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Age and Source Areas of Detrital Zircons from the Rocks of the Yenisei Tectonic Zone: to the Problem of Identification of Archean Metamorphic Complexes in the Transangarian Yenisei Ridge

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Abstract—The petrogeochemical and geochronological correlations were carried out between boudined fragments of tonalitic rocks previously dated at Neoarchean, quartzite sandstones, and host amphibolites in the Yenisei Regional Shear Zone of the Yenisei Ridge in order to solve the problem of age of the Transangarian Yenisei Ridge basement. Detrital zircons in metasandstones can be derived from the Neoarchean–Paleoproterozoic crystalline rocks of the Angara–Kan block. Interpretation of available data does not confirm the inferred presence of the Early Precambrian basement of the Siberian Craton beneath the Transangarian Yenisei Ridge.

Keywords: geochemistry, quartzites, amphibolites, U–Pb dating, zircon, Yenisei Ridge

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INTRODUCTION

The present-day western margin of the Siberian craton comprises the Early Precambrian basement inlier (Angara–Kan block) and the Meso–Neoproterozoic marginal–continental fold area of the Transangarian Yenisei Ridge (Nozhkin et al., 2011). The Precambrian Isakovka and Predivinsk terranes are mainly made up of tectonized fragments of ophiolites and island arc complexes accreted in Vendian to the Siberian margin (Nozhkin et al., 2007). This accretionary–collisional event led to the formation of the extended Sayan–Yenisei accretionary belt and significant continental growth of the craton (Nozhkin et al., 2016). An importance of our studies is determined by paucity of geochemical and age data on the geological complexes of the Transangarian Yenisei Ridge, which provide insight in the early stages of its evolution. This hampers the time correlation of its evolution both between different segments of the Sayan–Yenisei accretionary belt and with global geological processes in the Earth's evolution. Such studies are of great importance not only for understanding the tectonic evolution of mobile belts in the framing of ancient cratons, but also for solving the hotly debatable problem of the incorporation of the Siberian craton in ancient supercontinents (e.g., Zhao et al., 2004).

The solution of the problem of basement age is related to the geological interpretation of the Yenisei Ridge structure. There is no consensus concerning the tectonic structure and evolution of the Central–Angara Block (CAB) that composes the most part of the Transangarian Yenisei Ridge. It is regarded either as an exotic terrane accreted to the Siberian Craton in the middle Late Neoproterozoic (around 760 Ma) (Vernikovsky and Vernikovskaya, 2006), or as a large collisional–accretionary structure on the western margin of the Siberian Craton, which was consolidated during the Meso–Neoproterozoic evolution (1380–560 Ma) (Likhanov et al., 2014). At the same time, U–Pb–Th and Rb–Sr data allowed some researchers to ascribe the older Neoarchean and Paleoproterozoic rocks to the Nemtikha and Malaya Garevka complexes of the Transangara region (Volobuev et al., 1973; Kachevsky et al., 1994), which may indicate the presence of the Archean crystalline basement in the region. These assumptions were recently supported by U–Pb SHRIMP dating of zircons (2611 ± 12 Ma) from tonalite veins cutting across garnet amphibolites from the junction zone of the Isakovka terrane and Siberian Craton (Kuzmichev and Sklyarov, 2016). It was concluded, correspondingly, that the Early Precambrian basement of the Siberian Craton previously known in the Angara–Kan block is widespread in the Transangara region and was significantly reworked during subsequent tectonothermal events. Since attempts to reproduce these results have failed, this interpretation of the geological evolution of the region based on single date is controversial and must be confirmed by the wider complex of data.

