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Sources of the Paleoproterozoic Terrigenous Rocks of the Nizhnekhani Graben-Syncline, Western Part of the Aldan Shield, According to the U–Th–Pb (LA-ICP-MS) Geochronological and Nd Isotopic Studies: To the Question of Correlation of the Udokan Complex Deposits

V. P. Kovach[a, *], E. V. Adamskaya[a], A. B. Kotov[a], B. I. Berezkin[b], V. F. Timofeev[b], N. V. Popov[c], Yu. V. Plotkina[a], T. M. Skovitina[d], A. M. Fedoseenko[a], N. Yu. Zagornaya[a], and B. M. Gorokhovsky[a]

[a] *Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg, 199034 Russia*
[b] *Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences, Yakutsk, 677000 Russia*
[c] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
[d] *Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences, Irkutsk, 664033 Russia*
**e-mail: v.p.kovach@gmail.com*

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Abstract—The results of U–Th–Pb (LA-ICP-MS) geochronological studies of detrital zircon and Sm–Nd isotopic studies of metaterrigenous rocks of the Udokan Complex of the Nizhnekhani graben-syncline in the western part of the Aldan Shield are discussed. On the basis of the data obtained, it was found that the accumulation of terrigenous deposits of the Nizhnekhani graben-syncline occurred after 2.65 and up to 1.9 Ga, probably at the Paleoproterozoic stage of the development of the region. The igneous and metamorphic rocks formed at ca. 2.65, 2.71, 2.82–2.86, 2.99, 3.10–3.21, and probably 3.26–3.42 Ga within the Chara–Olekma Geoblock, its junction zone with the West Aldan Megablock, and the Kurulta Block of the Stanovoi suture zone were the sources of detrital material. Metaterrigenous rocks of the Nizhnekhani graben-syncline were formed from crustal sources with the Paleo- and Mesoarchean Nd model ages, while a significant contribution of the Paleoproterozoic juvenile material was established for the metasedimentary rocks of the Kodar–Udokan Trough. Significant differences in the age and Nd isotopic characteristics of sources of terrigenous deposit of the Nizhnekhani graben-syncline and the Kodar–Udokan Trough suggest that they accumulated in isolated basins.

Keywords: Udokan Complex, Nizhnekhani graben-syncline, Aldan Shield, detrital zircon, geochronology, Sm–Nd isotope systematics

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INTRODUCTION

The Paleoproterozoic metasedimentary deposits of the Udokan Complex fill the extended Kodar–Udokan Trough and the whole set of smaller scale graben-synclines (Nizhnekhani, Oldongso, Ugui) located in the western part of the Aldan Shield (Fig. 1). Deposits of the Kodar, Chinei, and Kemen groups of the Udokan Complex of the Udokan zone of the Kodar–Udokan Trough are considered the Lower Proterozoic Hypostratotype of Eastern Siberia and the Far East. They serve as an age marker in the regional stratigraphic scale and enclose the world-largest deposits of copper sandstones (Fedorovsky, 1972; *Gosudarstvennaya*..., 2010). The recently obtained geochronological and Nd isotope data (Podkovyrov et al., 2006; Kotov et al., 2018; Kovach et al., 2018a, 2018b) indicate that the age of terrigenous deposits of the Kodar Group of the Udokan Complex of the Kodar–Udokan zone is in a range of about 2.3–2.1 Ga, and the age of terrigenous deposits of the Chinei and Kemen groups is in a range of about 1.90–1.87 Ga.

In stratigraphic schemes of Lower Proterozoic of the western part of the Aldan Shield, the metasedimentary strata of the Ugui, Oldongso, and Nizhnekhani graben-synclines correlate both with each other and with different parts of the Udokan Complex of the Udokan Trough (Salop, 1964; Mironyuk et al., 1971; Fedorovsky, 1972; Petrov, 1976; Sochava, 1986; *Gosudarstvennaya*..., 1998, 2010, 2015; etc.). However, geochronological and Nd isotopic data that allow us to

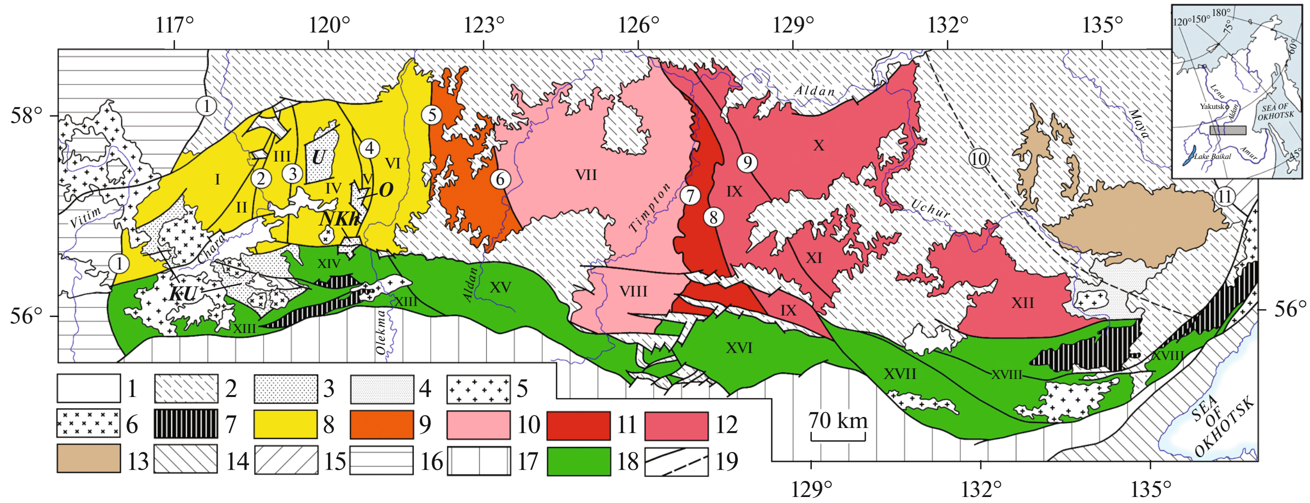

Fig. 1. The scheme of the block structure of the Aldan Shield and the junction zone with the Dzhugdzhur–Stanovoi fold area (Kotov, 2003). (1) Cenozoic deposits; (2) Mesozoic, Paleozoic, and Upper Proterozoic platform deposits; (3) Udokan Complex; (4) Ulkan complex; (5) Phanerozoic granitoids; (6) granitoids of the Kodar Complex; (7) anorthosites; (8–13) Aldan Shield: (8) Chara–Olekma Geoblock, (9) junction zone of Chara–Olekma and Aldan geoblocks, (10) West Aldan Megablock of the Aldan Geoblock, (11) junction zone of West and East Aldan Megablocks of the Aldan Geoblock, (12) East Aldan (Uchur) Megablock of the Aldan Geoblock; (13) Batomga Geoblock; (14) Mongol–Okhotsk fold area; (15) Verkhoyansk–Chukotka fold area; (16) Baikal fold area; (17) Dzhugdzhur–Stanovoi fold area; (18) junction zone of Aldan Shield and Dzhugdzhur–Stanovoi fold area; (19) faults. Faults (circled figures): (1) Zhuin, (2) Chara–Tokko, (3) Taryn–Yuryakh, (4) Olomokit, (5) Borsala–Nelyuki, (6) Aldan–Kilier, (7) Timpton thrust, (8) Idzhek–Sutam, (9) Tyrkanda, (10) Ulkan, (11) Nelkan. Roman numerals indicate blocks: I—West Olekma, II—Chara, III—Tokko, IV—Charuoda, V—Olomokit, VI—East Olekma, VII—Nimnyr, VIII—Melemken, IX—Kholbolokh, X—Sunnagin, XI—Gonam, XII—Tyrkan, XIII—Kalar, XIV—Kurulta, XV—Zverev, XVI—Sutam, XVII—Ayumkan, XVIII—Dzhugdzhur. Rocks of the Udokan Complex: KU—Kodar–Udokan Trough; U—Ugui, O—Oldongso, NKh—Nizhnekhani graben-synclines.

judge the age and sources of barren metasedimentary rocks of these structures are currently extremely limited. The results of U–Th–Pb (LA-ICP-MS) geochronological and Sm–Nd isotope-geochemical studies of metaterrigenous rocks of Nizhnekhani graben-syncline presented in the present paper are intended to fill this gap.

