ISSN 0145-8752, Moscow University Geology Bulletin, 2017, Vol. 72, No. 2, pp. 115–125. © Allerton Press, Inc., 2017.
Original Russian Text © I.D. Sobolev, A.N. Shadrin, V.A. Rastorguev, D.A. Kozyreva, 2017, published in Vestnik Moskovskogo Universiteta, Seriya 4: Geologiya, 2017, No. 1, pp. 22–32.

Early Island-Arc Granitoids of the Shchuchinskaya Zone of the Polar Urals: U–Pb (SIMS) Zircon Isotope Data

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Received October 6, 2016

Abstract—Granitoids of the Rechnoy and Yalya-Pe paleovolcanoes, which were ascribed to the Silurian Khoimpe complex during a geological mapping, and granitoids of the Nganotsky-1 and Nganotsky-2 plutons that were ascribed to the Early Devonian Yunyaga complex were studied in the Shchuchinskaya zone of the Polar Urals. It was established that according to the mineral and chemical compositions the rocks of the plutons studied correspond to island-arc granitoids of I-type. Zircons from granitoids of the Rechnoy and Yalya-Pe paleovolcanoes and the Nganotsky-1 pluton yielded concordant U–Pb (SIMS) isotope ages of 456 ± 6, 454 ± 4, and 463 ± 3 Ma, respectively, which indicates the existence of an island arc within the Shchuchinskaya zone starting from the Middle–Late Ordovician. Based on the obtained zircon ages of granitoids, the country volcanics were ascribed to the Syaday Formation; the upper stratigraphic boundary of their formation was specified as the Middle–Upper Ordovician.

Keywords: Polar Urals, granitoids, zircons, U–Pb geochronology, island arc, magmatism, geochemistry
DOI: 10.3103/S0145875217020065

INTRODUCTION

The Shchuchinskaya zone is the northernmost part of the Paleozoic island-arc system of the Urals (Fig. 1, a). The Shchuchinskaya zone consists of rocks of an ophiolite association (Kharcheruz, Syumkeu, Pusierka, and Nyarope ultramafic massifs), as well as Early–Middle Paleozoic island-arc igneous and sedimentary–volcanogenic formations located to the east (Fig. 1, b). Gabbroids are the most widespread rock type within the plutonic rocks; granitoids occupy a much smaller area and occur as small stock-like plutons of up to 10–16 km^2. The island-arc gabbroids and granitoids of the Shchuchinskaya zone were referred to different complexes (Sirin et al., 1962; Bevz, 1976; Okhotnikov, 1985; Starkov, 1985; Remizov, 1998). According to the explanatory note to the Polar Urals series of the sheets of the 1 : 200000 State Geological Map of the Russian Federation (2009), these formations are now referred to the Kharampe-Maslo gabbronorite, the Khoimpe gabbro-plagiogranite, Yunyaga gabbro–diorite–tonalite, and Yurmeneku plutonic granodiorite complexes.

The Khoimpe complex was first distinguished by V.N. Voronov in 1976 during the 1 : 50000 geological mapping (GM–50). Intrusions of the Khoimpe complex, which are common in the Khoimpe and Kharampe Ranges, as well as in the Yabtoyakha and Syadeyyakha river basins, consist of two phases. The first phase consists of gabbroids (98.5%); the second phase consists of plagiogranitoids (only 1.5%). Intrusive rocks of the Khoimpe complex cut island-arc volcanic formations of the Upper Ordovician-Lower Silurian Syaday Formation, the Lower Silurian Yanganape formation, and, supposedly, the Early Silurian gabbroids of the Kharampe–Maslo complex. The magmatic rocks belonging to Khoimpe complex, in turn, are cut by presumably Early to Middle Devonian gabbro–diorite–tonalite intrusions of the Yunyaga complex (Dushin et al., 2009, Zyleva et al., 2014). Based on studying the geological relationships, the age of gabbroids and granitoids of the Khoimpe complex was attributed to the Late Silurian. Due to the K–Ar age dating of the rocks of the Khoimpe complex (Dushin et al., 2009), a wide range of age data varying from the Cambrian to the Middle Devonian (526–386 Ma) with the Silurian datings prevailing was obtained.

The Yunyaga complex was first distinguished by V.N. Voronov during a geological mapping (1969–1976).

