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Geochemistry, Tectonic Settings, and Age of Metavolcanic Rocks of the Isakovskii Terrane, Yenisei Range: Indicators of the Early Evolution of the Paleo-Asian Ocean

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Abstract—The geodynamic nature of the Late Neoproterozoic island-arc dacites (691 ± 8.8 Ma) and rift basalts (572 ± 6.5 Ma) of the Kiselikhinskaya Formation, Kutukasskaya Group, in the Isakovskii terrane is inferred from geochemical data and U–Pb zircon (SHRIMP-II) dates. The volcanic rocks were produced during the late evolutionary history of the Yenisei Range, starting at the origin of oceanic crustal fragments and their accretion to the Siberian craton to the postaccretionary crustal extension and the onset of the Caledonian orogenesis. The reproduced sequence of geological processes marks the early evolution of the Paleo-Asian Ocean in its junction zone with the Siberian craton. The data refine the composition and age of volcanic rocks in the trans-Angara part of the Yenisei Range and specifics of the Neoproterozoic evolution of the Sayan–Yenisei accretionary belt.

Keywords: geochemistry, metadacite, basalt, U–Pb dates, Kutukasskaya Group, Yenisei Range, Paleo-Asian Ocean

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INTRODUCTION

The modern western margin of the Siberian craton is a Precambrian basement block (Angara–Kan block) and Meso- to Neoproterozoic continental marginal territory of the Yenisei Range (Nozhkin et al., 2011). The Precambrian terranes (Isakovskii and Predivinskii) are dominated by tectonized fragments of ophiolites and island-arc complexes, which were accreted to the margin of the Siberian craton in the Vendian (Nozhkin et al., 2007, 2016a). This Vendian accretionary–collisional event produced the extensive Sayan–Yenisei accretionary belt and resulted in the significant grown of the continental crust of the craton.

It is thought that the regional Mesoproterozoic accretionary–collisional processes were both genetically and spatially related to the origin of the Paleo-Asian Ocean, which was formed at the breakup of the Rodinia supercontinent (Dobretsov, 2003). Its earliest evolution is usually believed to have taken places within the time span from the early development of the paleocean to the Caledonian tectonism. Traces of these evolutionary events are most clearly discernible within the narrow stripe along the modern western and southern margins of the Siberian craton (Yarmolyuk et al., 2006) and correspond to continental marginal, ophiolite, and arc associations in the Precambrian terranes of various age and tectonic nature.

Many aspects of relations between the Precambrian terranes and the development of the Paleo-Asian Ocean and their later accretion to the Siberian craton are still not fully understood, and this stimulates much interest in the evolution of such structures in paleocean–continent transition zones. The scarcity of the reliable dates significantly narrows the possibility of age correlations between the evolution of the Paleo-Asian Ocean and global geological processes. In view of this, we conducted a geochronologic study of metavolcanic rocks and tectonic mélange in the shear zone to estimate their geodynamic nature and age.

GEOLOGICAL OVERVIEW AND MAJOR STRUCTURAL ELEMENTS OF THE YENISEI RANGE

The Yenisei Range submeridionally extends in the western margin of the Siberian craton for almost 700 km along the Yenisei River and has a width of 50 to 200 km (Fig. 1b). Geophysical lines of evidence on the vertical thickening in a transpressional environment are as follows: the width of the folded area of the Yenisei Range is twice as narrow at a depth of 10 km and is thus mushroom-shaped (Vernikovskii et al.,

