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New geochronological data on Palaeozoic igneous activity and deformation in the Severnaya Zemlya Archipelago, Russia, and implications for the development of the Eurasian Arctic margin

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Abstract – The Severnaya Zemlya Archipelago, located close to the continental edge of the Kara Shelf in the Russian high Arctic, represents, together with northern Tajmyr, the exposed Neoproterozoic and Palaeozoic part of the North Kara Terrane. This terrane has been interpreted as an independent microcontinent or part of a larger entity, such as Arctida or Baltica, prior to collision with Siberia in Late Carboniferous time. A major stratigraphic break, the Kan'on (canyon) River Unconformity, separates folded Late Cambrian from Early Ordovician successions in one area, October Revolution Island. New geochronological U–Th–Pb ion-microprobe data on volcanic and intrusive rocks from this island constrain the age of an important magmatic episode in the earliest Ordovician. A tuff, in association with Tremadocian fossils, overlying the Kan'on River Unconformity, has been dated to 489.5 ± 2.7 Ma. The youngest rocks beneath the unconformity are of the *Peltura minor* Zone, and the latter has been dated previously, in western Avalonia, to $490.1^{+1.7}_{-0.9}$ Ma. Thus, little time is available for the tectonic episode recorded by the unconformity, and the similarities in radiometric dates may indicate problems with the correlation of faunal markers for the Cambrian–Ordovician boundary across palaeo-continents. The other extrusive and intrusive rocks which have been related to Early Ordovician rifting in the Severnaya Zemlya area yield ages from 489 Ma to 475 Ma. An undeformed granite, cutting folded Neoproterozoic successions on neighbouring Bol'shevik Island has been dated to 342 ± 3.6 Ma and 343.5 ± 4.1 Ma (Early Carboniferous), in accord with evidence elsewhere of Carboniferous strata unconformably overlying the folded older successions. This evidence conflicts with the common interpretation that the structure of the Severnaya Zemlya Archipelago originated during the collision of the North Kara Terrane with Siberia in Late Carboniferous time. An alternative interpretation is that Severnaya Zemlya was located in the Baltica foreland of the Caledonide Orogen and that the eastward-migrating deformation of the foreland basin reached the area of the archipelago in latest Devonian to Early Carboniferous time. This affinity of the North Kara Terrane to Baltica is further supported by 540–560 Ma xenocrysts in Ordovician intrusions on October Revolution Island, an age which is characteristic of the Timanide margin of Baltica.

Keywords: geochronology, tectonics, Severnaya Zemlya, Baltica, Siberia.

1. Introduction

The Severnaya Zemlya Archipelago is located in the Eurasian high Arctic, close to the edge of the Kara Shelf, between the Kara and Laptev seas (Fig. 1). As one of few land areas along the Eurasian Arctic margin, it is important for understanding the bedrock geology and tectonic history of the surrounding shelves, and for tectonic reconstructions of the opening of the Arctic oceanic basins.

Severnaya Zemlya is dominated by four large islands (Fig. 2): Bol'shevik (11 540 km^2), October Revolution (14 200 km^2), Pioneer (1547 km^2) and Komsomolets (8502 km^2), and a small southwestern group of islands, the Sedov Archipelago. The topography is generally gentle, but there are some mountains in northern Bol'shevik Island and easternmost October Revolution Island. Ice-caps, rising to nearly 1000 m above sea level on Bol'shevik Island and October Revolution Island, and tundra constitute most of the terrain.

The Severnaya Zemlya Archipelago is part of the North Kara Terrane, which also comprises northernmost Tajmyr and large parts of the eastern Kara Shelf (Fig. 3). This fragment of continental crust has been interpreted as a small independent continent (e.g. Cocks & Torsvik, 2005; Metelkin *et al.* 2000) or may be a part of a larger entity, such as Arctida (Zonenshain, Kuzmin & Natapov, 1990). It has been suggested that the North Kara Terrane was accreted to Siberia in late Palaeozoic time to form the Tajmyr orogen (Zonenshain, Kuzmin & Natapov, 1990; Vernikovsky, 1994; Inger, Scott & Golionko, 1999), which is considered to be the eastern continuation of the Uralides (Zonenshain & Natapov, 1989).

Major structures strike northwards from northernmost Tajmyr and Severnaya Zemlya (Bol'shevik and

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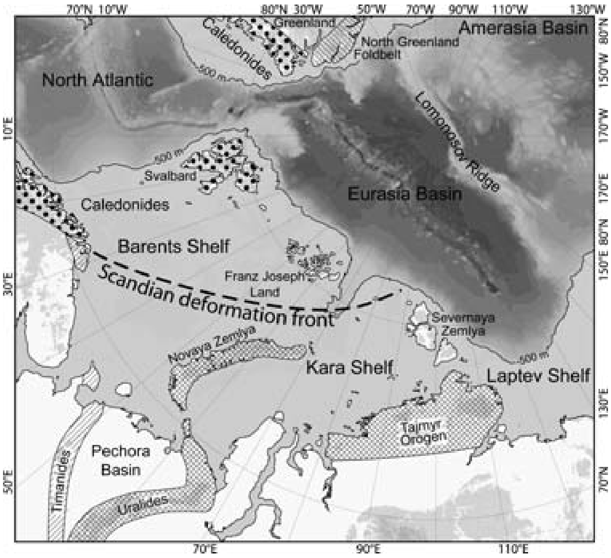

Figure 1. Major tectonic elements of the Eurasian high Arctic. Bathymetric data from Jakobsson *et al.* (2000).

October Revolution Islands) to the edge of the Eurasian shelf and are truncated by the continental slope at about 82° N (Fig. 1). They are therefore likely to be found beneath the Lomonosov Ridge, a sliver of continental lithosphere which was detached from the Eurasian Arctic shelf during the opening of the Eurasia basin (Fig. 1) in early Cenozoic time (Wilson, 1963; Lawver *et al.* 1988). Thus they may also be present beneath the margins of the Amerasia Basin (Fig. 1), which is thought to be largely of Cretaceous age (Embry & Dixon, 1990).

Tajmyr and the Severnaya Zemlya Archipelago have been visited by international geoscientific expeditions in 1998, 1999, 2002 and 2003 (Gee & Pease, 1999; Gee, 2002; Gee & Lorenz, 2003) to improve our knowledge of the geology of the North Kara Terrane and its relationships to Siberia. Investigations of regional tectonics included work on structural geology, stratigraphy and palaeontology, and collecting samples for palaeomagnetic and isotope age studies.

This paper presents new isotope age data from volcanics and related intrusive rocks of the Early Palaeozoic of October Revolution Island and Late Palaeozoic intrusions from Bol'shevik Island and addresses three tasks. The first is to date tuffs from the Early Ordovician strata of October Revolution Island, to get a minimum age for the deformation which caused a regional high-angle unconformity. Secondly, intrusive rocks from central and southern October Revolution Island have been analysed to get more information on the temporal extent of the magmatic episode. Finally, two samples from the Solnechnaya Bay Granite on Bol'shevik Island have been studied for an age comparison with respect to Uralian orogeny, and apparently similar syn- and post-tectonic granites in northern Tajmyr.

2. Bedrock geology

2.a. Stratigraphy and structure

Severnaya Zemlya's bedrock comprises Neoproterozoic to Permian strata (Fig. 2). Neoproterozoic (possibly also Early Cambrian) turbidite successions are overlain by both shallow marine and basinal Cambrian strata. Ordovician shallow water clastic sediments overlie Cambrian rocks with a pronounced angular unconformity and pass up into thick carbonate successions which dominate the Silurian. Siliciclastic (Old Red Sandstone) sedimentation is prevalent throughout the Devonian. These sediments are unconformably overlain by Late Palaeozoic sandstones, the age of these flat-lying strata varying across the archipelago.

Two major unconformities (Fig. 4) exist on October Revolution Island. The Kan'on River Unconformity (Lorenz, Gee & Bogolepova, in press) separates tightly folded rocks of Late Cambrian age from sediments of Tremadocian age, and the related deformation episode is here called the Kan'on River Deformation. The second unconformity separates east-vergent folded and thrust strata as young as Late Devonian in age from late Early Carboniferous to Permian beds and is here called the Severnaya Zemlya Unconformity.