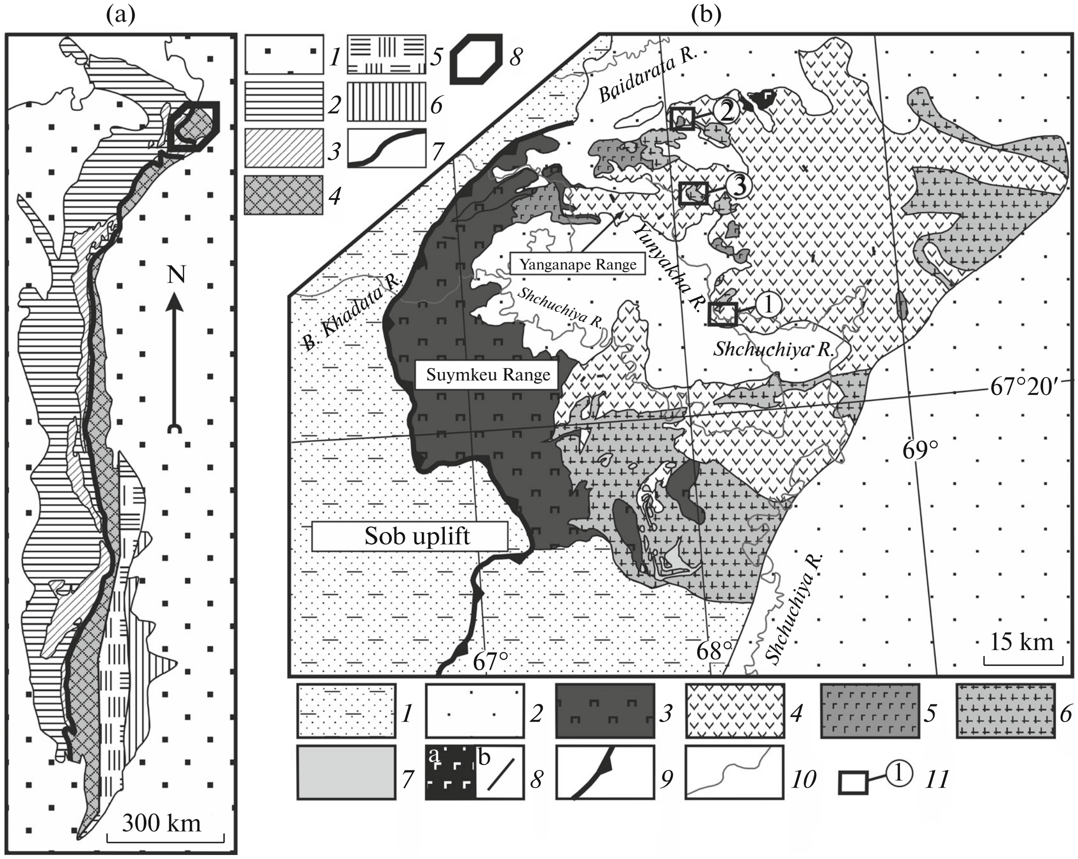

Fig. 1. Schemes of tectonic zoning of the Urals (a) and Shchuchinskaya zone of the Polar Urals (b): (a) tectonic scheme of the Ural Fold Belt, according to (Kuznetsov et al., 2000): *1*, Mesozoic–Cenozoic complexes of the cover of the East European Platform and the West Siberian Plate; *2–3*, Paleozoic and Precambrian complexes of the Western segment of the Urals: *2*, predominantly Paleozoic sedimentary complexes, *3*, predominantly Late Precambrian metamorphosed sedimentary, volcanogenic, and plutonic complexes; *4–5*, Paleozoic and Precambrian complexes of the Eastern segment of the Urals: 4, Early–Middle Paleozoic volcanic–sedimentary complexes, *5*, Precambrian and Paleozoic non-uniformly metamorphosed sedimentary, volcanogenic–sedimentary, ophiolitic, and granitoid complexes; *6*, Paleozoic and Precambrian complexes of the Trans-Urals Region; *7*, Main Urals Fault; *8*, outline of the tectonic scheme of the Shchuchinskaya zone of the Polar Urals; (b) the tectonic scheme of the Shchuchinskaya zone of the Polar Urals (compiled after (Zyleva et al., 2014)): *1*, Late Precambrian and Paleozoic formations of the West Uralian megazone; *2*, the Mesozoic–Cenozoic cover of the West Siberian Plate; *3–8*, Late Precambrian-Paleozoic formations of the Shchuchinskaya zone: *3*, Late Precambrian–Early Paleozoic ultramafic rocks of the Khadata massif, *4*, Paleozoic sedimentary–volcanogenic formations, *5*, Early Paleozoic gabbroids and plagiogranitoids of the Khoimpe plutonic complex, *6*, Early–Middle Devonian gabbroids and plagiogranitoids of the Yunyaga plutonic complex, *7*, Devonian–Early Carboniferous granitoids of the Yurmeneku plutonic complex, *8*, Late Paleozoic gabbro-dolerites of the Naunpe hypabyssal complex (a, stocks, b, dykes); *9*, Main Urals Fault; *10*, rivers; *11*, study areas.

According to the explanatory note to the Polar Urals series of sheets of the 1 : 200000 State Geological Map of the Russian Federation (2009), the Yunyaga complex has a three-phase structure. The first intrusive phase is made up of gabbro and gabbro-diorite. The second phase consists of diorite, plagiogranite, and granite. The third phase includes granite. The plutonic rocks of the Yunyaga complex cut the Silurian island-arc volcanics of the Yanganape formation and the Silurian formations of the Yanganape volcanic complex. In turn, these plutonic rocks are intruded by the Early Carboniferous dolerite dykes of the Naunpe complex. Until recently, there were only a few K–Ar age datings for granitoids of the Yunyaga complex (Starkov, 1985; Andreichev, 2004), which vary in a range from 419 to 291 Ma. Later, Rb–Sr and U–Pb age datings were obtained, according to which the Rb–Sr age of granitoids of the Yanganape and Sibilei plutons was determined to be the Early Devonian: 398 ± 18 and 401 ± 9 Ma, respectively (Andreichev, 2004; Andreichev and Larionov, 2008), and the U–Pb age of zircons from the granitoids of the Yanganape pluton turned out to be Llandoverian–Wenlockian (435 ± 5 Ma).

The geological position of the granitoids and their mineral composition. In the central and northern parts of the Shchuchinskaya zone (Fig. 1, b) we studied three stock-shaped bodies of plagiogranitoids which are eroded fragments of the Rechnoy and Yalya-Pe paleovolcanic ring structures (Fig. 2, a, b), and two

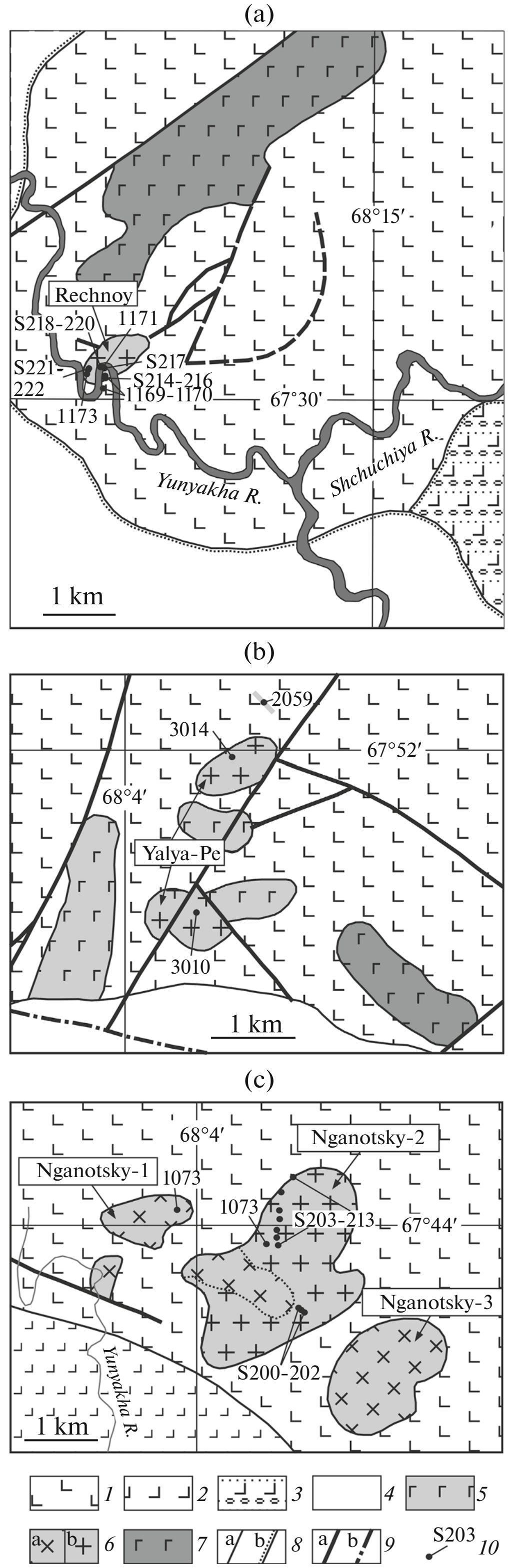

Fig. 2. The geological schemes of the studied areas according to GM-50 (1976), with changes: (a) Rechnoy paleovolcano; (b) Yalya-Pe paleovolcano; (c) granitoid plutons: Nganotsky-1, Nganotsky-2, Nganotsky-3: *1*, Middle to Upper Ordovician volcanics of the Syaday Formation; *2*, Middle Devonian sedimentary–volcanogenic rocks of the Enzor formation; *3*, Middle–Upper Devonian volcanogenic–sedimentary rocks of the Talbey formation; *4*, Upper Triassic terrigenous deposits; *5–6*, associations of the Khoimpe plutonic complex: *5*, gabbroids of the first intrusive phase, *6*, the granitoids of the second phase (a, diorites, quartz diorites, tonalites; b, plagiogranites and leucoplagiogranites); *7*, the Yunyaga complex: gabbro-diorites of the first intrusive phase; *8*, geological boundaries (a, conformable, b, non-conformable); *9*, faults (a, reliable, b, reliable, covered by the overlying formations); *10*, observation sites.