GEOLOGICAL STRUCTURE OF THE NIZHNEKHANI GRABEN-SYNCLINE AND OBJECTS OF RESEARCH

The Nizhnekhani structure represents an asymmetrical brachyanticline (30 × 20 km) with gently dipping limbs, limited by fault zones (Fig. 2) (Sochava, 1986; Berezkin et al., 2007). This structure is superimposed on Archean deposits of the Chara–Olekma Geoblock of the Aldan Shield and the Kurulta Block of the Stanovoi suture zone. The normal stratigraphic relations of the metasedimentary rocks of the Nizhnekhani graben-syncline with the surrounding Archean rocks have not been established.

Metasedimentary strata of the Nizhnekhani graben-syncline were combined into the Khani Group, which are subdivided (from bottom up) into the Atbastakh, Khani, and Stannakh formations (Sochava, 1986; Berezkin et al., 2007). The Atbastakh Formation (360–700 m) is dominated by white, pinkish, sometimes brownish red metasandstones and metaquartzite-sandstones, enclosing lenticular bodies (up to 140 m thick) of tremolite, diopside-tremolite, phlogopite-tremolite-diopside, and dolomite marbles and calciphyres, as well as interlayers, units, and lenses of calc-silicate rocks, calcareous metasandstones, metasiltstones, and less commonly metagravelstones and small-pebble metaconglomerates.

The Khani Formation (550–800 m) is composed of rhythmically interlaying metasandstones, metasiltstones, carbonaceous phyllites, and phyllite-like shales. The lower part of its section represents a rhythmic alternation of massive pink and pale gray medium-grained oligomictic metasandstones and metaquartzite-sandstones, gray metasiltstones with thin interbeds of phyllitic shales (metamudstones), and carbonaceous phyllites. The thickness of the rhythms varies from 12 to 15 m. The middle part of the section is characterized by a thin interbedding of metaaleurolitic, metapelitic, and metaargillaceous shales. The upper part of the section is composed of metapelitic and metaaleurolitic shales.

The Stannakh Formation (more than 500–600 m) is exposed in the central part of the Nizhnekhani graben-syncline. The formation is mainly composed of gray metasandstones and metasiltstones and less common yellowish and brownish gray metasandstones.

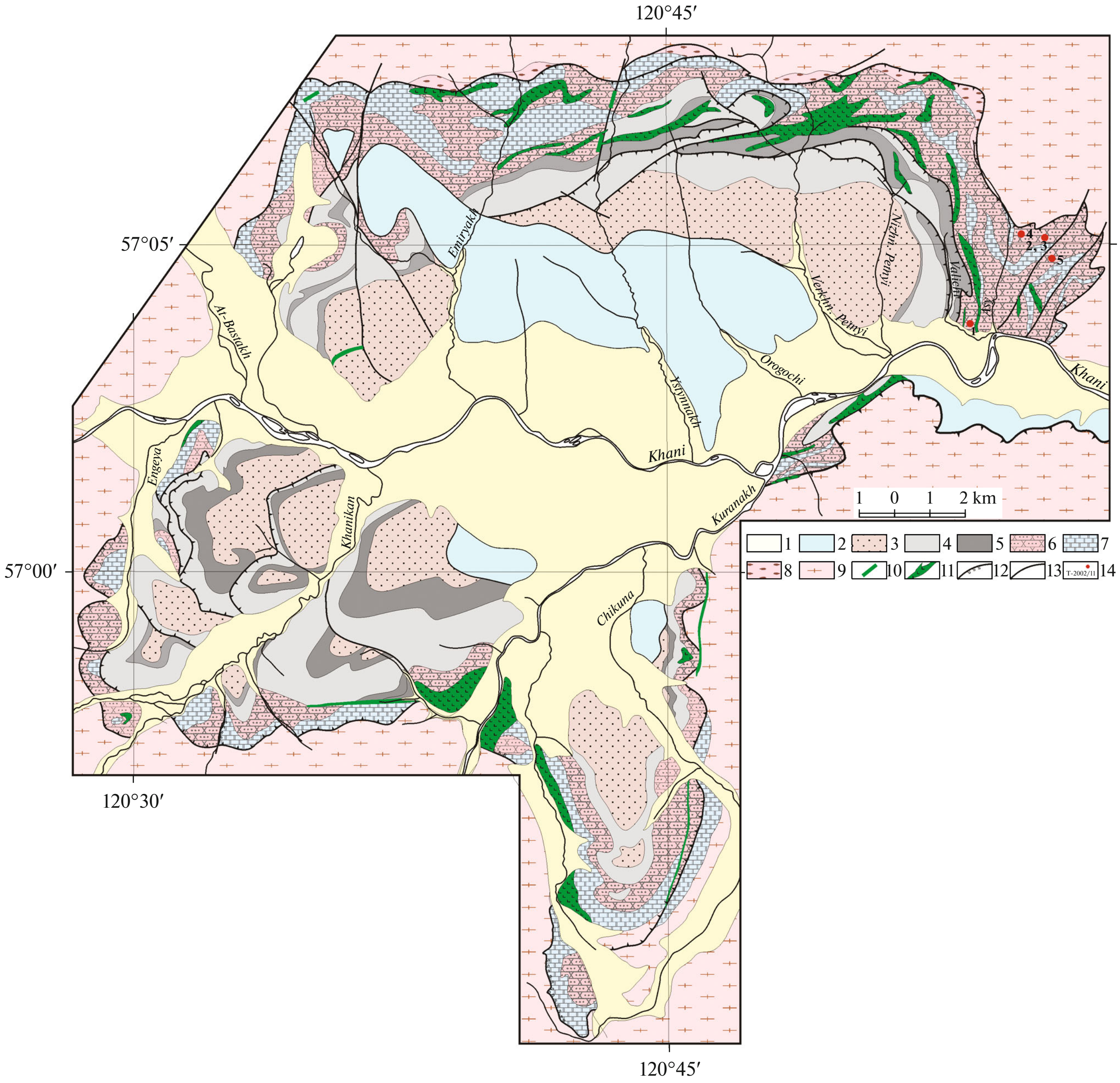

Fig. 2. Geological scheme of the Nizhnekhani graben-syncline (Berezkin et al., 2007, with amendments). (1) Quaternary deposits; (2) Jurassic deposits; (3–8) Paleoproterozoic metasedimentary rocks of the Khani Group: (3) Stannakh Formation: metasandstones, metasiltstones; (4, 5) Khani Formation: (4) metasandstones, metasiltstones, phyllite shales, quartzite-sandstones; (5) black carbonaceous metasiltstones, phyllite-like shales, and phyllites (black shales); (6–8) Atbastakh Formation: (6) metasiltstones, metasandstones, quartzite-sandstones; (7) dolomite marbles and calciphyres; (8) metaconglomerates and metagravelstones; (9) Archean formations of the Olekma complex: biotite and amphibole-biotite plagiogneisses, plagiogranites, crystalline schists, and amphibolites; (10) dikes of konga diabases and diabases of the Torsky Complex; (11) sills and dikes of metagabbro-diabases and metadiabases of the Kuranakh Complex; (12) thrusts; (13) faults; (14) sampling sites for geochronological study. The numbers of sites correspond to the numbers in Table 2.