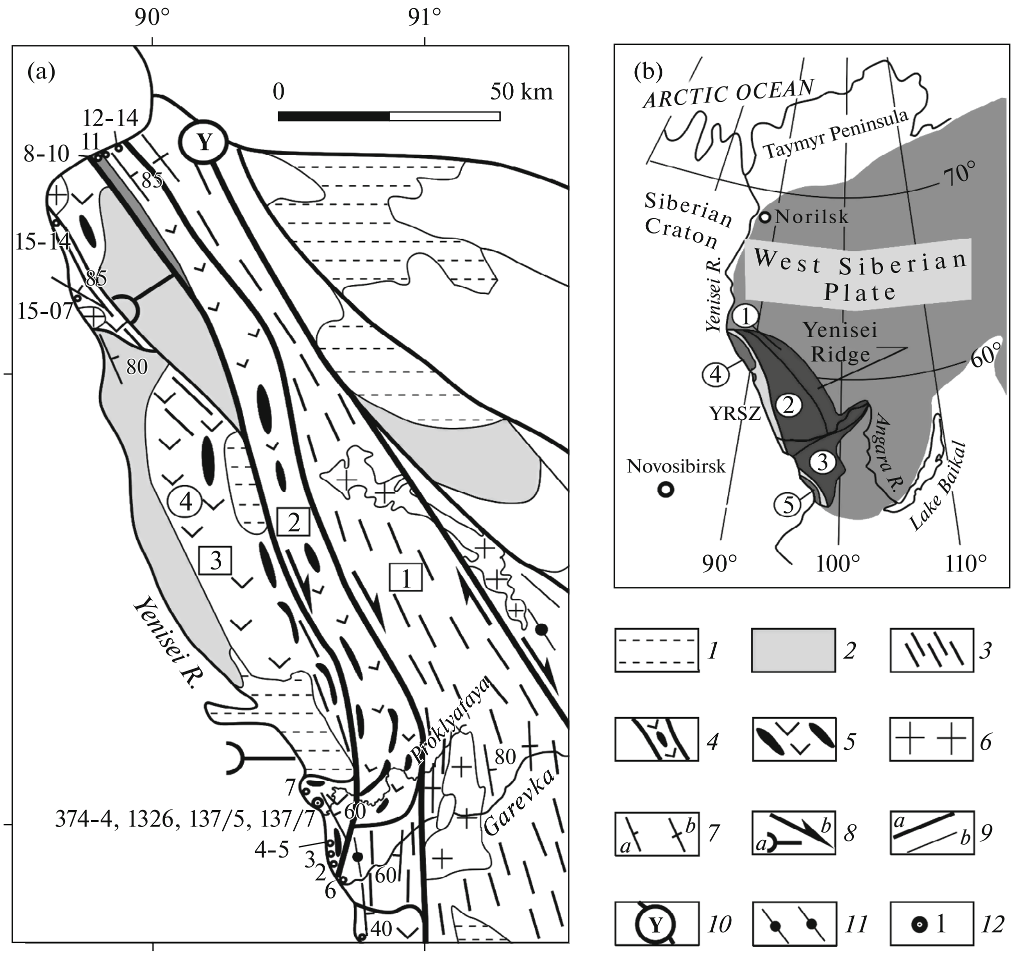

Fig. 1. (a) Scheme of the Yenisei Regional Shear Zone in the structure of the northern Yenisei Ridge; (b) position of the YRSZ (light gray) and tectonic blocks on the western margin of the Siberian craton: (1) Eastern and (2) Central blocks of the northern segment; (3) Angara–Kan block; (4) Isakovka and (5) Predivinsk terranes. (*1*) cover (Pz–Kz); (*2*) molasse (NP_{2-3}); (*3*) blastomylonite (NP) after rocks of the Garevka Complex (PP) (block 1); (*4*) high-pressure metabasite–ultrabasite and apogneissic blastomylonites (block 2); (*5*) metadacite–andesite–basalt and molasse complexes of the Isakovka terrane (block 3); (*6*) granitoid complexes; (*7*) dip and strike of foliation: inclined (a) and vertical (b); (*8*) direction of tectonic movements (NP): underthrusts (*a*) and strike-slips (*b*); (*9*) tectonic dislocations: faults (a), other boundaries (*b*); (*10*) Yenisei fault; (*11*) staurolite–garnet–kyanite tectonites; (*12*) sampling localities.

To solve this problem, we carried out geochemical and geochronological studies of light gray xenoliths in amphibolite, which are spaced at 1.5 km from each other and resemble previously described strongly tectonized “Archean” tonalites (Kuzmichev and Sklyarov, 2016). This paper reports the results of geochemical study and U–Pb zircon dating of these xenoliths made up of quartzite sandstones (quartzites), which provided insight into the nature and age of their protolith, including the position of possible source areas.

GEOLOGICAL POSITION AND MAJOR STRUCTURAL ELEMENTS OF THE YENISEI RIDGE

The Yenisei Ridge is located on the western margin of the Siberian Craton, extending NS along the Yenisei River for almost 700 km at a width from 50 to 200 km (Fig. 1b). Geophysical data indicate vertical thickening and transpression setting: the width of the Yenisei Ridge fold area at a depth over 10 km decreases two times, thus acquiring a mushroom shape (Vernikovsky et al., 2009). The Moho depth beneath the Yenisei Ridge as compared to the adjacent regions increased from 40 to 50 km (Salnikov, 2009). Thus, this fold orogen has a thickened crust, which has preserved during long geological time. The collisional model of the formation of the Earth’s crust in the region is confirmed by seismic profiling data and substantiated by “piling” of Neoproterozoic complexes (Mitrofanov et al., 1988). The Yenisei Ridge consists of the South Yenisei and Transangara segments, which are separated by the subatitudinal Lower Angara regional fault (Likhanov and Reverdatto, 2008). North of the Lower Angara Fault, in the Transangara segment, the Yenisei Ridge is made up of Paleoproterozoic and Meso-Neoproterozoic rocks, which compose the Eastern (near-platform) and Central craton blocks, and Isakovka (western) terrane represented by the Neoproterozoic ophiolites and island-arc complexes (Vernikovsky et al., 1994).

The tectonic blocks are split by large regional mainly NW-trending faults with subvertical dipping (Kheraskova et al., 2009). These structures represent a system of strike-slip, reverse fault, and overthrust kinematics (Korobeinikov et al., 2006). They are hundreds of kilometers long at a wide of stress metamorphism zone from hundreds meters to few tens of kilometers; these usually linear zones are areas of intense interaction of tectonic blocks. Blastomylonites are developed in the fault-related zones (Kozlov et al., 2012). They are characterized by widespread shear flow textures at meso- and micro-scale (Referdatto et al., 2017). These include linear deformation-induced foliation, ordered ductile flow textures, extension and break-up of en-echelon flow folding and faulting, kink bands in micas, "strain shadows" in recrystallized quartz, S-shaped and strongly deformed garnet grains with "snow ball" textures, disruption of mineral grains with displacement and development of "patchy" banding, development of deformation twins and lamellae in plagioclases, parallel arrangement of fine-grained lenticular mineral aggregates, as well as shearing, cataclasis, and boudinage (Likhanov and Reverdatto, 2014).

The regional faults (Yenisei, Tatar–Ishimba, and others.) are accompanied by subsidiary structures of higher order and overthrusts (Egorov, 2004). This causes a regionally heterogeneous pressure field of metamorphism in combination with facies series of low and moderate pressures (Likhanov et al., 2004, 2006; 2011, 2015). A detailed review of geochronological data, tectonic position, and geodynamic nature of complexes that compose the region structure are given in (Likhanov et al., 2014). This paper also presents a chronological sequence of major stages and events in the geological history of the Yenisei Ridge, which formed its tectonic appearance.