In the following description of the unconformities, the stratigraphic units, following the Russian literature, are referred to as 'svitas'. Our mapping on October Revolution Island suggests that these 'svitas' usually correspond either to formations or groups in the generally accepted international lithostratigraphic nomenclature; however, pending remapping and formal definition of lithostratigraphic units, this paper retains the Russian terminology. Detailed descriptions of the Palaeozoic stratigraphy are to be found in Kaban'kov & Lazarenko (1982) and Gramberg & Ushakov (2000); a summary of the Cambrian stratigraphy is provided by Bogolepova, Gubanov & Raevskaya (2001).

2.a.1. *Kan'on River Unconformity*

The Kan'on River Unconformity (Lorenz, Gee & Bogolepova, in press; Fig. 5) marks the contact between the Late Cambrian Kurchavaya Svita and the Early Ordovician Kruzhilikha Svita in southern and south-central October Revolution Island and is the main subject of this isotope-age study. It was first referred to as an unconformity by Egiazarov (1957), but later as a fault-contact by some authors (Makar'ev, Lazarenko & Rogozov, 1981). Recently, Proskurnin (1999) and, in more detail, Lorenz, Gee & Bogolepova (in press) described the Kan'on River Unconformity. This high-angle unconformity is well exposed in the Kruzhilikha River, Lake Fiordovoe and Kan'on River areas (Fig. 6).

All strata below the Kan'on River Unconformity belong to one stratigraphic unit, the Kurchavaya Svita. According to Makar'ev, Lazarenko & Rogozov (1981),

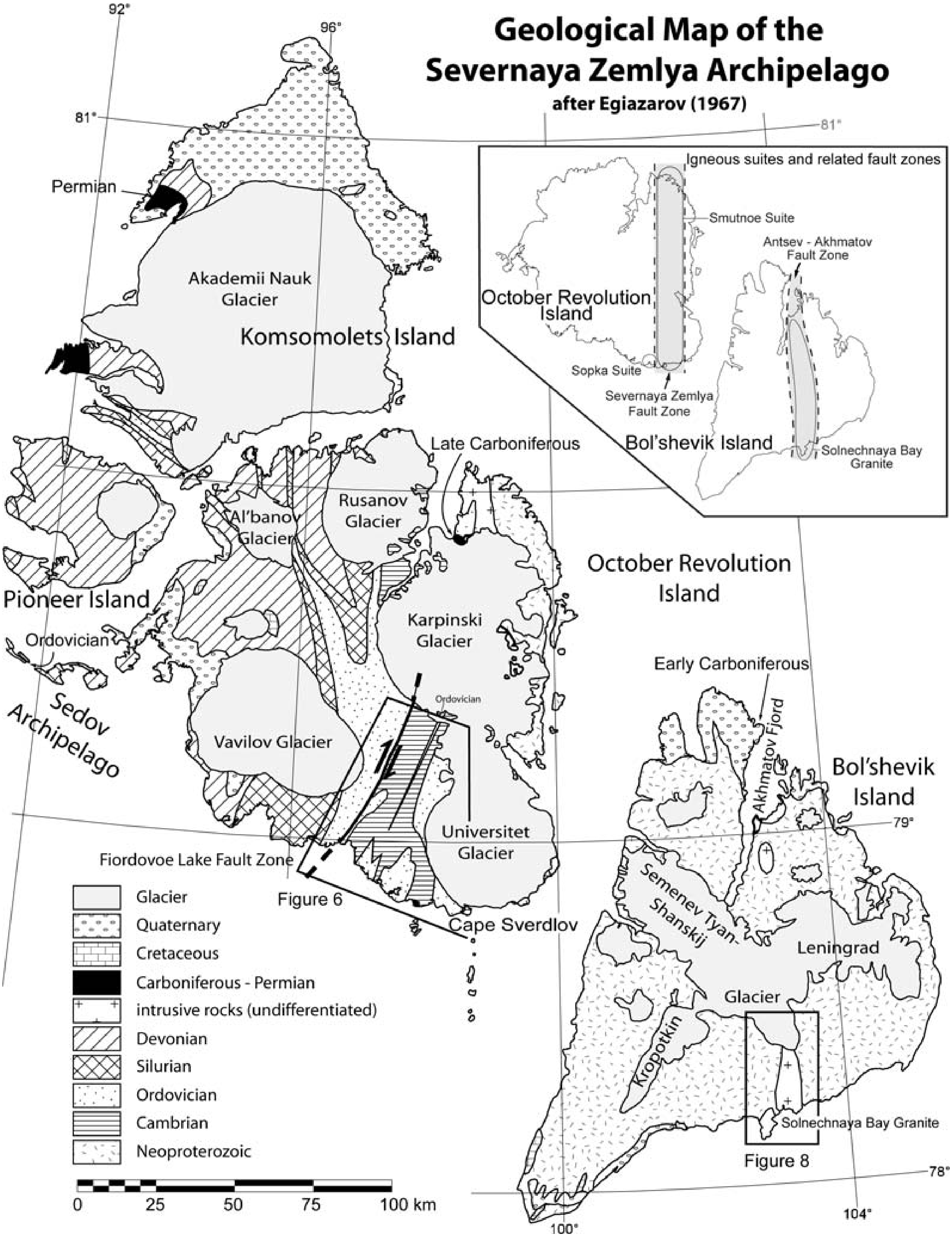

Figure 2. Geological map of the Severnaya Zemlya Archipelago, mainly from Egiazarov (1967). Inset shows the location of intrusive suites which are discussed in this paper (after Proskurnin & Shul'ga, 2000 and V. Proskurnin, pers. comm.).