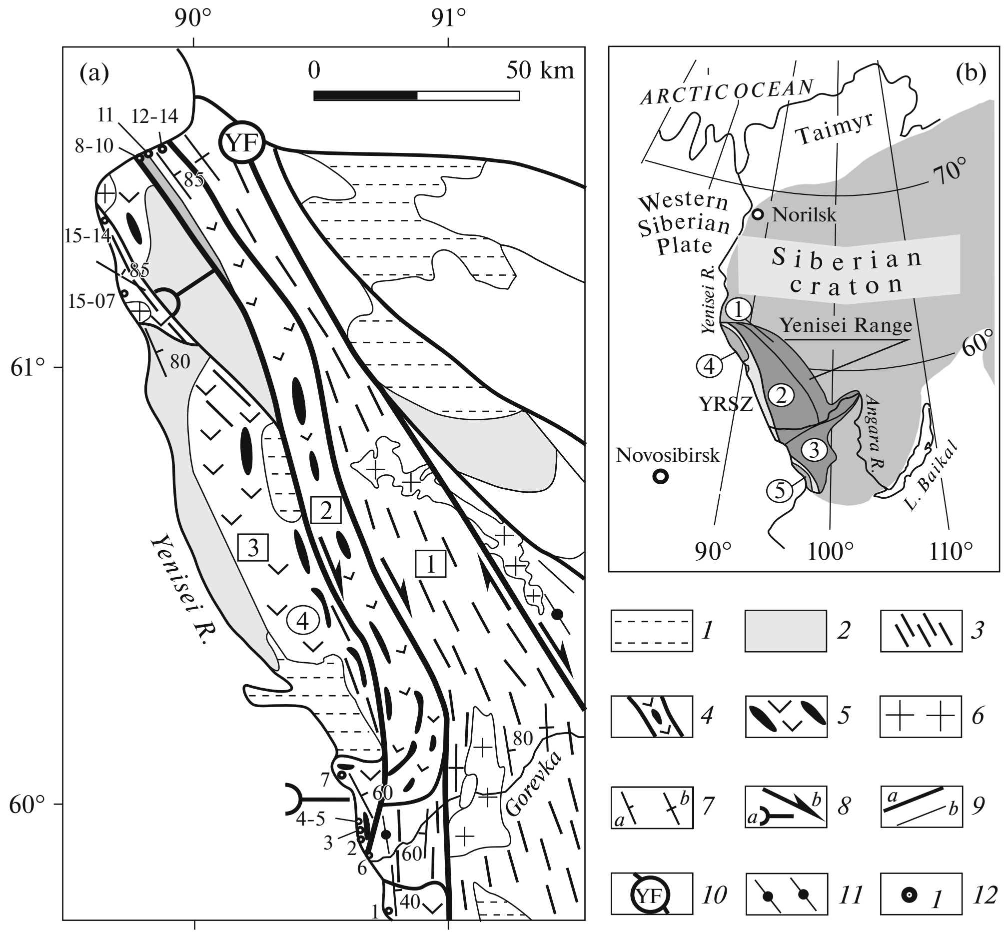

Fig. 1. (a) Schematic map of the Yenisei Regional Shear Zone (YRSZ) in the northern part of the Yenisei Range. (b) Yenisei Regional Shear Zone (pale gray) and tectonic blocks in the western margin of the Siberian craton: (1) Eastern block, Northern Segment; (2) Central block, Northern Segment; (3) Angara–Kan block; (4) Isakovskii terrane; (5) Predivinskii terrane. (*1*) Paleozoic–Cenozoic cover; (*2*) Middle–Late Neoproterozoic molasses; (*3*) Neoproterozoic blastomylonites after rocks of the Paleoproterozoic Garevskii Complex (zone 1); (*4*) high-pressure metabasite–ultrabasite and apogneiss blastomylonites (zone 2); (*5*) metabasalt and molasse complexes of the Isakovskii terrane (zone 3); (*6*) granitoid complexes; (*7*) strike and dip symbols of foliation: (a) oblique and (b) vertical; (*8*) direction of Neoproterozoic tectonic motions: (*a*) underthrusts and (*b*) strike-slip faults; (*9*) tectonic features: (*a*) faults, (*b*) overthrusts, (*c*) other boundaries; (*10*) Yenisei Fault; (*11*) staurolite–garnet–kyanite tectonized rocks; (*12*) sampling sites.

2009). The Moho occurs at depths of 50 km beneath the range and 40 km beneath neighboring territories (Sal'nikov, 2009). This folded orogen is thus a structure with a thickened crust, which was preserved as such during a long enough geological time. The collisional model of the development of the regional crustal structure is confirmed by seismic sounding and is interpreted as "staking" of the Neoproterozoic formations (Mitrofanov et al., 1988). The Yenisei Range consists of two major segments (Southern Yenisei and Trans-Angara ones), which are separated by the sublatitudinal Lower-Angara Regional Fault (Nozhkin et al., 2016b). In the Trans-Angara part, north of the Lower-Angara Fault, the Yenisei Range is made up of Paleoproterozoic and Meso- Neoproterozoic rocks, which compose the Eastern (near the platform) and Central cratonic blocks and the Isakovskii (western) terrane, which consists of Neoproterozoic ophiolites and arc complexes (Vernikovskii et al., 1994).

The tectonic blocks are separated by large regional faults of dominantly northwestern trend, which dip subvertically (Kheraskova et al., 2009). The structures are an array of faults of strike-slip, reverse, and overthrust kinematics (Korobeinikov et al., 2006). The faults are hundreds of kilometers long, and the stress metamorphic zones range from hundreds to a few dozen kilometers in width. These are usually linear zones of active interaction between the tectonic blocks (Likhanov et al., 2006). Zones near these fault contain blastomylonites. They typically show shear flow textures, which are ubiquitously discernible at both the meso- (rock) and the microlevel (Reverdatto et al., 2017). These are linear deformational gneissosity, the occurrence of ordered ductile-flow textures, stretching and breakup of flow folds of *en-echelon* morphology, kink bands in the micas, "pressure shadows" of recrystallized quartz, S-shaped and strongly deformed "snowball" garnet grains, breakup of mineral grains with displacement and the development of "patchy" bands, development of deformation twins and lamellas in plagioclase, a parallel arrangement of fine-grained lenticular mineral aggregates, as well as shearing, cataclasis, and boudinage (Likhanov and Reverdatto, 2014a, 2014b).

The regional faults (Yenisei, Tatarsko–Ishimninskii, and others) are accompanied by splay structures of higher orders, near which overthrusts developed (Egorov, 2004; Likhanov and Reverdatto, 2002). This induced regional metamorphism of variable pressure in the form of combinations of low- and medium-pressure facies series (Likhanov et al., 2001, 2004, 2005). The geochronology, tectonic setting, and geodynamic nature of the regional complexes are summarized in much detail in (Likhanov et al., 2014). This paper also presents a geochronologic sequence of the major stages and events in the geological history of the Yenisei Range that "shaped" its tectonics.

MATERIALS

Our study areas in the northwestern part of the Yenisei Range were constrained within the Yenisei Regional Shear Zone (YRSZ) (Likhanov et al., 2013), which is closely related to the Baikal–Yenisei Fault and extends along the western margin of the Siberian craton for at least 200 km at a width of 30–50 km (Fig. 2, inset). It consists of closely spaced subparallel faults accompanied by near-fault cataclasis, mélange, and dynamometamorphism (Likhanov, 2003). In our study area, it consists of the following three large Precambrian blocks (listed from east to west, Fig. 1): (1) a continental gneiss–amphibolite block, (2) a metaophiolite metabasite–ultrabasite block, and (3) a volcano-plutonic block (Krylov and Likhanov, 2017). The first block is made up of rocks of the Garevskii metamorphic complex, which is dominated by biotite plagiogneisses of the Nemtikhinskii unit and porphyroblastic granite-gneisses and garnet–muscovite–biotite crystalline schists of the Malogarevskii unit. The later two blocks belong to the Isakovskii terrane, which was accreted to the Siberian craton in the Vendian. The ophiolite associations of the other block consist of melanged nappes and lenses of amphibolized tholeiitic metabasalts (antigorite metadunites and metaharzburgites with subordinate volumes of antigoritized pyroxenites), which are classed with the Lower Riphean Firsovskaya unit and the Lower to Middle Riphean Surnikhinskii Complex (*Legenda...,* 2002). The volcano-plutonic block consists mostly of rocks of a metadacite–andesite–basalt association metamorphosed to the greenschist facies and ascribed to the mid-Riphean Kiselikhinskaya Formation (*Legenda...,* 2002).

The rocks belong to a subduction–accretionary complex and are found as tabular bodies, lenses, and blocks in serpentinite mélange. The tectonic mélange of blocks of different age and size, consisting of high- and low-grade metamorphic rocks of variegated composition suggests that YRSZ was repeatedly reactivated in the Neoproterozoic (Likhanov et al., 2015; Kuzmichev and Sklyarov, 2016).

Our filedwork was carried out in the northwestern part of the Yenisei Range, on the western margin of the Isakovskii terrane (IT) (Fig. 2), which contains widespread weakly metamorphosed metasedimentary–volcanic rocks of the Otravikhinskaya and Kiselikhinskaya formations of the Kutasskaya Group, which were previously thought to be of Mesoproterozoic age (*Legend...,* 2002; Kachevskii, 2006). The rocks are penetrated by protrusions of serpentinized ultramafic rocks of the Surnikhinskii Complex, whose age estimates lie within a broad range from the Mesoproterozoic (*Legend...,* 2002) to the Late Neoproterozoic (682 Ma) (Kuz'michev et al., 2008). The volcanic rocks of the Otravikhinskaya and Kiselikhinskaya formations of IT still have not been reasonably accurately dated. Below we report newly obtained U–Pb zircon ages of metavolcanic rocks of IT. These dates led us to constrain the age of the Kiselikhinskaya Formation to the Neoproterozoic and revise the stratigraphic chart of the Late Precambrian for the northwestern Yenisei Range.