Rocks of the Khani Formation were metamorphosed under greenschist and epidote-amphibolite facies at $T = 400–580°C$ and $P = 3$ kbar (Berezkin et al., 1983, 2007). The age of this metamorphic event is estimated at 1.95 ± 0.11 Ga (Rb–Sr whole-rock dating; Gorokhov et al., 1989).

Metasedimentary rocks of the Khani Group are intruded by metadiabase and metagabbro-diabase dikes and sills of the Kuranakh Complex (Mironyuk et al., 1971), with an age of 1863 ± 9 Ma (U–Pb (ID-TIMS) zircon age; Popov et al., 2012), as well as by thin konga diabases of the Neoproterozoic Torsky

Table 1. Major element (wt %) compositions of metaterrigenous rocks of the Atbastakh Formation of the Nizhnekhani graben-syncline

Components	Sample number								
	B-2402	B-2402/2	B-2404/1	B-2404/2	B-2404/3	B-2404/6	B-2412	B-2412/2	B-2412/3
SiO_2	92.15	73.27	84.84	84.74	87.85	77.35	63.55	76.40	67.40
TiO_2	0.07	0.39	0.17	0.12	0.14	0.33	0.39	0.40	0.58
Al_2O_3	2.65	12.46	5.12	5.46	5.02	9.22	12.87	11.43	12.23
$Fe_2O_3^t$	1.99	3.19	3.21	2.98	2.51	3.73	3.74	2.73	8.45
MnO	<.01	<.01	<.01	0.02	<.01	<.01	0.03	<.01	0.03
MgO	1.08	3.20	2.39	1.87	1.54	4.40	2.50	2.04	3.79
CaO	0.22	1.12	0.07	0.16	0.07	0.15	5.45	0.54	1.08
Na_2O	<.1	3.76	<.1	<.1	<.1	1.89	6.35	6.02	3.23
K_2O	0.86	1.55	1.92	2.11	1.56	0.30	0.39	0.08	1.60
P_2O_5	<.05	<.05	0.08	<.05	<.05	<.05	0.10	<.05	0.07
LOI	0.56	0.81	1.39	1.76	1.45	2.65	4.60	0.47	1.43
Total	99.57	99.74	99.18	99.22	100.14	100.01	99.96	100.11	99.89
CIA	68.67	58.43	69.74	68.54	73.27	72.08	44.87	52.19	60.36
CIW	90.49	63.41	97.21	96.00	97.15	73.95	45.54	52.39	66.00

Components	Sample number								
	B-2413	B-2413/1	B-2415	B-2416	B-2420/2	B-2421	B-2424	B-2429	B-2430
SiO_2	73.66	56.34	62.28	81.47	95.21	88.07	76.37	63.02	82.69
TiO_2	0.33	0.40	0.26	0.23	0.04	0.19	0.09	0.47	0.26
Al_2O_3	11.68	12.06	9.95	7.92	1.71	4.96	12.78	13.72	7.16
$Fe_2O_3^t$	3.49	4.88	2.83	3.62	1.84	2.86	1.63	2.59	2.66
MnO	0.02	0.07	<.01	<.01	<.01	<.01	<.01	<.01	<.01
MgO	2.90	10.43	2.31	1.61	<.1	1.12	0.74	8.06	2.34
CaO	0.64	8.96	8.98	0.95	0.08	0.10	0.69	3.75	0.81
Na_2O	3.28	3.71	1.62	1.34	<.1	0.47	6.65	7.79	0.76
K_2O	2.71	0.84	3.85	2.43	0.53	1.66	0.40	0.03	2.55
P_2O_5	0.06	0.12	0.05	<.05	<.05	<.05	<.05	<.05	<.05
LOI	1.25	2.19	7.93	0.28	0.11	0.58	0.45	0.56	0.78
Total	100.02	99.99	100.06	99.85	99.50	100.00	99.81	99.98	100.01
CIA	56.74	44.32	39.89	58.17	70.27	65.02	51.58	45.79	60.17
CIW	66.17	45.85	47.89	72.12	91.68	85.12	52.50	45.83	78.30

Samples nos. B-2402, B-2420/2—metaquartzite-sandstones; B-2402/2, B-2404/1, B-2404/2, B-2404/3, B-2404/6, B-2412/2, B-2412/3, B-2413, B-2416, B-2421, B-2430—metasandstones; B-2413/1—calcareous metasandstone; B-2415—calcareous metagravelstone; B-2424—metagravelstone; B-2412, B-2429—metaconglomerate. CIA—chemical index of alteration (Nesbitt and Young, 1982); CIW—chemical index of weathering (Harnois, 1988).

Complex, and are overlain by Jurassic coal-bearing deposits.

For U–Th–Pb (LA-ICP-MS) geochronological research, zircons from samples of metasandstones (B-2404/1, B-2412/2), metagravelstone (B-2424), and small-pebble conglomerate (B-2412, B-2429) of the Atbastakh Formation were extracted. The Sm–Nd isotope analysis for metasandstones, metaquartzite-sandstones, metagravelstones, and small-pebble metaconglomerates of the same formation was performed. In terms of chemical composition (Table 1), the studied rocks mainly correspond to monomictic, oligomictic, and polymictic psammitolites after (Neelov, 1980). On a log(Fe_2O_3/K_2O)–log(SiO_2/Al_2O_3) diagram (Herron, 1988), metasandstones, metaquartzite-sandstones, and metagravelstones lie in fields of greywacke, lithoid

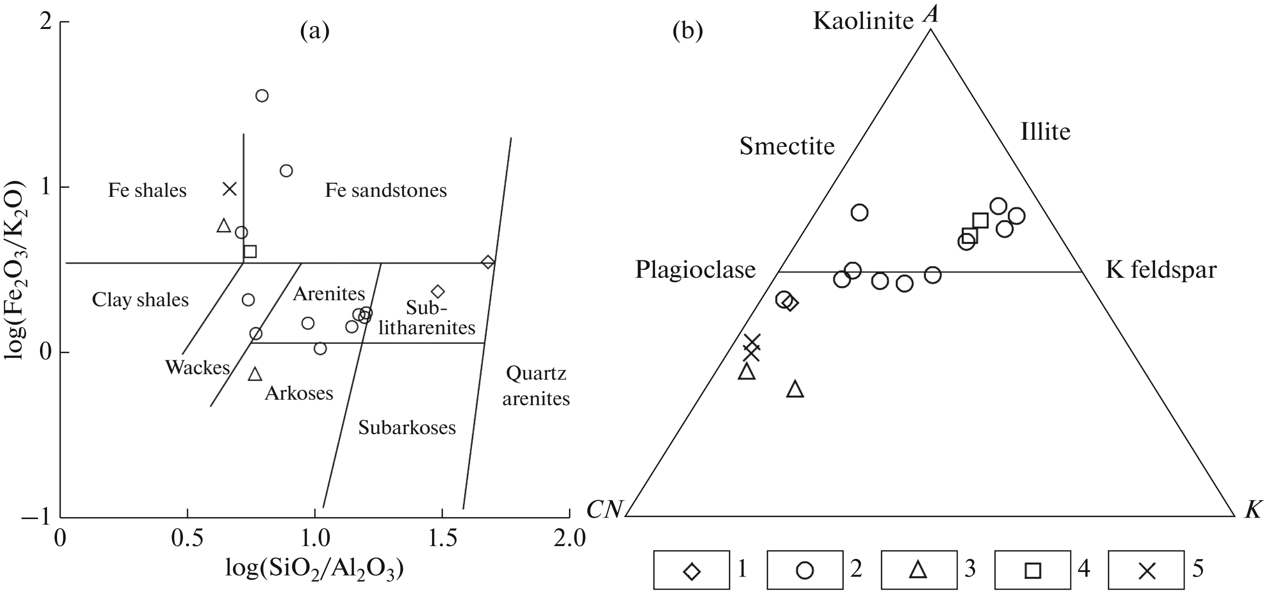

Fig. 3. The (a) log(Fe_2O_3/K_2O)–log(SiO_2/Al_2O_3) (Herron et al., 1988) and (b) A–CN–K (Nesbitt and Young, 1982) diagrams for metasedimentary rocks of the Atbastakh Formation of the Khani Group of the Nizhnekhani graben-syncline. (1) Metaquartzite-sandstones; (2) metasandstones; (3) calcareous metasandstones; (4) metagravelstones; (5) metaconglomerates.