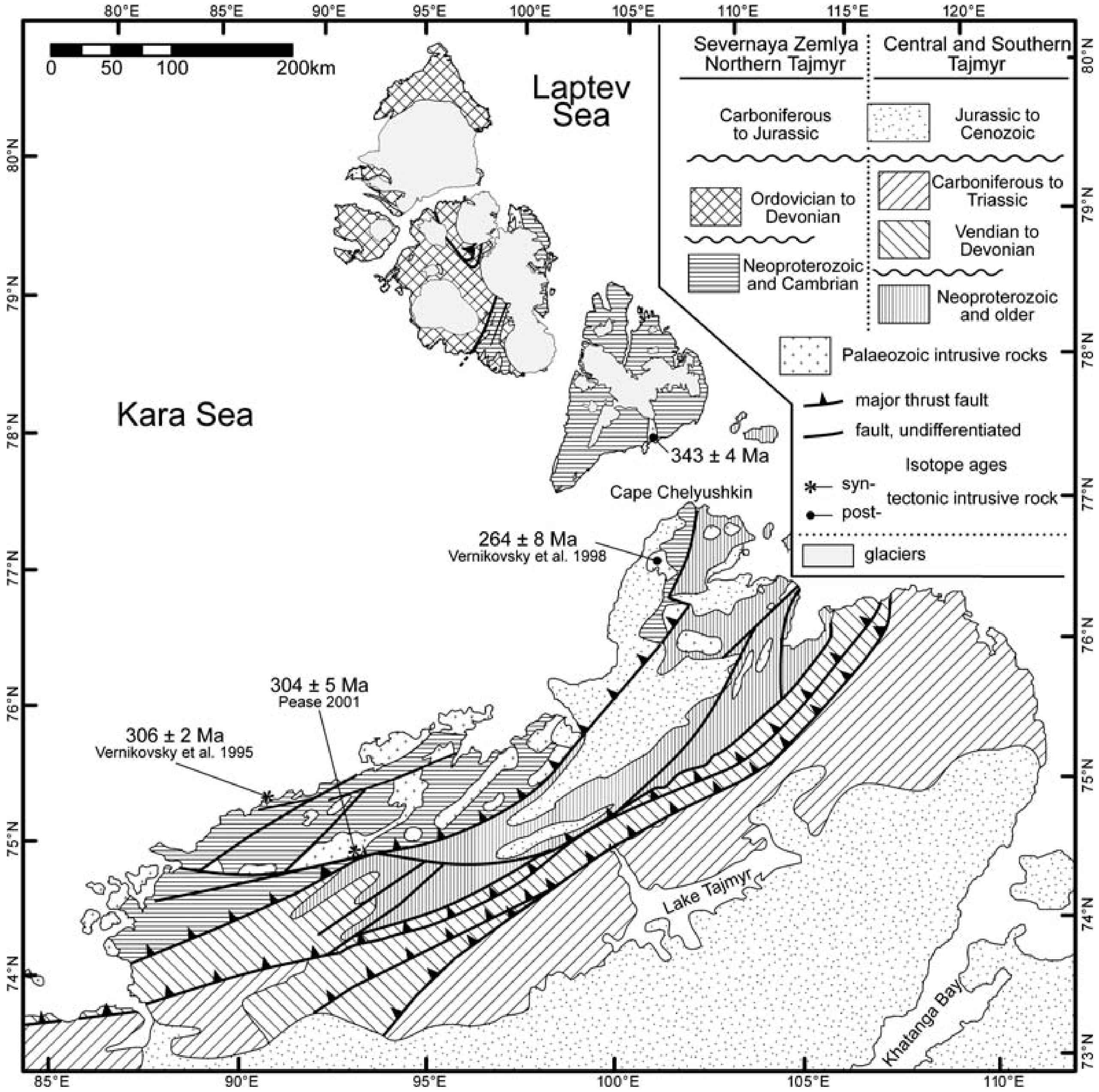

Figure 3. U/Pb and Pb/Pb zircon ages of Carboniferous granitic rocks in the Tajmyr-Severnaya Zemlya area (geological maps simplified from Egiazarov, 1967 and Bezzubtsev *et al.* 1983).

this unit is about 800 m thick, but Lorenz, Gee & Bogolepova (in press) suggested a thickness of at least 2000 m in the Kurchavaya River type area. The Kurchavaya Svita appears in two facies; one is dominated by dark shales with graded sandstone beds and is present in the Kan'on River and Kruzhilikha River areas, and the other is sand- and siltstone dominated and occurs in the Lake Fiordovoe area (Fig. 6). The strata above the unconformity belong to the Kruzhilikha and Ushakov svitas, the latter overlying the former, where it is present. Generally, the basal beds are dominated by coarse-grained and pebbly sandstones and basal conglomerates. Further up, they give way to sandstones and carbonate rocks with a prominent green tuff higher up in the succession. These are overlain by red and green siltstones of the Ushakov Svita, which at Lake Fiordovoe directly overlies the unconformity with a basal conglomerate (Lorenz, Gee & Bogolepova, in press). In this area, multicoloured volcaniclastic sandstones and cyclic evaporites dominate the Ushakov Svita.

In the Kan'on River Area (Fig. 6), the Cambrian and Ordovician strata are folded into the NNE-trending Kan'on River syncline, which is cut by several tributaries to the Kan'on River. In these sections, the western limb exposes a high-angle relationship between W-dipping black shales of the Kurchavaya Svita and the E-dipping basal conglomerates of the Kruzhilikha Svita (Fig. 5). In the steep to overturned

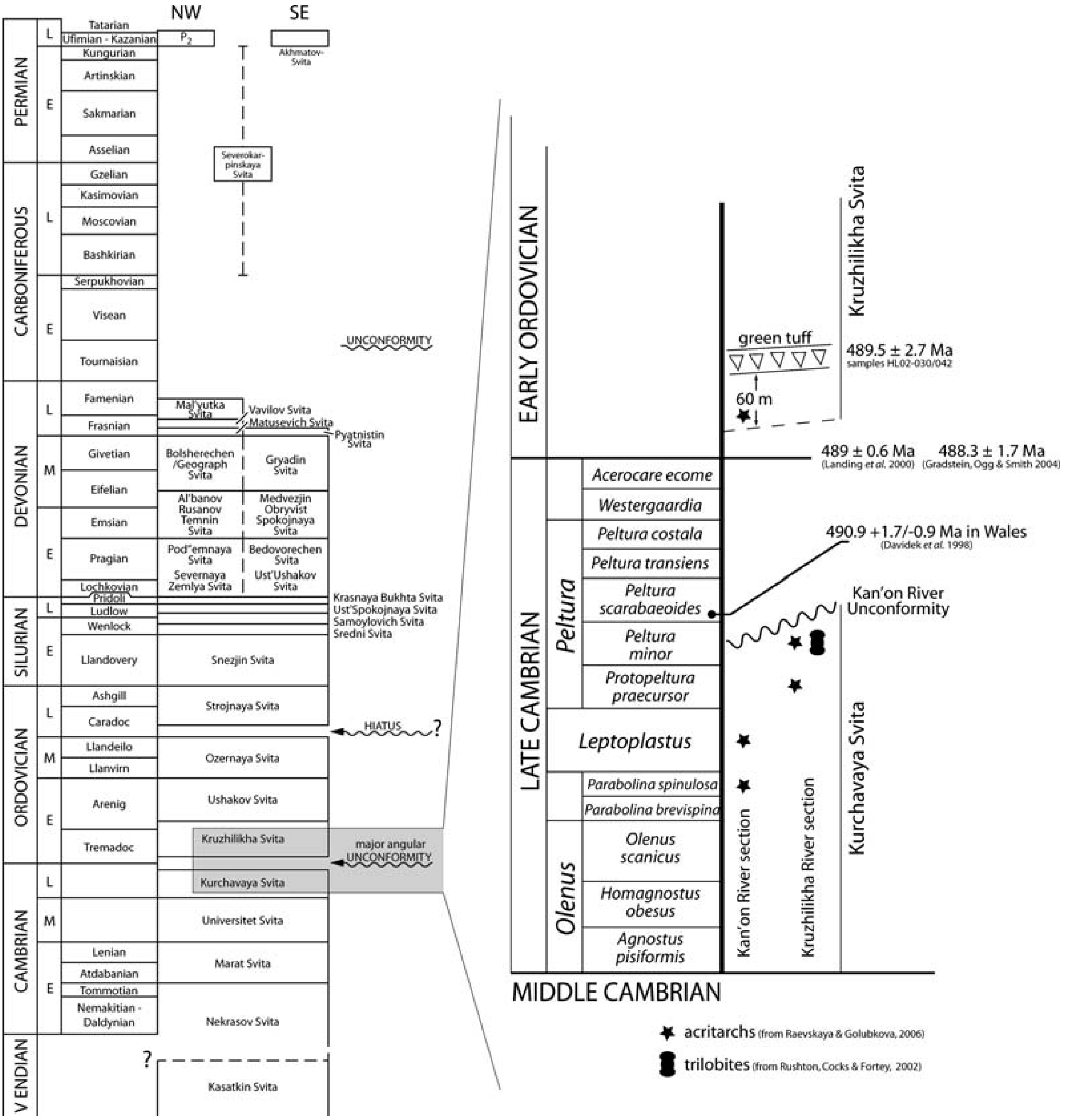

Figure 4. Stratigraphic units of the Severnaya Zemlya archipelago (based on Shul'ga, 2000; time scale after Gradstein, Ogg & Smith, 2004) and enlargement of the Late Cambrian and Early Ordovician (Cambrian divisions after Geyer & Shergold, 2000).

eastern limb, exposed along the Kan'on River itself, tightly folded black shales have axial planes approximately perpendicular to the unconformity and basal Kruzhilikha Svita conglomerates.