intrusions of quartz diorites and plagiogranites (Nganotsky-1 and Nganotsky-2 plutons) (Fig. 2, c), which were attributed by V.N. Voronov at GM-50 (1976) to the Silurian–Devonian Khoimpe and the Middle–Late Devonian Yunyaga complexes, respectively. D.N. Remizov [2004] ascribed both plutons to the Early Devonian Yanganape volcano-plutonic andesitoid association.

The granitoid intrusion of the Rechnoy paleovolcano is located in the central part of the Shchuchinskaya structure, in the lower reaches of the Yunyakha River (Fig. 2, a). It is the plutonic part of the paleovolcanic ring structure, cutting island-arc volcanics, which were attributed by V.N. Voronov at GM-50 to the Upper Silurian Yanganape formation. The intrusive body 1 × 0.5 km in diameter has an irregular shape elongated in a northeasterly direction and is composed of leucoplagiogranites and plagiogranites with gradual transitions between them. The rocks are characterized by a massive structure, medium- to fine-grained hypidiomorphic granular texture, sometimes in combination with micrographic. They are composed of plagioclase (55 vol %), quartz (40 vol %), potassium feldspar (5 vol %) and chloritized dark-colored mineral (up to 1 vol %). Leucoplagiogranites contain small (up to 15 × 25 cm) pegmatoid sites made of pink medium- to coarse-grained leucoplagiogranites (sample no. S221). The marginal chill zones of the intrusive body are composed of porphyrytic plagioclasites with a fine-grained aplite quartz–plagioclase ground mass. In the contact zone between granitoids and volcanics abundant vein-disseminated pyrite–chalcopyrite mineralization occurs. This is the Rechnoe copper–pyrite ore occurrence.

The granitoid intrusions of the Yalya-Pe paleovolcano are exposed on Mt. Yalya-Pe in the northern part of the Shchuchinskaya zone (Fig. 2, b). These intrusive bodies are slightly extended in the sublatitudinal direction and are 0.7 × 1 and 0.5 × 1 km in plan view. According to GM-50 (1976) the first body cuts through the volcanics of the Syaday Formation; the second one intersects gabbroids of the first intrusive phase of the Khoimpe complex, the volcanics of the Syaday Formation, and the Yanganape formation. Based on finds of Rugose and Tabulate corals and crinoid fossils, the age of the volcanics of the Syaday Formation that crop out to the east of the Yalya-Pe paleovolcano (the Syadeiyabtoyakha stream valley) is Late Ordovician–Early Silurian (Zyleva et al., 2014). The K–Ar age of the subvolcanic facies of the Syaday volcanic complex exposed in the northwestern part of the Shchuchinskaya zone is estimated to be Wenlockian (Dushin et al., 2009). The age of the volcanics of the Yanganape formation, exposed 8 km to the southeast of the Yalya-Pe paleovolcano has been faunistically substantiated by E.G. Katasonov and S.M. Andronov (1969) as Wenlockian–Ludlovian.

Plagiogranites in the marginal part of the southernmost intrusive body of the Yalya-Pe ring structure have a porphyric texture and a fine-grained structure of the groundmass. Microphenocrysts 1.5–2.5 mm in size consist of plagioclase and quartz. With distance from the contact zone, the grain size of the groundmass gradually increases; the texture becomes fine- to average-grained. In the central part of the pluton, plagiogranites have a massive structure and a porphyric fine- to medium-grained diorite-like texture. Rock-forming minerals consist of calcium-rich plagioclase (35% vol %), quartz (30% vol %), hornblende (30 vol %), and biotite (5 vol %).

The Nganotsky-1 and Nganotsky-2 plutons are located in the northern part of Shchuchinskaya zone in the upper reaches of the Yunyakha River (Fig. 2, c). These intrusives are of a subisometric irregular shape and are 1.3 × 0.8 and 2.5 × 3.3 km in plan view, respectively. The Nganotsky-1 pluton is characterized by a zonal structure. The central part is composed of gabbro and gabbro-diorites; the marginal parts are made of diorites and quartz diorites. The Nganotsky-2 pluton is predominantly composed of plagiogranites, as well as subordinate diorites and tonalites. Based on numerous finds of faunistical remains collected by V.N. Voronov at GM-50 (1976), country volcanic rocks of the Yanganape formation in the vicinity of Mt. Sibilepe and in the Enzoryakha and Nganotayakha river basins are of Ludlovian–Pridolian age.

Quartz diorites in the marginal part of the Nganotsky-1 pluton have a porphyric texture and a fine-grained hypidiomorphic granular texture of the groundmass. They are composed of plagioclase (40 vol %), quartz (40 vol %), hornblende (20 vol %), and biotite (<1 vol %). The phenocrysts consist of plagioclase and hornblende 1–3 mm in size. The groundmass is composed of plagioclase, hornblende, quartz, and biotite flakes. The grain size is 0.3–0.8 mm. The plagioclase is highly sossuritized and epidotized. The hornblende is epidotized and weakly chloritized. Rare biotite flakes occur usually as intergrowths with hornblemde and are often replaced by chlorite or chlorite–leucoxene aggregate.

The plagiogranites of the Nganotsky-2 pluton are characterized mainly by a porphyric hypidiomorphic granite-like texture and a massive structure. Rock-forming minerals consist of plagioclase (40–50 vol %), quartz (30–40 vol %), potassium feldspar (5–15 vol %), and hornblende (5–7 vol %). Phenocrysts (8–20 vol %) are dominated by tabular crystals of sericitized and sossuritized plagioclase (2–6 mm). Prismatic grains of hornblende (2–3 mm) are less common and are often replaced by chlorite and epidote. The groundmass is fine- to medium-grained (the grain size is 0.5–2.0 mm) and is composed of subidiomorphic hornblende and plagioclase crystals, as well as xenomorphic segregations of quartz and potassium feldspar. There is evidence of reaction relationship between the feldspar grains with the formation of myrmekites. Crystals of accessory magnetite 0.1–0.7 mm in size are spatially associated to hornblende grains. The grain size of the groundmass of the plagiogranite-porphyry decreases to 0.01–0.50 mm toward the contact of the pluton.