MATERIALS

The study area is located in the northwestern part of the Transangarian Yenisei Ridge within the Yenisei Regional Shear Zone (PRSZ) (Likhanov et al., 2013). It is tightly related to the Baikal–Yenisei fault, extending along the western margin of the Siberian Craton for no less than 200 km at a width of 30–50 km (Fig. 1b). Its structure is represented by a system of closely spaced subparallel faults accompanied by cataclasis, melange, and local dynamometamorhism (Likhanov, 2003). In the studied area, the PRSZ consists of three large Precambrian bocks (from east westward, Fig. 1a): (1) a continental gneiss–amphibolite block (2) a metaophiolite metabasite–ultrabasite block, and (3) a volcano-plutonic block (Likhanov et al., 2017). The first block is made up of the rocks of the Garevka metamorphic complex, which is dominated by biotite plagiogneisses of the Nemtikha sequence, and porphyroblastic granite gneiss and garnet–two mica schists of the Malaya Garevka Sequence. The latter two blocks are ascribed to the Isakovka terrane, which was accreted to the Siberian Craton in the Vendian (Nozhkin et al., 2007). The ophiolite associations of the second block consist of melanged nappes and lenses of amphibolized tholeiite metabasalts and more rarely metabasite–ultrabasites (antigorite metadunites and metaharzburgites with subordinate antigoritized pyroxenites), which are ascribed to the Lower Riphean Firsovskaya sequence and the Lower–Middle Riphean Surnikha Complex (Legend, 2002). The volcano-plutonic block includes mainly rocks of the metadacite–andesite–basalt association metamorphosed under the green-schist facies and ascribed to the Middle Riphean Kiselikha Formation (*Legend,* 2002).

These rocks belong to the subduction accretion complex, where occur as tectonic nappes, lenses, or blocks mainly in serpentine melange. The tectonic mélange of high and low-grade blocks of different age, size, and composition indicates a repeated reactivation of YRSZ in the Neoproterozoic (Kuzmichev and Sklyarov, 2016; Likhanov and Santosh, 2017).

MINERALOGY AND PETROGRAPHY

We studied the outcrops of rocks (samples 374-4 and 1326-2) localized in the tectonic suture on the junction of accretionary and continental blocks in the mouth of the Ostyatsky Creek emptying into the Yenisei River (59°59′34.8 N/90°39′51.5 E) (Fig. 1). Visually, they are represented by light gray quartzite sandstones forming boudins and lenses 10–30 cm thick among black carbonated garnet amphibolites (Fig. 2). The quartzite sandstones have weakly expressed lenticular banded structure and uneven fine to medium-grained texture with well rounded grains no more than 0.4 mm in size. The lenses of fine-grained quartz from 2 × 5 to 8 × 30 mm in size are outlined by thin frequently interrupted calcite bands from 0.5 to 1.5 mm thick. Microscopic study revealed a relict psammitic texture in a carbonate matrix (Fig. 3a) and more rarely granoblastic texture of the rock (Fig. 3b). The quantitative mineral composition is as follows (in wt %): quartz (90–95), plagioclase (1–3), calcite (5–7), muscovite, biotite, and chlorite (1–3); accessories are zircon and monazite.

Quartz occurs in two types. Allothigenic (detrital) quartz is represented by well rounded grains from 0.05 to 0.2–0.4 mm in size in a calcite matrix (micro to fine-psammitic texture) (Figs. 3c, 3d); more rarely, psammite grains are preserved among quartz grains with granobastic texture. Metamorphic quartz has granoblastic texture; it usually forms lenses consisting of grains no more than 0.3–0.5 mm with no wave extinction. *Plagioclase* much more rarely occurs, being formed by fine-psammitic polysynthetically twinned

Fig. 2. Photos of exposures of the garnet amphibolites and quartzites in the Ostyatsky Creek bed on the Yenisei bank (a) and their detailed textural–structural relationships (b). Asterisks show the geochronological and geochemical sampling localities.

