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Geochronology (SHRIMP II) of Zircons from Archean Stratotectonic Associations of Karelian Greenstone Belts: Significance for Stratigraphic and Geodynamic Reconstructions

V. N. Kozhevnikov[a], N. G. Berezhnaya[b], S. L. Presnyakov[b], E. N. Lepekhina[b],
A. V. Antonov[b], and S. A. Sergeev[b]

[a] *Institute of Geology, Karelian Scientific Center, Russian Academy of Sciences, Petrozavodsk, Russia*
[b] *A. P. Karpinsky All-Russia Research Institute of Geology, St. Petersburg, Russia*

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Abstract—Individual grains of zircon from the Archean Kostomuksha, North Karelian and Matkalakhta greenstone belts, which are situated respectively in western, northern and eastern Karelia, are studied using the ion microprobe SHRIMP II. As a result, the oldest ^{207}Pb/^{206}Pb ages of 3151 ± 4.6 and 3329 ± 16 Ma are first determined for detrital zircons from northern and eastern Karelia. The ^{207}Pb/^{206}Pb ages estimated for two subsequent metamorphic events of Archean Eon in eastern Karelia correspond to 3.25 and 3.17–3.10 Ga. The age value of 2711 ± 9.6 Ma is determined for silicic volcano-plutonic complex and quartz stockwork in northern Karelia and the date 2821 ± 15 Ma for magmatic rocks of eastern Karelia. Silicic volcanics from an oceanic plateau section in the Kostomuksha belt are dated at 2791.7 ± 6.1 Ma for the first time in the Archean of Fennoscandia. The oldest detrital zircons from siliciclastic metasediments determine the stabilization time of Archean continental nuclei in East Fennoscandia. The younger generation of greenstone belts is exemplified in the Karelian craton by the Matkalakhta and Kostomuksha structures comprising rock associations less than 2.82 Ga old, mafic rocks of the Kontokki Group included. Geological history of these belts corresponds to geodynamic mesocycle 90–110 Ma long and to the Archean global epoch of metallogeny, which was responsible for origin of most valuable deposits of base and precious metals.

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Key words: Archean, greenstone belt, isotopic age, collaged succession, geodynamic settings, detrital zircon, craton.

INTRODUCTION

Archean complexes of Karelian craton, the largest structural element of the southeastern Fennoscandian Shield (Fig. 1), are represented by age-variable associations of sedimentary-volcanogenic rocks and granitoids. The oldest (>3.0 Ga) Vodlozero Complex is an analog of "ancient gneiss complexes" characteristic of many Early Precambrian nuclei of cratons. Original sedimentary or volcanogenic structures of its rocks are deleted or blurred considerably by intense structural and metamorphic transformations. In four younger (<3.0 Ga) granite-greenstone associations of Archean greenstone belts (GSB), initial sedimentary or volcanogenic origin of rocks can be reconstructed with proper confidence.

Archean sedimentary and volcanogenic rocks attributed to the Lopian Complex in regional stratigraphic schemes are observable now within elongated structures of intricate configuration, which are traced down to the depth 5 to 7 km by geophysical methods. In the Precambrian stratigraphic scale of 1990 accepted in the USSR (Semikhatov et al., 1991), the Lopian (Archean) succession of the Hautavaara and Kostomuksha structures is divided into three the Hautavaara, Kontokki, and Gimoly groups. After comprehensive study, it has been shown that lateral variations of Lopian successions are extremely diverse not only over the craton, but also within the individual GSB and structures, and creation of a uniform stratigraphic scheme for the entire region is impossible therefore. The Kostomuksha, Hautavaara and Pebozero type sections (*Precambrian Stratigraphy…*, 1984) have been referred to in a very general manner by combining structural elements into a particular GSB, because they do not exemplify all the section varieties. Attempts of regional correlation are full of reservations of the following type: "… a uniform reference horizon is unavailable;" "… as is postulated, the basalt-komatiitic volcanism commenced simultaneously over the entire territory," "… the Lopian section base is unknown being resorbed by granitoids," etc. (*Greenstone Belts…*, 1988; *Evolution of Metallogeny…*, 1993). In fact, correlations and reservations of this kind represent a tribute to the traditional standpoint that processes of a uniform type only (e.g., intracra-

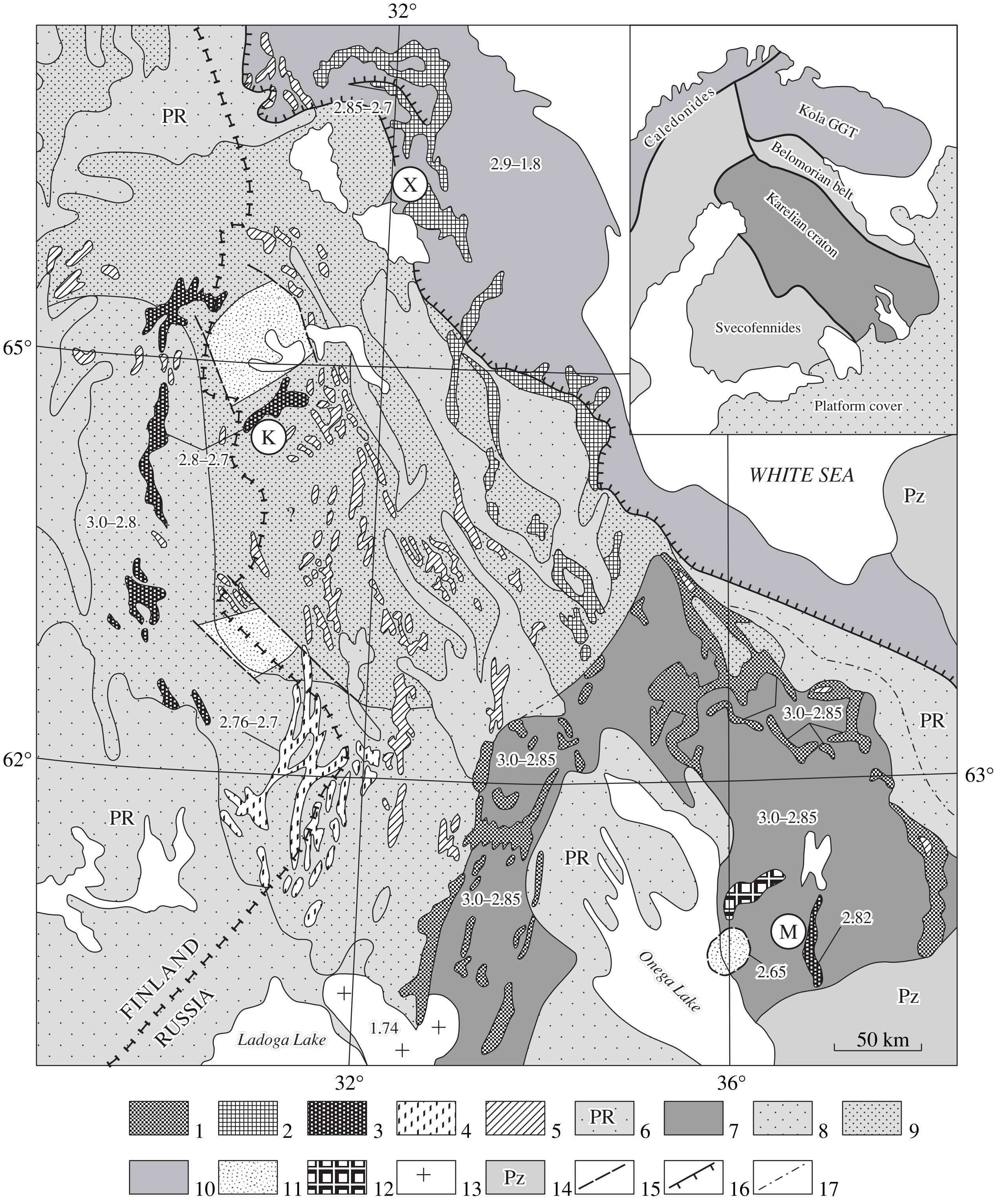

Fig. 1. Schematic geological structure of the Karelian craton (modified after Rybakov and Kulikov, 1985; Chekulaev, 1996; Kozhevnikov, 2000): (1–5) Archean greenstone belts of >3.0–2.9 (1), 2.9–2.8 (2), 2.8–2.7, (3) <2.75 Ga (4) and of uncertain age (5) with Khizovaara structure (X), Kostomuksha (K) and Matkalahta (M) GSB; (6) Paleoproterozoic supracrustal rocks; (7–9) Archean crust of 3.5–2.85 (7) and 3.0–2.8 Ga (8) or of uncertain age (9); (10) Belomorian mobile belt; (11) high-grade metamorphic complexes; (12) Burakovo massif; (13) Salma massif of rapakivi; (14) Paleozoic platform cover; (15) thrust and strike-slip faults; (16) deformation zone between the Belomorian belt and Karelian craton; (17) presumable boundary of the Vodlozero block; numerals on the scheme denote ages (Ga) of relevant complexes.

tonic rifting, geosynclinal regime) dominated during the GSB formation.

Multidisciplinary study of the GSBs by traditional and modern methods showed in the last 10–15 years, that many belts different in age and distinguished in the Karelian craton can be regarded as tectonic collages. Their evolution is divisible into three the initial, lateral-accretion and terminal collision stages (Kozhevnikov, 2000).

At the initial stage, typomorphic rock complexes or lithostratigraphic units have been formed either concurrently or successively in different paleogeographic and geodynamic settings. Geological, lithological, volcanological, petrochemical, isotopic-geochemical and structural data suggest that these units accumulated in very variable settings characteristic of the active ocean–continent transition zones and intraplate (oceanic or continental) environments (Kozhevnikov, 1992, 2000; Lobach-Zhuchenko et al., 1997; Svetova and Svetov, 2001; Svetov and Svetova, 2004; Svetov, 2005; Slabunov, 2001, 2005; Shchipansky et al., 1998, 1999; *Geological Development…*, 1993; Luukkonen, 1992; Puchtel et al., 1998). Polymodal graywackes, the mixed products of destructed volcanic arcs, mafic allochthons and continental granitoids, accumulated at the stage of lateral accretion, plate convergence, crustal shortening and thickening (Kozhevnikov, 2000; Svetov, 2002; Svetov and Svetova, 2004). In some GSBs, e.g., in the Hattu belt of Finland, there is distinguished the terminal tectonic collision stage interpreted as the "arc–craton" interaction (Sorjönen-Ward et al., 1997). Shear deformations related to this stage controlled development of narrow structures filled with coarse-grained deposits, which resemble the pull-apart basins with sediments of the Timiskaming type indicative of collision environments at the terminal stage of the GSB evolution in the Superior craton (Williams et al., 1992). In the Karelian craton, regional associations of late discordant basins separate mafic oceanic complexes from the Late Archean silicic associations of continental margins (Kozhevnikov, 2003).

By the end of the Archean, the GSBs of the Karelian craton represented suture zones composed of lithotectonic units formed in different settings at particular stages of Archean evolution. Suture of this kind represent tectonic collages with juxtaposed allochthonous and autochthonous lithotectonic units determined in this work as "stratotectonic associations" (STA). The STA is close in sense to English term "tectonic assemblage" designating "… a packet of stratified volcanic and sedimentary sequences formed during a certain time span in a common setting of sedimentation and volcanism" (Williamson et al., 1992, p. 1256). The STA notion comprising autochthonous sequences besides the others is distinct from the term "tectonostratigraphic subdivision (terrane)" that is widespread in Russian publications and means the allochthonous position of a given unit. As a descriptive term, the STA is close to units of stratigraphic nomenclature, e.g., to a group or formation, and reflects simultaneously the lithostratigraphic character of boundaries frequently separating rock associations. In general, certain STAs can be bounded by faults, discordant and intrusive boundaries (Thurston and Chivers, 1990). Many examples of collaged Archean GSB have been described in the Karelian craton and Belomorian mobile belt (Kozhevnikov, 1992, 2000; Lobach-Zhuchenko et al., 1997; Puchtel et al., 1996, 1998, 1999; Slabunov, 2001, 2005; Svetov, 2002, 2005; Luukkonen, 1988).