The chemical composition of granitoids. The granitoids of the Rechnoy and Yalya-Pe paleovolcanoes are characterized by normal to low content of ($Na_2O + K_2O$) and, according to the petrochemical classification, they are primarily attributed to leucoplagiogranites and plagiogranites (*Petrograficheskii* ..., 2008). According to Barker's classification (Barker, 1979) these granitoids are ascribed to trondhjemites; pegmatoid differences are granites (Fig. 3, a). The rocks are characterized by the sodium type of alkalinity and the following variations in composition (wt %): SiO_2 (66.5–78.6); TiO_2 (0.2–0.5); Al_2O_3 (11.1–14.9); Fe_2O_{3total} (1.0–5.9); MgO (0.2–3.5); CaO (0.5–4.4); Na_2O (2.4–6.5); and K_2O (0.1–1.3) (Table 1). Within the pegmatoid segregations of leucoplagiogranites, the K_2O content increases to 3.6%. Near the contact with country rocks the Rechnoy intrusion is composed by quartz diorite with normal to high ($Na_2O + K_2O$) content (Table 1). Leucoplagiogranites of the Rechnoy paleovolcano are characterized by low total REE contents (54–98 ppm) (Table 2). The chondrite-normalized REE distribution plot shows a slight prevalence of LREE over HREE (La_N/Yb_N = 1.74 × 2.33) and a distinct depletion in Eu (Fig. 3, b). The rocks are characterized by slight enrichment in large-ion lithophile elements and the occurrence of an insignificant Ta–Nb minimum (Fig. 3, c).

The granitoids of the Nganotsky-1 and Nganotsky-2 plutons belong to the petrochemical series of low and normal alkalinity and are characterized by the sodium type of alkalinity. According to this, they are attributed to quartz diorites, tonalites, and plagiogranites (*Petrograficheskii*..., 2008). As follows form Barker's classification (Barker, 1979), granitoids of the Nganotsky-1 pluton are attributed to tonalites; those of the Nganotsky-2 pluton are trondhjemites and tonalites (Fig. 3, a). The rocks are characterized by the following variations in composition (wt %): SiO_2 (60.2–73.0); TiO_2 (0.3–0.7); Al_2O_3 (12.1–14.4); Fe_2O_3 total (3.2–9.4); MgO (1.0–3.0); CaO (1.8–6.7); Na_2O (2.9–5.2); and K_2O (0.1–1.3) (Table 1).

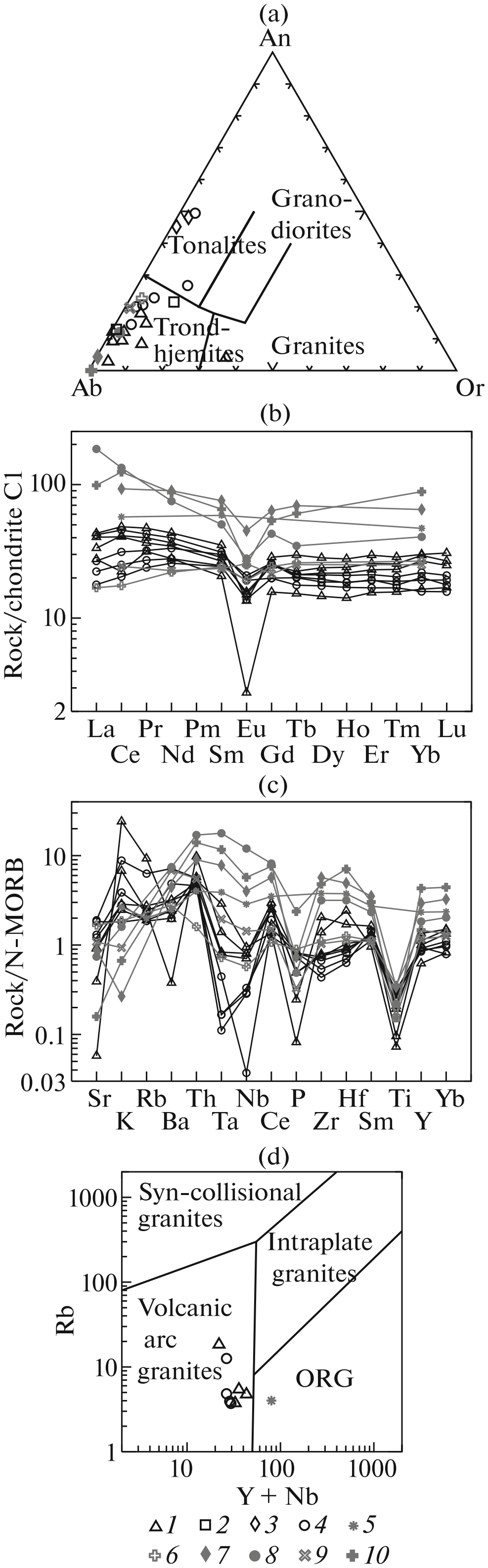

Fig. 3. Diagrams for granitoids of the Shchuchinskaya zone of the Polar Urals: a, the Ab–An–Or classification diagram, after (Barker, 1979); b, Chondrite-CI normalized REE plot for granitoids, after (Sun and McDonough, 1989); c, N-MORB-normalized multi-element diagram for granitoids, according to (Pearce,1982); d, the Rb–(Y + Nb) diagram for reconstruction of the geodynamic settings of the formation of granitoids, according to (Pearce et al., 1984). *1–4*, the composition points of granitoids of the Shchuchinskaya zone: *1*, Rechnoy paleovolcano, *2*, Yalya-Pe paleovolcano, *3*, Nganotsky-1 pluton, *4*, Nganotsky-2 pluton. For comparison, the following composition points are plotted: model plagiogranites of the Mid-Ocean Ridge (ORG) (*5*), island arc granitoids of Oman (*6*), as well as ophiolite granitoids of the Smartville Block (*7*), Mid-Atlantic Ridge (*8*), Troodos (9), and Tucson (10), according to (Pearce et al., 1984). The chemical compositions of the granitoids of the Shchuchinskaya zone are given in Tables 1 and 2.

The plagiogranites of the Nganotsky-2 pluton are similar to the leucoplagiogranites of the Rechnoy paleovolcano in the distribution pattern of trace elements (Table 2). They are characterized by low REE contents (52–86 ppm), a weak enrichment in LREE (La_N/Yb_N = 1.57 × 2.91), and a distinct depletion in europium (Fig. 3, b). In contrast to leucoplagiogranites of the Rechnoy paleovolcano, plagiogranites of the Nganotsky-2 pluton have a more pronounced negative Ta–Nb anomaly (Fig. 3, c).