About 8 km south of the above-described sections in the Kan'on River canyon, a tributary to the Kruzhilikha River cuts the Kan'on River syncline (Figs 6, 7) and exposes a section in its western limb, where the strata dip at moderate angles eastwards. The basal pebbly and coarse-grained sandstone of the Kruzhilikha Svita is exposed in the eastern part of the section. All overlying rocks are visible in the scree only; the bright green tuff approximately 150 m east of the basal sandstone is almost continuously traceable northwards to the Kan'on River. In this section the basal sandstones are underlain with a low-angle unconformity by an about 300 m thick succession of red, green, violet and grey mudstones, sandstones, marls and limestones (Fig. 7). These rocks have not been reported before and, because of the lack of a name with geographical meaning, are referred to as the River Bend Formation (Fig. 7). The lower boundary of the River Bend Formation is not exposed, but the W-dipping grey shales and sandstones of the Kurchavaya Svita crop out a few hundred metres

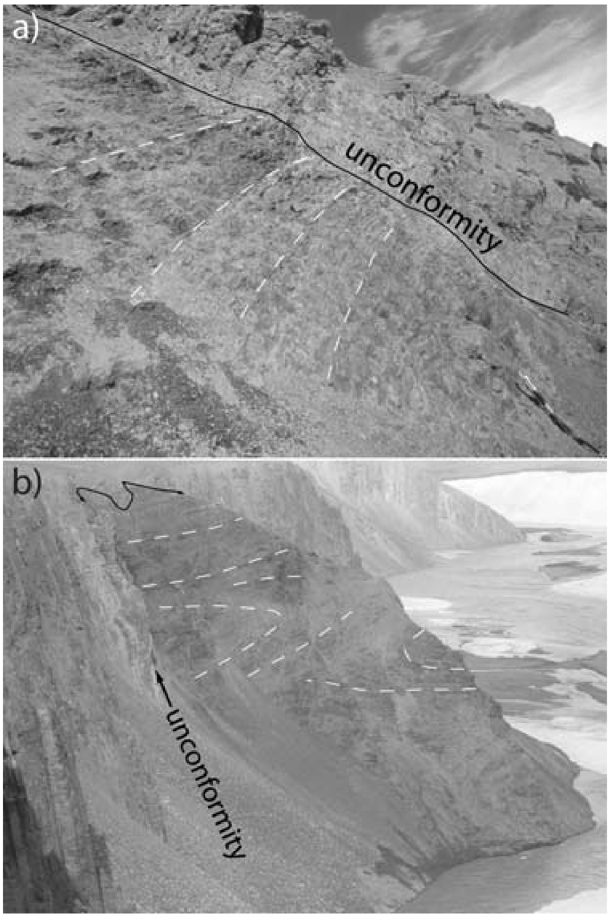

Figure 5. The Kan'on River Unconformity in the Kan'on River area. Section through the (a) western and (b) eastern limbs of the Kan'on River Syncline.

to the west. This and the presence of Tremadocian conodonts in the River Bend Formation (samples K2 and K3, Fig. 7; T. Tolmacheva, pers. comm.) suggest that the major Kan'on River Unconformity is located between the Kurchavaya Svita and the River Bend Formation, and that the low-angle unconformity between this formation and the Kruzhilikha Svita is local.

2.b. Igneous rocks and previous geochronology

Ordovician intrusions rocks on October Revolution Island were previously described by Proskurnin & Shul'ga (2000). They reported that these rocks are concentrated in a 20–30 km wide and more than 100 km long belt between Cape Sverdlov in the south and Rovnaya River in the north, the Smutnoe Suite (Fig. 2). This belt is mostly covered by the Universitet and Karpinski glaciers, but can be traced by a distinct positive magnetic anomaly. Stocks, batholiths and smaller bodies intrude Cambrian and Early Ordovician host rocks. Commonly reported rocks are gabbros, syenites and granites. Volcanic rocks, which are thought to be associated with the intrusions rocks of the Smutnoe Suite, are frequent in the Early Ordovician Kruzhilikha and Ushakov svitas. Proskurnin (1995) interpreted the magmatism as rift-related, occurring along the inferred Severnaya Zemlya Fault Zone (Fig. 2). K–Ar dating resulted in ages between 411 ± 32 Ma to 456 ± 15 Ma (Proskurnin, 1995; Proskurnin & Shul'ga, 2000). Kaplan *et al.* (2001) reported a gabbro from eastern October Revolution Island, which yielded an Ar/Ar amphibole age of 434 ± 2 Ma, and a granite, which gave a U/Pb zircon age of 470 ± 15 Ma.

In the Snezhnaya Bay area of southernmost October Revolution Island, east of the mouth of Kurchavaya River (Fig. 6), the Sopka Suite has been interpreted (Proskurnin & Shul'ga, 2000), on the basis of petrology and geochemistry, to belong to the same intrusive suite as the Solnechnaya Bay Granite on Bol'shevik Island. Quartz-feldspar porphyry sills and associated feeder dykes of the Sopka Suite intrude rocks of the Late Cambrian Kurchavaya Svita.

The Solnechnaya Bay Granite, on southeastern Bol'shevik Island, is exposed in a 10 km wide zone between Solnechnaya Bay in the south (Figs 2, 8) and Akhmatov Fjord in the north (Fig. 2; Proskurnin & Shul'ga, 2000). Results from K–Ar dating range from 292 ± 10 Ma to 439 ± 37 Ma for the same igneous body (Proskurnin & Shul'ga, 2000).

3. New geochronology

The tuff layers and volcaniclastic rocks in the Early Ordovician strata of October Revolution Island have been dated to obtain a minimum age for the Kan'on River Deformation. Intrusive rocks have been analysed to constrain poorly documented earlier dating attempts and their affiliation with the Early Ordovician volcanic rocks. The age of the Solnechnaya Bay granite is important for a comparison with similar rocks from northern Tajmyr and interpretation of the extent of Uralian tectonic activity in Severnaya Zemlya.

3.a. Methods

High spatial resolution zircon U–Pb data were obtained using the Cameca ims1270 secondary ionization mass spectrometer (SIMS) at the Swedish Museum of Natural History (Nordsim facility). Prior to analysis, all grains were imaged by cathodoluminescence in order to reveal their internal structure. The SIMS analytical method closely follows that described in detail by Whitehouse *et al.* (1997) and Whitehouse, Kamber & Moorbath (1999). A ∼ 5 nA O_2^- primary beam at −13 kV illuminated a ∼ 100 µm aperture, producing a ∼ 30 µm (long-axis) elliptical analytical crater. Centring of the ion beam in the field aperture was achieved manually during the first three analytical sessions (March 2004) and incorporated into a fully automated run sequence during the fourth session (October 2004). Sputtered secondary ions with an energy of ∼ +10 kV were admitted into the mass spectrometer operating at a mass resolution (M/ΔM) of 4500, sufficient to resolve Pb isotopes from potential