According to predominantly plate-convergence regimes of Archean endo- and exogenic processes, which are recorded in the GSB sections and structures of the Karelian craton, the belts can be regarded as accretionary orogens (Kozhevnikov, 2000). Tectonic collages of the accretionary stage and subsequent formation of lenticular folds (Miller, 1988) and thrust sheets (Kozhevnikov, 1992, 2000) at the collision stage are responsible for a very complicated structure of the GSBs. The Late Archean GSBs different in age originated with time lags about 100 m.y. long, but their development scenarios were likely similar, and it is very important therefore to date precisely the main STAs from the GSB sections.

The main objective of this work was to estimate the STA ages in three greenstone structures of western (Kostomuksha GSB), northern (Khizovaara structure) and eastern (Matkalahta GSB) Karelia. In the Kostomuksha GSB, our attention was concentrated on dating the silicic volcanics of a mafic plateau, since earlier only the Sm–Nd age was determined for this structure (Lobach-Zhuchenko et al., 2000; Puchtel et al., 1998). Detrital zircons from quartz arenites of the Khizovaara structure and Matkalahta GSB were dated to determine types and ages of provenances of enclosing clastic quartzites. Rocks of the Matkalahta GSB, which was provisionally attributed to an early generation, have never been dated before by isotopic methods. Consequently, it was necessary to determine age of this belt situated in the ancient Vodlozero block (Fig. 1).

The U–Pb dating of zircons is performed on ion microprobe SHRIMP-II at the VSEGEI Center of Isotopic Research in accord with procedure described by Williamson (1998). Analytical data are processed using the program SQUID (Ludwig, 2000). Uncertainties of calculated ratios and ages are quoted here at the 1σ level. The concordant and concordia-intercept ages are estimated with uncertainty 2σ. Diagrams with concordia are plotted using the program ISOPLOT/EX (Ludwig, 1999).

U–Pb AGE OF MAFIC PLATEAU IN THE KOSTOMUKSHA GSB

Structure of the Kostomuksha GSB. The belt includes the synonymous structure, an elongated synform about 200 km^2 in area, that is composed of volca-

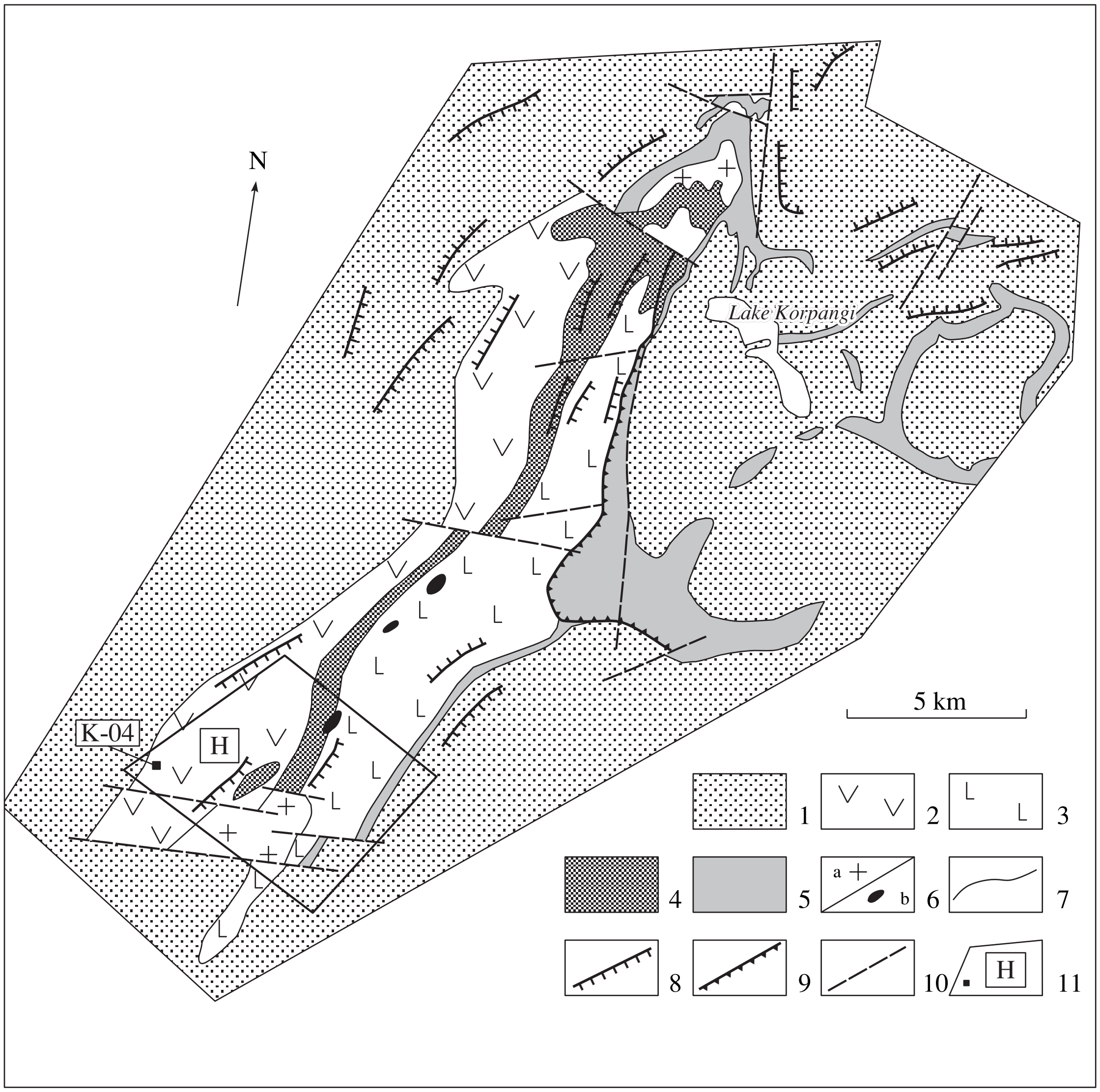

Fig. 2. Schematic geology of the Kostomuksha GSB (simplified after Kozhevnikov, 1982, 2000): (1) flanking TTG complexes; (2) mafic STA, Niemijarvi Formation; (3) komatiite-basaltic STA, Ruvinvaara Formation; (4) Shurlovaara Formation of silicic volcanic to subvolcanic and sedimentary rocks; (5) Gimoly Group of polymodal turbidites, silicic tuffs and BIF with komatiitic horizons; (6) inner granitoids of plagioclase-microcline to subalkaline (a) and sanukitoid (b) types; (7) STA boundaries; (8) generalized rock attitude; (9) thrust-fault plane of ore deposit; (10) faults; (11) Niemijarvi area with sampling site K-04.

nics of the so-called "western reach" and of deposits of the Gimoly Group. A vast area adjacent from the east is composed of granitoids with preserved relicts of supracrustal rocks (Fig. 2).

Basic volcanics of the western reach have been attributed initially to the Sumian Complex discordantly overlying rocks of the Gimoly Group and complicating the belt structure (Kratz, 1963; Chernov, 1964; Lazarev, 1971). The three-member structure of supracrustal complex that has been established later on is represented by the Njukozero siliciclastic sequence below the Kontokki Group that is discordantly overlain by sediments of the Gimoly Group with embedded Kostomuksha banded iron formation (BIF). Based on idea of the west–eastward accretion of the Archean succession (Gor'kovets et al., 1981), the Kontokki Group was divided into the lower Niemijarvi and upper Ruvinvaara formations separated by silicic volcanics and sediments of the Shurlovaara Formation (Fig. 3).

After careful mapping of the western reach and comparative analysis of its section, Kozhevnikov (1982) concluded that complex of basic volcanics and komatiites of the reach discordantly overlies rocks of the Shurlovaara Formation (Fig. 3). This formation, the entire section of the Kostomuksha BIF, and sections in the northern structural closure, the Korpangi deposit included, and in narrow nonlinear structures located eastward have been considered as stratigraphic equivalents. Formation of mafic to ultramafic volcanics of the western reach was interpreted in terms of Archean his-

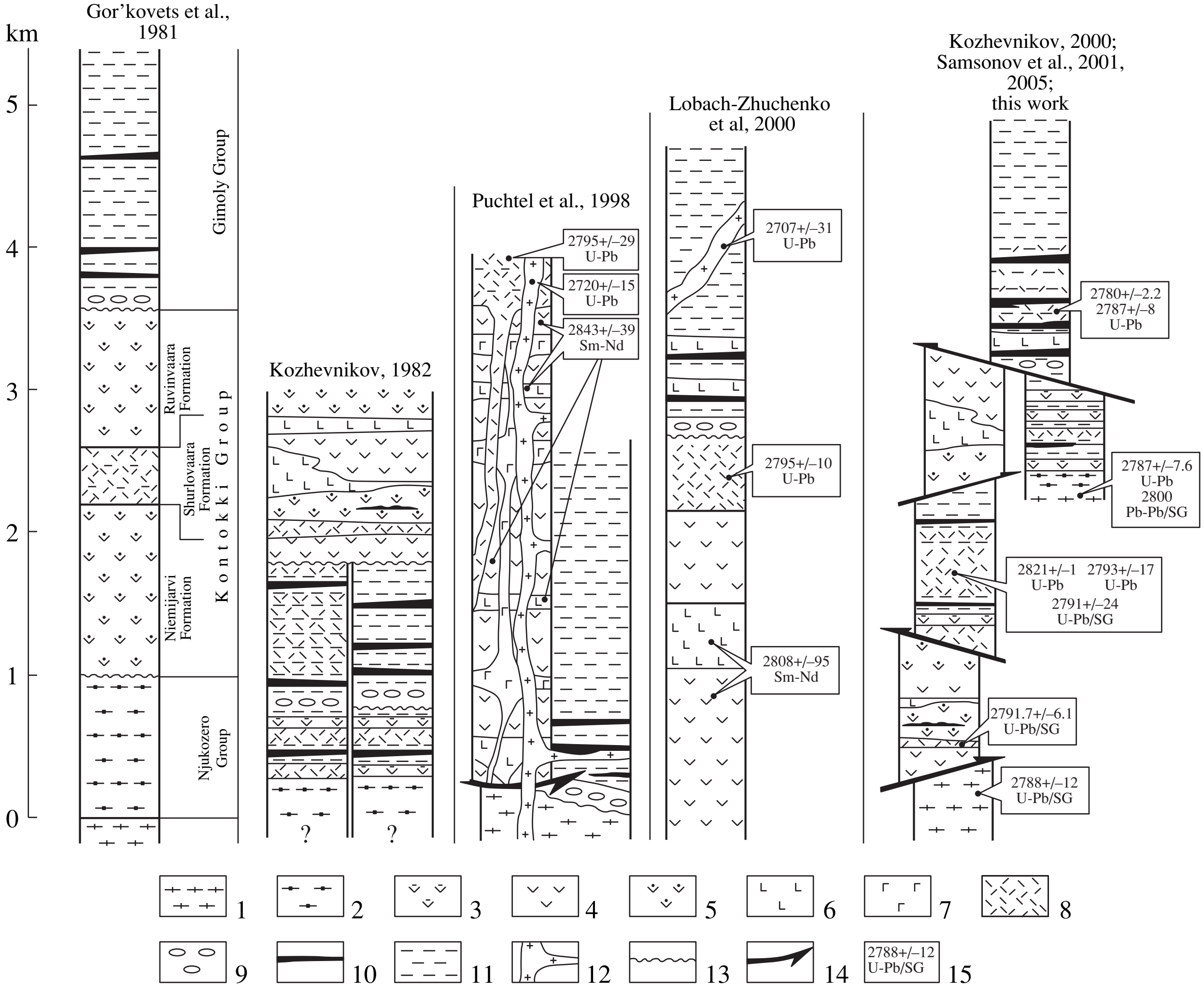

Fig. 3. Lithostratigraphy of the Kostomuksha greenstone belt in different interpretations: (1) flanking TTG complex; (2) Njukozero Group of mica-quartz crystalline schists; (3) feldspar-hornblende (± biotite and epidote) crystalline schists; (4) pillow basalt; (5) massive basalt; (6) komatiite; (7) gabbro sills; (8) silicic volcanics; (9) polymictic conglomerate; (10) BIF, schists; (11) polymodal graywackes with admixed dacitic tuff; (12) granite-porphyry; (13) discordance above weathering crust; (14) thrust faults separating allochthonous STAs; (15) concordant isotopic age (SG—ditto for separate grains).