and sublithoid arenites, and less commonly ferruginous sandstones (Fig. 3a). Metasandstones of metaquartzites and metaquartzite-sandstones of the Atbastakh Formation are characterized by mainly moderate and high values of the chemical index of alteration (CIA; Nesbitt and Young, 1982)—52–60 and 65–73, respectively. The chemical index of weathering (CIW; Harnois, 1988) ranges from 52 to 66 and from 72 to 97, respectively (Table 1). Calcareous metasandstones and gravelstones, as well as metaconglomerates are characterized by high CaO content and, as a consequence, low CIA and CIW indexes. In addition, metaconglomerates, metagravelstone, and one of metasandstone samples are characterized by high Na_2O content (6.0–7.8 wt %), which can be related to albitization of rocks in the course of superimposed metamorphism (Berezkin et al., 2007). On the A–CN–K diagram (Fig. 3b) data points of metasandstones and metaquartzite-sandstones of the Atbastakh Formation lie close to or above the field of unaltered igneous rocks.

ANALYTICAL TECHNIQUES

Accessory zircon grains were extracted using heavy liquids following a standard procedure. The morphological features of zircon were studied using a TESCAN VEGA3 scanning electron microscope in the secondary electron and cathodoluminescence modes.

The U–Th–Pb (LA-ICP-MS) geochronological study of zircons was performed at the Institute of Precambrian Geology and Geochronology of the Russian Academy of Sciences (St. Petersburg) using an ICP ELEMENT XR mass spectrometer equipped with a NWR213 laser ablation system with a TwoVolumeTwo camera. The laser beam was 25 μm in dimeter; the measurement duration was 100 s (40 s—a gas blank, 60 s—ablation). Calibration was performed using the GJ-1 zircon standard (Jackson et al., 2004). Standard zircons 91500 and Plešovice were used for data quality control. For the standard Harvard 91500 zircon, the average weighted age values were obtained according to $^{207}Pb/^{206}Pb$ of 1068 ± 5 Ma (2σ, $n = 40$, MSWD = 0.44, probability = 0.999) and according to $^{206}Pb/^{238}U$ of 1067 ± 6 Ma (2σ, $n = 40$, MSWD = 0.080, probability = 1.000). For the standard Plešovice zircon, the average weighted age value was obtained according to $^{206}Pb/^{238}U$ of 336 ± 2 Ma (2σ, $n = 43$, MSWD = 0.23, probability = 1.000). The dates obtained for standard zircons are in good agreement with the recommended data (91500: $^{207}Pb/^{206}Pb$—1066.01 ± 0.61 Ma, $^{206}Pb/^{238}U$—1063.51 ± 0.39 Ma; Plešovice: $^{206}Pb/^{238}U$—337 ± 2 Ma) (Horstwood et al., 2016). The U–Th–Pb isotope ratios were calculated using the GLITTER 4.0 GEMOC software program (Van Achterbergh et al., 2001). The common lead correction was introduced using the ComPb software program (Andersen, 2002). Concordia ages were calculated using IsoplotR software (Vermeesch, 2018). Only Concordia ages were taken into consideration when constructing age histograms with relative probability curves and calculating peak ages (Gehrels, 2012). The data obtained are presented in supplementary materials to the article (ESM_Table 1).

Sm–Nd isotopic analyses were performed at the Institute of Precambrian Geology and Geochronology. Samples of about 100 mg of whole rock powder were dissolved in Teflon buckets in a mixture of HCl, HF, and HNO_3 at a temperature of 110°C. A ^{149}Sm–^{150}Nd spike solution was added to all samples before dissolution. The completeness of dissolution was controlled under a binocular microscope. Rare earth elements (REE) were separated on Bio-Rad AG® 50W-X8 200–400 mesh resin using standard cation exchange chromatography. Sm and Nd were separated by extraction chromatography with a Eichrom LN-Spec 100–150 mesh resin. The Sm and Nd isotope compositions were determined on a TRITON TI multicollector mass spectrometer in static mode. The measured $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$ and adjusted relative to $^{143}Nd/^{144}Nd = 0.512115$ for the JNdi-1 standard. The weighted average of $^{143}Nd/^{144}Nd$ for the JNdi-1 standard over the measurement period was 0.512098 ± 5 ($n = 10$). The accuracy of determination of the Sm and Nd concentrations was ±0.5%; for $^{147}Sm/^{144}Nd$, it was ±0.5%; for $^{143}Nd/^{144}Nd$, it was ±0.005% (2σ). The total blank did not exceed 0.2 ng for Sm and 0.5 ng for Nd.

The $\varepsilon_{Nd}(t)$ values and model ages $t_{Nd}(DM)$ were calculated using the present-day values for the chondritic uniform reservoir (CHUR) after (Jacobsen and Wasserburg, 1984) ($^{143}Nd/^{144}Nd = 0.512638$, $^{147}Sm/^{144}Nd = 0.1967$) and DM after (Goldstein and Jacobsen, 1988) ($^{143}Nd/^{144}Nd = 0.513151$, $^{147}Sm/^{144}Nd = 0.21365$). To take the possible fractionation of Sm and Nd in intracrustal processes into account, "crustal" (two-stage) Nd model ages $t_{Nd}(C)$ (Keto and Jacobsen, 1987) were calculated for the $^{147}Sm/^{144}Nd$ ratio (0.12) in the Archean upper crust (Taylor and McLennan, 1985).

RESULTS OF INVESTIGATION

U–Th–Pb (LA-ICP-MS) Geochronology

Zircon separated from the metasedimentary rocks of the Atbastakh Formation is represented by grains of various degrees of rounding—from subidiomorphic crystals (Figs. 4h, 4m) to well-rounded grains and their fragments (Figs. 4i, 4o, 4q). Most zircon grains are characterized by fine and coarse oscillatory (for example, Figs. 4b, 4c, 4g), less often sectorial (Fig. 4t) zonality and the presence of molten inclusions, which indicates their magmatic genesis. Gray and dark gray grains not zonal or with poorly expressed zonality (Figs. 4i, 4u), which contain numerous gas-liquid inclusions, are less common. Zircon of this type is probably of metamorphic origin. Some zircon grains are characterized by the presence of rounded and nonrounded zonal cores surrounded by a thin nonzonal rim with high luminescence and idiomorphic habit (Figs. 4e, 4f, 4w).