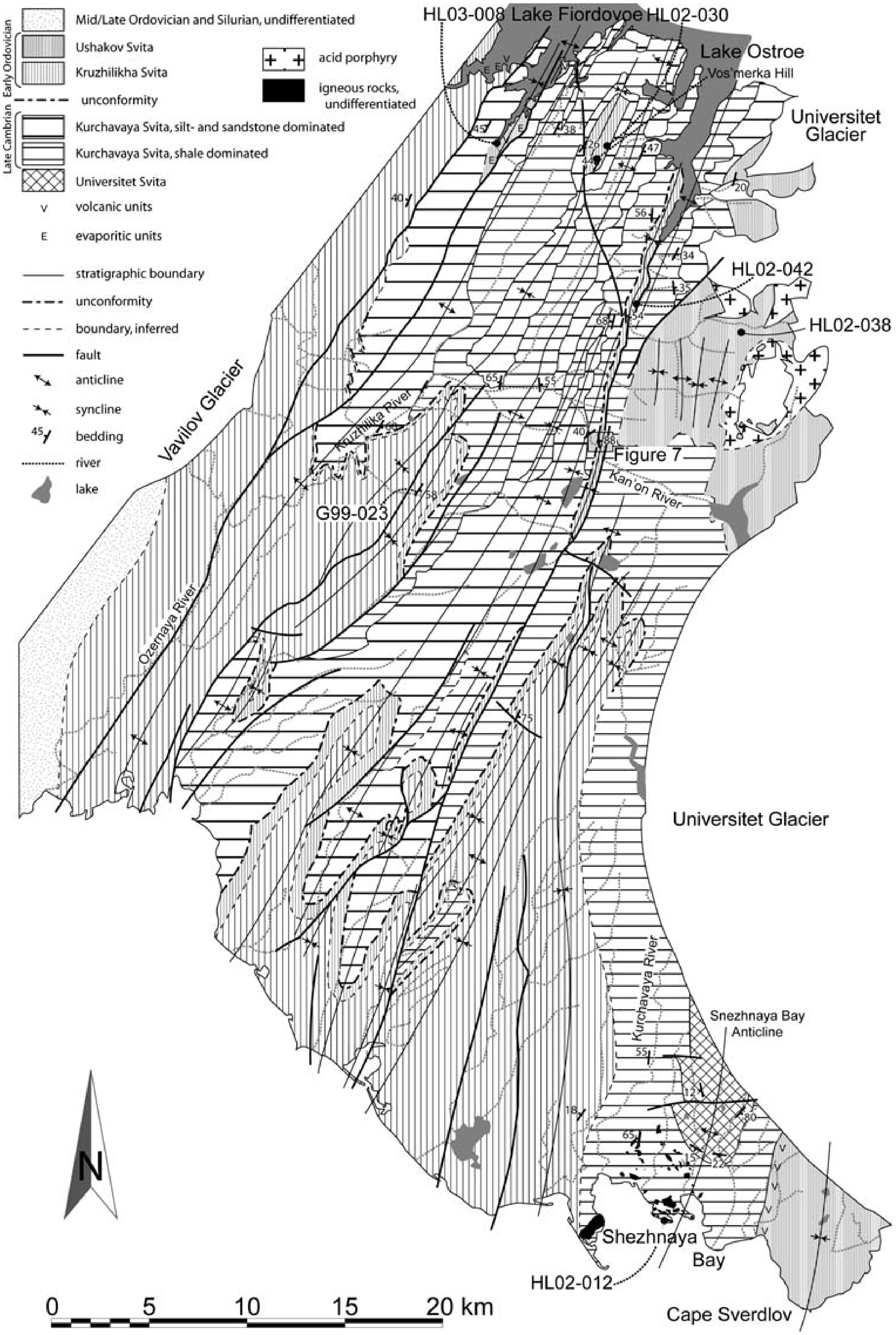

Figure 6. Geological interpretation of southeastern October Revolution Island, based on fieldwork in key areas and successive image interpretation (modified from Lorenz, 2004), with locations of samples. For location of map see Figure 2.

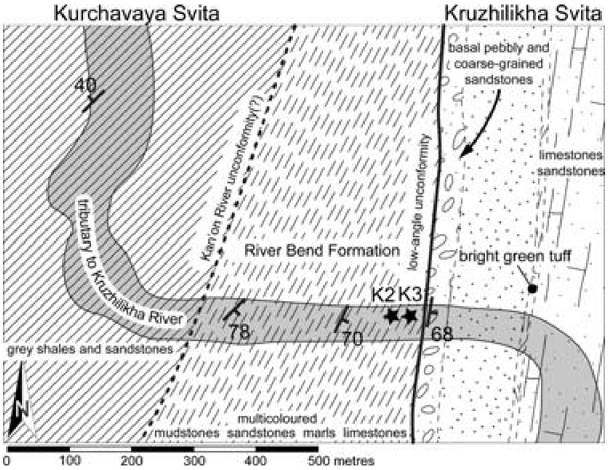

Figure 7. Map of a locality ~ 7 km south of Kan'on River, showing the relationship between the Kurchavaya Svita, the River Bend Formation and the Kruzhilikha Svita. For location of map see Figure 6.

molecular interferences. Mass calibration and energy adjustments were performed automatically during all sessions. Secondary ions were detected using a secondary electron multiplier attached to ion counting electronics with a gated dead-time of 44 ns. Following a 120 s pre-sputter to remove the Au coating and centring routines, the total acquisition time was 660 s per sample. Analyses of sample zircons were interspersed with analyses of the 1065 Ma Geostandards 91500 reference zircon (Wiedenbeck *et al.* 1995) and the Pb/U age calculation was performed using an empirical power law relationship ($y = ax^b$) between Pb/U and UO_2/U ratios (Fig. 9).

For Phanerozoic zircons such as those in the present study, the $^{206}Pb/^{238}U$ ages are generally more reliable than the $^{207}Pb/^{206}Pb$ ages, which are subject to rapidly increasing error magnification in converting from ratio to age towards younger ages. The $^{206}Pb/^{238}U$ ages, however, may be highly sensitive to the calibration slope determined from repeated measurements of the standard during an analytical session, particularly when the UO_x/U value for sample zircons falls outside the range defined by standards. Earlier studies from this laboratory (e.g. Whitehouse, Kamber & Moorbath, 1999) have assumed a constant slope ($b = 1.26$) in the power law relationship, in accord with similar assumptions in Pb/U v. UO/U space (see discussion and references in Ireland & Williams, 2003), but observations that the slope changes over a range in b from ~ 1.2 to 1.8 (possibly related to slow drift in the plasma conditions of the duoplasmatron source (e.g. Black & Jagodzinski, 2003) and/or erosion of the primary beam aperture, changing primary beam density) indicate that an optimized slope is desirable for each analytical session. Even for cases such as the present study, in which the range of unknown UO_x/U ratios mostly falls within that defined by the standards for a given session (Fig. 9), changes in slope yield small, but significant, changes in age. For this reason, we have applied the best fit calibration slope (the slope that yields lowest external error on the standard Pb/U ratios) for each analytical session, an approach that is consistent with recent SIMS U–Pb studies of Phanerozoic zircons (e.g. Compston, 2000; Compston, Wright & Toghill, 2002).

3.b. Samples and results

Tables 1 to 3 present the data of the U–Th–Pb ion-microprobe analyses. Sample descriptions of the analysed rocks and results are presented in the next sections. All age calculation results are quoted with 35% confidence level uncertainties.

3.b.1. *Intrusive rocks from October Revolution Island*

HL02-012, quartz-feldspar porphyry (N 78.810189°, E 98.114415°). This sample is from the subvolcanic sills of the Sopka Suite in the Snezhnaya Bay area, southeastern October Revolution Island, east of the mouth of Kurchavaya River (Fig. 6).

Zircons are euhedral and clear. Growth zoning is well-developed, cores are common and visible in the optical microscope. Zircons are 200–350 μm long and have few cracks and inclusions. Eighteen spots (Figs 10a, 11) have been analysed. Five spots are interpreted to have suffered Pb loss. Three spots from cores of zircons yield ages between *c.* 540 and 560 Ma, interpreted as the age of xenocrysts. The remaining ten spots give an age of 488.7 ± 3.9 Ma for these intrusive rocks.

HL02-038, plagio-granite (N 79.226001°, E 98.245483°). This sample is from an intrusion into sand- and siltstones of the Early Ordovician Ushakov Svita (Fig. 6).

The euhedral zircons have a clear to yellow-brown colour and show little to no growth zoning. Crystals are free of inclusions, but show abundant cracks. Zircons are about 200 μm long and have been analysed in ten spots (Figs 10b, 11). Two of the analyses plot to the left of the regression line. Possibly, the common Pb composition of the analysed zircons differs (perhaps caused by the abundant cracks) from the estimation according to Stacey & Kramers (1975) model for the terrestrial lead isotopic composition. The latter has been used for common Pb correction in this study (cf. Whitehouse *et al.* 1997). The remaining eight spots yield an age of 474.4 ± 3.5 Ma.