tory. Two different structural patterns were distinguished in the region: linear within the western reach of volcanics and nonlinear within distribution areas of the Gimoly Group sediments to the north and east of the Kostomuksha settlement (Kozhevnikov, 1982). Afterward, this was interpreted as a consequence of tectonic imbrication of domains with supracrustal complexes formed originally in different tectonic settings, and the Kostomuksha GSB was considered as an "imbricated morphotype of Lopian structures" (Kozhevnikov, 1992).

In the 1980s, the Precambrian succession of the Kostomuksha GSB was ranked as the Upper Archean type of the Baltic Shield, and idea of successive west–eastward accretion was retained in monograph summarizing data on the succession (*Reference Sections…*, 1992).

Scientists from the Institute of Precambrian Geology and Geochronology studied petrology, isotopic geochronology (Sergeev et al., 1990; *Greenstone Belts…*, 1988), lithology, geochemistry (Mil'kevich and Myskova, 1998), and structural geology (Miller, 1988) of the Kostomuksha GSB. They determined the U–Pb isochron age of 2801 ± 7 Ma for zircons from the Shurlovaara Formation and formulated the idea that some komatiites and basalts of the Kontokki Group were contaminated by sialic crustal material. The suggested models based on geochemistry of trace elements argued for the bimodal composition (basalts + silicic volcanics) of provenances for clastic material of the Gimoly Group, while possible presence there of ultramafic rocks and granitoids was discarded. The current understanding of the Kostomuksha GSB stratigraphy appeared in the course of geochemical and geochronological research of rocks from the Kontokki Group.

In the suggested scheme, the mafic complex of the group includes the Niemijarvi and Ruvinvaara formations concurrent in age (Sm–Nd isochron date of 2808 ± 95 Ma) and overlain by silicic volcanics of the Shurlovaara Formation, which is 2795 ± 10 Ma old (U–Pb method, upper intercept; Lobach-Zhuchenko et al., 2000; Fig. 3). Geochemical similarity between komatiites of the Ruvinvaara Formation and ultramafic schists in the Gimoly Group lower part led to the conclusion that ultramafic volcanism was active during accumulation of the group sediments. Based on the Nd isotopic systematics, Lobach-Zhuchenko and her colleagues showed that some tholeiitic basalts and komatiites of the Niemijarvi and Ruvinvaara formations are contaminated by ancient sialic material. They considered these facts as arguments in favor of intracratonic rifting responsible for origin of the Kostomuksha GSB (Lobach-Zhuchenko et al., 2000).

Isotopic-geochronological study of basalts, komatiites, dacites, and granitoids of the Kostomuksha GSB was in progress during the last decade. Samsonov (2004), who collaborated with scientists from several institutions of Russian Academy of Sciences, determined age of silicic volcanics from the Shurlovaara Formation (2793 ± 17 Ma, U–Pb method, upper intercept, and 2791 ± 24 Ma, individual zircon grains) and of granitoids in the eastern (2782 ± 5 Ma, individual zircon grains) and western (2788 ± 12 Ma, individual zircon grains) flanks of the structure. In the other work (Samsonov et al., 1996), there were reported isotopic dates for silicic volcanics of the Gimoly Group near the Kostomuksha are deposits (2787 ± 8 Ma, individual zircon grains) and for granitoids, which intruded volcanic rocks of the western reach (2720 ± 15 Ma, U–Pb method, upper intercept). The Sm–Nd and Pb–Pb isochron ages of 2843 ± 39 and 2813 ± 78 Ma have been obtained for rocks of two mafic formations. The established depletion in LREE and positive Nb anomaly (Nb_{PM}/Th_{PM} = 1.5–2.1 and Nb_{PM}/La_{PM} = 1.0–1.5) imply, along with Nd isotopic parameters (εNd(T) from +2.8 to +3.4), that the studied rocks originated within an ancient oceanic plateau. These rocks are cardinally different from mafic and ultramafic rocks contaminated by material of continental crust, as typical of the latter are the negative Nb anomaly (Nb_{PM}/Th_{PM}, La_{PM} <1), enrichment in LREE, and negative εNd values. In contrast, silicic volcanics of the Shurlovaara Formation originated from a magma source that resided in continental crust according to geochemical criteria. All the data considered above substantiate the allochthonous position of the Kostomuksha GSB (Fig. 3) and a model of an oceanic terrane obduction (Kontokki Group) onto shelf sediments of the Gimoly Group deposited within a continental margin (Puchtel et al., 1998)

At present, age relations between the Gimoly and Kontokki groups and between the Niemijarvi, Ruvinvaara, and Shurlovaara formations represent main problems to be solved in the region. In contrast to our opinion, other researchers who studied the region consider volcanics of the Niemijarvi Formation as the oldest sequence in the Kostomuksha GSB, but they have never been subjected to the U–Pb zircon dating. That is why we studied zircons from silicic volcanics of that formation.

Isotopic-geochronological data. Rocks of the Niemijarvi, Shurlovaara and Ruvinvaara formation, the Njukozero sequence, and granitoids of eastern and western flanks are exposed within the Niemijarvi area, where southern termination of the Kostomuksha structure is divided in two branches by a massif of plagioclase-microcline granite (Fig. 2). The Niemijarvi Formation is composed here of massive to pillowed and amygdaloidal tholeiitic basalts and lava breccias, which are metamorphosed under conditions of amphibolite facies, being more and more foliated in westward direction. Separate thin horizons of the formation are composed of the BIF oxide (± sulfide) facies and komatiitic or silicic tuffs.

In a western exposure of Niemijarvi Formation, we sampled a horizon (a few meters thick) of thin-laminated fine-grained tuff corresponding in composition to Na-dacite. The zircon fraction separated from Sample K-04 about 15 kg in weight includes prismatic and long-prismatic crystals. Dark brown large (up to 400 μm) crystals having elongation coefficients of 1.8 to 4.0 reveal a fine magmatic zoning (Fig. 4a, grains 1.1–3.1). They contain 212 to 408 μg/g U and 113 to 161 μg/g Th; Th/U ratio ranges therewith from 0.41 to 0.55 (Table 1). Small, transparent, light pink crystals have subidiomorphic acicular habit and zoning detectable by cathodoluminescence method (Fig. 4a, grains 5.1–6.1). These crystals contain 201 to 391 μg/g U and 54 to 104 μg/g Th; ratio Th/U = 0.28 (Table 1). The estimated $^{207}Pb/^{206}Pb$ ages range from 2792.4 ± 5.3 to 2787.2 ± 7.5 Ma (Fig. 5a). In addition, there is one short-prismatic grain (Fig. 4a, grain 4.1) with abnormally high U (442 μg/g) and Th (1615 μg/g) concentration; Th/U = 3.78 (Table 1). Judging from morphology and geochemical characteristics, zircon crystals from Sample K-04 are of magmatic origin in general, although grain 4.1 belongs likely to hydrothermally-altered zircon described by Hoskin (2005), i.e., to magmatic zircons altered under influence of postmagmatic fluids enriched in Th, U, REE (predominantly in LREE) and other trace elements. The upper discordia intercept with concordia (Fig. 5a) determines age value of 2791.7 ± 6.1 Ma (MSWD = 0.96) for zircons from sample K-04.

Discussion. The established age of magmatic zircons determines the manifestation time of silicic volcanism in oceanic plateau, rocks of which occur in the Niemijarvi and Ruvinvaara formations. Being of a low thickness and thin-laminated structure, the dated and other horizons of fine-grained dacitic tuffs of the Niemijarvi Formation represent a distal facies of silicic volcanism. It is admissible, therefore, that plateau was probably situated close to an area of continental volca-

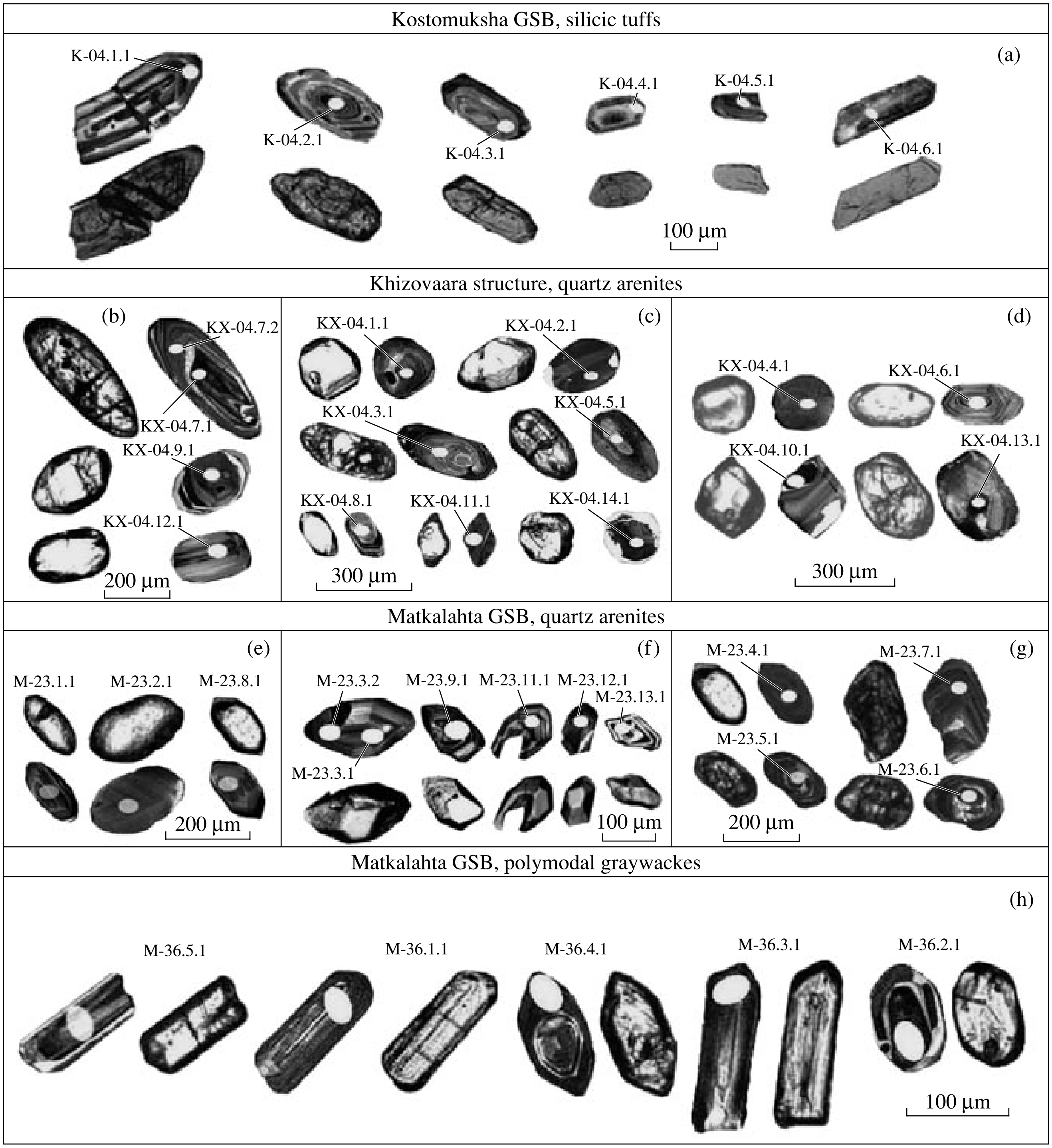

Fig. 4. Optical and cathodoluminescent photographs of studied zircon grains from rocks of the Kostomuksha GSB, Khizovaara structure, and Matkalahta GSB.