MINERALOGY AND PETROGRAPHY

We studied dacites of the metarhyolites–andesite–basalt association and amygdaloidal basalts sampled in the right-hand riverside of the Yenisei (Figs. 1, 2). The metadacites occur as thin alternating layers of gray massive and schistose rocks that differ in mineralogical composition from one another. The rocks consist of microgranoblastic aggregates of quartz (60–70%), deformed albite–oligoclase phenocrysts up to 2 mm (10–20%), muscovite, biotite, and chlorite (up to 20%), which define the lenticular–schistose texture of the metavolcanic rocks. The secondary alterations of the rocks involve plagioclase replacement by epidote. The accessory minerals are zircon and more rare apatite. This study was carried out with sample 15-07 from a layer of massive metadacite, which was least affected by shearing and metamorphism.

Amygdaloidal basalts were found in a unit of plagioclase–muscovite–biotite schists (metavolcanic rocks) and calcareous sandstones as a small (1.5 × 2 m) lens-shaped body. The peripheral portions of the body are sheared and affected by greenschist metamorphism. The central part of this body, from which sample 15-14 was taken, consists of fresh massive amygdaloidal rock with rare phenocrysts of pilitized

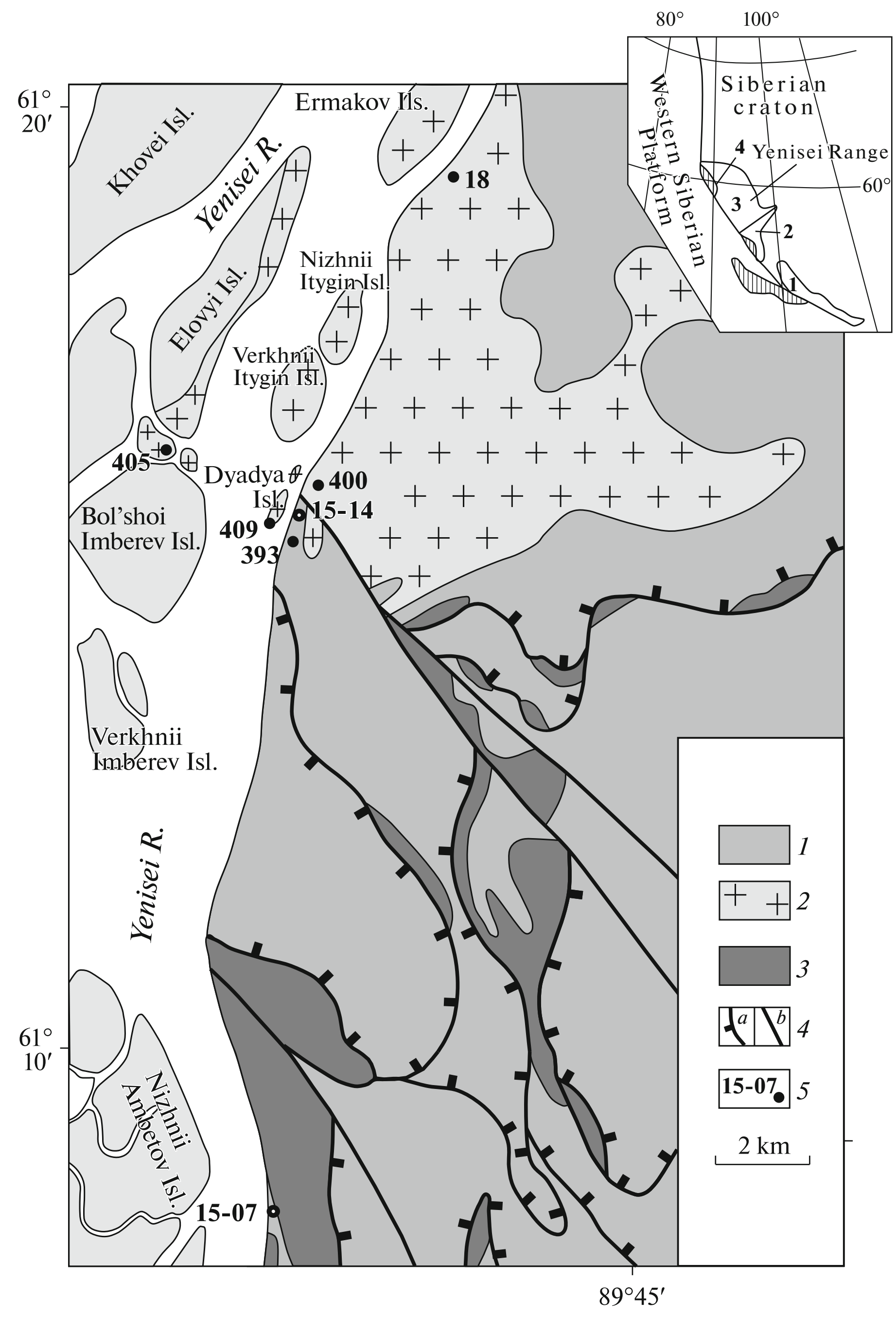

Fig. 2. Schematic geological map of the study area (modified after Kachevskii, 2006). Inset: (1) Sayan and (2) Angara–Kan basement blocks in the southwestern margin of the Siberian craton; (3) Proterozoic continental marginal region of the Yenisei Range; the shaded area is ophiolites and island-arc complexes of the accretionary belt ((4) Isakovskii terrane). (*1*) Volcanic rocks of the metarhyolites–andesite–basalt association, phyllites, metasandstones and tuff-sandstones, limestones (undifferentiated Ust'-Kutukasskaya, Otravikhinskaya, and Kiselikhinskaya formations); (*2*) subalkaline leucogranites and biotite granites of the Osinovskii massif; (*3*) serpentinites after dunites and harzburgites; (*4*) faults: (*a*) oblique, (*b*) subvertical; (*5*) sampling sites.

andesine (up to 5–7 mm). The outermost portions of the amygdules consist of opaque minerals, zeolites, and chlorite, and their cores are made up of chalcedony and carbonate. The groundmass (99%) of the basalt consists of greenish brown masses of decomposed isotropic volcanic glass with minor amounts of chlorite (10–15%), carbonate (4%), and small laths of secondary albite (15–20%). The opaque minerals occur as unevenly distributed disseminations in the groundmass of the rocks and typical sawtooth-shaped skeleton crystals at contacts between amygdules and groundmass. The accessory mineral is zircon.