3.b.2. *Volcanic rocks from October Revolution Island*

G99-023, white rhyolite (N 79.145278°, E 097.441944°). This sample is from a rhyolite layer within the Ushakov Svita of the Kruzhilikha River area. The stratigraphic thickness between the Kan'on River

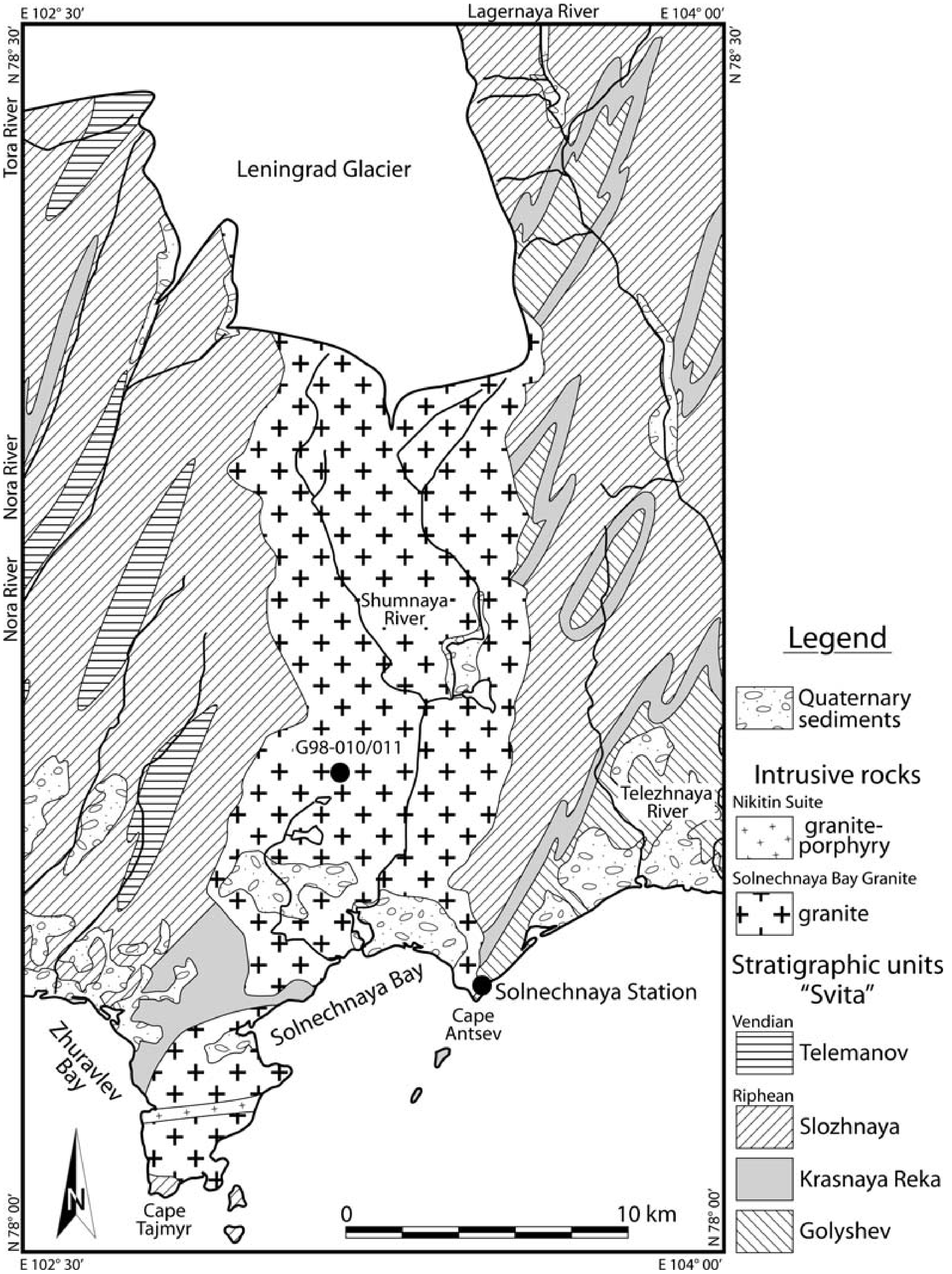

Figure 8. Geological map of southeastern Bol'shevik Island (after Markovsky, 1988), with location of samples. For location of map see Figure 2.

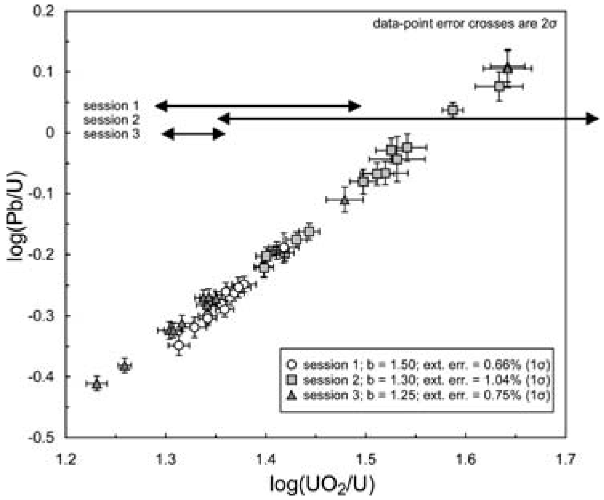

Figure 9. Plot of log(Pb/U) v. log(UO_2/U) for the Geostandards 91500 reference zircon from three analytical sessions in March 2004. Data from the October 2004 session have been omitted for clarity. b refers to the optimum calibration slope for each session assuming a power law relationship, $y = ax^b$; the slightly higher slope for session 1 is evident in the plotted data. Horizontal double ended arrows show the range of UO_2/U ratios obtained from sample zircons in each of the three sessions.

Unconformity and the tuff layer is estimated to be a few hundreds of metres (section is only partially exposed).

Zircons are euhedral, elongated and have a brownish-yellow colour. Growth zoning is well-developed. Zircons are at least 200 μm long, have no cracks, only few inclusions and have been analysed in thirteen spots (Figs 10c, 12). Three spots are interpreted to have suffered Pb loss and were excluded from the age calculation. The age calculated from the remaining ten spots is 482.0 ± 4.2 Ma.

HL02-030, bright green rhyolite (N 79.3116975°, E 97.914036°). From the top of Vos'merka Hill (Fig. 6), a ridge continues northwards; along its crest and parts of the western slope, an approximately 5 m thick bright green layer crops out. This unit can be recognized as a stratigraphical marker within the Kruzhilikha Svita in the areas south of Lake Fiordovoe and Lake Ostroe. The stratigraphic thickness between the Kan'on River Unconformity and the tuff layer is difficult to estimate at this location.

Zircons are euhedral and have a pinkish colour. Growth zoning is well-developed, and cracks and inclusions are abundant. Most of the strongly elongated zircons are broken and the analysed pieces have a length of 150–250 μm. Four of 17 analyses show signs of Pb loss; one analysis was rejected in the error-weighted average calculation. The remaining 12 yield an age of 491.0 ± 3.2 Ma.

HL02-042, bright green rhyolite (N 79.270456°, E 98.168937°). Along the lower reaches of Kan'on River (Fig. 6) and at least 15 km southwards, the bright green tuff, corresponding to HL02-030, can be

Table 1. U–Th–Pb data for ion-microprobe spot-analyses on intrusive rocks from October Revolution Island