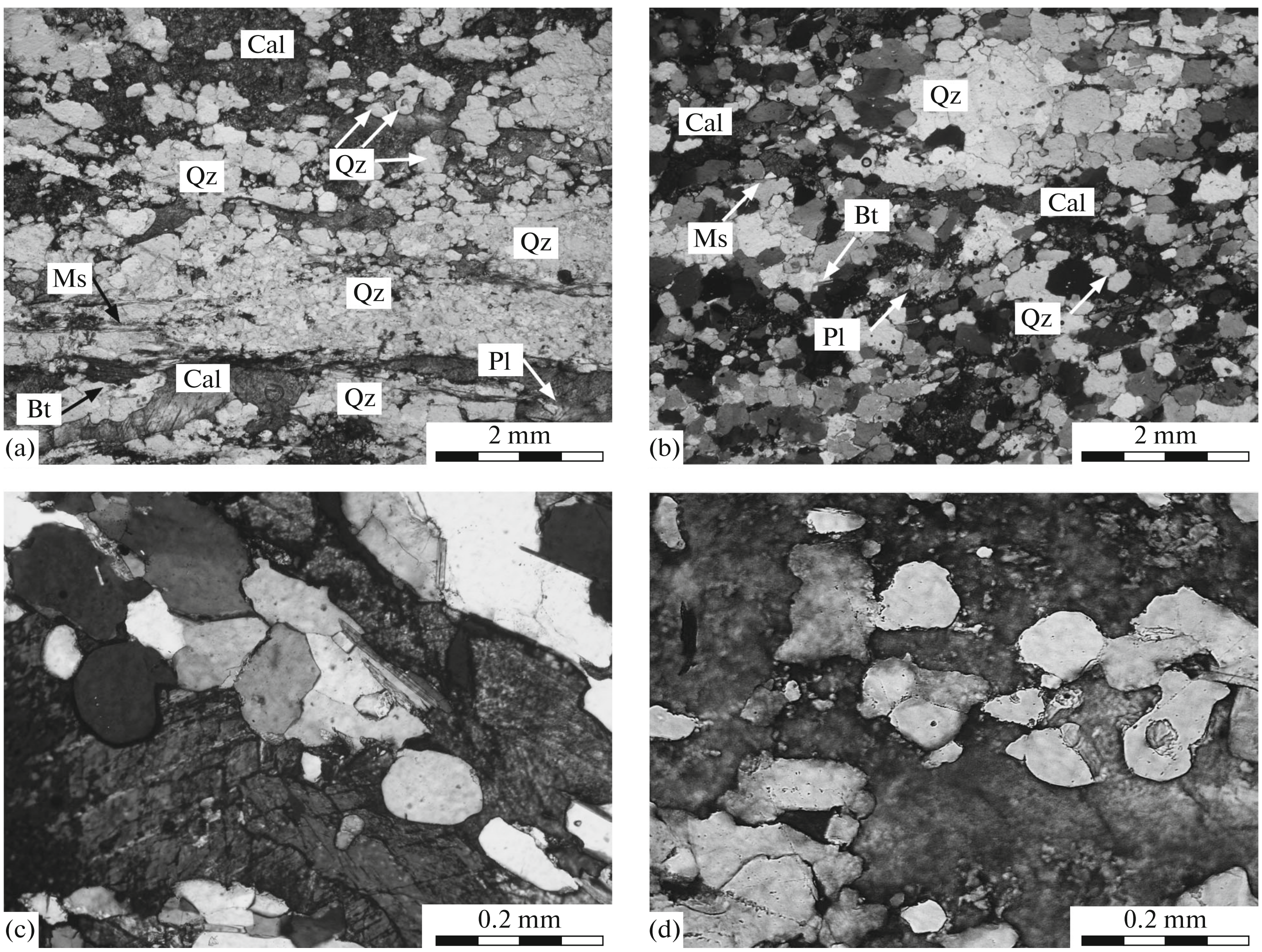

Fig. 3. Microphotos of the polished thin sections with inequigranular finely psammitic texture (a) and mainly granoblastic texture with relicts of psammitic texture (b); rounded quartz grains in a carbonate matrix (c, d). Crossed nicols. Mineral abbreviations: Bt—biotite, Ms—muscovite, Pl—plagioclase, Cal—calcite, and Qz—quartz.

weakly sericitized albite–oligoclase grains, which are comparable with quartz grains in size. *Muscovite* and *biotite* (metamorphic assemblage) are observed as flakes up to 0.5 mm long oriented along schistosity. *Calcite* composes thin interrupted lamina and small clots in the interstices between quartz, where it is represented by relatively large crystals no more than 0.5 mm in size or fine-grained finely schistose aggregate developed after quartz. Sometimes, the mineral forms thin veinlets of later redeposited calcite cutting across schistosity and banding. Secondary alterations are expressed in the development of *chlorite* after *biotite,* locally with formation of sagenite. *Accessory minerals* are represented by small grains of zircon and monazite no more than 0.05–0.1 mm in size.

Tonalites form veins up to 50 cm thick in garnet amphibolites and are made up of fine-grained quartz–plagioclase aggregates with biotite flakes, sometimes completely replaced by chlorite. The rocks also contain carbonate and epidote; more rarely, garnet and hornblende (Kuzmichev and Sklyarov, 2016). Judging from mineral assemblages, the tonalites were subjected to metamorphism and represent their metamorphosed varieties.

Amphibolites are made up of massive melanocratic medium to coarse-grained rocks. Uneven distribution of *garnet* and *plagioclase* determines vague metamorphic banding oriented perpendicular to the regional schistosity. The rocks are locally sheared, but mainly retained massive texture. Locally expressed strong cleavage causes boudinage of solid quartzite interbed and shearing of metabasite.

MAJOR AND TRACE ELEMENT COMPOSITION AND GEOTECTONIC SETTINGS OF THE PROTOLITH FORMATION

Contents of major elements were determined by XRF on a VRA-20R Carl Zeiss Jena microanalyzer with measurement error no more than 5 rel %. Contents of trace and rare-earth elements were determined by ICP-MS on a high-resolution ELEMENT (Finnigan Mat) mass spectrometer equipped with an U-5000AT+ ultra-sonic nebulizer. The analysis accuracy was 2–7 rel %. The works were carried at the Center for Collective Use of Multielement and Isotope Studies of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk) using standard techniques (Likhanov, 1988). Analytical results are given in Table 1.

Quartzite sandstones are characterized by the following chemical composition (in wt %): SiO_2 77.32, TiO_2 0.26, Al_2O_3 3.28, Fe_2O_3 1.91, MnO 0.09, MgO 1.50, CaO 7.18, Na_2O 1.0, K_2O 0.31, P_2O_5 0.06, L.O.I 6.43. Tonalites differ in the lowered contents of SiO_2 (61.59 wt %) and elevated contents of other rock-forming components (Table 1). The chondrite-normalized rare-earth element patterns (REE) of quartzite sandstones are characterized by the negative Eu anomaly (Eu/Eu* = 0.75) and ratios of $(La/Yb)_n = 9.4$ and (LREE/HREE) = 8.65 (Table 1). As compared to the REE distribution pattern in tonalite, that of quartzite sandstone is less differentiated and differs in the lower contents of radioactive (U, Th, and K), rare-earth (total REE = 54 ppm against 140 ppm in tonalites), large-ion lithophile (Rb, Ba, K), and high-filed strength (Nb, Ta) elements except for Zr and Hf (Table 1; Fig. 4). Geochemical characteristics of the quartzites in the $Zr–TiO_2–Al_2O_3$ diagram (Garcia, 1994) correspond to fields of clastic sedimentary rocks. In the Eu/Eu*–$(Gd/Yb)_n$ (Taylor and McLennan, 1995) and La–Th (McLennan, 1989) diagrams, the composition of the quartzites fall in the field of post-Archean cratonic sediments. Revealed features could be caused by the presence of erosion products of felsic composition, which follows from lower Th/U ratio and elevated La/Th ratio relative to those of average PAAS (post-Archean Australian Shales) after (Tayor and McLennan, 1988). Such geochemical features of the rocks could be inherited from disintegration products of aluminous hypersthene plagiogneisses and two-feldspar gneisses—initially magmatic rocks of felsic composition (Bibikova et al., 1993). The Ce/Ce* ratio in the the quartzites is (0.92), which together with high (8.64) LREE/HREE ratios (Balashov, 1976) can be explained by the accumulation of initial sediments on the marginal-continental shallow shelf under humid climatic conditions and calm tectonic regime facilitating rock weathering (Murray, 1990).