Table 1. Concentration of major (wt %) and trace (ppm) elements and their indicator ratios in the dated silicic (sample 15-07) and mafic (sample 15-14) metavolcanic rocks

Component	Sample	
	15-07	15-14
SiO_2	72.50	47.24
TiO_2	0.33	1.53
Al_2O_3	13.92	14.83
Fe_2O_3	2.31	9.79
MnO	0.02	0.14
MgO	1.18	5.41
CaO	0.51	9.10
Na_2O	3.90	2.91
K_2O	3.65	0.38
P_2O_5	0.09	0.31
SO_3	<0.03	0.22
LOI	1.48	8.12
Total MC	99.66	100.07
Rb	152	6.0
Sr	50	455
Y	21	32
Zr	208	177
Nb	15.4	13.6
Cs	5.2	1.15
Ba	426	250
La	31	24
Ce	57	48
Pr	6.6	6.2
Nd	22	24
Sm	3.8	5.0
Eu	0.57	1.50
Gd	3.8	5.4
Tb	0.59	0.91
Dy	3.3	5.4
Ho	0.70	1.13
Er	1.90	3.2
Tm	0.32	0.51
Yb	2.0	3.3
Lu	0.30	0.46
Hf	6.4	4.2
Ta	1.67	0.88
Th	18.7	4.7
U	0.96	1.02
f	0.51	0.57
$La/Yb_{(n)}$	10.45	4.90
$Gd/Yb_{(n)}$	1.53	1.32
Eu/Eu*	0.45	0.87
Ce/Ce*	0.92	0.93
LREE/HREE	10.74	6.14
Total REE	133.9	129.0

$Eu/Eu^* = Eu_n/(Sm_n + Gd_n) \times 0.5$; f (molar) = $(Fe_2O_3)/(Fe_2O_3 + MgO)$; LOI is loss on ignition, LREE/HREE is the ratio of the light to heavy rare-earth elements, Total MC is the total of major components, and Total REE is the total of rare-earth elements.

MAJOR- AND TRACE-ELEMENT COMPOSITION AND GEOTECTONIC ENVIRONMENTS IN WHICH THE ROCKS WERE FORMED

Rock sample were analyzed for major components by XRF on a VRA-20R (Carl Zeiss Jena) at the Sobolev Institute accurate to no worse than ±5 relative %. Trace elements and REE were analyzed by ICP-MS on an ELEMENT (Finnigan Mat) high-resolution mass spectrometer equipped with an U-5000AT+ ultrasonic nebulizer. The analyses were accurate to 2–7 relative % (Likhanov and Reverdatto, 2007). The results of the analyses are presented in Table 1.

According to their major-component composition, the metadacites (sample 15-07) are acid volcanic rock, which are peraluminous (ASI = $Al_2O_3/(Al_2O_3 + K_2O + Na_2O)$ = 1.23), sodic–potassic ($K_2O + Na_2O$ = 7.55 wt % at K_2O/Na_2O = 0.9), and magnesian ($f = Fe_2O_3/(Fe_2O_3 + MgO) = 0.62$) granitoids belonging to the calc–alkaline series. The chondrite-normalized (Boynton, 1984) REE patterns of the granites show clear Eu anomalies (Eu/Eu* = 0.45) and a significant negative slope at LREE: $(La/Yb)_n$ = 10.5 and LREE/MREE = 10.7. The REE patterns are flat at MREE and HREE (from Gd to Lu) (Fig. 3a). The concentrations of most chemical elements in the rocks are comparable to those in low alkaline plagiogranite porphyry in the Porozhninskii Massif of island-arc nature (Vernikovskii et al., 2001). Significant petrochemical differences are found when the rocks are compared to subalkaline leucocratic K–Na postcollisional granites of the Osinovskii Massif, whose melts were derived from the highly differentiated continental crust of the western margin of the Siberian craton. The metadacites contain much lower concentrations of radioactive elements (U, Th, and K), HFSE (Nb and Ta), and REE (the total REE concentration is 130 ppm against 200–216 ppm in the granites) (Fig. 3b). In the Rb–Hf–Ta (Harris et al., 1986) and Nb–Y (Pearce et al., 1984; Pearce, 1996) discriminant diagrams, the composition points of the metadacites plot within the field of arc granites, whereas the points of the leucogranites fall within the field of postcollisional and intraplate granites (Fig. 4).

The amygdaloidal basalts (sample 15–14) (SiO_2 = 47.24 wt %) generally contain moderate concentrations of alkalis ($Na_2O + K_2O$ = 3.3 wt %, with Na_2O significantly dominating over K_2O), Fe_2O_3 (9.79 wt %), MgO (5.41 wt %), TiO_2 (1.53 wt %), and P_2O_5 (0.31 wt %). The REE patterns of the rocks are enriched in LREE ($(La/Yb)_n$ = 4.9, the total REE concentration is 105 ppm) compared to those of N- and E-MORB and are flat at MREE and HREE ($(Gd/Yb)_n$ = 1.32) (Fig. 5a). The rocks typically contain higher concentrations of Ti, P, alkalis, Sr, LILE (Rb, Ba, and K), radioactive elements (Th and U), LREE, and HFSE (Nb, Ts, Zr, Hf) than those of N-

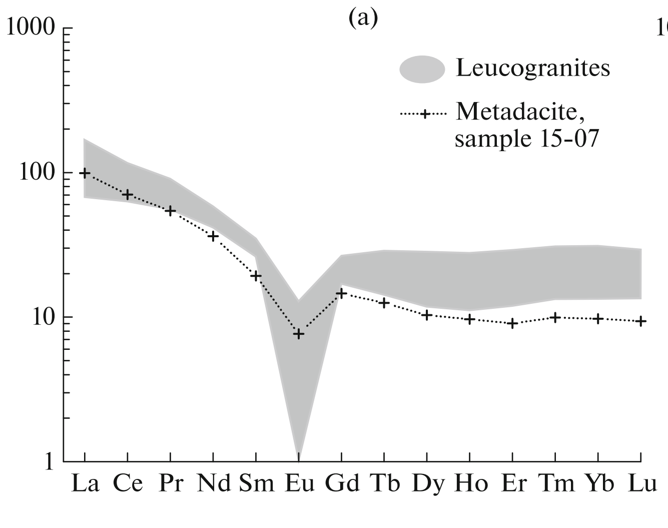

Fig. 3. (a) Chondrite-normalized (Boynton, 1984) REE patterns and (b) primitive mantle-normalized (Sun and McDonough, 1989) multielemental patterns for metadacites of the Kiselikhinskaya Formation in comparison with postcollisional leucogranites of the Osinovskii Massif (gray shading).