Analysis	U (ppm)	Th (ppm)	Pb (ppm)	Th/U meas.	f_{206} (%)	^{207}Pb/^{206}Pb	±σ (%)	^{238}U/ ^{206}Pb	±σ (%)	^{206}Pb/^{238}U age (Ma) (^{207}Pb corr.)
HL02-012										
n1441-1	119	12	50	0.42	{0.19}	0.0578	1.1	12.37	1.6	500.7 ± 8.2
n1441-2	171	16	69	0.40	{0.09}	0.0566	1.5	12.57	1.6	493.7 ± 8.2
n1441-3	138	12	76	0.54	1.32	0.0626	2.5	13.01	1.7	473.6 ± 8.1
n1441-4	174	16	48	0.27	{0.18}	0.0583	1.1	12.81	1.6	483.4 ± 8.0
n1441-5	176	16	67	0.38	{0.13}	0.0580	1.1	12.72	1.6	486.8 ± 8.0
n1441-6[a]	468	50	163	0.34	0.17	0.0601	0.5	10.86	1.6	566.6 ± 9.3
n1441-7	147	14	71	0.48	{0.14}	0.0569	1.3	12.62	1.6	491.5 ± 8.1
n1441-8[a]	529	53	113	0.21	{0.08}	0.0594	0.5	11.32	1.6	544.6 ± 9.0
n1441-9	488	47	265	0.54	{0.08}	0.0578	0.6	12.71	1.6	487.6 ± 8.0
n1441-10	49	4	21	0.43	1.91	0.0620	2.6	12.55	1.8	491.0 ± 8.9
n1441-11	107	10	35	0.32	{0.12}	0.0569	1.5	12.96	1.6	478.8 ± 7.9
n1441-12	270	25	117	0.43	{0.16}	0.0576	1.0	12.71	1.6	487.8 ± 8.0
n1441-13	238	20	166	0.69	0.72	0.0618	0.9	14.68	1.6	421.1 ± 7.0
n1441-14	149	13	59	0.39	0.83	0.0603	1.4	13.09	1.6	472.0 ± 7.8
n1441-15	282	28	180	0.63	0.24	0.0576	0.9	12.74	1.6	486.3 ± 8.0
n1441-16[a]	568	63	204	0.36	{0.06}	0.0593	0.7	10.62	1.7	579.7 ± 9.6
n1441-17	100	9	38	0.37	{0.30}	0.0592	1.4	13.13	1.6	471.5 ± 7.8
n1441-18	112	10	56	0.50	0.91	0.0646	2.4	13.79	1.7	446.1 ± 7.5
HL02-038										
n1437-1	137	13	119	0.86	0.62	0.0562	2.1	13.25	0.9	469.0 ± 4.6
n1437-2	2510	413	7654	3.05	8.94	0.1256	1.1	10.75	1.0	524.6 ± 8.5
n1437-3	128	14	149	1.16	0.51	0.0570	1.5	12.90	1.0	480.9 ± 4.8
n1437-4	84	8	58	0.68	0.76	0.0588	2.4	12.97	0.9	477.2 ± 4.7
n1437-5	100	10	83	0.83	0.63	0.0589	2.3	13.24	1.0	467.9 ± 4.7
n1437-6	92	9	67	0.72	0.62	0.0593	2.4	12.97	0.9	476.9 ± 4.7
n1437-7	98	9	75	0.76	0.90	0.0564	1.8	13.04	0.9	476.1 ± 4.6
n1437-8	1014	122	1434	1.41	6.21	0.1017	0.9	11.66	0.9	501.0 ± 6.2
n1437-9	165	16	133	0.80	0.39	0.0578	1.7	13.00	1.0	476.7 ± 4.7
n1437-10	69	6	49	0.70	0.92	0.0576	2.6	13.21	1.1	469.6 ± 5.2

a – xenocryst.

Table 2. U–Th–Pb data for ion-microprobe spot-analyses on volcanic rocks from October Revolution Island

Analysis	U (ppm)	Th (ppm)	Pb (ppm)	Th/U meas.	f_{206} (%)	^{207}Pb/^{206}Pb	±σ (%)	^{238}U/ ^{206}Pb	±σ (%)	^{206}Pb/^{238}U age (Ma) (^{207}Pb corr.)
G99-023										
n1440-1	464	46	312	0.67	0.37	0.0595	1.4	12.61	0.9	490.1 ± 4.8
n1440-2	416	40	287	0.69	1.79	0.0709	0.9	12.69	0.9	480.1 ± 4.8
n1440-3	150	14	87	0.58	0.74	0.0584	1.8	12.91	1.0	479.8 ± 4.7
n1440-4	848	83	607	0.71	5.74	0.1012	1.0	12.22	1.7	478.9 ± 9.0
n1440-5	586	53	268	0.45	0.11	0.0579	1.6	13.02	1.7	475.9 ± 8.1
n1440-6	534	45	313	0.58	3.25	0.0797	1.6	13.92	1.7	433.6 ± 7.6
n1440-7	1126	77	857	0.76	11.27	0.1361	1.4	16.14	1.7	347.2 ± 8.0
n1440-8	167	15	62	0.37	1.74	0.0657	2.8	12.97	1.7	473.1 ± 8.2
n1440-9	208	20	108	0.51	0.73	0.0571	2.2	12.74	1.7	486.9 ± 8.3
n1440-10	183	17	86	0.47	0.55	0.0586	2.3	12.79	1.7	483.9 ± 8.3
n1440-11	351	31	131	0.37	1.73	0.0639	2.2	12.93	1.7	475.7 ± 8.1
n1440-12	662	59	419	0.63	4.78	0.0868	1.4	13.07	1.8	457.0 ± 8.5
n1440-13	688	67	610	0.88	0.90	0.0609	1.7	13.05	1.7	473.2 ± 8.1
HL02-030/042										
n1434-1	294	29	175	0.59	{0.16}	0.0588	1.0	12.82	0.9	482.7 ± 4.7
n1434-2	605	50	334	0.55	7.99	0.1169	0.8	13.37	0.9	429.0 ± 6.3
n1434-3	569	58	430	0.75	0.12	0.0574	0.7	12.59	0.9	492.3 ± 4.7
n1434-4	485	47	209	0.43	{0.09}	0.0566	0.8	12.46	1.0	497.9 ± 4.9
n1434-5	634	66	508	0.80	0.11	0.0569	0.7	12.51	0.9	495.7 ± 4.8
n1434-6	573	57	311	0.54	{0.07}	0.0569	0.8	12.36	0.9	501.8 ± 4.8
n1434-7	131	13	80	0.60	{0.15}	0.0578	1.7	12.56	0.9	493.1 ± 4.8
n1434-8	434	38	218	0.50	1.60	0.0688	0.9	13.47	0.9	454.0 ± 4.5
n1434-9	672	69	461	0.68	5.04	0.0996	0.6	11.86	0.9	494.0 ± 6.0
n1434-10	676	57	404	0.59	18.86	0.2038	1.0	11.55	1.0	435.9 ± 13.8
n1434-11	769	76	618	0.80	2.25	0.0730	1.1	12.64	0.9	480.6 ± 4.8
n1434-12	722	68	350	0.48	0.50	0.0599	0.7	12.64	0.9	488.7 ± 4.7
n1434-13	485	50	362	0.74	0.31	0.0584	0.8	12.56	1.0	492.6 ± 4.8
n1434-14	485	50	362	0.74	0.31	0.0584	0.8	12.56	1.0	492.6 ± 4.8
n1434-15	421	43	319	0.75	0.16	0.0577	0.9	12.50	0.9	495.4 ± 4.8
n1434-16	375	37	239	0.63	0.56	0.0617	1.2	12.59	0.9	489.6 ± 4.8
n1434-17	540	54	339	0.62	0.60	0.0600	0.8	12.52	0.9	493.5 ± 4.8
n1435-1	373	27	129	0.34	{0.54}	0.0610	1.3	16.07	1.0	385.7 ± 3.8
n1435-2	228	21	100	0.43	{0.18}	0.0566	1.8	12.89	0.9	481.6 ± 4.7
n1435-3	271	26	124	0.45	{0.19}	0.0572	1.1	12.62	0.9	491.2 ± 4.8
HL03-008										
n1436-1	780	74	424	0.54	{0.04}	0.0564	0.6	13.01	0.9	477.5 ± 4.6
n1436-2	456	42	141	0.30	{0.04}	0.0556	0.9	12.69	0.9	489.5 ± 4.8
n1436-3	386	35	194	0.50	0.21	0.0579	0.9	13.43	0.9	461.7 ± 4.5
n1436-4[a]	221	26	143	0.64	4.29	0.0905	0.8	10.21	0.9	578.9 ± 6.4
n1436-5	591	42	306	0.51	0.95	0.0622	0.8	16.65	0.9	372.0 ± 3.6
n1436-6	193	18	108	0.56	{0.08}	0.0571	1.3	13.23	0.9	469.3 ± 4.6
n1436-7	223	21	99	0.44	{0.14}	0.0568	1.2	12.61	0.9	492.1 ± 4.8
n1436-8	1077	48	717	0.66	0.98	0.0658	0.7	25.81	0.9	240.4 ± 2.4
n1436-9	957	67	535	0.55	0.42	0.0601	0.7	16.68	0.9	372.5 ± 3.6
n1436-10	96	9	60	0.63	{0.16}	0.0582	1.7	12.95	1.0	478.3 ± 4.7
n1436-11	79	7	36	0.45	{0.18}	0.0560	2.2	13.26	1.1	468.7 ± 5.1
n1436-12	837	78	360	0.43	0.49	0.0634	0.5	12.53	0.9	491.0 ± 4.8
n1436-13	895	73	500	0.55	0.37	0.0600	0.6	14.68	0.9	422.2 ± 4.1
n1436-14	308	29	141	0.45	{0.15}	0.0581	1.1	12.74	1.0	486.3 ± 4.8
n1436-15	311	28	137	0.43	0.44	0.0576	1.7	12.98	1.1	477.8 ± 5.4
n1436-16	1617	84	1992	1.23	2.28	0.0763	0.7	24.23	0.9	252.4 ± 2.7

a – xenocryst.

followed in outcrop and scree. It has been sampled in the eastern limb of the Kan'on River syncline, where this stratigraphic marker lies about 60 m above the Kan'on River Unconformity (Lorenz, Gee & Bogolepova, in press).