nism but not in an intraoceanic setting as suggested by Puchtel et al. (1998). According to all U–Pb dates obtained for zircons from volcanic and volcanogenic-sedimentary rocks of the Kostomuksha GSB, dacites and rhyolites of the Shurlovaara (2793 ± 17 and 2795 ± 25 Ma) and Niemijarvi (2791.7 ± 6.1 Ma) formations of the Kontokki Group are practically concurrent in origin to silicic tuffs (2787 ± 8 Ma) of the Gimoly Group (Samsonov et al., 2005). The oceanic plateau under consideration was formed at the same time.

Because silicic (Gimoly Group, Shurlovaara and Niemijarvi formations) and basalt-komatiitic volcan-

Table 1. U-Pb isotopic characteristics of zircons from three Archean greenstone belts of the Karelian craton

Grain no.	% $^{206}\mathrm{Pb}_c$	Concentration, μg/g			$^{232}\mathrm{Th}/^{238}\mathrm{U}$	Age, Ma				Discordance, %
		U	Th	$^{206}\mathrm{Pb}^*$		(1) $^{206}\mathrm{Pb}/^{238}\mathrm{U}$ age	±1σ	(1) $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ age	±1σ	
Sample K-04, Kostomuksha GSB, dacitic tuff										
K-04.1.1	0.17	212	113	93.0	0.55	2.656	±29	2.775	±8	4
K-04.2.1	0.00	408	161	182.0	0.41	2.696	±39	2.794	±5	3
K-04.3.1	0.02	291	126	131.0	0.45	2.709	±29	2.791	±6	3
K-04.4.1	0.49	442	1615	122.0	3.78	1.796	±22	2.762	±10	35
K-04.5.1	0.00	391	104	178.0	0.28	2.742	±28	2.792	±5	2
K-04.6.1	0.05	201	54	88.5	0.28	2.666	±39	2.787	±7	4
Sample KX-04, Khizovaara structure, quartz arenite										
KX-04.1.1	0.01	82	65	37.3	0.82	2.740	±30	2.705	±10	–1
KX-04.2.1	0.02	123	134	57.6	1.13	2.807	±30	2.728	±8	–3
KX-04.3.1	0.01	145	80	66.1	0.57	2.745	±28	2.727	±7	–1
KX-04.4.1	0.00	467	201	199.0	0.44	2.599	±25	2.674	±4	3
KX-04.5.1	0.26	155	97	67.1	0.65	2.631	±30	2.732	±8	4
KX-04.6.1	0.03	68	58	30.1	0.88	2.670	±30	2.687	±11	1
KX-04.7.1	0.02	253	209	90.2	0.85	2.238	±23	2.832	±6	21
KX-04.7.2	0.01	169	44	63.1	0.27	2.326	±24	2.735	±7	15
KX-04.8.1	0.02	52	36	23.1	0.72	2.673	±30	2.709	±11	1
KX-04.9.1	0.00	231	62	117.0	0.28	2.986	±29	3.151	±5	5
KX-04.10.1	0.32	96	14	35.1	0.15	2.280	±25	2.676	±10	15
KX-04.11.1	0.03	113	127	50.8	1.16	2.717	±28	2.711	±8	0
KX-04.12.1	0.00	116	106	53.8	0.94	2.780	±29	2.811	±7	1
KX-04.13.1	0.01	978	79	404.0	0.08	2.532	±24	2.651	±3	4
KX-04.14.1	0.03	261	127	116.0	0.5	2.680	±29	2.747	±5	2
Sample M-23, Matkalahta GSB, quartz arenite										
M-23.1.1	0.00	39	21	22.0	0.55	3.281	±39	3.331	±10	1
M-23.2.1	0.05	21	9	12.0	0.44	3.275	±45	3.289	±19	0
M-23.3.1	0.11	51	35	23.1	0.71	2.735	±32	2.825	±12	3
M-23.4.1	0.02	316	69	172.0	0.23	3.159	±30	3.248	±4	3
M-23.5.1	0.06	457	409	184.0	0.92	2.479	±24	3.098	±4	20
M-23.6.1	0.08	391	154	197.0	0.41	2.980	±28	3.159	±4	6
M-23.7.1	0.04	414	9	221.0	0.02	3.109	±29	3.236	±3	4
M-23.3.2	0.11	90	67	42.1	0.77	2.793	±30	2.819	±9	1
M-23.8.1	0.04	33	17	19.1	0.54	3.311	±41	3.334	±11	1
M-23.9.1	0.80	78	62	35.5	0.83	2.724	±30	2.827	±12	4
M-23.11.1	2.29	66	44	32.2	0.68	2.850	±64	2.779	±41	–3
M-23.12.1	0.07	75	52	35.0	0.72	2.786	±63	2.805	±27	1
M-23.13.1	0.24	76	55	37.0	0.74	2.883	±63	2.860	±18	–1
Sample M-36, Matkalahta GSB, graywacke										
M-36.1.1	0.15	223	34	113.0	0.16	2.973	±19	3.172	±7	7
M-36.2.1	–	107	50	54.4	0.49	2.996	±27	2.938	±31	–2
M-36.3.1	0.10	464	130	238.0	0.29	3.011	±18	3.106	±6	3
M-36.4.1	0.07	310	130	163.0	0.43	3.078	±23	3.157	±6	3
M-36.5.1	0.22	97	25	51.7	0.27	3.095	±110	3.259	±72	5

Note: ($^{206}\mathrm{PB}_c$) and ($^{206}\mathrm{Pb}^*$) are common and radiogenic leads, respectively, standard calibration uncertainty is 0.37%; (1) correction for common lead is based on measured ^{204}Pb.

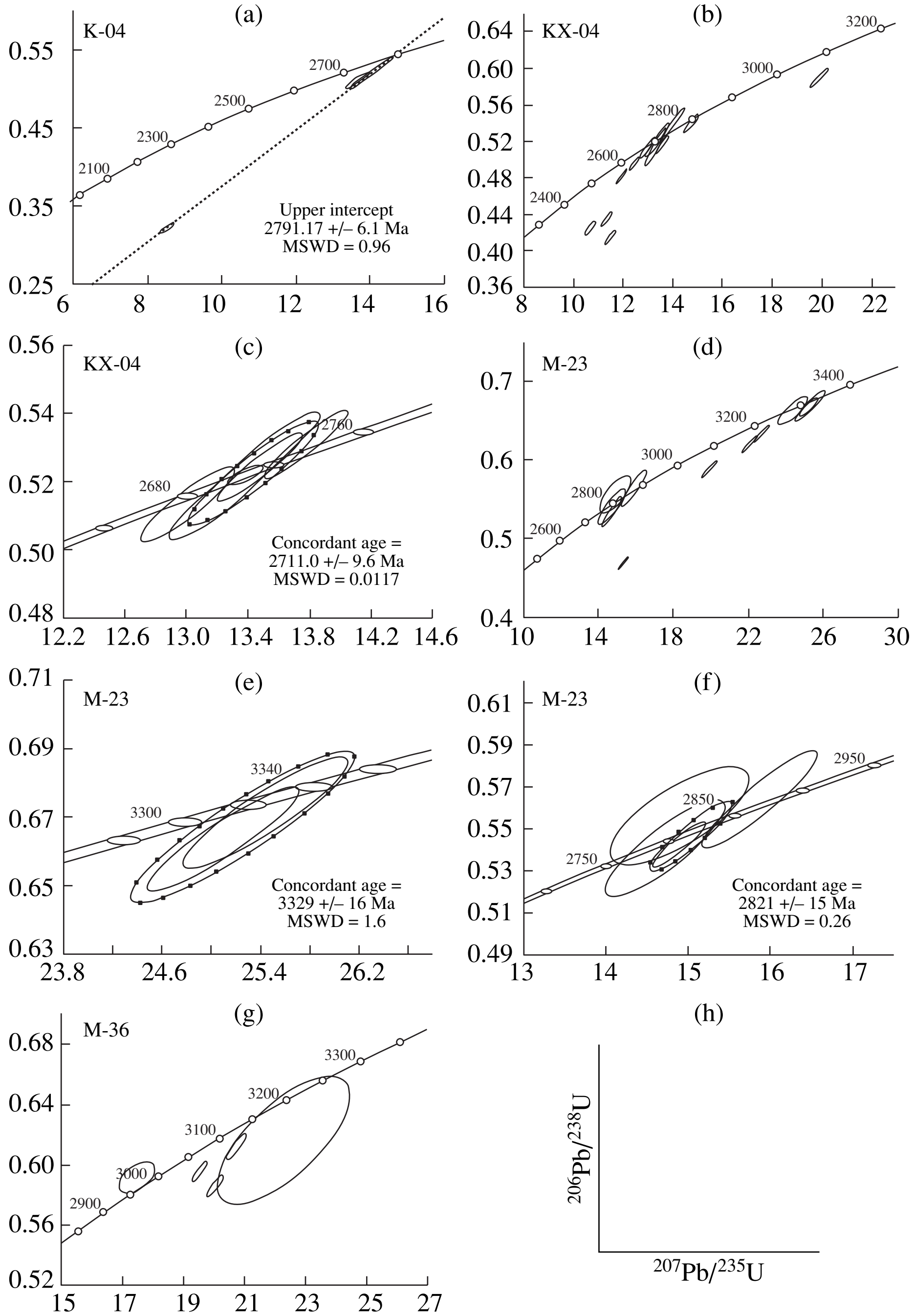

Fig. 5. Diagrams with concordia for studied zircons from Archean rocks: (a) silicic tuff, Kostomuksha GSB; (b) quartz arenite, Khizovaara structure; (c) concordant age estimated for five grains; (d) quartz arenite, Matkalahta GSB; (e) concordant age of the early zircon generation; (f) concordant age of the late zircon generation; (g) polymodal graywacke, Matkalahta GSB; (h) designation of coordinate axes; resultant ellipses shown in diagrams b, d, and e are used to calculate concordant ages of relevant zircon grains.

ism of the western reach is synchronous to granitoid magmatism on both flanks of the structure, we suggest the following conclusions.

(1) The Kostomuksha GSB represents a collage of STAs imbricated in the course of convergence and originated almost concurrently in different geodynamic settings: in an oceanic plateau, active continental margin or mature island arc and back-arc, probably foreland basin.