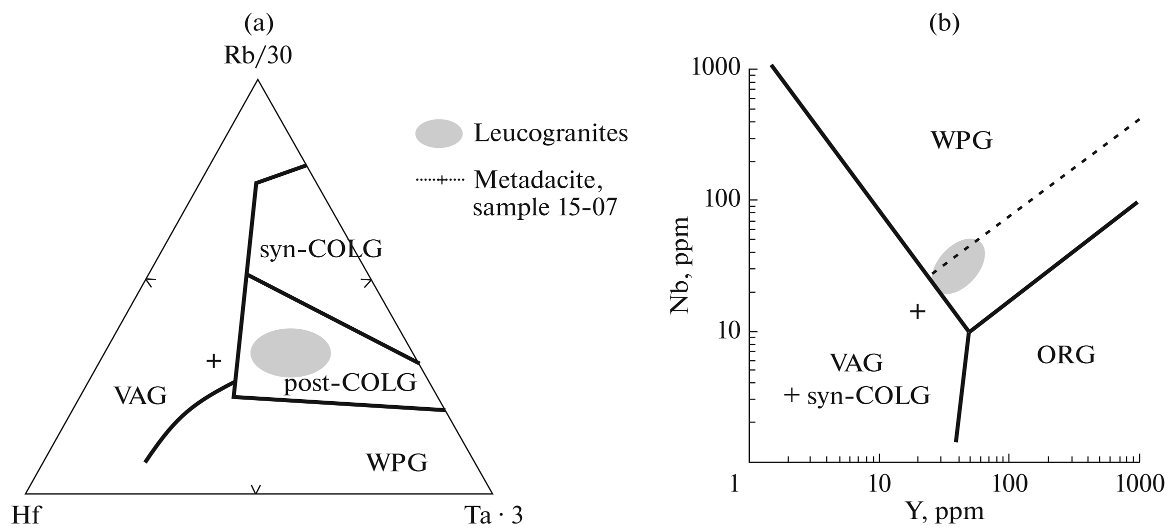

Fig. 4. Discriminant diagrams (a) Rb–Hf–Ta (Harris et al., 1986) and (b) Nb–Y (Pearce et al., 1984; Pearce, 1996) for metadacites of the Kiselikhinskaya Formation in comparison with postcollisional leucogranites of the Osinovskii Massif (gray shading). Abbreviations: post-COLG—postcollisional granitoids, syn-COLG—syncollisional granitoids, VAG—island-arc granitoids, WPG—intraplate (within-plate) granitoids.

and E-MORB (Sun and McDonough, 1989) and basalts of the Isakovskii terrane (Krylov and Likhanov, 2017) (Fig. 5b). The rocks generally show well fractionated normalized multi-element patterns, which plot near the patterns of OIB and intraplate basalts typical of rift environments. Certain petro- and geochemical parameters make these rocks principally different from metabasites of the Rybinsk–Paninmbinskii Volcanic Belt in the Trans-Angara part of the Isakovskii terrane, which belong to the group of normal and enriched basalts (Vernikovskii et al., 1994; Likhanov and reverdatto, 2015, 2016). This is also seen from the identification diagrams Zr–Nb–Y (Meschide, 1986) (Fig. 6a), TiO_2–MnO–P_2O_5 (Hooper, 1982) (Fig. 6b), P_2O_5–TiO_2 (Hooper, 1982) (Fig. 7a), and Zr/Y–Nb/Y (Fitton et al., 1997) (Fig. 7b), in which the composition points of the amygdaloidal metabasites plot mostly within the region of intraplate basalts, between E-MORB and OIB or volcanic rocks at oceanic islands (Likhanov et al., 2008). These rocks differ from classic arc basalts in bearing lower concentrations of Al_2O_3 (14.8 wt %), Ba (250 ppm), and Sr (455 ppm) and ele-

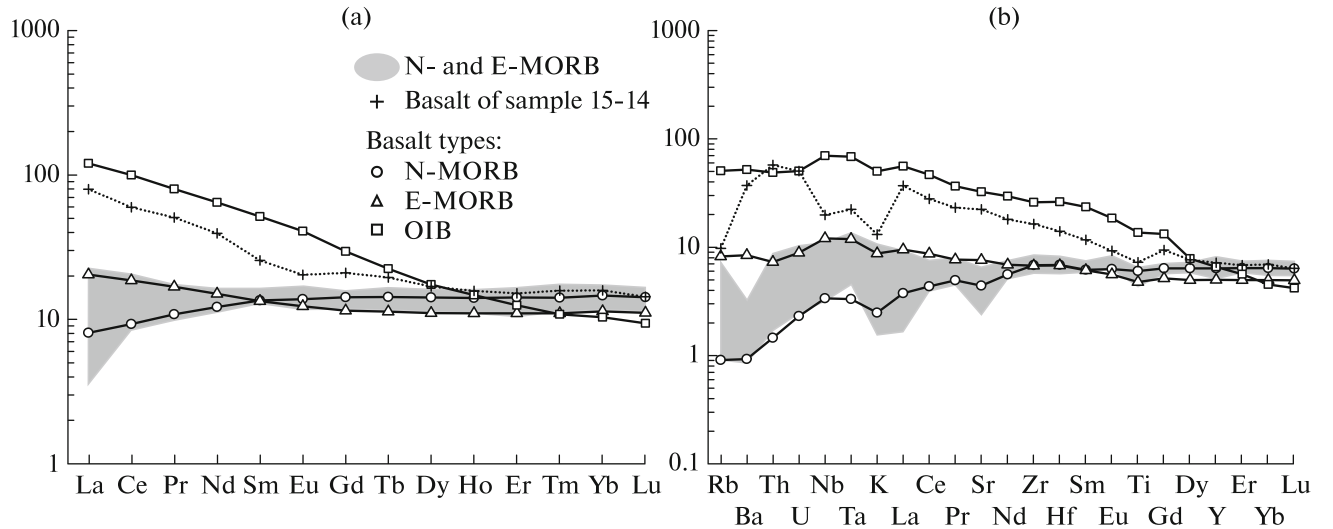

Fig. 5. (a) Chondrite-normalized (Boynton, 1984) REE patterns and (b) primitive mantle-normalized (Sun and McDonough, 1989) multielemental patterns for amygdaloidal basalts of the Kiselikhinskaya unit in comparison with basalts of the Isakovskii terrane (gray shading) and major basalt types: N-MORB, E-MORB, and OIB are according to (Sun and McDonough, 1989).