Composition of amphibolite is characterized by the moderate total alkali contents ($Na_2O + K_2O$ = 2.06 wt %), with significant Na_2O predominance over K_2O, and contents of Fe_2O_3 (14.73 wt %), MgO (9.16 wt %), TiO_2 (1.31 wt %) and P_2O_5 (0.14 wt %) at Fe mole fraction (f = 0.5). Based on the elevated Mg number, lowered alumina content (Al_2O_3 = 14.8 wt %), and low K_2O content (0.07 wt %), these rocks can be ascribed to picrobasalts. Their weakly fractionated REE pattern is depleted in LREE with total REE = 48 ppm and has a flat shape ($(La/Yb)_n = 1.12$), occupying an intermediate position between N- and E-MORB basalts (Fig. 4). In terms of major and trace-element parameters, these rocks are comparable with metabasites of the Panimba–Rybinsk volcanic belt (Likhanov and Reverdatto, 2016) and the Isakovka terrane in the Transangara region (Vernikovsky et al., Likhanov et al., 2017). Their affiliation to the group of normal and enriched basalts is confirmed by position of data points in the diagnostic diagrams based on relations of Zr–Nb–Y (Meschide, 1986), $TiO_2–MnO–P_2O_5$, $P_2O_5–TiO_2$ (Hooper, 1982), and Zr/Y–Nb/Y (Fitton et al., 1997). The multielement spectra are peculiar in the depletion relative to the large-ion lithophile elements (Rb and Ba) and clearly expressed K and Sr minima. This differs them from older gabbroic rocks of the dike belt (Likhanov et al., 2013c) and orthoamphibolites from the continental block of the western margin of the Yenisei Ridge (Kozlov et al., 2012), which are ascribed to within-plate basalts and island-arc tholeiites. Unlike the studied rocks, the adjacent amphibolites with tonalite xenoliths correspond in composition to the high-Ti and high-Fe picrobasalt resembling ocean island basalts (Kuzmichev and Sklyarov, 2016). The amphibolite has the higher contents of all incompatible elements, including REE, as well

Table 1. Contents of major (wt %) and trace elements (ppm) and their indicator ratios for garnet amphibolite (sample 1326-2) and quartzite sandstone in comparison with Archean amphibolite (sample 137/5-05) and tonalite

Component	1326-2	137/5-05	137/7-05	374-4
	amphibolite1	amphibolite2	tonalite	quartzite sandstone
SiO_2	45.13	44.94	61.59	77.32
TiO_2	1.31	2.97	0.58	0.26
Al_2O_3	14.80	13.9	13.71	3.28
Fe_2O_3	14.73	18.08	4.58	1.91
MnO	0.41	0.26	0.15	0.09
MgO	9.16	7.1	2.79	1.50
CaO	8.28	9.51	5.99	7.18
Na_2O	1.99	0.8	4.34	1.00
K_2O	0.07	0.73	0.61	0.31
P_2O_5	0.14	0.27	0.2	0.06
L.O.I.	2.81	1.48	5.48	6.43
Total	99.36	100	99.98	99.48
Rb	0.68	18.2	18.9	8.6
Sr	66	90.8	204	160
Y	31	48.8	11.7	10.5
Zr	77	195	134	187
Nb	4.3	41.4	13.6	2.9
Ba	9.5	168	140	103
La	4.8	15.6	35.8	11.6
Ce	11.3	44.3	62.2	22
Pr	1.66	6.51	6.39	2.6
Nd	8.5	28	21.5	9.7
Sm	2.6	7.9	3.85	2.00
Eu	1.01	2.42	1.34	0.49
Gd	4.3	8.38	3.56	1.93
Tb	0.78	1.46	0.45	0.30
Dy	4.9	8.65	2.13	1.75
Ho	1.05	1.7	0.44	0.31
Er	3.1	4.83	1.04	0.86
Tm	0.48	0.67	0.13	0.14
Yb	2.9	4.7	0.69	0.83
Lu	0.43	0.65	0.13	0.13
Hf	2.1	5.09	3.32	4.3
Ta	0.33	2.57	0.8	0.21
Th	0.36	2.37	9.66	2.3
U	0.14	3.53	1.02	0.74
f	0.50	0.62	0.51	0.45
$La/Yb_{(n)}$	1.12	2.24	34.98	9.38
$Gd/Yb_{(n)}$	1.21	1.44	4.16	1.87
Eu/Eu*	0.91	0.89	1.08	0.75
Ce/Ce*	0.96	1.06	0.92	0.92
LREE/HREE	1.87	3.79	16.20	8.64
Total REE	47.9	135	140	54.6
La/Th	13.5	6.6	3.7	5.1
Th/U	2.57	0.67	9.5	3.18

$Eu/Eu^* = Eu_n/(Sm_n + Gd_n) \times 0.5$; f (mol %) = $(FeO + 0.9\ Fe_2O_3)/(FeO + 0.9\ Fe_2O_3 + MgO)$; L.O.I. are loss on ignition. Petrogeochemical data on samples 137/5-05 and 137/7-05 were taken from (Kuzmichev and Sklyarov, 2016).