(2) Silicic volcanics and subvolcanic bodies of the Shurlovaara Formation correspond, jointly with plutonic rocks flanking the structure, to one volcano-plutonic association that was formed at the time of mafic allochthons obduction onto the continental margin.

(3) The oceanic plateau originated close or inside the convergence zone "microocean–microcontinent," as it is evident from synchronism of endo- and exogenic processes. This suggests a very quick development of that zone in distinction from the idea of intracratonic rifting (Lobach-Zhuchenko et al., 2000) or a model postulating that an older oceanic plateau was buried under silicic continental volcanics in the course of its thrusting over the continental shelf (Puchtel et al., 1998).

Earlier models of the Kostomuksha GSB formation (Gor'kovets et al., 1981; Puchtel et al., 1998) have been discussed by Kozhevnikov (2000) who expounded geological, structural-tectonic, geochemical, and isotopic-geochronological arguments in favor of a new model. According to the suggested model, the STAs corresponding to former formations have been formed initially in different geodynamic settings. The Niemijarvi and Shurlovaara formations represent fragments of an oceanic plateau integral in the past and separated after obduction and erosion by volcanic and sedimentary rocks of a volcanic arc situated on continental margin (Shurlovaara Formation). Deposits of the Kontokki Group have been thrust under rocks of the back-arc marginal basin (Gimoly Group) in the course of convergence. Syncollision massifs of sanukitoids (2720 ± 15 Ma), plagioclase-microcline granites (2679 ± 8 Ma), and plagiophyres (2707 ± 31 Ma) intruded the crust at the formation time of Belomorian mobile belt (Bibikova et al., 1999; Lobach-Zhuchenko et al., 2000, 2005; Samsonov et al., 1996). Intrusive activity has been controlled by longitudinal shearing in the western reach and by formation of arcuate structure of the Kostomuksha ore deposit (Kozhevnikov, 2000). In fact, the Kostomuksha GSB is an analog of ophiolite sutures in younger orogenic belts. The model synthesizes recent data, ideas of some researchers, and results of comprehensive study of structural geology in the Kostomuksha GSB (Kozhevnikov, 1982, 1992). The isotopic age of the reference silicic volcanics in the oceanic plateau section and recent data on isotopic geochemistry, geology, and geochronology (Samsonov, 2004) are important for better understanding of accretionary mechanisms (Fig. 3) responsible for the Archean GSBs formation.

STRATOTECTONIC ASSOCIATIONS, PROVENANCE AND U–Pb AGE OF ZIRCONS FROM ARENITES OF THE KHIZOVAARA STRUCTURE

Geology, stratotectonic associations. The Khizovaara structure is a part of the North Karelian GSB situated in eastern margin of the Karelian craton, in a zone influenced by collision processes related to evolution of the Belomorian mobile belt (Fig. 1). The structure corresponds to a complex asymmetric synform flanked by granitoids and filled with metavolcanic and metasedimentary rocks of the Khizovaara Formation (Kratz, 1963), an age analog of the Iringora Formation in the Tikshozero Group (Kharitonov, 1955). In the Lopian Eonothem, the last group is basal unit of the Lower Proterozoic (Early Karelian). In resolutions of the All-Russia stratigraphic conference held in Ufa (1977), which were approved by the ISC of the USSR in 1978, now abandoned geosynclinal formations of the Lower Proterozoic (Tikshozero Group included) were attributed to the Upper Archean. Like its analog Iringora Formation, the Khizovaara Formation was interpreted for a long time as a succession of metasedimentary rocks (siliciclastic, chemogenic and volcaniclastic) intercalated with metavolcanics of basic to silicic composition (*Geology of Karelia*, 1987). As it was shown recently (Kozhevnikov, 1992, 2000), metasediments and metavolcanics of the formation represent several STAs different in composition and origin (Fig. 6a).

In the northern part of the structure, the lower volcanogenic STA-1 up to 1 km thick is composed of basalts (Fe-varieties included) and komatiites with the 1-m-thick horizon of rocks corresponding to boninites in geochemical parameters (Shchipansky et al., 1999). Among volcanics of the STA-1, there are rare pillowed rocks and thin intercalations of hyaloclastites and layered tuffs. Absence of terrigenous sediments suggests that lavas were erupted in a marine setting remote from provenance of siliciclastic material. The STA-1 is intruded near the base by trondhjemites containing zircon 2804 ± 27 Ma old according to results of the U–Pb dating (Bibikova et al., 2003). Age determined by the same method for felsic dikes crosscutting the STA-1 is 2803 ± 35 Ma (Kozhevnikov, 1992). Intense carbonatization, foliation, and pencil cleavage of Fe-basalts near the contact with the STA-2 point to the tectonic character of boundary separating two associations.

The volcanogenic STA-2 about 100 to 700 m thick is composed of massive amygdaloidal glomerophyric andesites and their coarse pyroclastic derivatives. According to chemical composition, Na-andesites commonly belong to tholeiitic and sometimes to calc-alkaline series. A succession of massive amygdaloidal, unclearly pillowed, and glomerophyric andesites has been observed in the thickest section of STA-2. A thin horizon of glomerophyric andesite with weathering crust overlain by quartzite has been traced here for a distance of several kilometers. The U–Pb age of zircons from andesites equal to 2775 ± 5 Ma is interpreted as determining time of the early metamorphism (Bibikova et al., 2003).

The STA-3 is represented by succession of sedimentary and volcanogenic-sedimentary rocks up to 500 m thick. Its lower 40-m-thick horizon of quartzites and quartz gravelstones and basal quartz conglomerates. The horizon grades upward into a thick sequence of rhythmical turbidites with elements of Bouma cycles, which are intercalated with interlayers of chemogenic sediments, silicic lavas, tuffs and tuffites, characteristic of which are complicated lateral relations.

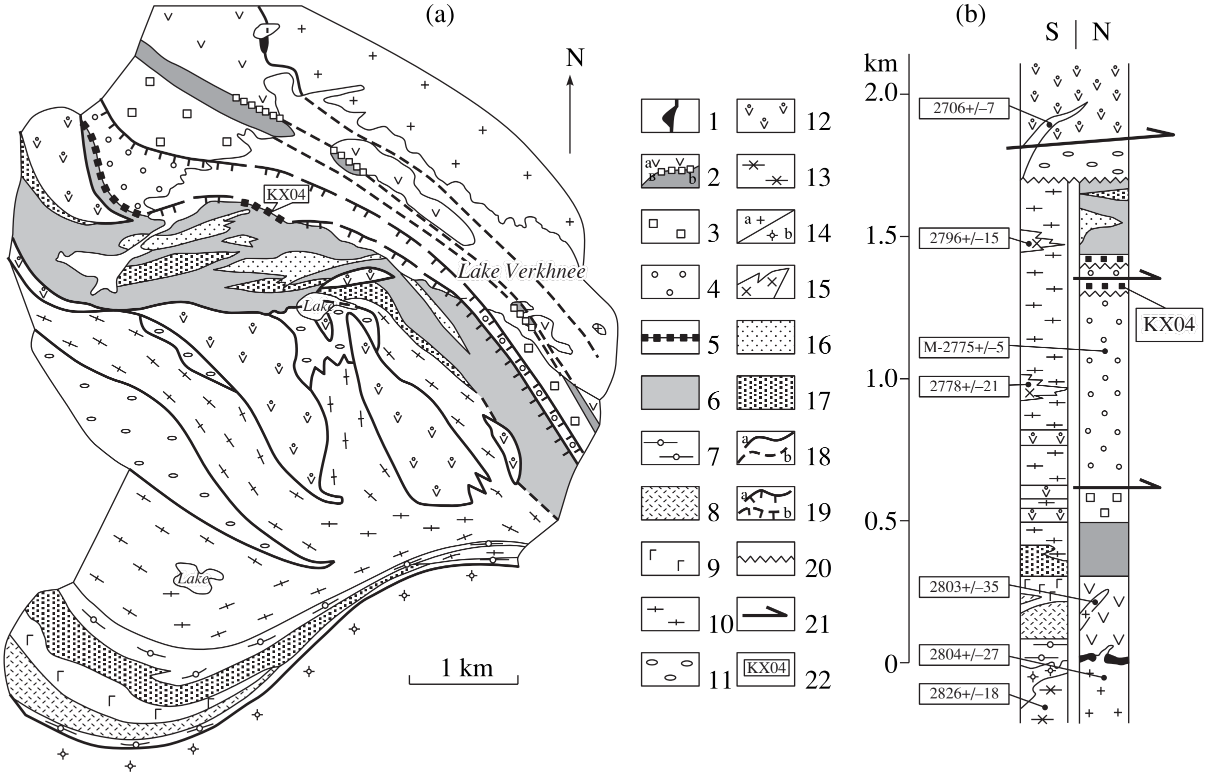

Fig. 6. Geological scheme (simplified after Kozhevnikov, 2000), lithostratigraphy of the Khizovaara structure (right column with additions from Bibikova et al., 2003) with reference zircon ages (Ma) and stratotectonic associations (STA): (1) peridotite cumulates, (2) tholeiitic basalts (a), komatiites (b) and boninites (c) of STA-1; (3) Fe- basalts of STA-2; (4) tholeiitic and calc-alkaline andesites of STA-3; (5) quartz arenites and (6) silicic volcanics intercalated with turbidites and horizons of carbonaceous rocks of STA-4; (7) foliated tholeiitic basalts, (8) calc-alkaline andesites, (9) gabbro sills, and (10) siliciclastic deposits with thin silicic tuff and BIF horizons of STA-5; (11) oligomictic conglomerates with silicic clasts and subordinate tuff-breccias of STA-6; (12) tholeiitic pillow basalts; (13) southern granodiorite complex; (14) northern adakitic tonalites (a) and muscovite-microcline granites (b) of the southern flank; (15) STA-6 and (16) STA-3 intruded by hypabyssal dacite and rhyodacite bodies; (17) bodies of metasomatic rocks; (18) STA boundaries documented (a) and inferable (b); (19) thrust faults documented (a) and presumable (b); (20) unconformity above weathering crust after andesites of STA-2; (21) directions of displacements between and inside stratotectonic associations; (22) sampling site.

In the southern part of the Khizovaara structure, the STA-4 up to 1.5 km thick is age analog of associations described above. It is composed of siliciclastic sediments, which are intercalated with pillow basalts, basic, intermediate and rare silicic tuffs. The BIF horizons and lenses a few meters thick have been observed in association with sediments and basalts. The STA-4 is bounded from below by tectonized intrusive contact with granitoids. Its upper boundary is overlain by younger deposits for a considerable distance, but in places, it is faulted and marked by linear bodies of metasomatites and silicic intrusions. This boundary separates STA-4 and STA-3.

Rudaceous rocks attributed to separate STA-5 are exposed within two broad fields in the center of structure, where they have discordant contacts with underlying and overlying associations. The STA-5 estimated to be 100 m thick is composed of oligomictic and volcaniclastic conglomerates with rewashed tuffaceous matrix. Clasts of dacites and rhyolites are more silicic in composition than matrix. Association of volcaniclastic rocks and silicic lava breccias has been observed in some outcrops. The STA-5 is likely related in origin with a pull-apart basin traceable fragmentarily northward of the Khizovaara structure for a distance of 70 km (Kozhevnikov, 2003).

The STA-6 exposed in the structure central part is composed of tholeiitic pillow basalts with thin komatiitic sills occurring in places at the base and contaminated by material of continental crust. In distinction from komatiites of the STA-1, these sills characterized by a prominent negative Nb anomaly are enriched in Zr, Ti, Th, LREE. The isotopic age of sills has not been determined. The STA-6 discordantly rests on all other associations except for the STA-1 perhaps. The U–Pb age of zircons from dikes of rhyodacites crosscutting the STA-6 is 2706 ± 7 Ma (Shchipansky et al., 1999).