In total, 71 zircon grains (a size fraction of 70–100 μm) and 57 grains (a fraction of >100 μm) were extracted from a metasandstone sample (sericite-chlorite schist) B-2404/1. Of these, 118 zircon crystals were analyzed and 43 concordant ages were obtained. They are mainly in the age range from 2597 to 2997 Ma with peaks on the probability density curve of ages of about 2.65 ($n = 14$), 2.70 ($n = 3$), 2.88 ($n = 3$), and 2.98 ($n = 8$) Ga (Table 2). Single grains yielded Paleoproterozoic and Neoarchean (2437–2528 Ma), as well as Mesoarchean (3088–3217 Ma) concordant ages (Table ESM_1.xlsx). Zircon cores yielded ages of 2879, 3194, and 2626 Ma (analysis B-2404-1-14C in ESM_Table 1); one of the rims yielded 2646 Ma (analysis B-2404-1-34R in ESM_Table 1).

Fractions of 62 and 16 zircon grains of 70–100 and >100 μm in size, respectively, were selected from a sample of small-pebble metaconglomerate B-2412. Of these, 58 zircons grains were analyzed and 21 concordant age estimates were obtained, which are mainly in the range from 2581 to 3041 Ma with peak ages on the age probability curve of about 2.64 ($n = 3$), 2.72 ($n = 3$), 2.77 ($n = 3$), 2.86 ($n = 3$), and 2.99 ($n = 3$) Ga (Table 2). Two grains have concordant ages of 3173 and 3200 Ma. Concordant age estimates of 2867 and 3041 Ma were obtained for zircon cores.

A fraction of 26 zircon grains of 70–100 μm in size was separated from a sample of banded metasandstone B-2412/2; 21 grains of them were analyzed and 7 concordant age estimates were obtained, which are in the ranges of 2603–2706 and 2853–2991 Ma and did not give statistically significant peak ages (Table 2).

The fractions of 93 and 78 zircon grains of 75–100 and 100–150 μm in size, respectively, were selected from the metagravelstone sample (B-2424); 153 zircon grains of them were analyzed, and crystal cores and rims were analyzed in three of them. A total of 60 concordant age estimates were obtained, which are in the range of 2598–2905 Ma with peaks on the age probability curve of ~2.72 ($n = 19$), 2.82 ($n = 13$), and 2.86 ($n = 6$) Ga (Table 2). Two zircon grains yielded concordant ages of 2996 and 3162 Ma (ESM_Table 1). Zircon cores yielded concordant ages of 2717, 2715, 2799, 2825, 2905, and 2996 Ma. Unfortunately, we have not been able to obtain reliable age estimates for the rims of these zircons.

The fractions of 48 and 77 zircon grains of >100 and 75–100 μm in size, respectively, were selected from the small-pebble metaconglomerate sample (B-2429); 45 and 61 zircon grains, respectively, were analyzed. In total, 109 zircon grains were analyzed from this sample; 54 concordant ages were obtained, which are mainly in the range of 2593–3139 Ma with peak ages of ~2.66 ($n = 13$), 2.71 ($n = 6$), 2.74 ($n = 6$), 2.80 ($n = 4$), 2.91 ($n = 3$), 2.99 ($n = 5$), and 3.10 ($n = 3$) Ga (Table 2) on the age probability curve. Single grains have concordant age estimates in the range of 3221–3416 Ma. Concordant ages of 2637, 2738, 2750 and 3097 Ma were obtained for zircon cores, and 2690 Ma was obtained for one rim (ESM_Table 1).

As seen from the above description and Table 2, it was not possible to obtain a significant number of con-

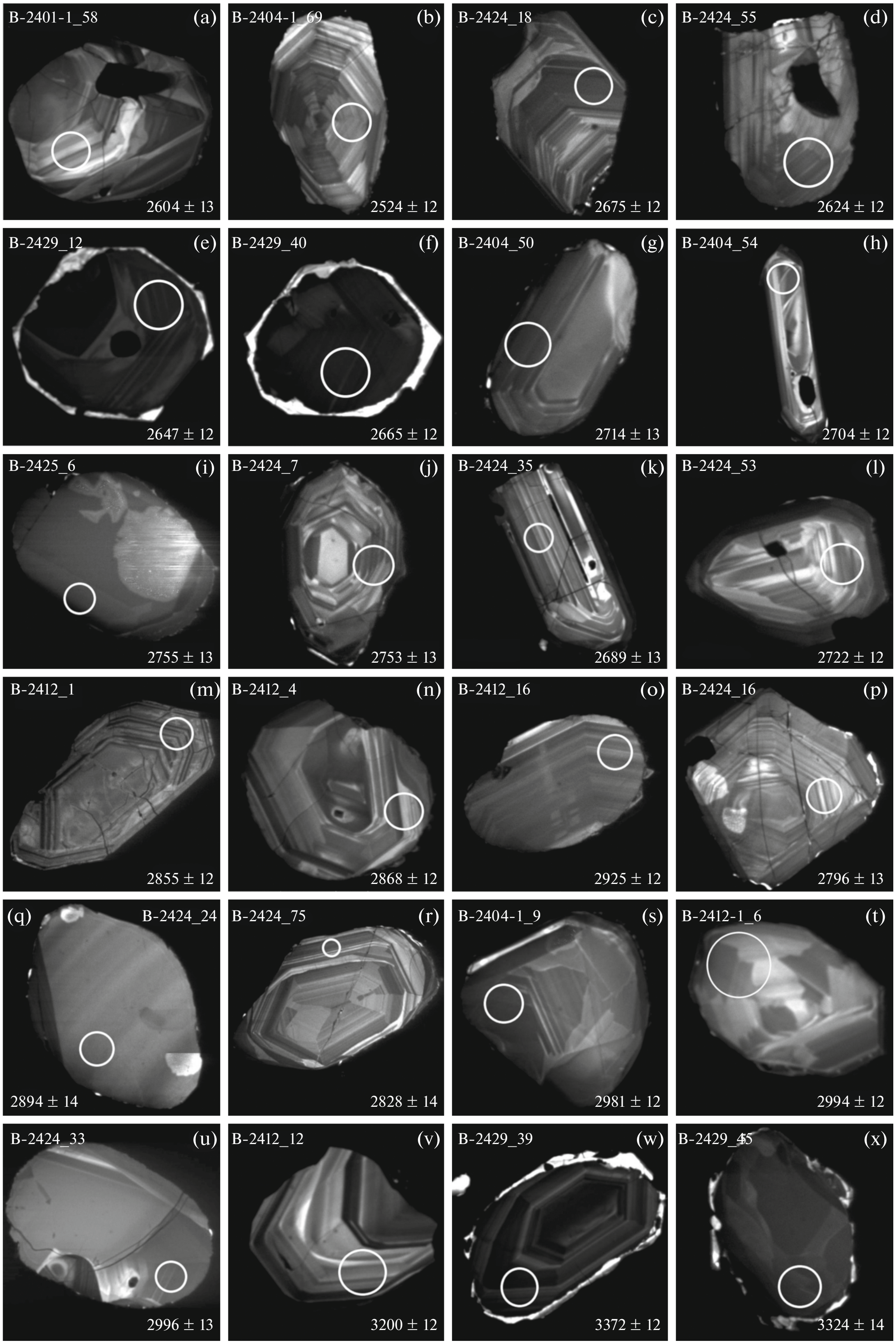
B-2401-1_58
(a)
2604 ± 13
B-2404-1_69
(b)
2524 ± 12
B-2424_18
(c)
2675 ± 12
B-2424_55
(d)
2624 ± 12
B-2429_12
(e)
2647 ± 12
B-2429_40
(f)
2665 ± 12
B-2404_50
(g)
2714 ± 13
B-2404_54
(h)
2704 ± 12
B-2425_6
(i)
2755 ± 13
B-2424_7
(j)
2753 ± 13
B-2424_35
(k)
2689 ± 13
B-2424_53
(l)
2722 ± 12
B-2412_1
(m)
2855 ± 12
B-2412_4
(n)
2868 ± 12
B-2412_16
(o)
2925 ± 12
B-2424_16
(p)
2796 ± 13
(q)
B-2424_24
2894 ± 14
B-2424_75
(r)
2828 ± 14
B-2404-1_9
(s)
2981 ± 12
B-2412-1_6
(t)
2994 ± 12
B-2424_33
(u)
2996 ± 13
B-2412_12
(v)
3200 ± 12
B-2429_39
(w)
3372 ± 12
B-2429_45
(x)
3324 ± 14

