River, Kotuykan River after [4]) and Kuonamka LIP [8]). (a) Multi-element diagram with element concentrations normalized to the primitive mantle [16], (b) Th/Yb-Nb/Yb diagram [17].

tioned. This imposed important constraints on the evolution of the Siberian Platform at the end of the Precambrian and suggests that its northern margin in the interval 570−544 Ma existed in a generally calm geodynamic environment of the passive margin.

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## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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