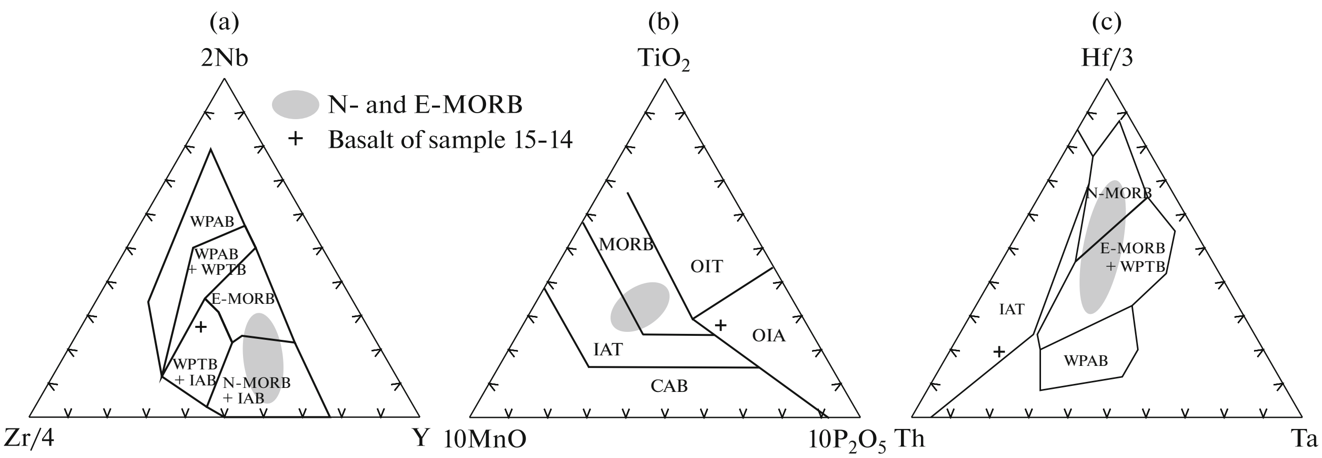

Fig. 6. (a) Zr–Nb–Y (Meshide, 1986), TiO_2–MnO–P_2O_5 (Mullen, 1983), and Hf–Th–Ta (Wood, 1980) diagrams for amygdaloidal basalts of the Kiselikhinskaya Formation. Abbreviations of basalt types and their composition fields: N- and E-MORB—“normal” and “enriched” mid-oceanic ridge basalts, WPAB—intraplate alkaline basalts, WPTB—intraplate tholeiites, CAB—calc–alkaline basalts, IAB—island-arc basalts, IAT—island-arc tholeiites, OIB—oceanic-island basalts, OIA—oceanic-island andesites, OIT—oceanic-island tholeiites.

vated concentrations of TiO_2 and P_2O_5. We cannot rule out that the amygdaloidal basalts inherit certain chemical features from the host arc rocks of the Isakovskii terrane, as is reflected in the Hf–Th–Ta diagram (Wood, 1980) (Fig. 6c). The data presented above, and considered together with the significant time gap (~120 Ma) found between the origin of the arc volcanics and seafloor basalts (see below) and with the fact that the rocks were practically not affected by metamorphism, suggest that the amygdaloidal basalts were produced during the postaccretionary crustal extension or rifting.

GEOCHRONOLOGY

Zircons from the metadacite (sample 15-07) and basalt (sample 15-14) were dated by U–Pb technique based on SHRIMP-II analyses conducted by conventional techniques at the Center for Isotopic Studies at the Karpinskii All-Russia Research Institute of Geology (VSEGEI) in St. Petersburg, using zircon standard reference samples 91500 and Temora (Larionov et al., 2004). As seen in their cathodoluminescence images, the zircons form long- and short-prismatic crystals with thin sectorial zoning and normal ratios of Th/U < 1, which indicate a magmatic genesis of the

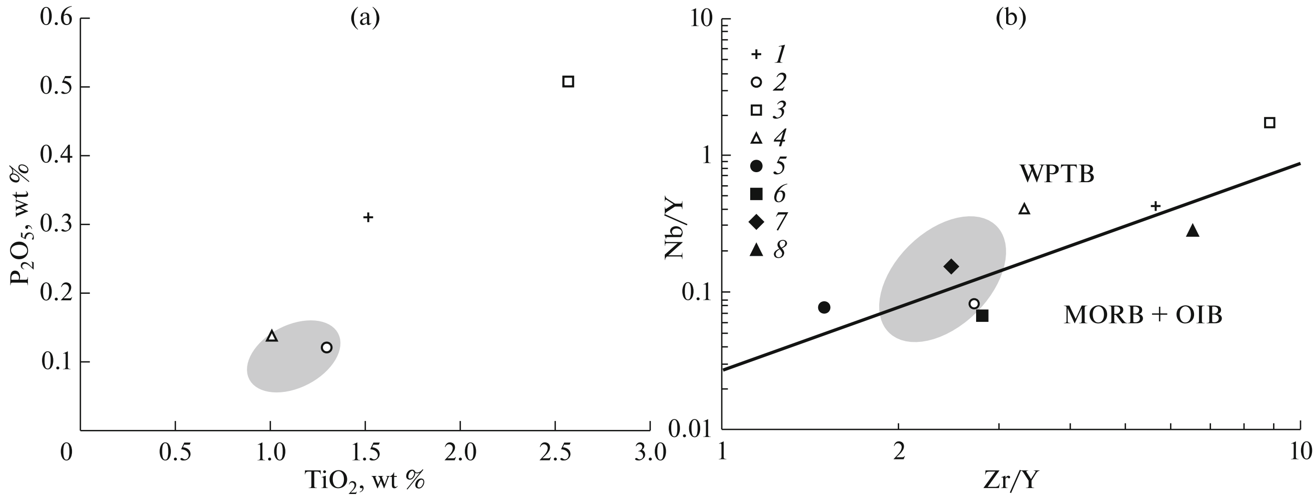

Fig. 7. Diagrams (a) P_2O_5–TiO_2 (Hooper, 1982) and Zr/Y–Nb/Y (Fitton et al., 1997) for (*1*) amygdaloidal basalts of the Kiselikhinskaya Formation and major basalt types: (*2*) N-MORB, (*3*) OIB, (*4*) E-MORB. Mantle components are after (Condie, 2005): (*5*) DEP—deep depleted mantle; (*6*) DM—depleted mantle, (*7*) PM—primitive mantle, (*8*) EN—enriched mantle. The oblique line separates the field of intraplate basalts (top) from MORB and island-arc volcanics (bottom).

zircons (Fig. 8). The composition points of nine spots analyses in the cores and margins of zircon grains from sample 15-07 plot along the concordia within a segment corresponding to an age of 674–713 Ma, with an average of 691.8 ± 8.8 Ma (Fig. 9a). The ages of the cores and margins are similar (Table 2). The U–Pb zircon age of the metadacite is similar (within the errors) to the zircon ages of arc plagiogranites from the Porozhninskii Massif (697.2 ± 3.6 Ma) (Vernikovskii et al., 2001) and those of metagabbro of the Borisikhinskii ophiolite massif (682 ± 13 Ma) (Kuz'michev et al., 2008), which belong to the Isakovskii terrane.