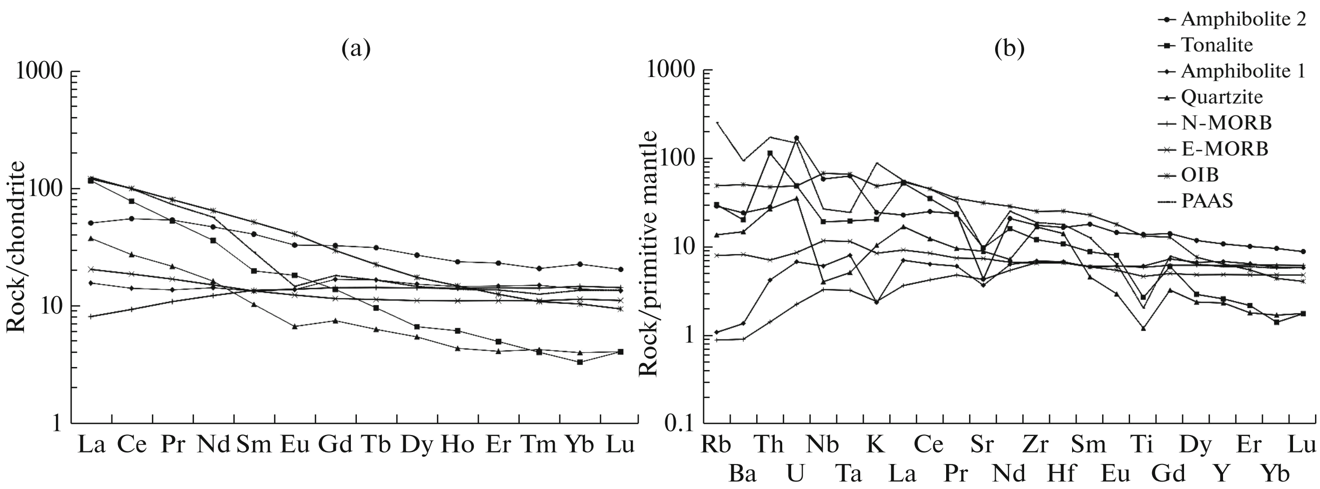

Fig. 4. Chondrite-normalized (Boynton, 1984) REE distribution patterns (a), and primitive mantle-normalized (Sun and McDonough, 1989) trace element spidergrams (b) for garnet amphibolites-1 (sample 1326-2) and quartzites (sample 374-4) as compared to the Archean amphibolites-2 (sample 137-5) and tonalites (sample 137-7) after (Kuzmichev and Sklyarov, 2016), with PAAS after (Taylor and McLennan, 1985) and main basaltic varieties: N–MORB, E–MORB and OIB after (Sun and McDonough, 1989). Sample numbers correspond to those of Table 1.

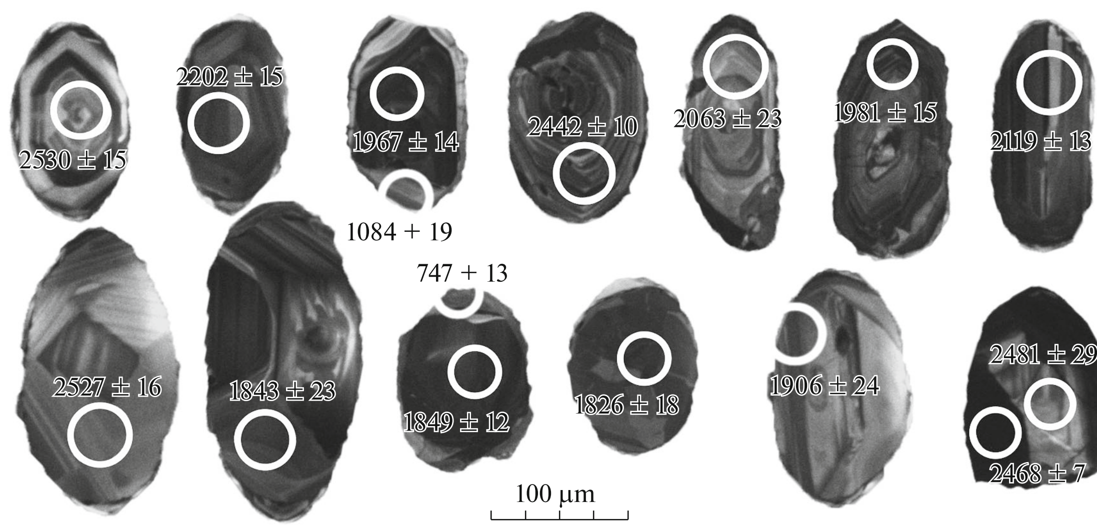

Fig. 5. Cathodoluminescence image of zircons from quartzites with dating points and ages (Ma).

as relatively flat distribution patterns, elevated contents of large ion lithophile (Rb, Ba, K), radioactive (Th, U), and high-field strength (Nb, Ta, Zr, Hf) elements, which indicates their formation in a within-plate setting of ocean plateau or volcanic islands (Condie, 1999, 2005).

RESULTS OF U–Pb DATING OF DETRITAL ZIRCONS

U–Pb zircon dating of quartzite sample 374-4 was carried out on a SHRIMP-II ion microprobe at the Center for Isotope Research of the Karpinskii All-Russia Research Institute of Geology, in St. Petersburg using standard technique and zircon standard reference samples 91500 and Temora (Larionov et al., 2004). Thirteen grains 100–400 μm in size were analyzed in 16 points (Table 2). As seen in the CL images, zircons form euhedral prismatic bipyramidal light brown crystals with smoothed edges and elongation coefficient of 1.5–4 (Fig. 5). Most zircons are zoned with clearly expressed cores and rims. Morphologically, they are identical to zircons from Neoarchearn tonalites.