Fig. 4. CL images of zircon grains from metaterrigenous rocks of the Nizhnekhani graben-syncline taken on a TESCAN VEGA3 scanning electron microscope. The analytical point is outlined by a white circle (25 μm). The number of the sample and zircon grain (B-2401_58; etc.) and the concordant age in Ma (2604 ± 13, etc.) are shown.

cordant age estimates of detrital zircons from single samples (from 7 to 60 determinations). Apparently, this causes differences in peak ages of zircons from individual samples but not variations in their sources. Considering that all samples were taken from the Atbastakh Formation of the Nizhnekhani graben-syncline at a slight distance from each other (Fig. 2), it seems appropriate to calculate the peak ages on the age probability curve for all concordant ages ($n = 185$).

They are mainly in the age ranges of 2581–3005 and 3041–3221 Ma with age peaks of about 2.65 ($n = 33$), 2.71 ($n = 33$), 2.82 ($n = 18$), 2.86 ($n = 16$), 2.99 ($n = 19$), 3.10 ($n = 5$), 3.17 ($n = 3$), and 3.21 ($n = 4$) Ga (Table 2, Fig. 5). Single zircon grains have Paleoproterozoic–Neoarchean and Paleoarchean concordia ages.

Sm–Nd Isotope Systematics

Metaterrigenous rocks of the Atbastakh Formation of the Nizhnekhani graben-syncline are characterized by isotope ratios ^{147}Sm/^{144}Nd = 0.0878–0.1254 (Table 3), which are close to ^{147}Sm/^{144}Nd = 0.105 in the upper continental crust (Taylor and McLennan, 1985; Rudnick and Gao, 2003). The

Table 2. The results of the U–Th–Pb LA-ICP-MS geochronological study of detrital zircon from metaterrigenous rocks of the Atbastakh Formation of the Nizhnekhani graben-syncline, Aldan Shield

No.	Sample no.	Rock	Age range, Ma	Peak age, Ma*	Number of grains**
1	B-2404/1	Metasandstone	2437, 2524, 2528	2649	14
			2597–2759	2703	3
			2808–2997	2875	3
			3088–3217	2981	8
2	B-2412	Metaconglomerate	2581	2639	3
			2615–3041	2715	3
			3173, 3200	2864	3
				2993	3
3	B-2412/2	Metasandstone	2603–2706	–	–
			2853–2991		
4	B-2424	Metagravelstone	2598–2905	2716	19
			2996, 3162	2822	13
				2863	6
5	B-2429	Metaconglomerate	2593-3139	2655	13
			3221-3416	2712	6
				2740	6
				2804	4
				2910	3
				2988	5
				3102	3
	All samples		2437, 2524, 2528	2650	33
			2581–3005	2713	33
			3041–3221	2820	18
			3256, 3324, 3371, 3416	2864	16
				2987	19
				3098	5
				3166	3
				3213	4

* Peak age—the peak age of the age probability density curve, calculated using the AgePick software program (Gehrels, 2012).
** Number of grains—the number of analyses that contribute to the probability of peak age.

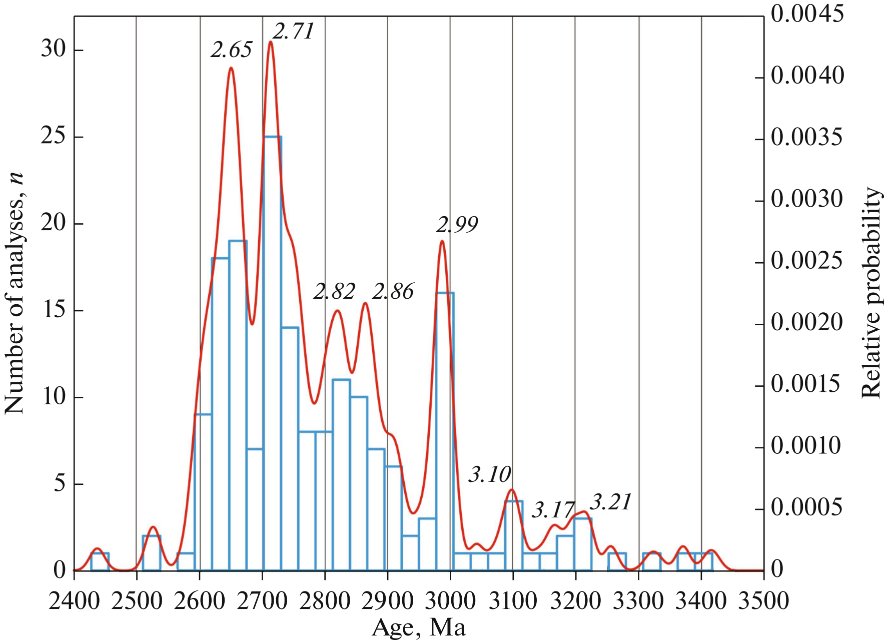

Fig. 5. Histogram and the relative U–Pb age probability curves for detrital zircon from metaterrigenous rocks of the Nizhnekhani graben-syncline.

exception is two metasandstone samples with high ^{147}Sm/^{144}Nd ratios (0.1653–0.2149), which, apparently, is due to the enrichment of these samples in HREE-rich minerals. The ε_{Nd}(t) values calculated for the age of the last event of regional metamorphism in the Chara–Olekma Geoblock as part of the Aldan Shield and the Stanovoi suture zone (~1900 Ma; Kotov, 2003) are in the range from –12.4 to –7.2, while Nd model ages t_{Nd}(DM) are from 3.3 to 2.8 Ga (t_{Nd}(C) = 3.4–3.0 Ga), regardless of the type of rock (Table 3).

DISCUSSION

The U–Th–Pb (LA-ICP-MS) geochronological data obtained for metaterrigenous rocks of the Atbastakh Formation of the Khani Group of the Nizhnekhani graben-syncline indicate that Neo- and Mesoarchean rocks were widely developed in the provenance areas, having formed about 2.65, 2.71, 2.82–2.86, 2.99, and 3.10–3.21 Ga (Table 2, Fig. 5). Probably, there were also Paleoarchean rocks (~3.26–3.42 Ga) in the provenance areas (ESM_Table 1). It should be noted that Paleoarchean tonalite gneisses of 3212 ± 8 Ma crop out only at one site of the Chara–Olekma Geoblock (Nutman et al., 1992). One can suggest a wider development of Paleoarchean complexes during the accumulation of the Nizhnekhani deposits.

Single concordant age estimates, which do not have statistically significant peaks on the relative age probability curve, do not exclude the possibility of the occurrence of rocks with an age of about 2.44 and 2.53 Ga in the provenance areas. However, owing to the fact that relatively large errors can mask Pb loss and lead to apparent concordance (Gehrels, 2012), this assumption requires additional geochronological studies.

Morphological features of detrital zircons from metaterrigenous rocks from the Khani Group (Fig. 4) indicate that both igneous and metamorphic rocks were present in the provenance areas. The varying degree of roundness of zircon grains indicates both proximal and distal sources of their supply. One should note the presence of rounded and subrounded zircon grains with an age of ~2.65 Ga. They represent cores surrounded by a thin nonzonal rim with high luminescence and idiomorphic habit (Fig. 4e, 4f). The formation of the latter was associated with overprinting metamorphic processes. This indicates the presence of reworked igneous rocks with an age of ~2.65 Ga in the provenance areas and, accordingly, a younger age of rocks of the Khani Group.