According to the genetic classification by Chappell and White (Whalen et al., 1987), all these granitoids can be classified as I-type granites and the felsic I-type granites.

Thus, in terms of mineral and chemical compositions, these granitoids are considered to be rather "primitive" plagiogranitoids, which could be formed in the geodynamic setting of oceanic ridges or immature island arcs. Therefore, in order to clarify the origin of these plagiogranitoids, we compared their trace-element compositions with the model composition of the oceanic ridge granites (ORG), with the compositions of plagiogranitoids from oceanic ridges not related to subduction processes: from the "normal" ophiolites of Toscana and the "anomalous" ophiolites of Mid-Atlantic Ridge (45° N); with the compositions of plagiogranites from subduction-related oceanic ridges: the ophiolites of the Smartville block formed in the back-arc setting and the suprasubduction ophiolites of Troodos formed in the fore-arc setting, and with the island arc plagiogranites of Oman (Pearce et al., 1984). Plagiogranitoids of the Shchuchinskaya zone differ from most of the ophiolite plagiogranitoids in that they are enriched in large-ion lithophile elements (K, Rb, and Th) and depleted in high-field-strength elements (REE, Ta, Nb, Zr, Hf, and Y) (Fig. 3, c). They are remarkable similar to trondhjemites from early island arc complexes of Oman and the suprasubduction ophiolites of Troodos, which formed in a fore-arc setting. On Pearce diagrams (Pearce et al., 1984), in particular on the Rb–(Y + Nb) diagram (Fig. 3, d), the composition points of the studied plagiogranitoids lie in the field of volcanic arc granitoids.

Table 1. The chemical compositions (wt %) of granitoids of the Shchuchinskaya zone

Sample no.	Rock	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Granitoids of the Rechnoy paleovolcano														
1169	Quartz diorites	58.40	0.81	16.17	5.22	–	0.10	2.39	7.56	7.68	0.06	0.27	1.40	100.05
1170		61.91	0.65	14.82	8.78	–	0.09	3.51	2.33	4.97	0.51	0.17	2.30	100.03
S221-A	Plagiogranites	70.22	0.50	11.08	3.44	2.17	0.11	3.49	1.25	3.32	0.54	0.07	3.82	100.00
S220	Leucoplagiogranites	74.27	0.29	12.68	0.58	1.50	0.05	0.88	2.06	5.79	0.37	0.06	1.47	100.00
S218		75.74	0.24	12.79	0.53	1.23	0.04	1.03	1.20	5.63	0.43	0.06	1.09	100.00
S221		76.90	0.16	11.79	0.24	1.19	0.01	0.30	0.51	4.08	3.61	0.01	0.45	99.12
S219		77.01	0.20	11.74	0.60	1.31	0.04	0.84	1.13	5.74	0.19	0.04	1.15	100.00
1171		77.25	0.20	11.59	0.24	1.32	0.03	0.53	1.38	5.29	1.01	0.03	1.14	100.00
1172		78.55	0.15	11.76	0.96	–	0.02	0.15	0.96	6.48	0.41	0.00	0.60	100.04
Granitoids of the Yalya-Pe paleovolcano														
2059	Tonalites	66.52	0.51	14.87	0.49	3.60	0.10	1.26	5.02	2.43	0.34	0.25	4.40	99.79
3010	Plagiogranites	69.59	0.25	13.32	0.54	2.45	0.09	0.44	4.42	4.40	1.26	0.19	3.34	100.29
3014		72.38	0.43	13.36	0.86	2.16	0.07	0.84	1.88	5.69	0.11	0.25	1.69	99.72
Granitoids of the Nganotsky-1 pluton														
1072	Quartz diorites	60.22	0.67	14.38	3.26	5.62	0.08	2.95	6.67	2.88	0.28	0.25	2.95	100.21
Granitoids of the Nganotsky-2 pluton														
1073	Tonalites	67.23	0.41	13.26	2.91	2.16	0.08	1.34	6.12	2.97	0.11	0.30	3.03	99.92
S204	Plagiogranites	70.60	0.52	13.38	1.98	2.56	0.09	1.00	3.22	3.83	1.32	0.09	1.18	99.77
S201		71.64	0.55	13.27	1.79	2.34	0.08	1.14	2.60	4.22	0.58	0.10	1.42	99.72
S202		71.64	0.39	13.08	1.84	2.42	0.06	1.63	2.43	4.57	0.41	0.12	1.42	100.00
S200		72.08	0.32	12.05	1.18	1.87	0.07	2.08	3.17	4.70	0.27	0.10	2.12	100.00
S210		72.98	0.36	12.81	1.45	1.98	0.05	1.51	1.80	5.17	0.42	0.10	1.36	100.00

The chemical composition was determined with X-ray fluorescence (XRF) analysis in Laboratory of Mineral Raw Materials Chemistry of the Institute of Geology of the Komi Scientific Center of Ural Branch of the Russian Academy of Sciences. The composition of Sample no. S221 was determined using classical chemical analysis in the same Laboratory. The compositions of samples nos. 2059, 3010, 3014, 1072, and 1073 were determined using the X-ray fluorescence (XRF) analysis method in the Tyumen Central Laboratory; The compositions of samples nos. 1169, 1170, 1172 were determined with X-ray fluorescence (XRF) in the Laboratory of Physical and Chemical Research of the Zavaritsky Institute of Geology and Geochemistry (UB RAS).

Results of U–Pb zircon isotope dating of granitoids. The U–Pb zircon isotope age datings were performed for pegmatoidal leucoplagiogranites of the Rechnoy paleovolcano (Sample no. S221) and plagiogranites of Yalya-Pe paleovolcano (Sample no. 3010) from the second intrusive of the Khoimpe complex. In addition, zircons from quartz diorites of the Nganotsky-1 pluton (Sample no. 1072) of the first phase of the Yunyaga complex were dated. Sample preparation and measurements using SHRIMP-II secondary-ion mass spectrometer were carried out at the Center of Isotopic Research (VSEGEI, St. Petersburg) following the procedure described in (Ireland, 1995; Larionov et al., 2004).