Results of isotope-geochronological studies show the beginning of magmatic crystallization of zircon at

Table 2. Results of isotope analysis and age of zircons from quartzite sandstone

Points no.	U, ppm	Th, ppm	$\frac{^{232}Th}{^{238}U}$	Isotope ratios						Rho	Age, Ma	D, %
				$\frac{^{207}Pb}{^{206}Pb}$	1σ	$\frac{^{207}Pb}{^{235}U}$	1σ	$\frac{^{206}Pb}{^{238}U}$	1σ		$\frac{^{206}Pb}{^{238}U}$	
4.2	325	15	0.05	0.0627	5.3	1.06	5.6	0.1228	1.9	0.332	747 ± 13	–7
12.2	203	28	0.14	0.0735	3.4	1.86	3.9	0.1832	1.9	0.493	1084 ± 19	–5
11.1	283	24	0.09	0.1116	1.0	4.74	2.0	0.3077	1.7	0.856	1826 ± 18	6
10.1	239	95	0.41	0.1127	1.3	5.41	2.4	0.3482	2.1	0.857	1843 ± 23	–4
4.1	596	132	0.23	0.1131	0.7	5.01	1.8	0.3213	1.6	0.926	1849 ± 12	3
5.1	173	259	1.54	0.1167	1.4	5.53	2.2	0.3439	1.7	0.788	1906 ± 24	0
12.1	405	187	0.48	0.1207	0.8	5.58	1.9	0.3353	1.7	0.901	1967 ± 14	6
8.1	325	263	0.83	0.1217	0.8	5.85	1.9	0.3487	1.7	0.890	1981 ± 15	3
6.1	128	30	0.24	0.1274	1.3	6.42	2.3	0.3655	1.9	0.824	2063 ± 23	3
3.1	422	114	0.28	0.1315	0.7	6.88	1.8	0.3791	1.6	0.913	2119 ± 13	2
2.1	245	177	0.75	0.1380	0.9	7.58	1.9	0.3986	1.7	0.895	2202 ± 15	2
9.1	383	227	0.61	0.1587	0.6	10.1	1.8	0.4625	1.6	0.937	2442 ± 10	0
13.2	849	135	0.16	0.1611	0.4	9.41	1.7	0.4233	1.6	0.965	2467 ± 7	8
13.1	127	98	0.79	0.1624	1.7	8.97	2.5	0.4007	1.8	0.722	2481 ± 29	14
7.1	159	155	1.00	0.1669	0.9	10.7	2.0	0.4664	1.7	0.878	2527 ± 16	2
1.1	144	96	0.69	0.1672	0.9	11.0	2.0	0.4772	1.7	0.885	2530 ± 15	1

c—core, r—rim. Errors are given at 1σ level. D—discordance, Rho—correlation coefficient of $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ratios. Points are arranged in order of upward increasing age.

around 2530 ± 15 Ma (in the Neoarchean) with subsequent variations of U–Pb system up to the Neoproterozoic (Fig. 6a; Table 2). The magmatic and metamorphic zircon generations are separated on the basis of morphology and inner structure of grains and Th/U ratio. According to the age density distribution, the analyzed grains could be subdivided into two main clusters (Fig. 6b), which correspond to the major important stages of the crustal growth in the region.

The first group (five grains) includes detrital zircon cores with ages of 2530–2442 Ma (average $^{207}Pb/^{206}Pb$ = 2475 Ma) (Fig. 6). The second group (nine grains) is represented by zircons with ages of 2202–1826 Ma (average $^{207}Pb/^{206}Pb$ = 1901 Ma) (Fig. 6). Fine sectorial zoning and elevated Th/U ratios (0.6–1) of zircons of the first cluster indicate in support of their magmatic nature. The older rocks of the first group were probably derived by melting of continental Neoarchean–Paleoproterozoic quartz–fepdspathic rocks, the protolith for which could be the nearest aluminous hypersthene plagiogneisses and two-feldspar gneisses of the Kan Group of the Yenisei Ridge with an age of 2.4–2.8 Ga (Bibikova et al., 1993; Urmantseva et al., 2012; Nozhkin et al., 2016). The younger zircon population could be inherited from disintegration and redeposition products of mafic and felsic granulites and amphibolites of the Angara–Kan block (2.2–1.9 Ga), including zircons related to the migmatization of host rocks and emplacement of different phases of the granitoids of the Tarak massif under conditions of the postcollisional extension (Turkina et al., 2012).

The rare latest thermal metamorphic transformations of detrital zircon with low Th/U ratios (0.05–0.14) were recorded at 1084 ± 19 and 747 ± 13 Ma (Fig. 6). The early stage is related to the Grenvillian orogeny, while the late stage correlates with resumption of magmatic activity and associated Late Riphean rifting caused by the plume activity and break-up of the Rodinia supercontinent. The $^{40}Ar/^{39}Ar$ dates of amphiboles from metabasites of the near-Angara Complex are regarded as the close age analogues of the Grenville events within the Yenisei Ridge (Likhanov and Reverdatto, 2016). The last event with an age of 747 ± 13 Ma in the Yenisei Fault Zone of the Transangarian Yenisei Ridge is correlated with the formation of the Glushikha, Strelkovka, Lendakha, Chernaya Rechka, and Garevka massifs (Likhanov et al., 2014).