The upper age boundary of the deposits of the Khani Group is determined by the age of regional metamorphism of ~1.9 Ga (Gorokhov et al., 1989; Kotov, 2003) and by the age of cross-cutting metadiabases of the Kuranakh Complex (1863 ± 9 Ma; Popov et al., 2012). Thus, the accumulation of terrigenous deposits in the Nizhnekhani graben-syncline occurred after 2.65 and before 1.9 Ga, i.e., at the Paleoproterozoic stage of the region's development.

Nd isotope data obtained for deposits of the Khani Group ($t_{Nd(DM)}$ = 3.3–2.8 Ga, t_{Nd}(C) = 3.4–3.0 GA; Table 3) are consistent with the idea of their origin

Table 3. Sm–Nd isotope data for metaterrigenous rocks of the Atbastakh Formation of the Nizhnekhani graben-syncline

Sample no.	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma_{meas.}$)	$\varepsilon_{Nd}(0)$	$\varepsilon_{Nd}(t)$	$t_{Nd(DM)}$, Ma	$t_{Nd(C)}$, Ma
B-2402	0.95	5.47	0.1045	0.510955 ± 4	–32.8	–10.5	3054	3244
B-2402/2	0.65	3.12	0.1254	0.511368 ± 5	–24.8	–7.5	3066	2999
B-2404/1	23.9	67.3	0.2149	0.511054 ± 2	–30.9	–35.5	–	–
B-2404/2	6.53	39.2	0.1006	0.510861 ± 3	–34.7	–11.3	3073	3316
B-2404/3	2.20	12.60	0.1055	0.510984 ± 4	–32.3	–10.1	3040	3216
B-2404/6	3.49	19.83	0.1065	0.510955 ± 3	–32.8	–10.9	3111	3284
B-2412	3.03	19.40	0.0944	0.510915 ± 4	–33.6	–8.8	2847	3105
B-2412/2	0.43	1.56	0.1653	0.511879 ± 5	–14.8	–7.2	–	2978
B-2412/3	3.18	18.08	0.1064	0.511060 ± 2	–30.8	–8.9	2961	3114
B-2413	1.95	13.39	0.0878	0.510844 ± 4	–35.0	–8.5	2785	3088
B-2413/1	3.96	23.6	0.1016	0.510975 ± 3	–32.4	–9.3	2947	3152
B-2415	2.19	13.23	0.0998	0.510904 ± 3	–33.8	–10.3	2996	3231
B-2416	0.77	3.81	0.1224	0.511237 ± 3	–27.3	–9.3	3183	3150
B-2420/2	0.63	3.48	0.1086	0.511043 ± 3	–31.1	–9.7	3046	3185
B-2421	2.57	17.32	0.0898	0.510792 ± 4	–36.0	–10.0	2892	3210
B-2424	0.35	1.88	0.1130	0.510961 ± 5	–32.7	–12.4	3300	3404
B-2429	3.73	21.1	0.1068	0.511070 ± 2	–30.6	–8.8	2958	3106
B-2430	4.74	30.6	0.0937	0.510789 ± 2	–36.1	–11.1	2990	3295

The $\varepsilon_{Nd}(t)$ values and crustal (two-stage) Nd model ages calculated for the age of 1900 Ma.

from Archean rock complexes and, possibly, Paleoproterozoic rocks with Archean isotope constraints. On the $\varepsilon_{Nd}(t)$–age diagram (Fig. 6), the field of Nd isotopic evolution of rocks of the Nizhnekhani graben-syncline lies completely in the field of Nd isotopic evolution of Archean rocks of the Chara–Olekma Geoblock of the Aldan Shield and Kurulta Block of the Stanovoi suture zone.

The geochronological and Nd isotopic data obtained suggest that the sources of sedimentary rocks of the Nizhnekhani graben-syncline were Mesoarchean gneisses, granitoids, and metavolcanics of the Chara–Olekma Geoblock (from 3212 ± 8 to 2967 ± 10 Ma), its junction zone with the West Aldan Megablock (from 3184 ± 85 to 3005 ± 4 Ma), and the Kurulta Block of the Stanovoi suture zone (from 2964 ± 22 to 2846 ± 33 Ma), as well as Meso- and Neoarchean syn- and postcollisional granitoids of the Chara–Olekma Geoblock (from 2913 ± 8 to 2738 ± 8 and from 2675 ± 15 to 2608 ± 18 Ma) and the Stanovoi suture zone (from 2708 ± 7 to 2703 ± 20 and from 2627 ± 16 to 2614 ± 7 Ma) (Nutman et al., 1992; Kotov et al., 1993; Kotov, 2003; Neymark et al., 1993; Salnikova et al., 1996, 1997, 2004a, 2004b; Larin et al., 2006; Glebovitsky et al., 2009; Velikoslavinsky et al., 2018; Kovach et al., 2020; and authors' unpublished data). Neoarchean–Paleoproterozoic A-type granitoids of the Nelyuki complex at the junction zone of the Chara–Olekma Geoblock and West Aldan Megablock (from 2522 ± 2 to 2398 ± 4 Ma; Salnikova et al., 1997; Kotov et al., 2004) could have served as sources of detrital zircons with an age of ~2.53 Ga. One should particularly note a high probability of the occurrence of the Nizhnekhani graben-syncline rocks of Paleoarchean age (about 3.21–3.42 Ga) in provenance areas. To date, the Paleoarchean tonalite-trondjemite gneisses are established only in two areas of the Aldan Shield: in the eastern part of the Chara–Olekma Geoblock (3212 ± 8 Ma; Nutman et al., 1992) and in the West Aldan Megablock (3335 ± 3 Ma; Nutman et al., 1992). It is likely that Paleoarchean complexes were more widespread in the structure of the Aldan Shield, which is in agreement with Nd isotope data obtained for rocks of these blocks ($t_{Nd(DM)}$ up to 3.9–3.7 Ga; Salnikova, 1993; Salnikova et al., 1996, 1997; Jahn et al., 1998).

On the basis of the supposed similarity of the sections of metasedimentary rocks of the Nizhnekhani, Oldongso, and Ugui graben-synclines, they are often combined into a single series (for example, Ugui after (Petrov, 1976)), distinguishing the following formations (from bottom to top): Charadokan, Namsala, Khani, Kebekta (Stannakh in the Nizhnekhani structure) (Salop, 1964; Mironyuk et al., 1971; Fedorovsky, 1972; *Gosudarstvennaya*..., 1998, 2015). All of these formations are considered as a stratigraphic analog of various parts of the Udokan series of the Kodar-