Zircon grains from pegmatoidal leucoplagiogranites of the Rechnoy paleovolcano (Sample no. S221) were subdivided into two types. The first-type zircons are idiomorphic transparent pale-yellow subisometric or slightly elongated (C_{el} = 1–2.5) with bipyramidal crystals 70–120 μm in size. On CL images zircons are bright and have an oscillatory zoning (Fig. 4, a). Some zircon grains contain less bright oval cores. The sharply predominating second-type zircons consist of subidiomorphic, sometimes xenomorphic grains, usually with uneven edges, as well as idiomorphic bipyramidal prismatic, isometric and slightly elongated (C_{el} = 1–2.5), semi-transparent, pale-brown crystals 40–200 μm in size. It is observable on CL images (Fig. 4, a) that the second-type zircons are characterized by a very weak homogeneous glow. In addition, they contain a large number of black inclusions. Some zircon grains have a

Table 2. The trace-element composition of granitoids of the Shchuchinskaya zone

Component	Leucoplagiogranites of the Rechnoy paleovolcano				Plagiogranites of the Nganotsky-2 pluton			
	S220	S218	S221	1171	S204	S201	S200	S210
Li	1.97	2.26	0.45	0.56	1.93	2.97	4.23	3.54
Sc	11.35	9.80	1.76	7.49	17.23	6.97	14.84	12.93
Ti	1869.10	1731.95	654.30	857.50	2544.75	2507.11	2333.72	2770.61
V	32.09	29.21	3.35	7.52	84.61	45.90	47.42	62.09
Cr	22.00	27.93	17.79	2.74	18.73	4.71	22.06	85.27
Mn	269.00	238.87	41.36	130.09	646.43	517.50	471.17	324.58
Co	1.81	2.37	0.43	1.17	7.00	3.70	6.57	4.59
Ni	1.69	1.96	2.39	1.30	1.50	2.06	4.68	4.48
Cu	3.49	0.22	5.22	3.67	3.17	7.63	170.84	–
Zn	33.19	23.59	1.99	8.58	31.78	40.08	24.83	12.08
Rb	3.77	5.48	18.52	4.79	12.57	4.83	3.93	3.71
Sr	109.20	111.12	6.91	46.76	226.97	156.71	219.70	145.24
Y	29.95	33.46	18.67	40.45	25.42	26.31	27.61	28.33
Zr	67.66	71.13	124.47	183.49	39.18	66.01	60.21	48.31
Nb	2.82	2.47	3.31	2.78	1.02	0.13	1.00	1.16
Mo	4.00	3.12	2.94	0.23	3.14	1.19	2.56	8.58
Ag	0.19	0.21	0.46	0.18	0.10	0.22	0.24	0.09
Cs	0.13	0.11	0.07	0.00	0.14	0.07	0.09	0.04
Ba	48.48	63.89	39.03	7.55	143.48	–	97.08	39.96
La	7.92	9.57	6.54	10.23	9.97	5.29	6.34	4.22
Ce	25.34	24.84	3.65	29.57	27.93	15.36	19.17	12.47
Pr	3.79	3.47	2.99	4.48	4.05	2.58	3.05	2.27
Nd	17.12	16.12	13.04	20.27	18.67	13.00	15.57	12.03
Sm	4.35	4.09	3.15	5.38	4.77	3.78	4.58	3.72
Eu	0.87	0.91	0.16	0.78	1.13	1.11	1.21	0.80
Gd	5.12	5.07	3.22	5.87	5.23	4.10	5.30	4.08
Tb	0.79	0.84	0.57	1.11	0.76	0.75	0.79	0.66
Dy	5.52	6.05	3.70	7.18	4.96	4.74	5.35	4.43
Ho	1.23	1.36	0.80	1.57	1.04	1.05	1.18	0.96
Er	3.81	4.25	2.57	4.89	3.20	3.16	3.50	2.79
Tm	0.59	0.65	0.40	0.73	0.45	0.48	0.52	0.43
Yb	4.55	5.01	2.80	5.10	3.43	3.27	3.73	2.69
Lu	0.63	0.68	0.43	0.78	0.45	0.49	0.53	0.40
Hf	2.12	2.21	5.80	4.07	1.52	2.49	1.95	1.69
Ta	0.15	0.14	0.52	0.25	0.03	0.08	0.02	0.03
Pb	3.30	2.17	0.25	–	2.18	6.74	2.63	1.58
Th	1.15	0.99	1.07	1.96	1.12	0.82	0.92	1.00

The contents of trace elements were determined by inductively coupled plasma mass spectrometry in the Laboratory for Analysis of Mineral Substance (IGEM RAS).

spotted fragmentary mosaic zoning; other zircons have oscillatory zoning (Fig. 4, a).

A wide range of $^{206}Pb/^{238}U$ age datings (985–438 Ma) were obtained for 10 zircon grains from Sample no. S221 (Table 3). The concordant age 456 ± 6 Ma (2σ], MSWD = 0.33) was calculated for nine zircon grains (Fig. 4, b) with age datings ranging from 478 to 438 Ma. This age corresponds to the terminal Darrivillian Age (Middle Ordovician)–Katian Age (Late Ordovician). This association of grains contain zircons of both types