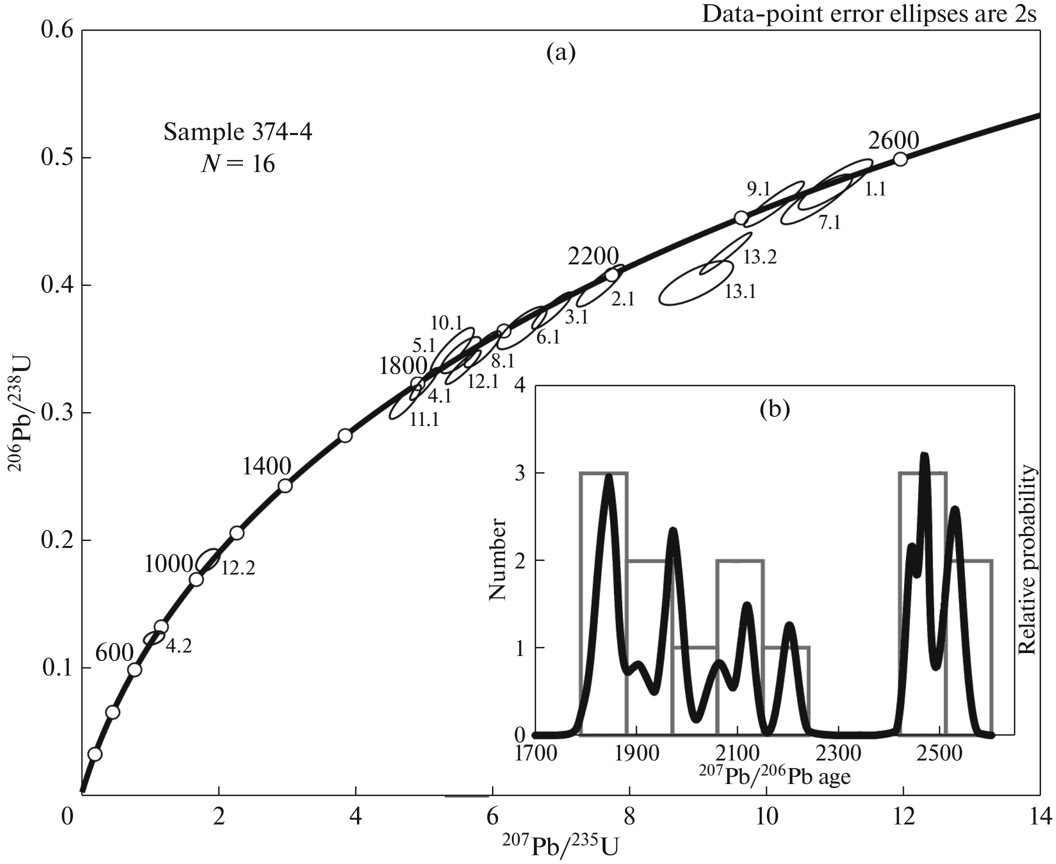

Fig. 6. (a) U–Pb concordia diagram for zircons from quartzite sample (374-4), (b) histogram of U–Pb isotope ages and curves of relative age probability.

CONCLUSIONS

The comparative analysis of obtained and published age and geochemical data on host amphibolites and boudins of quartzite sandstones/tonalites makes it possible to formulate the following conclusions.

(1) These rocks are confined to the junction zone of the accretionary Islakovka terrane with continental block and form lenses and boudins represented by alternation of relatively rigid and ductile deformed blocks in the tectonic mélange of the shear zone

(2) Revealed differences in major and trace-element composition between amphibolites indicate a different nature of their magmatic sources. Magmatic protoliths of low-Ti metabasites (with quartzite xenoliths) were derived from mantle sources producing N- and E-MORB basalts, whereas protoliths of high-Ti varieties (with tonalite xenoliths) are comparable with within-plate basalts and tholeiite basalts of ocean islands.

(3) Geochemical differences between quartzite sandstones and tonalites are less significant and could be explained by the chemical heterogeneity of rocks expressed in different contents of quartz, mica, and plagioclase. This may indicate a common source. Such rock peculiarities could be inherited from disintegration products of aluminous hypersthene plagiogneisses and two-feldspar gneisses—initially magmatic felsic rocks of the Angara–Kan block with Neoarchean age of 2.5–2.8 Ga, and late products of their regional metamorphism with an age around 1.9 Ga.

(4) The complete absence of relict granulite-facies mineral assemblages, which are typical of the rocks complexes of the Precambrian basement inlier on the southwestern Siberian margin, and precision geochronological data do not confirm the ancient age of the Transangara rocks. In spite of the great number of new geochronological data, none of its early dates was reproduced by the modern methods of isotope geochronology. The oldest dated objects of this region are the plagiogneiss granites of the Nemtikha metamorphic complex in the Central Transangara region with an age of 1360–1380 Ma (Popov et al., 2010). According to Sm–Nd isotope studies, the protolith of these rocks was derived from a crustal source represented by the Lower Proterozoic complexes of the Siberian Craton with model ages of 2.44 Ga (Popov et al., 2010). Archean age of the protoliths of the Transangara rocks, the Kan and Yenisei groups of the Angara–Kan block, also was not confirmed by model ages (Nozh-

kin et al., 2008; Turkina et al., 2012), which casts doubts concerning the presence of Archean crust in the region. At the same time, Kuzmichev and Sklyarov (2016) believe that "Archean" tonalite was derived by melting of garnet amphibolite, but show no any petrographic evidence for its magmatic nature, in particular, microphotos of its polished thin sections with magmatic or relict magmatic texture. Even more serious problems of their interpretation consists in the absence of Archean amphibolites in the Transangara area; moreover, tonalites form 50 cm thick veins in garnet amphibolites (Kuzmichev and Sklyarov, 2016). A combination of available zircon dates on the magmatic complexes of the Isakovka terrane indicates that they were formed in the Neoproterozoic, within 700–620 Ma (Vernikovsky et al., 1994, 1999, 2001; Kuzmichev, 2009; Kuzmichev et al., 2008; Nozhkin et al., 2016, 2017; Likhanov et al., 2017). Isotope dates on the felsic and mafic rocks of the Malaya Garevka Sequence of the Central Angara continental block are constrained by an age of 900 Ma (Kozlov et al., 2012). Data on the morphology and inner structure of zircons in the tonalite do not provide unambiguous conclusion on their genesis. Only more strict evidence from the Lu–Hf and Sm–Nd isotope systems or Hf–Nd systematics, including dating of host basites, could provide the correct interpretation of U–Pb data and zircon origin. By analogy with quartzite sandstones, cores of zircons from tonalites are detrital and presumably could be inherited from products of tectono-thermal stages in the evolution of the Early Precambrian crust of the Siberian Craton. Inferred wide distribution of the Early Precambrian basement, which is close in composition and thermodynamic metamorphic parameters to the Angara–Kan granulite–gneiss block of the Kan Group, in the Transangara area requires additional geological mapping using precision geochronological and geochemical studies.

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