The data points of eight zircon grains from sample 15-14 plot along the concordia within the range corresponding to 556–587 Ma, with an average age value of 572.9 ± 6.5 Ma (Fig. 9b, Table 3), which corresponds to the timing of the magmatic crystallization of the amygdaloidal basalts. These events occurred somewhat earlier than the emplacement of the Late Vendian postcollisional granitoids of the Osinovskii Massif (540–550 Ma), which also occurs within the Isakovskii terrane, the granitoids of the Verkhnekanskii Massif (555 ± 5 Ma) of the Kan block (Nozhkin et al., 2001), and the upper age limit of the metaterrigenous–carbonate rocks of the Sayan Group in the Derbinskii block, Eastern Sayan (Nozhkin et al., 2015) in the southeast of the Sayan–Yenisei accretionary belt.

Table 2. Data of isotopic analysis of zircons from sample 15-07

Analytical spot	U, ppm	Th, ppm	$^{232}Th/^{238}U$	Isotopic ratios						Rho	Age, Ma	*D*, %
				$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ		$^{206}Pb/^{238}U$	
1.2c	504	525	1.08	0.0598	5	0.94	5.3	0.1141	1.8	0.334	696 ± 12	–15
2.2c	664	503	0.78	0.0551	14	0.86	14	0.1126	1.9	0.140	688 ± 13	–39
3.1r	1624	1002	0.64	0.05941	1.6	0.774	2.4	0.0945	1.7	0.249	685 ± 11	–14
4.1r	699	608	0.90	0.055	53	0.85	53	0.1133	3	0.056	692 ± 19	–43
4.2c	384	329	0.89	0.0602	15	0.97	15	0.1169	1.9	0.126	713 ± 13	–14
5.1r	800	797	1.03	0.0619	7.9	0.941	8.1	0.1102	1.8	0.219	674 ± 11	0
6.2c	915	644	0.73	0.0618	7.3	0.973	7.5	0.1143	1.8	0.235	697 ± 12	–4
7.1r	577	540	0.97	0.075	34	1.17	34	0.1132	3.4	0.102	691 ± 22	55
7.2c	448	256	0.59	0.066	20	1.05	21	0.1149	2.2	0.105	701 ± 14	16

c and r are the cores and rims of the grains, respectively. All errors are reported on 1σ level. *D* is the discordance, Rho is the correlation coefficient between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$. Age is in Ma.

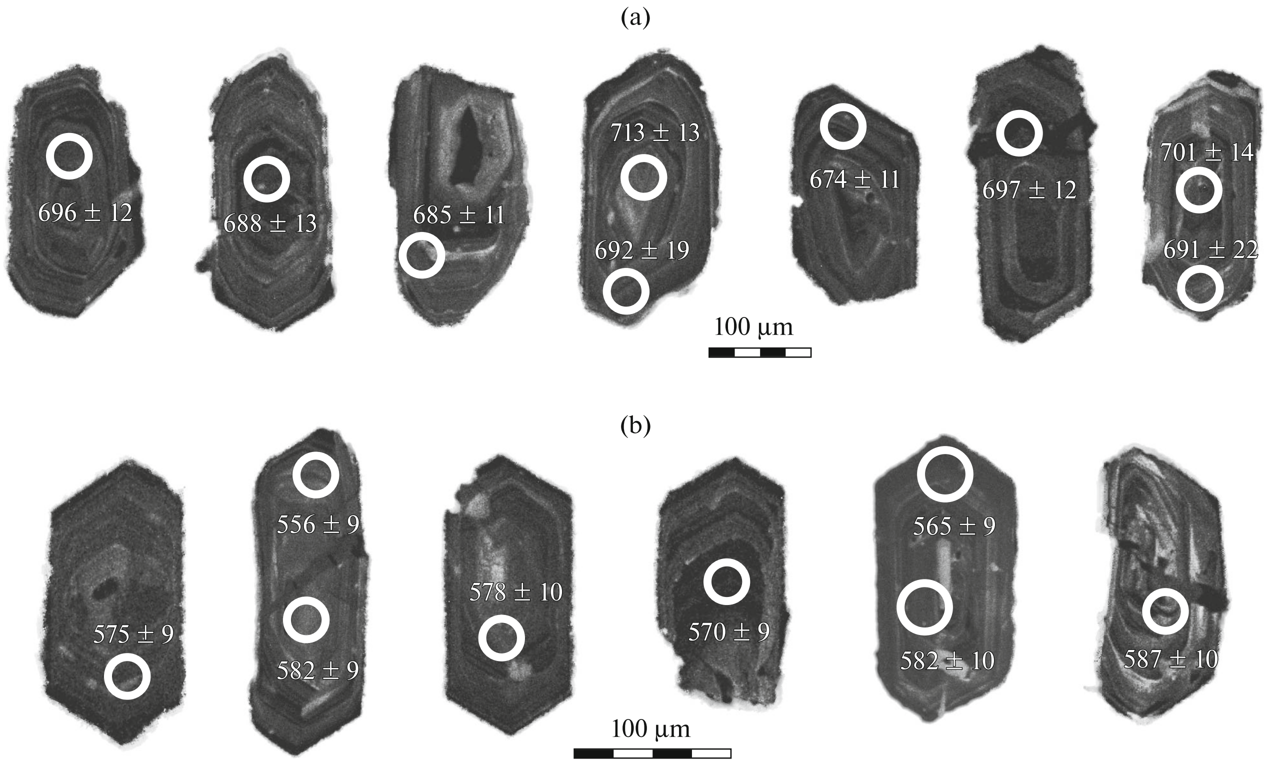

Fig. 8. Cathodoluminescence images of zircons from (a) the metadacite (sample 15-07) and (b) amygdaloidal basalt (sample 15-14) of the Kiselikhinskii unit.