Lithology and geochemistry of quartz arenites. Quartz arenites and associated andesites traceable in northern limb of the Khizovaara structure for a distance of several kilometers have been comprehensively studied in several outcrops. Hummocky cross-stratification of the rocks is sloping at low angles. The rocks lacking lithoclasts contain insignificant amount of plagioclase, and their position on the quartz–feldspar tie line close to quartz apex in triangular discrimination diagram by Dickinson et al. (1983) suggests a cratonic provenance of clastic material. In addition, structural features of the rocks containing subangular zircon grains and laminae enriched in heavy minerals are indicative of the provenance proximity, quick transportation and deposition of clastic material. The rocks contain 87.5 to 97.0% SiO_2; the Na_2O/K_2O ratio is high because of low content of pelitic components and presence of unaltered plagioclase grains. The low chemical index of alteration (CIA = 37–73%) characterizes chemical immaturity of matrix in arenites of the Khizovaara structure. This unusual combination of high SiO_2 content and immature matrix determines specific distribution of trace elements in the rocks relatively depleted in Zr (56–101 μg/g) and Y (4–11 μg/g). The only sample with extremely high Zr (933 μg/g) and Th (338 μg/g) concentrations is apparently enriched in clastic zircon. The high in general though variable Cr concentration (42–581 μg/g) points to the ultramafic rocks influence on geochemistry of quartz arenites. According to quantitative modeling based on distribution of REE, HFSE, Cr and Ni, the provenance of clastic material was of polymodal type. The rocks can be regarded as mixtures containing different proportions of silicic volcanics, tonalite and komatiite with 1.1- to 5.6-fold dilution by quartz (Kozhevnikov, 2000). The quartz dilution exactly is responsible for the REE deficiency in Archean quartz arenites (McLennan et al., 1984; Wronkiewicz and Condie, 1989) and for the REE concentration decrease in sand relative to associated clay in recent deep-water turbidites (McLennan et al., 1990).

Mineral and isotopic-geochronological systematics of zircons from arenites. Quartz arenites of gravely to sandy type have been sampled in northern coast of the Lake Verkhnee. At the sampling site, there are exposed two andesite (A1 and A2) and quartz arenite (Q1 and Q2) horizons (Fig. 6B). At the base of Horizon Q1, there is thin (ca. 20 cm) layer of quartz conglomerate resting on weathered glomerophyric andesite and composed of closely set, moderately rounded pebbles up to 3 cm in diameter of white vein quartz. Sample KX-04 approximately 10 kg in weight has been taken from quartz gravelstone overlying that conglomerate. Gravelstone is composed of subangular to angular clasts of white vein quartz 1 to 1.5 cm across. In the gray quartzite matrix, quartz grains are usually angular, ranging in size from 1 to 2 mm. There are three types of plagioclase grains in the matrix: (1) small angular grains retaining crystallographic facets; (2) small grains with dark powder-like material dispersed along cleavage planes; (3) interstitial plagioclase newly formed between quartz grains in association with garnet, amphibole, mica, kyanite, staurolite, and chlorite. Accessory minerals are represented by zircon, sphene, and ore minerals.

Zircon fraction separated from Sample KX-04 included at least three groups of grains different in morphology, optical characteristics, and age. Two groups of predominantly light pink, variably rounded grains represent about 70% of zircon fraction. Group 1 (10% of fraction) is represented by well-rounded large grains (300–500 μm, elongation coefficient 1.5 to 2.0) of intact or broken large crystals with a complex inner structure visible under cathodoluminescence. Dark cores of these grains are surrounded by light and darker rims (Fig. 4b). The oldest $^{207}Pb/^{206}Pb$ age of 3151.5 ± 4.6 Ma (Fig. 5b) is determined for core of a rounded grain (Fig. 4b, grain 9.1) containing 231 μg/g U and 62 μg/g Th; Th/U = 0.28 (Table 1). Younger $^{207}Pb/^{206}Pb$ ages from 2832 ± 6 to 2811 ± 7 Ma are obtained for rounded fragments of large unzoned zircon crystals (Fig. 4b, grains 7.1 and 12.1) containing 116–253 μg/g U and 106–209 μg/g Th; Th/U ratio is high, equal to 0.85 and 0.94 (Table 1). Geochemical and morphological characteristics of younger zircons suggest that grains could be derived from rocks of intermediate composition. The grains are surrounded by metamorphic rims, and $^{207}Pb/^{206}Pb$ age decreases from 2832.4 ± 6 Ma in the core to 2735.4 ± 6.9 Ma in outer rim; U and Th concentrations and Th/U ratios decline in this direction as well.

Group 2 (60% of separated fraction) consists mainly of pink rounded zircon grains with characteristic cavernous surface (Fig. 4c, grains 1.1, 2.1, 3.1, 5.1, 8.1, 11.1 and 14.1). Grains are either isometric or elongated (100–250 μm, elongation coefficient 2.0 to 2.5), and some of them represent fragments of large crystals unzoned or having fine and sectorial zoning. Dark metamorphic-metasomatic outer rims are characteristic of some fragments, and completely overgrown grains are euhedral. Zircons of this group contain 52 to 261 μg/g U and 36 to 134 μg/g Th; Th/U ratio ranges from 0.27 to 1.16, and estimated interval of $^{207}Pb/^{206}Pb$ ages is from 2746.7 ± 5.3 to 2705.4 ± 9.7 Ma (Table 1). Concordant age (Ludwig, 1999) corresponds to 2711 ± 9.6 Ma, MSWD = 0.0117 (Fig. 5B).

Zircons of Group 3 (nearly 30% of whole fraction) are represented by dark brown cloudy grains 150 to 400 μm long of prismatic, isomorphic and irregular shape, which are idiomorphic to subidiomorphic or rounded (Fig. 4d). As a rule, finely zoned cores of the grains are surrounded by dark broad rims, while some completely dark grains have poorly visible zoning. Elongation coefficient of most idiomorphic grains is 1.0 to 2.5. Rims and completely altered grains are almost black in cathodoluminescent images. Zircons of Group 3 have very variable U (96–978 μg/g) and Th (14–201 μg/g) concentrations, the lowest Th/U ratios (0.08–0.44), and relatively young $^{207}Pb/^{206}Pb$ ages ranging from 2687 ± 11 to 2651.3 ± 3.5 Ma (Table 1). Geochemical and morphological peculiarities of these zircons originated mist likely under influence of metamorphic and/or metasomatic processes.

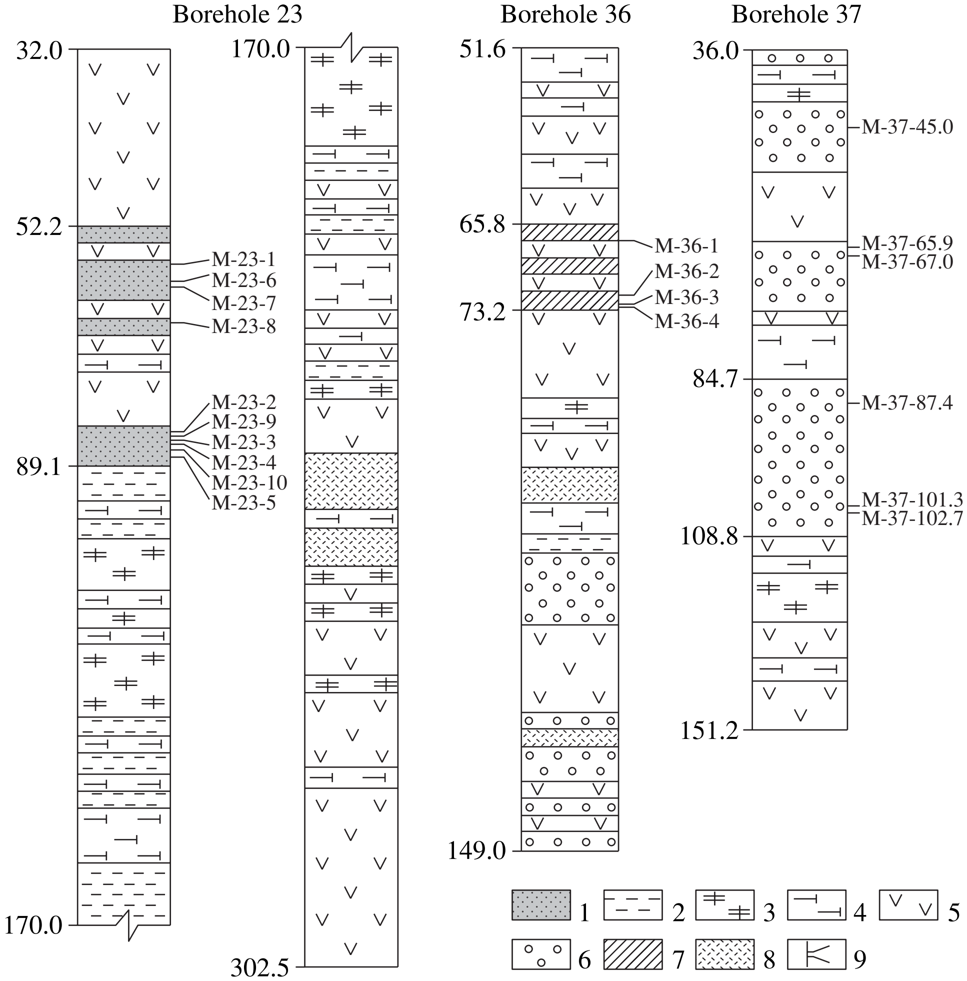

Fig. 7. Core sections recovered by drilling in the Matkalahta GSB (after Tytyk and Fedyuk, 2003): (1) quartz and biotite-quartz-feldspar (±epidote) arenites; (2) biotite-chlorite-feldspar- quartz (± cordierite and carbon) schists; (3) serpentinites after dunite and peridotite (sills or komatiitic cumulates in thick flows); (4) tremolite-talk-chlorite-carbonate and talk-chlorite-carbonate schists after metamorphosed pyroxenites and pyroxene komatiites; (5) tholeiitic and subordinate basalts and Fe-basalts; (6) metasomatic quartzites with pyrrhotite and carbonate-garnet or other metasomatic paragenesis; (7) epidote-actinolite-biotite-quartz-feldspar schists after bimodal graywackes; (8) foliated silicic volcanics; (9) sampling levels of zircon fractions.

Discussion. The isotopic dates determined for zircons of different types separated from quartz arenites shed some light on problems related to interpretation of geological, lithological, petrographic and geochemical data (Kozhevnikov, 2000; Thurston and Kozhevnikov, 2001) with respect to age and composition of rocks in provenance of clastic material and to the STA boundaries and ages in the Khizovaara structure. The studied arenites lacking lithoclasts do not yield much information about source rocks of clastic material. Important in this aspect are data on REE distribution, chemical composition of rocks, and pebbles of vein quartz. As there are no indications that the weathered island-arc andesites influenced lithology and geochemistry of overlying quartzites, the hummocky cross-stratification and elements of Bouma cycles detectable in the latter imply that quartz arenites represented not sediments of the first cycle (Cox and Lowe, 1995) but allochthonous deposits of turbidity flows, which transported material from a polymodal provenance. Among rocks of the provenance, there were likely ancient cratonic tonalites about 3.15 Ga old, which are unknown so far in North Karelia, and granitoids or volcanics of ancient volcanic arc, which are 2829 ± 30 Ma old according to age assessments obtained in the North Karelian GSB (Bibikova et al., 2003). Typical magmatic zircons derived from these source rocks are represented in Group 1. It is important therewith that in grain 7.1 metamorphic rim is by 100 Ma younger than core and exhibits signs of abrasion. Consequently, metamorphic event that took place 2.73 Ga ago predated commencement of erosion in provenance and deposition of quartz arenites.