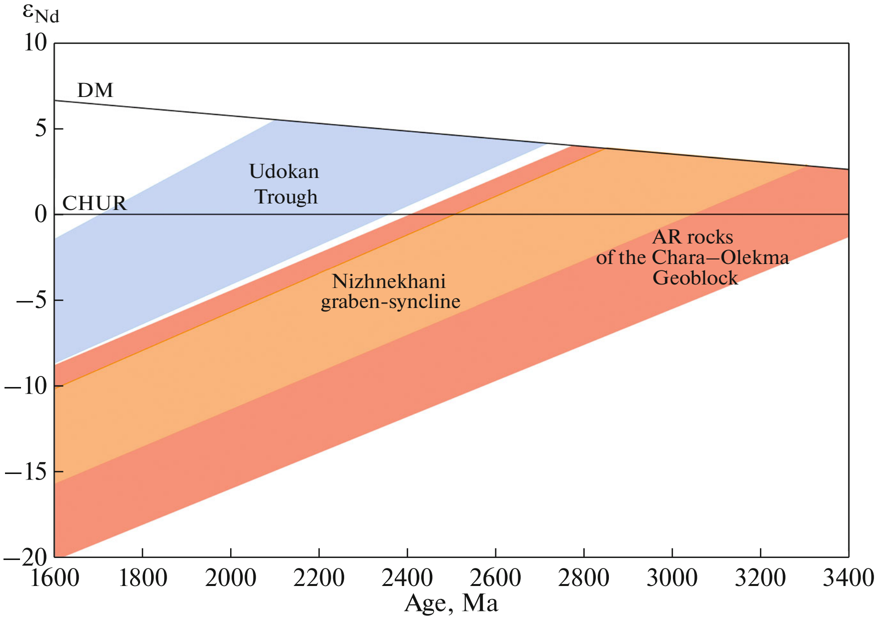

Fig. 6. The ε_{Nd}–age diagram for metaterrigenous rocks of the Nizhnekhani graben-syncline. The fields of evolution of Nd isotope composition in rocks of the Udokan Complex of the Kodar-Udokan Trough and Nizhnekhani graben-syncline and in Archean rocks of the Chara–Olekma Geoblock of the western part of the Aldan Shield are shown. Sources: Neymark et al., 1993; Salnikova et al., 1996, 1997; Jahn et al., 1998; Podkovyrov et al., 2006; Kotov et al., 2006; Kovach et al., 2020; this work; and authors' unpublished data.

Udokan Trough. Thus, for example, Salop (1964) correlates the Lower Proterozoic Charadokan, Namsala, and Khani formations of the Ugui, Oldongso, and Nizhnekhani graben-synclines with the Chinei subseries and the Upper Proterozoic Kebekta (Stannakh) Formation with the lower part of the Kemen' subseries of the Udokan series of the Kodar-Udokan Trough. Mironyuk et al. (1971) considers the Charadokan, Namsala, and Khani formations as analogs of the Kodar subseries, and correlates the Stannakh Formation with the lower part of the Chinei subseries of the Udokan series. Petrov (1976) correlates the Charadokan Formation with the Kodar subgroup, the Namsala and Khani formations with the Chinei subseries, and the Kebekta and Stannakh formations with the Kemen subseries of the Udokan series. Many researchers take rocks of the Kebekta Formation of the Ugui and Oldongso grabens from the composition of the Udokan Complex (for example, Petrov, 1976; Fedorovsky, 1985) and even consider them as Riphean (Meso-Neoproterozoic) deposits (Latysheva et al., 2018).

On the basis of stratigraphic, structural-metamorphic, and petrochemical studies, A.V. Sochava and V.F. Timofeev (Sochava, 1986) came to a conclusion about stratigraphic discrepancy of sections of the Ugui, Oldongso, Nizhnekhani graben-synclines and combined metasedimentary rocks of the latter into the independent Khani Group, more ancient than the formations of the Oldongso and Ugui structures (Berezkin et al., 2007). On the basis of stratigraphic and petrochemical correlations, it is suggested that terrigenous deposits of the Nizhnekhani structure are the most similar to the Kodar and the Lower Chinei subseries of the Udokan series of the Kodar–Udokan Trough (Sochava, 1986).

The Nd isotope data available for metaterrigenous rocks of the metaterrigenous rocks of the Udokan Complex of the Kodar-Udokan Trough (Podkovyrov et al., 2006; authors' unpublished data) and the Nizhnekhani graben-syncline (Table 3) indicate significant differences in the composition of provenance areas. Thus, rocks of the Khani Group are characterized by Paleo- and Mesoarchean Nd model ages $t_{Nd}(DM)$ = 3.3–2.8 Ga ($t_{Nd}(C)$ = 3.4–3.0 Ga), whereas metasedimentary rocks of the Kodar Group of the Udokan Complex similar in grade of metamorphism yield Paleoproterozoic dates $t_{Nd}(DM)$ = 2.5–2.1 Ga ($t_{Nd}(C)$ = 2.6–2.2 Ga). Also, metasandstones and medamudstones of the Chinei ($t_{Nd}(DM)$ = 2.6–2.4 Ga, $t_{Nd}(C)$ = 2.7–2.5 Ga) and Kemen ($t_{Nd}(DM)$ = 2.7–2.5 Ga, $t_{Nd}(C)$ = 2.8–2.6 Ga) groups of the Udokan Complex yielded younger Nd model ages than those obtained for rocks of the Nizhnekhani graben-syncline.

The $\varepsilon_{Nd}(t)$–age diagram (Fig. 6) clearly shows that the field of Nd isotopic evolution of rocks of the Khani Group of the Nizhnekhani graben-syncline lies below the field of Nd isotopic evolution of terrigenous deposits of the Udokan Complex of the Kodar–Udokan Trough.

Differences in the provenance areas of metaterrigenous rocks of the Nizhnekhani graben-syncline and Kodar–Udokan Trough were also established by the results of U–Th–Pb (LA-ICP-MS) geochronological studies of detrital zircons. As shown above, Archean igneous and metamorphic complexes and, possibly, rocks with an age of about 2.44 and 2.53 Ga were the provenance areas of the deposits of the Khani Group (Fig. 5). In contrast, the provenance areas of terrigenous deposits of the Udokan Complex of the Kodar–Udokan Trough were dominated by Paleoproterozoic igneous and metamorphic rocks with ages of 2.08 Ga (Kodar Group), 1.90, 1.98, and 2.50 Ga (Chinei Group), and 2.02, 2.16, 2.18, 2.38, and 2.54 Ga (Kemen Group) (Kovach et al., 2018a, 2018b; Adamskaya et al., 2022). The Paleoproterozoic provenance areas (about 2.0 Ga) were also established for metasandstones of the Ugui graben-syncline (Samsonov et al., 2015).

Thus, despite certain similarities in the structure of the sections and petrochemical features of the deposits of the Kodar and Chinei groups, on one hand, and the Khani Group, on the other hand (Sochava, 1986), there are significant differences in the age and Nd isotope characteristics of the provenance areas of terrigenous rocks of the Nizhnekhani graben-syncline and Kodar–Udokan Trough, which suggest that their accumulation occurred in isolated basins.

CONCLUSIONS

(1) On the basis of U–Th–Pb (LA-ICP-MS) geochronological and Sm–Nd isotope data, it was established that the accumulation of terrigenous deposits of the Khani Group of the Nizhnekhani graben-syncline occurred after 2.65 Ga and before 1.9 Ga, probably at the Paleoproterozoic development stage of the region.

(2) Igneous and metamorphic rocks of the Chara–Olekma Geoblock, its conjunction zone with the West Aldan Megablock, and the Kurulta Block of the Stanovoi suture zone are considered the sources of terrigenous rocks of the Khani Group. Probably, among the sources of detrital material, there were also Paleoarchean rocks (about 3.26–3.42 Ga), which are of limited occurrence at the present-day erosion section.

(3) Significant differences in the composition of the provenance areas of metasedimentary rocks of different structures of the Udokan Complex have been established. Metaterrigenous rocks of the Nizhnekhani graben-syncline were formed from crustal sources with Paleo- and Mesoarchean Nd model ages (t_{Nd}(DM) = 3.3–2.8 Ga), while a significant contribution of the Paleoproterozoic juvenile material was established for the metasedimentary rocks of the Kodar–Udokan Trough (t_{Nd}(DM) = 2.7–2.1 Ga). Significant differences in the age and Nd isotopic characteristics of sources of terrigenous deposit of the Nizhnekhani graben-syncline and the Kodar–Udokan Trough suggest that they accumulated in isolated basins.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY INFORMATION

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