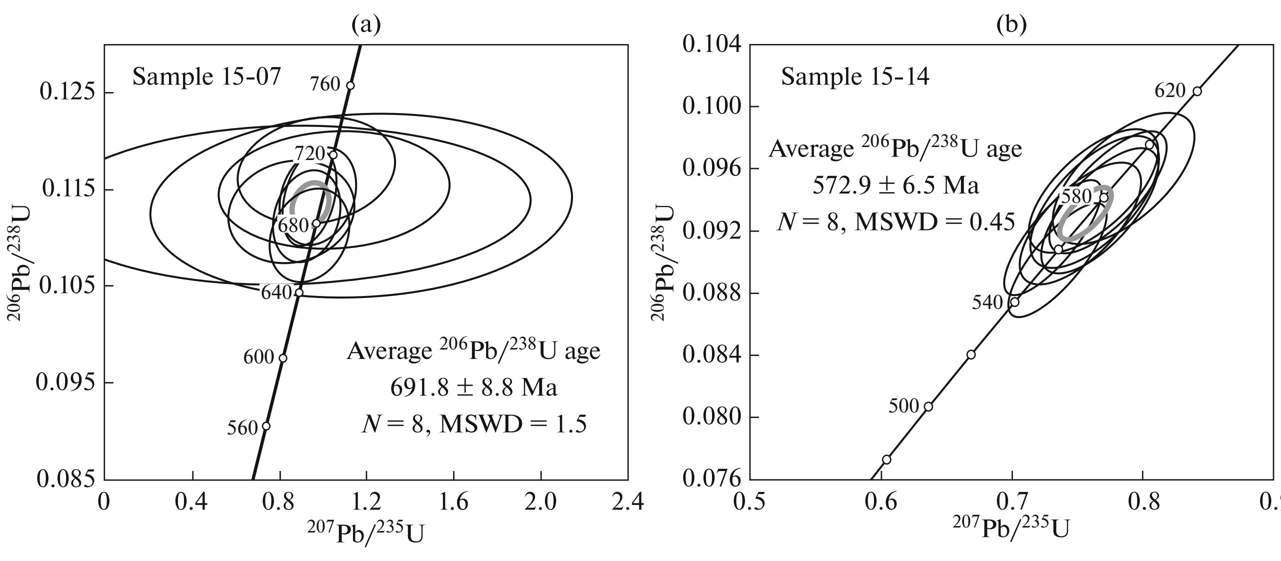

Fig. 9. Concordia plots for zircons from (a) the metadacite (sample 15-07) and (b) amygdaloidal basalt (sample 15-14) of the Kiselikhinskii unit.

In the sequence of geological events of the Yenisei Range, the mafic magmatism occurred immediately after the Vendian deformation–metamorphic events (~600–620 Ma), which marked the termination of the Neoproterozoic evolutionary history of the area and were related to the intense tectonic reworking of the suture-zone rocks after accretion–subduction processes in the area (Likhanov et al., 2015). The emplacement age of the basalts is constrained by the emplacement of the Late Vendian postcollisional

Table 3. Data of isotopic analysis of zircons from sample 15-14

Analytical spot	U, ppm	Th, ppm	$^{232}Th/^{238}U$	Isotopic ratios						Rho	Age, Ma		D, %
				$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ		$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	
1.1r	445	387	0.90	0.0597	1.7	0.768	2.4	0.0933	1.7	0.706	592 ± 38	575 ± 9	3
2.1r	1159	1240	1.11	0.05916	1.3	0.735	2.1	0.0901	1.7	0.793	573 ± 28	556 ± 9	3
2.2c	420	191	0.47	0.05941	1.6	0.774	2.4	0.0945	1.7	0.725	582 ± 35	582 ± 9	0
3.2c	316	280	0.92	0.059	2	0.763	2.7	0.0938	1.8	0.666	582 ± 35	578 ± 10	−2
4.2c	402	369	0.95	0.059	1.8	0.752	2.5	0.0925	1.7	0.683	568 ± 40	570 ± 9	0
5.1r	745	462	0.64	0.05794	1.3	0.731	2.1	0.0915	1.7	0.795	528 ± 28	565 ± 9	−7
5.2c	311	217	0.72	0.0585	1.9	0.762	2.6	0.0945	1.7	0.672	548 ± 42	582 ± 10	−6
6.2c	256	198	0.80	0.0598	2.2	0.786	2.8	0.0953	1.8	0.633	596 ± 47	587 ± 10	2

c and r are the cores and rims of the grains, respectively. All errors are reported on 1σ level. *D* is the discordance, Rho is the correlation coefficient between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$.

unmetamorphosed leucogranites of the Osinovskii Massif (550–540 Ma), which cut the arc complexes and related ophiolites of the Isakovskii terrane.

CONCLUSIONS AND GEODYNAMIC IMPLICATIONS

Our data on the isotopic geochronology and petrochemistry of volcanic rocks of the Kiselikhinskaya Formation in the Isakovskii terrane led us to the following conclusions. The significant differences in the petrochemistry of the metadacites and amygdaloidal basalts indicate that they were derived from different sources that had different ages. The dacites were emplaced in an island arc environment, whereas the amygdaloidal basalts can be correlated with intraplate basalts and oceanic-island basalts, which are indicative of crustal extensional environments. The arc metadacites and rift amygdaloidal basalts have a Late Neoproterozoic U–Pb zircon age (691 ± 8.1 Ma and 572 ± 6.5 Ma, respectively), which allowed us to refine the stratigraphic chart of the Yenisei Group and the legend of the geological map and elucidate certain detail in the evolution of the Sayan–Yenisei accretionary belt during its late Neoproterozoic history.

Our age values of the amygdaloidal basalts show that they were formed 120 Ma after the host arc and ophiolite complexes and 30–50 Ma after the beginning of accretion of these complexes to the Siberian craton. These events marked the final Neoproterozoic evolutionary history of the Yenisei Range, which was related to the completion of accretion of oceanic crustal fragments to the western margin of the Siberian craton, subsequent postaccretionary extension of the crust and the onset of the Caledonian orogenesis. The Late Neoproterozoic tectono-metamorphic evolution of the Isakovskii terrane is correlated with the final breakup of Rodinia, separation of the Siberian craton, and the opening of the Paleo-Asian Ocean (Yarmolyuk et al., 2006). The reproduced sequence of geological processes corresponds to the early evolution of the Paleo-Asian Ocean in its junction zone with the western margin of the Siberian craton.

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