Coarse-grained components of arenites from the Khizovaara structure are represented by clasts of vein quartz only. It is reasonable to suggest that these clasts were derived from a quartz stockwork probably associ-

Table 2. Chemical composition of rocks from the Matkalahta GSB

Components	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	P_2O_5	L.O.I.	Σ
Borehole 23, quartz arenites														
M-23-1	91.20	0.09	1.53	0.26	1.93	0.11	1.63	2.43	0.03	0.02	0.14	0.02	0.34	99.72
M-23-3	95.56	0.09	1.65	0.18	0.92	0.02	0.40	0.21	0.29	0.15	0.09	0.02	0.22	99.80
M-23-4	92.60	0.10	1.78	0.01	2.90	0.04	1.00	0.28	0.10	0.12	0.20	0.03	0.67	99.81
Borehole 23, mylonitic quartz arenites														
M-23-6	94.56	0.09	1.34	0.87	1.38	0.03	0.42	0.11	0.16	0.15	0.02	0.08	0.52	99.72
M-23-7	96.50	0.04	1.02	0.22	1.12	0.03	0.37	0.11	0.07	0.03	0.02	0.10	0.07	99.70
M-23-8	93.30	0.12	2.15	0.18	1.75	0.05	0.60	0.28	0.49	0.27	0.03	0.18	0.31	99.70
M-23-9	89.20	0.18	2.40	0.01	3.18	0.10	1.56	1.61	0.27	0.19	0.02	0.16	0.95	99.82
M-23-10	91.90	0.15	2.35	0.12	2.41	0.05	1.00	0.42	0.09	0.28	0.03	0.18	0.83	99.81
Borehole 23, quartz-feldspar arenites														
M-23-2	72.35	0.38	5.80	0.55	4.83	0.31	5.64	7.43	0.40	0.25	0.12	0.04	1.50	99.60
M-23-5	63.55	0.68	15.46	0.31	5.23	0.07	8.22	1.72	2.72	0.27	0.11	0.12	1.44	99.89
Borehole 36, polymodal graywackes														
M-36-1	58.78	0.69	12.92	0.35	8.05	0.09	10.55	2.98	3.54	0.03	0.15	0.08	1.38	99.59
M-36-2	57.48	0.80	18.33	0.55	5.82	0.07	9.36	1.89	3.33	0.31	0.21	0.12	1.54	99.81
M-36-3	56.68	0.83	18.72	0.46	5.03	0.12	7.26	2.48	4.99	0.06	0.20	0.17	2.20	99.50
M-36-4	58.94	0.67	14.84	0.80	6.46	0.07	6.98	3.70	3.02	2.65	0.16	0.16	1.36	99.50
Borehole 37, metasomatic quartzites														
M-37-1	81.00	0.03	0.14	8.15	4.94	0.40	1.90	1.40	0.02	0.01	0.05	0.18	1.31	99.53
M-37-2	86.00	0.02	0.16	2.32	5.63	0.24	1.40	2.28	0.03	0.01	0.05	0.10	1.27	99.50
M-37-3	86.40	0.01	0.33	3.27	5.23	0.37	1.30	1.93	0.02	0.01	0.06	0.11	0.64	99.57
M-37-4	85.30	0.03	0.14	0.14	6.98	0.27	2.14	2.98	0.03	0.01	0.05	0.18	1.40	99.65
M-37-5	70.10	0.03	0.22	0.01	11.70	0.79	5.50	6.31	0.06	0.02	0.09	0.13	3.17	99.93
M-37-6	79.12	0.08	1.53	1.29	10.92	0.30	1.24	1.96	0.05	0.22	0.07	0.09	2.63	99.50

ated with hypabyssal bodies of silicic rocks, which were identified as one of end members of two- or three-component mixing by computational modeling of REE distribution in a series of quartz arenite samples (Kozhevnikov, 2000). The inference is consistent with results obtained in this work and implying that zircons of Group 2 represent one age generation (2.75–2.70 Ga). The concordant age 2711 ± 9.6 Ma estimated for this group corresponds most likely to manifestation time of silicic magmatism responsible for origin of the postulated quartz stockwork.

Metamorphism of studied rocks took place 2687 ± 11 to 2651.3 ± 3.5 Ma ago as is evident from $^{207}Pb/^{206}Pb$ ages estimated for zircons of Group 3. Metamorphic events of that time are detectable all over the Karelian craton, but proportion of metamorphic zircons in fraction separated from the arenite sample is not as great as could be expected. This is perhaps an effect of geochemical inertness of quartz-rich rocks, which conserve the early zircon generations, as it is established (Fedo et al., 2003; Hoskin and Ireland, 2000).

Finally, the accumulation period of siliciclastic sediments of the Khizovaara structure lasted, as we estimate, from crystallization time of "youngest" grains among magmatic zircons of Group 2 (2705.4 ± 9.7 Ma), or from 2711 ± 9.6 Ma (concordant age of this group), to the formation time of oldest metamorphic zircons of Group 3 (2687 ± 11 Ma). The estimated time span of quartz arenite accumulation dictated necessity to divide the former STA-2 (Kozhevnikov, 2000; Thurston and Kozhevnikov, 2001) in two associations, one volcanogenic, composed of island-arc andesites (STA-2), and the other one of volcanogenic-sedimentary rocks (STA-3), which are separated by stratigraphic unconformity and hiatus not less than 80 Ma long. In this work, both are considered exactly in this understanding.

Table 3. Trace element concentrations (μg/g) in rocks from the Matkalahta GSB

Elements	Rb	Sr	Y	Zr	Nb	Pb	Th	Ti	Ba	V	Cr	Ni	Co
Borehole 23, quartz arenites													
M-23-1	<2	17	4	55	6	7	<7	571	193	27	173	27	5
M-23-3	<2	15	<2	54	3	9	<7	686	264	7	177	18	<1
M-23-4	<2	9	2	38	11	9	<7	659	160	22	203	73	45
Borehole 23, mylonitic quartz arenites													
M-23-6	<2	7	<2	43	5	<7	<7	624	186	38	142	33	11
M-23-7	<2	10	<2	36	<2	<7	<7	383	184	4	135	16	2
M-23-8	<2	24	2	53	9	<7	<7	1925	160	75	448	59	26
M-23-9	<2	19	3	46	4	<7	<7	1092	150	37	353	38	26
M-23-10	<2	8	<2	47	2	<7	<7	1013	<150	27	265	30	4
Borehole 23, quartz-feldspar arenites													
M-23-2	<2	57	17	73	6	<7	<7	825	182	35	220	33	8
M-23-5	<2	70	19	120	18	<7	<7	3677	177	145	195	240	18
Borehole 36, polymodal graywackes													
M-36-1	<2	82	9	22	5	9	<7	3101	<150	180	278	367	32
M-36-2	5	84	16	141	11	13	7	4369	<150	149	183	102	34
M-36-3	11	96	21	142	15	10	<7	4354	181	222	188	104	31
M-36-4	<2	71	15	117	12	15	10	3406	161	184	132	134	20
Borehole 37, metasomatic quartzites													
M-37-1	<2	12	2	7	8	<7	<7	204	150	4	35	6	5
M-37-2	<2	4	2	13	3	<7	<7	157	<150	14	36	4	4
M-37-3	<2	11	<2	8	<2	<7	<7	106	<150	14	32	12	16
M-37-4	<2	11	4	13	<2	<7	<7	227	<150	30	61	90	5
M-37-5	<2	13	8	4	2	12	<7	187	<150	<15	19	72	21
M-37-6	<2	12	6	19	9	8	<7	565	320	<15	<5	<1	123

U–Pb AGES OF THE MATKALAHTA GSB AND PROVENANCES OF SILICICLASTIC ROCKS IN THE BELT

The Matkalahta GSB located in central zone of the ancient Vodlozero block (Fig. 1) is, like the other Archean GSBs rimming the block, a structure of the early (>2.9 Ga) generation (Kozhevnikov, 2000; *Mineral Reserves…*, 2005; Chekulaev, 1996). Geology of the GSB in question is known based on drilling and geophysical data, because the relevant area is practically unexposed. Some boreholes, which were drilled in recent years by Finish Company KIVIJARVI in the course of prospect work for Ni deposits, recovered in the Matkalahta GSB a section very unusual for the Karelian craton. In that section, horizons of quartz arenites and polymodal graywackes are intercalated with basalts and komatiites. Similar association of quartzites, basalts, carbonaceous slates, komatiites, silicic to basic tuffs and tuffites was recovered by drilling in the Kamennoe Ozero and Toksha structures situated in northern and eastern flanks of the Vodlozero block. Quartzites are here of chemogenic origin (*Komatiites…*, 1988), but terrigenous quartzites discovered later on in the Kamennoe Ozero structure offered a possibility to distinguish a platform STA in the structure section (Kozhevnikov, 2000).

The term “platform STA” is close in meaning to assemblage of komatiites and pillow basalts intercalated with quartz arenites, conglomerates, wackes and arkoses, the products of destruction of silicic crustal material, which have been described by Canadian geologists in a western GSB of the Superior craton (*Geology of Ontario*, 1991). Similar STAs have been described later on in the Zimbabwe craton of South Africa (Manjeri Formation; Fedo and Eriksson, 1996) and in other Archean regions. Rock associations of this kind commonly occur on flanks of ancient continental nuclei or microcontinents (Williams et al., 1992). One of such nuclei is the Vodlozero block, where the oldest rocks of the Karelian craton have been discovered. For instance, age values of 3210 ± 12, 3166 ± 14, 3151 ± 18, and 3138 ± 63 Ma were determined for individual zircon grains from tonalites and leucosome of early migmatites of the block (Lobach-Zhuchenko et al., 1993).

It was naturally to expect that quartz arenites of the intracratonic Matkalahta GSB could contain ancient zircons bearing information about age of continental crust in the Vodlozero protocraton.

Keeping this idea in mind, we examined rocks recovered by boreholes 23, 36, and 37 (Fig. 7), which had been drilled in the so-called eastern branch of the Matkalahta GSB. The typical platform STA of non-carbonate type had been drilled through by boreholes 23 and 36. In addition, boreholes 36 and 37 recovered metasomatic quartzites, which have been studied in geochemical aspect to understand behavior of zirconium and other trace elements by metasomatism.

Boreholes 23 and 36 penetrated through two types of siliciclastic sediments intercalated with basalts. Borehole 23 recovered quartz arenites similar to those of the Khizovaara structure but metamorphosed under conditions of greenschist facies. These silica-rich rocks are depleted in Al_2O_3, Na_2O, K_2O, P_2O_5, Sr, Y, Zr, Th, Ti, and V (Tables 2 and 3). Clastic quartz grains not greater than 1 mm in diameter are granulated by recrystallization, and the rock is converted into fused quartzite retaining relict stratification. Because of mylonitization in discrete zones, we sampled core section very carefully to obtain zircon fraction, although alteration did not changed significantly the Ti, V and Cr concentrations in the rock according to results of XRF spectroscopy and chemical analysis. In quartzites, there are rare and thin interlayers of quartz–feldspar arenites enriched in Ti, Y, Zr, and Cr as compared to feldspar-free rocks.