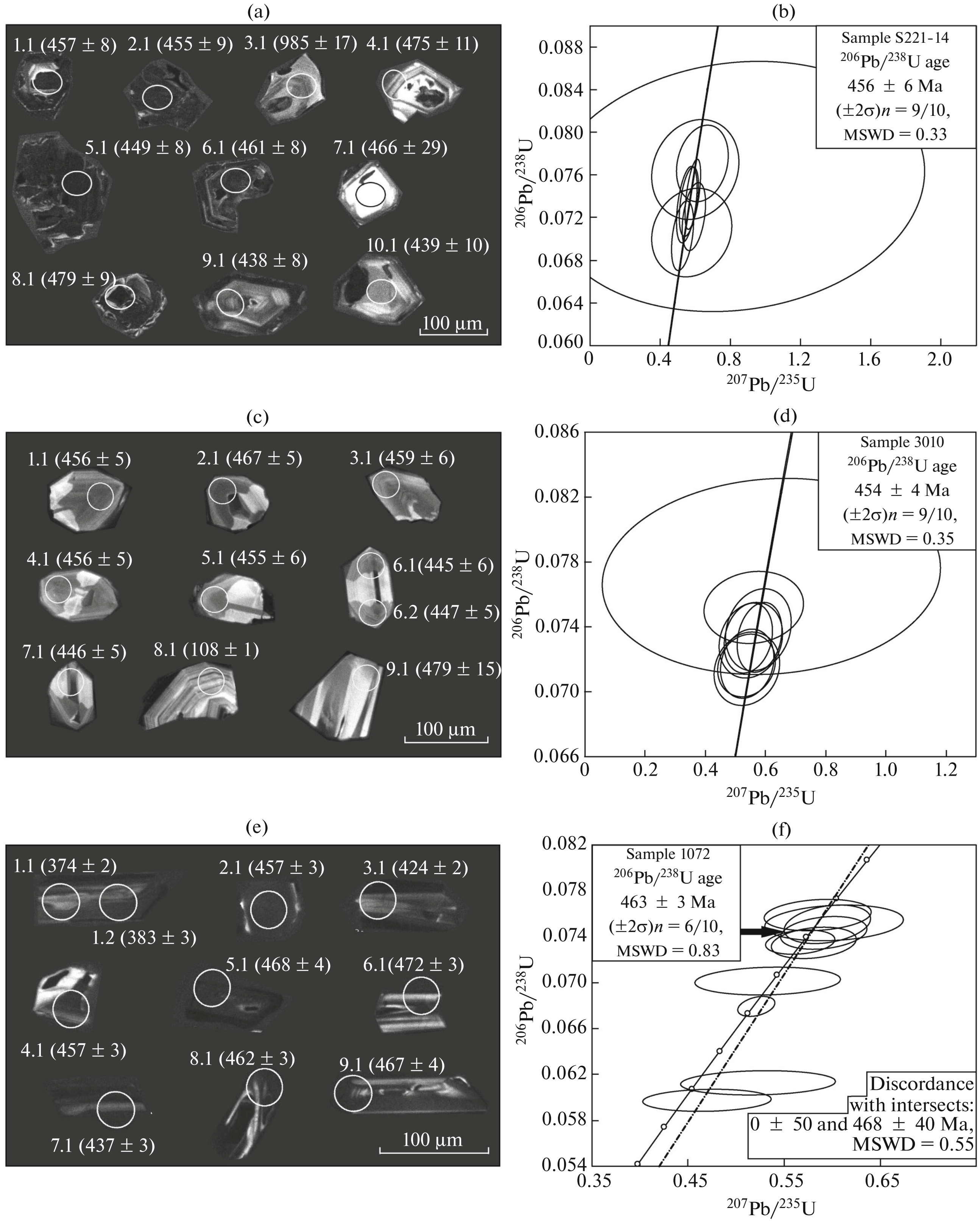

Fig. 4. CL images of zircons with the numbers of the dated grains and their ages (Ma) and concordia age diagrams for zircons from granitoids of the Rechnoy (a, b) and Yalya-Pe (c, d) paleovolcanoes, and the Nganotsky-1 pluton (d, e) respectively. Error ellipses are at 2σ level. The results of the SIMS U–Pb zircon dating are given in Table 3.

Table 3. Results of U–Th–Pb isotope analysis of zircon grains from granitoids of the Rechnoy and Yalya-Pe paleovolcanoes (sample no. S221 and 3010, respectively) and the Nganotsky-1 pluton (Sample no. 1072)

Analysis no.	$^{206}Pb_c$, %	Content, ppm			$^{232}Th/^{238}U$	Isotope ratios, ±%(1σ)						Rho	Age, Ma, ±1σ				*D*, %
		U	Th	$^{206}Pb^*$		$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$			$^{206}Pb/^{238}U$		$^{207}Pb/^{206}Pb$		
S221_9.1	0.47	461	113	28.0	0.25	0.0543	±4.5	0.527	±4.9	0.0703	±1.9	0.39	438	±8	384	±100	–12
S221_10.1	2.19	138	82	8.6	0.61	0.0596	±16.0	0.580	±16.0	0.0706	±2.4	0.15	439	±10	590	±340	34
S221_5.1	1.54	1398	265	88.0	0.20	0.0597	±4.2	0.593	±4.6	0.0721	±1.8	0.39	449	±8	592	±91	32
S221_2.1	0.56	808	125	51.1	0.16	0.0548	±3.8	0.553	±4.3	0.0732	±2.0	0.46	455	±9	404	±85	–11
S221_1.1	0.57	713	144	45.3	0.21	0.0556	±3.5	0.564	±3.9	0.0735	±1.8	0.46	457	±8	437	±78	–4
S221_6.1	0.14	881	185	56.2	0.22	0.0575	±2.5	0.588	±3.1	0.0742	±1.8	0.58	461	±8	511	±55	11
S221_7.1	9.32	17	7	1.2	0.41	0.0800	±52.0	0.830	±53.0	0.0749	±6.4	0.12	466	±29	1200	±1000	157
S221_4.1	1.92	121	66	8.1	0.56	0.0572	±17.0	0.600	±17.0	0.0765	±2.5	0.15	475	±11	498	±370	5
S221_8.1	3.32	506	212	34.7	0.43	0.0603	±9.3	0.641	±9.5	0.0771	±1.9	0.20	479	±9	614	±200	28
S221_3.1	0.41	250	86	35.7	0.36	0.0728	±4.9	1.657	±5.2	0.1651	±1.8	0.35	985	±17	1008	±99	2
3010_8.1	0.40	449	236	6.6	0.54	0.0462	±5.7	0.108	±5.7	0.0169	±0.9	0.16	108	±1	8	±132	–93
3010_6.1	0.81	108	78	6.7	0.75	0.0547	±8.2	0.539	±8.3	0.0714	±1.3	0.16	445	±6	400	±174	–10
3010_7.1	0.74	116	101	7.2	0.90	0.0544	±7.2	0.537	±7.3	0.0716	±1.1	0.15	446	±5	388	±154	–13
3010_6.2	0.64	110	91	6.8	0.85	0.0546	±6.6	0.540	±6.7	0.0717	±1.2	0.18	447	±5	396	±141	–11
3010_5.1	0.76	72	28	4.6	0.40	0.0546	±7.7	0.551	±7.8	0.0732	±1.3	0.17	455	±6	396	±164	–13
3010_1.1	0.47	79	33	5.0	0.44	0.0539	±5.8	0.544	±6.0	0.0733	±1.2	0.20	456	±5	367	±126	–20
3010_4.1	0.43	87	49	5.5	0.58	0.0573	±5.1	0.580	±5.2	0.0733	±1.2	0.22	456	±5	503	±108	10
3010_3.1	0.64	58	27	3.7	0.47	0.0566	±7.6	0.577	±7.7	0.0738	±1.4	0.18	459	±6	476	±160	4
3010_2.1	1.44	139	90	9.1	0.67	0.0542	±12.0	0.562	±12.0	0.0752	±1.2	0.10	467	±5	379	±250	–19
3010_9.1	7.89	41	17	2.9	0.43	0.0590	±37.0	0.620	±37.0	0.0771	±3.2	0.09	479	±15	567	±650	18
1072_1.1	3.33	763	578	40.5	0.78	0.0570	±5.8	0.470	±5.8	0.0598	±0.6	0.11	374	±2	492	±130	32
1072_1.2	3.86	745	874	40.8	1.21	0.0619	±6.3	0.523	±6.3	0.0613	±0.7	0.12	383	±3	670	±130	75
1072_3.1	0.06	880	1147	51.4	1.35	0.0556	±1.4	0.521	±1.5	0.0679	±0.5	0.35	424	±2	437	±30	3
1072_7.1	1.38	874	786	53.5	0.93	0.0551	±5.7	0.533	±5.8	0.0702	±0.7	0.12	437	±3	417	±130	–5
1072_4.1	0.29	337	202	21.4	0.62	0.0574	±3.0	0.581	±3.1	0.0735	±0.8	0.25	457	±3	505	±66	11
1072_2.1	0.22	381	288	24.1	0.78	0.0559	±2.5	0.567	±2.6	0.0735	±0.6	0.23	457	±3	450	±56	–2
1072_8.1	0.29	584	260	37.4	0.46	0.0576	±3.0	0.591	±3.1	0.0743	±0.8	0.25	462	±3	516	±65	12
1072_9.1	0.57	494	440	32.1	0.92	0.0575	±2.9	0.595	±3.1	0.0751	±0.9	0.30	467	±4	511	±65	10
1072_5.1	0.92	513	797	33.4	1.61	0.0580	±4.8	0.602	±4.9	0.0752	±0.9	0.18	468	±4	531	±110	14
1072_6.1	0.53	394	261	25.9	0.68	0.0559	±3.8	0.585	±3.9	0.0759	±0.7	0.19	472	±3	448	±84	–5