Siliciclastic rocks of the second type are distinguished in three horizons of basaltic sequence penetrated by Borehole 36. These are chlorite (±amphibole ± cordierite)–epidote–quartz–plagioclase rocks corresponding in chemical composition to polymodal graywackes, the mixed products of destruction of silicic and mafic rocks. This is evident from a low SiO_2 content in the rocks, which are simultaneously enriched in MgO, Na_2O, Al_2O_3, Sr, Y, Zr, Nb, Ni, Pb, and Th. The metasomatic quartzites with pyrrhotite, which have been recovered by Borehole 37, have low contents of all major and trace elements except for SiO_2, Fe, and Mn. Extremely low Zr concentrations in these rocks exclude the zircon formation during metasomatism that, like mylonitization, was unable therefore to influence considerably the U–Pb isotopic systems of the early zircon generations.

Zircons from quartz arenite, Sample M-23. Zircons separated from this sample are divisible into four groups according to size, morphology, and inner structure of grains.

Group 1 (Fig. 4e) comprising about 30% of separated fraction consists of light pink round to oval grains frequently representing crystal fragments. The grains have wavy cavernous surface and reveal fine magmatic or sectorial zoning under cathodoluminescence, which is invisible in transmitted light. Grains ranging in size from 100 to 250 μm, elongation coefficient 1.0 to 2.5, contain 21–39 μg/g U and 9–21 μg/g Th; Th/U = 0.44–0.55. The $^{207}Pb/^{206}Pb$ ages of zircons from Group 1 range from 3334 ± 11 to 3289 ± 19 Ma. The concordant age estimated for two points is 3329 ± 16 Ma, MSWD = 1.6 (Fig. 5e).

Group 2 (nearly 20% of whole fraction) includes pinkish brown, subangular prismatic crystals and their fragments, which exhibit fine zoning and sectorial structure by cathodoluminescence (Fig. 4f). Magmatic zoning is clearly seen as well in transmitted light. Crystals from 100 to 250 μm in size (elongation coefficient 1.8 to 2.5) contain 51–90 μg/g U and 35–67 μg/g Th; Th/U = 0.68–0.83. The $^{207}Pb/^{206}Pb$ ages are within the interval from 2860 ± 18 to –2779 ± 41 Ma (Table 1), and averaged value of 2821 ± 15 Ma is calculated based on four points, MSWD = 0.26 (Fig. 5f).

Group 3 (Fig. 4g, grains 4.1 and 7.1) is represented by pinkish brown, fissured zonal crystals, which are slightly rounded, representing ca. 20% of separated grains. By cathodoluminescence, the crystals are almost black, having poorly visible zoning. They are 200 to 400 μm in size (elongation coefficient 2.0 to 2.5), having high concentration of U (316–414 μg/g) and variable concentration of Th (9–69 μg/g); the Th/U ratio is low (0.02–0.23). The $^{207}Pb/^{206}Pb$ ages are in the interval from 3248 ± 3.8 to 3236.1 ± 3.5 Ma (Table 1). Judging from geochemical and morphological characteristics, this zircon generation is of metamorphic origin.

The most abundant (ca. 40% of the fraction) crystals of Group 4 (Fig. 4g, grains 5.1 and 6.1) are dark brown, cloudy to semitransparent, faceted or slightly rounded, sometimes broken. They are of a complex structure with marginal zoned rims displaying signs of recrystallization. By cathodoluminescence, the crystals are dark and zoned, with light colored recrystallized areas. Being from 150 to 200 μm in size (elongation coefficient 1.8 to 2.5), the crystals contain 391–457 μg/g U and 154–409 Th; the Th/U ratio is high, ranging from 0.41 to 0.92. The estimated $^{207}Pb/^{206}Pb$ ages are from 3158.8 ± 4.4 to 3098.3 ± 3.7 Ma (Table 1).

Zircons from polymodal graywacke, Sample M-36. Zircon grains from this sample are of three morphological types. Rounded isometric transparent grains of the first type are from 100 to 300 μm in size, elongation coefficient 1.8 to 3.0. Their cores with magmatic zoning are surrounded by metamorphic rims. Cloudy euhedral or slightly rounded elongated crystals of the second type and their fragments frequently contain cores with magmatic zoning, which are rimmed by outer metamorphic zones. Clear transparent anisometric zircons of euhedral habit and their fragments belong to the third group. They range in size from 60 to 200 μm having elongation coefficients from 2.0 to 3.0.

We studied isotopic systematics of five zircon grains (Fig. 4h), which turned out to be of three age generations (Fig. 5g) with different geochemical characteristics. The maximal $^{207}Pb/^{206}Pb$ age 3259 ± 72 Ma is obtained for core of a light pink prismatic crystal (M-36.5.1) with magmatic zoning and recrystallized outer rim. As compared to other zircons from Sample M-36, this crystal of the first morphological type is most depleted in U (97 μg/g) and Th (25 μg/g), Th/U = 0.27 (Table 1). In the next zircon generation with ^{207}Pb/^{206}Pb ages from 3172 ± 7 to 3105.9 ± 5.7 Ma, the U concentration is higher (223–464 μg/g), Th concentration is very variable (34–130 μg/g), and Th/U ratio is as low as 0.16–0.43 (Table 1). Zircons of this generation belong to second and third morphotypes (Fig. 4h, grains 1.1, 3.1, 4.1) and are likely of metamorphic origin according to some features, for instance grain 4.1 has dark outer rim. Finally, the lowest ^{207}Pb/^{206}Pb age 2938 ± 31 Ma is estimated for a small rounded pink-brown grain of the second type, which has dark zoned core and light recrystallized rim (Fig. 4h, grain 2.1). This grain seems to be of magmatic origin according to its morphology and rather low U (107 μg/g) and Th (50 μg/g) concentrations; Th/U = 0.49 (Table 1).

Discussion of zircon geochronology, the Matkalahta GSB. The dated zircons of different types from quartz arenites (Sample M-23) and polymodal graywackes (Sample M-36) elucidate some peculiarities of provenance they are derived from. The oldest rounded and euhedral magmatic zircons occurring exclusively in quartz arenites (grains M-23.1.1, M-23.2.1, M-23.8.1) are 3334 ± 11 to 3289 ± 19 Ma old and have low U and Th concentrations but high Th/U ratio. Metamorphic zircons of the second age generation (3259 ± 72 to 3236 ± 3 Ma) exhibit the high U concentration, variable and generally low Th concentration, and low Th/U ratio. These are grains M-23.4.1 and M-23.7.1 from quartz arenites and grain M-36.5.1 from graywackes. The fact that both age generations are detected in supermature quartz arenites may be indicative of a long-lasted erosion down to the deep ancient crustal source composed of granitoids 3329 ± 16 Ma old and of metamorphic rocks ranging in age from 3259 ± 72 to 3236 ± 3 Ma.

Zircons of the third generation (3172 ± 7 to 3098.3 ± 3.7 Ma) are present in both samples. These are grains M-23.5.1 and M-23.6.1 from quartz arenites and M-36.3.1 and M-36.4.1 from graywackes, which have high U and Th concentrations and high Th/U ratio, i.e., a combination of geochemical parameters typical of magmatic zircons affected by postmagmatic fluids. This age generation indicates the next endogenic pulse or second metamorphic-metasomatic event that postdates by 100 m.y. the first stage of metamorphism happened between 3259 ± 72 and 3236 ± 3 Ma ago. At the same time, the second event is by ca. 200 Ma younger that the first crust-forming process in the Vodlozero block, which is dated at 3329 ± 16 Ma based on the oldest age generation of magmatic zircons from quartz arenites. It is very likely that the third age generation can be regarded as concurrent to zircons from tonalites and leucosome of the early migmatites, which range in age from 3210 ± 12 to 3138 ± 63 (Lobach-Zhuchenko et al., 1993). The other age analogs could be zircons determining the U–Pb date of 3.16–3.17 Ga for protoliths of gneisses (Chekulaev, 1996).

The youngest zircon generation with U–Pb age of 2821 ± 15 Ma, MSVD = 0.26, and ^{207}Pb/^{206}Pb ages ranging from 2938 ± 31 to 2779 ± 41 Ma is represented by rounded grains having magmatic morphological and geochemical characteristics: fine and sectorial magmatic zoning, low U concentration and high Th/U ratio. In majority, zircons of this generation date the third endogenic event. They are most typical of quartz arenites thus reflecting genetic links of clastic material with hypabyssal silicic magmatic rocks of relevant age. The source could correspond to apical parts of trondhjemite and rhyolite-porphyry intrusions 2.91 Ga old (Sergeev, 1989). The age of 2821 ± 15 Ma estimated for detrital zircon and likely corresponding to the minimal age of magmatic rocks, which have been eroded, determines, as far as we can judge at present, the maximal age of the Matkalahta GSB.

Of special interest are general distinctions between zircons from siliciclastic rocks of contrasting maturity. Among zircons of variable morphology and broad age diapason, which are separated from quartz arenites, there are many isometric and rounded grains with magmatic zoning. These features, along with mineralogical and geochemical characteristics of host arenites, suggest the age and compositional heterogeneity of the clasts provenance subjected to a long-lasted abrasion at the early stage of multicyclic sedimentogenesis that terminated with deposition of quartz-rich sediments at the time of pulsating komatiite-basaltic volcanism.

Zircons from polymodal graywackes are represented mostly by less rounded anisometric grains derived from a provenance more homogeneous in geochronological and compositional aspects as compared to source rocks of zircons buried in quartz arenites. Crust in that provenance could be composed to a considerable extent of silicic magmatic rocks metamorphosed in the course of second endogenic pulse, as it is evident from ages of 3259 ± 72 to 3236 ± 3 Ma characterizing metamorphic zircons of the second age generation. This generation is concurrent to zircons from leucosome of migmatites, which is dated at 3210 ± 10 Ma and corresponds in composition to plagiogranite. Melanosome corresponding to mafic-ultramafic association is termed in the Vodlozero block as "ancient amphibolites of the Vyg and Vodla middle reaches" (Lobach-Zhuchenko et al., 1993). Clastic material derived from this bimodal association could be deposited by turbidity flows 2.82–2.87 Ga ago at the time of komatiite–basaltic volcanism in a trough of the Matkalahta GSB opening by spreading.

CONCLUSIONS

The new data obtained characterize isotopic ages of zircons from volcanic and sedimentary rocks of

Archean greenstone belts of the Karelian craton. They suggest different settings, mechanisms, and periods of development of the belts proper and their structural units. The collaged structures of the belts are composed of stratotectonic associations formed either subsynchronously as, for instance, in the Kostomuksha GSB, or successively during a time span more than 100 Ma long like in the Khizovaara structure. The oldest detrital zircons from quartz arenites and polymodal graywackes imply that stable continental nuclei originated at least 3151.5 ± 4.6 and 3329 ± 16 Ma ago in the northern and eastern Karelia, respectively. Younger zircons from the same rocks characterize the manifestation time of subsequent magmatic and metamorphic events. In particular, it is estimated that the terrigenous sedimentary STA of the Khizovaara structure was deposited between 2711 ± 9.6 and 2687 ± 11 Ma, and that the maximum age of the Matkalahta GSB corresponds to 2.82 Ga. The last date and the U–Pb age of 2791.7 ± 6.1 Ma estimated for an oceanic plateau in the Kostomuksha GSB (actually the belt age) indicate that some greenstone belts of the Karelian craton originated in the terminal Archean. Geological history of these belts corresponds to a geodynamic mesocycle 90 to 110 Ma long (Kozhevnikov, 2003). As is known, the global epoch of metallogeny responsible for origin of numerous Au, Ni, PGE, base metals, and other mineral deposits corresponded exactly to the above period of Archean history and related origin of greenstone belts.

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