The standard calibration errors are 0.57% (Sample no. S221) and 0.35% (samples nos. 3010 and 1072); $^{206}Pb_c$ and $^{206}Pb^*$ are the contents of common and radiogenic lead, respectively; The isotope ratios are corrected using the measured ^{204}Pb; *D*, discordance: $D = 100$ [age ($^{207}Pb/^{206}Pb$)/age($^{206}Pb/^{238}U$) – 1]; Rho is the correlation coefficient between the determination errors of the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ isotope ratios.

described above (Fig. 4, a). One grain with an age of 985 ± 17 Ma (1σ) was characterized by a moderately bright glow and indistinct oscillatory zoning.

Zircons from plagiogranites of the Yalya-Pe intrusion (Sample No. 3010) consist of idiomorphic transparent pale-yellow short (C_{el} = 2–2.5) bipyramidal-prismatic crystals 60–125 μm in size. Cathodoluminescent images of zircons (Fig. 4, c) show contrast sectorial zoning in combination with oscillatory zoning; there are rare zircon grains only with oscillatory zonation. The U–Pb isotope dating of ten zircon grains from Sample no. 3010 yielded a scatter of the age data from 479 to 108 Ma (Table 3). The concordant age (454 ± 4 Ma; 2σ, MSWD = 0.35) was obtained for nine zircon grains (Fig. 4, d), the $^{206}Pb/^{238}U$ age of which varies from 479 to 445 Ma. This age corresponds to the Sandbian–Katian boundary (Late Ordovician). As seen on CL images, this association of zircons is characterized by sectorial and sectorial–oscillatory zoning (Fig. 4, c). One grain with thin oscillatory zoning has an age of 108 ± 1 Ma (1σ).

Granitoids of Yalya-Pe paleovolcano were formed 454 ± 4 Ma ago, at the Sandbian–Katian boundary (Late Ordovician). A young grain zircon grain of Albian age was crystallized as a result of superimposed dynamometamorphic processes that intensively developed in granitoids of the Yalya-Pe intrusion or due to mechanical contamination during sample preparation.

Zircons from quartz diorites of the Nganotsky-1 pluton (Sample no. 1072) consist of transparent pale-yellow well-faceted bipyramidal–prismatic elongated (C_{el} = 2.4) crystals 50–130 μm in size. Zircon crystals contain small black ore mineral inclusions. As seen on CL images, (Fig. 4, d), zircons are characterized by a weak homogenous dark-gray glow; rare grains yield a more intensive glow. The oscillatory zoning is weakly manifested and shaded, in some places, by spotted zoning. The U–Pb isotope dating of ten zircon grains from Sample no. 1072 yielded a wide scatter of age data from 472 to 374 Ma (Table 3). The discordia line is constructed for all ten points (Fig. 4, e) with a lower intersect of 0 ± 50 Ma and an upper intersect of 468 ± 40 Ma (MSWD = 0.55). As seen on CL images (Fig. 4, d), young zircons with most discordant ages of 374 ± 2 and 383 ± 3 Ma have a spotted zoning or have no zoning. The rest of the zircons (discordance from –5 to 14) have weakly manifested oscillatory zonation; sometimes, there are elements of spotted zoning.

At the upper concordia–discordia intersection, six of ten analytical points form a group with age datings ranging from 472 to 457 Ma (Fig. 4, e). For this group of points, a concordant age 463 ± 3 Ma (2σ, MSWD = 0.83) was calculated. The consistency of the concordant age with that of the upper concordia–discordia intersect indicates that the age of 463 ± 3 Ma corresponds with a high degree of probability to the melt crystallization time: the Darrivilian–Sandbian boundary (Middle Ordovician).

It should be noted that very similar isotope-age data have been obtained for zircons from hornblende gneissic plagiogranites that are common in the field of ophiolite metagabbroids of the Malyko complex (the western part of the Shchuchinskaya structure) (Andreichev et al., 2012). Based on the U–Pb (SIMS) zircon isotope data, Andreichev et al. calculated a concordant age of 451 ± 14 Ma (2σ, MSWD = 0.21) for five single zircon grains.

CONCLUSIONS

(1) Granitoids of the Rechnoy and Yalya-Pe paleovolcanoes, attributed to the Khoimpe complex, were formed in the young island-arc setting, as indicated by their spatial and cross-cutting relationships with the early island arc volcanics, as well as the copper-pyrite ore mineralization of the Rechnoy paleovolcano. The geochemical features of the studied granitoids are also characteristic of rocks formed in the suprasubduction settings.

(2) The granitoid intrusives of the Rechnoy and Yalya-Pe paleovolcanoes, as well as the Nganotsky-1 pluton were formed at the Middle–Late Ordovician boundary (456 ± 6, 454 ± 4, and 463 ± 3 Ma, respectively), but not in the Late Silurian and the Early–Middle Devonian, as was previously thought. According to this, it would be desirable to ascribe all the investigated granitoid bodies to the Khoimpe complex, whose specified age corresponds to the Middle–Late Ordovician.

(3) The studied granitoid complexes cut through island arc volcanics, which are usually attributed to the Upper Ordovician–Lower Silurian Syaday Formation and Silurian Yanganape formation, which are similar in composition. The Middle–Late Ordovician age datings obtained for granitoids enable us to estimate the upper stratigraphic boundary of the formation of the host volcanics as Middle–Upper Ordovician very reliably. This is close to the stratigraphic level of the Syaday Formation.

ACKNOWLEDGMENTS

We are grateful to the employees of the Center of Isotopic Research (VSEGEI) P.A. Lvov and E.N. Lepekhina for the U–Pb zircon isotope dating that was performed within the framework of GMM-200, sheet Q42-III), Ya.V. Bychkova for analysis of trace elements (ICP-MS), as well as S.T. Neverov, T.V. Kabanova, and N.P. Gorbunova for determination of petrogenic elements.

Thin-sections were made and the chemical analyses of rocks were performed with the support of a My First Grant of the Russian Foundation for Basic Research (project no. 16-35-00552). The analysis of trace elements was supported by the Program of Presidium of the RAS Arktika II 3P.

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Translated by D. Voroshchuk