In contrast to HL02-030, this sample yielded only a few zircons, but with the same physical properties, and individual analyses are within the same age range (Table 2, Fig. 12). Therefore the analyses from both samples have been used to calculate a single age for the green tuff. Five out of twenty spot analyses (including both samples) show signs of Pb loss. From the remaining 16 analyses, one was rejected in the error-weighted average calculation. Fourteen (whereof two from HL02-042) analyses give an age of 489.5 ± 2.7 Ma (Figs 10d, 12).

HL03-008, red volcaniclastic sandstone (N 79.309789°, E 97.607569°). At the southern tip of Lake Fiordovoe (Fig. 6), the Kan'on River Unconformity is overlain by volcaniclastic strata of the Early Ordovician Ushakov Svita. This sample was collected approximately 15 m above the unconformity.

Table 3. U–Th–Pb data for ion-microprobe spot-analyses on intrusive rocks from Bolshevik Island

Analysis	U (ppm)	Th (ppm)	Pb (ppm)	Th/U meas.	f_{206} (%)	$^{207}Pb/^{206}Pb$	±σ (%)	$^{238}U/^{206}Pb$	±σ (%)	$^{206}Pb/^{238}U$ age (Ma) (^{207}Pb corr.)
G98-010										
n1438-1	349	20	232	0.66	{0.10}	0.0545	1.5	20.50	0.9	306.2 ± 3.0
n1438-2	341	21	188	0.55	0.64	0.0587	1.6	18.79	1.0	331.8 ± 3.3
n1438-3	250	17	184	0.73	0.72	0.0546	1.7	17.97	1.0	348.5 ± 3.5
n1438-4	232	15	102	0.44	{0.34}	0.0540	1.9	18.62	1.0	336.8 ± 3.4
n1438-5	123	8	76	0.62	1.12	0.0542	2.5	18.42	1.0	340.2 ± 3.5
n1438-6	334	21	153	0.45	0.43	0.0542	1.5	18.44	0.9	340.0 ± 3.3
n1438-7	326	20	109	0.33	0.43	0.0530	1.6	18.31	0.9	342.9 ± 3.3
n1438-8	311	20	152	0.49	0.44	0.0539	2.5	18.32	1.0	342.3 ± 3.7
n1438-9	193	12	78	0.40	0.70	0.0544	2.2	17.84	1.0	351.2 ± 3.5
n1438-10	232	15	100	0.43	0.42	0.0530	1.8	18.04	1.0	347.8 ± 3.6
n1438-11	224	15	130	0.58	0.47	0.0543	1.6	18.32	1.0	342.1 ± 3.4
n1438-12	291	14	235	0.80	1.90	0.0636	2.2	23.53	1.0	264.1 ± 2.7
G98-011										
n1439-1	346	22	160	0.46	{0.17}	0.0526	1.3	18.22	1.0	344.7 ± 3.5
n1439-2	511	35	344	0.67	{0.14}	0.0531	1.3	18.32	1.0	342.6 ± 3.4
n1439-3	345	22	126	0.36	0.25	0.0551	1.5	18.40	1.0	340.3 ± 3.4
n1439-4	250	16	149	0.59	1.24	0.0586	1.8	19.11	1.0	326.4 ± 3.3
n1439-5	199	12	72	0.36	0.49	0.0560	1.9	18.62	1.1	335.9 ± 3.7
n1439-6	233	14	95	0.40	0.66	0.0568	2.1	18.55	1.0	336.8 ± 3.5
n1439-7	367	25	254	0.69	0.31	0.0546	1.5	18.39	0.9	340.7 ± 3.3
n1439-8	301	19	121	0.40	0.51	0.0517	1.5	17.93	1.0	350.5 ± 3.5
n1439-9	195	13	98	0.50	0.46	0.0544	1.8	18.00	1.0	348.0 ± 3.5

The brown to pink coloured zircons are edge- to well-rounded. All zircons show well-developed crystal zoning; many have cracks, few have inclusions. Zircons are 100–200 μm long and 16 spots were analysed (Figs 10e, 13). Eight zircons have suffered Pb loss; for five of them this loss is substantial. Two analyses plot to the left of the regression line. One is interpreted to be a discordant xenocryst, the other age is near concordant and may relate to the earlier volcanic activity, as is documented in samples HL02-030/042. An age of 482.2 ± 6.1 Ma has been calculated from six analyses.

3.b.3. Solnechnaya Bay Granite, Bol'shevik Island

G98-010 and G98-011, granite (no coordinates available). On southeastern Bol'shevik Island, the Solnechnaya Bay Granite is exposed in an area of about 10 × 20 km (Figs 2, 8), in the north covered by the Leningrad Glacier and, in the south, continuing into Solnechnaya Bay. It is apparently undeformed, cutting the folds and other structures in the Neoproterozoic country rock (Fig. 8).

Both samples contain euhedral, mostly elongated and slightly pinkish zircons. The analysed zircons are 150–200 μm in length and have only a few cracks and inclusions. They are well zoned and, in some cases, contain cores. Twelve spots have been analysed on zircons from sample G98-010 (Figs 10f, 14). Three spots are interpreted to have suffered Pb loss. The remaining nine analyses yield an age of 342.0 ± 3.6 Ma. From sample G98-011 (Figs 10f, 14), one of nine analysed spots on zircon is excluded from the age-calculation due to Pb loss. The remaining eight analyses give an age of 343.5 ± 4.1 Ma for the granite.

4. Discussion

4.a. Implications for the development of the Kan'on River Unconformity

The presence of the River Bend Formation, south of the Kan'on River, suggests that deposition across the Kan'on River Unconformity began in the southeast. A local unconformity developed before the subsequent deposition of the Kruzhilikha Svita. The latter oversteps the River Bend Formation and was also deposited directly on the Kan'on River Unconformity in the Kruzhilikha and Kan'on River areas, while the Cambrian bedrock was still exposed in the Lake Fiordovoe area. In the latter, the Ushakov Svita is inferred to have been deposited directly onto the unconformity with strata similar to the evaporite-bearing sediments of central October Revolution Island.

Determination of the age of the Kan'on River Unconformity and the related period of deformation, for correlation with areas outside the North Kara Terrane and for interpretation of its tectonic significance, is based on both palaeontological and isotope-age dating. The youngest strata underlying the Kan'on River Unconformity are of Late Cambrian age (Fig. 4). Acritarchs are correlated to the *Parabolina spinulosa* to *Leptoplastus* zones of Baltica in the Kan'on River and Kurchavaya River-Snezhnaya Bay areas and to the *Protopeltura praecursor* to *Peltura minor* zones in the Kruzhilikha River area (Raevskaya & Golubkova, 2006). Trilobite identifications support this correlation (Rushton, Cocks & Fortey, 2002). Overlying strata of the Kruzhilikha Svita at Kan'on River, Snezhnaya Bay and Vos'merka Hill have been assigned to the Tremadocian using acritarchs (Raevskaya &

Figure 10. (a–f) Cathodoluminescence images of zircons. Analysed spots are marked by an ellipse.

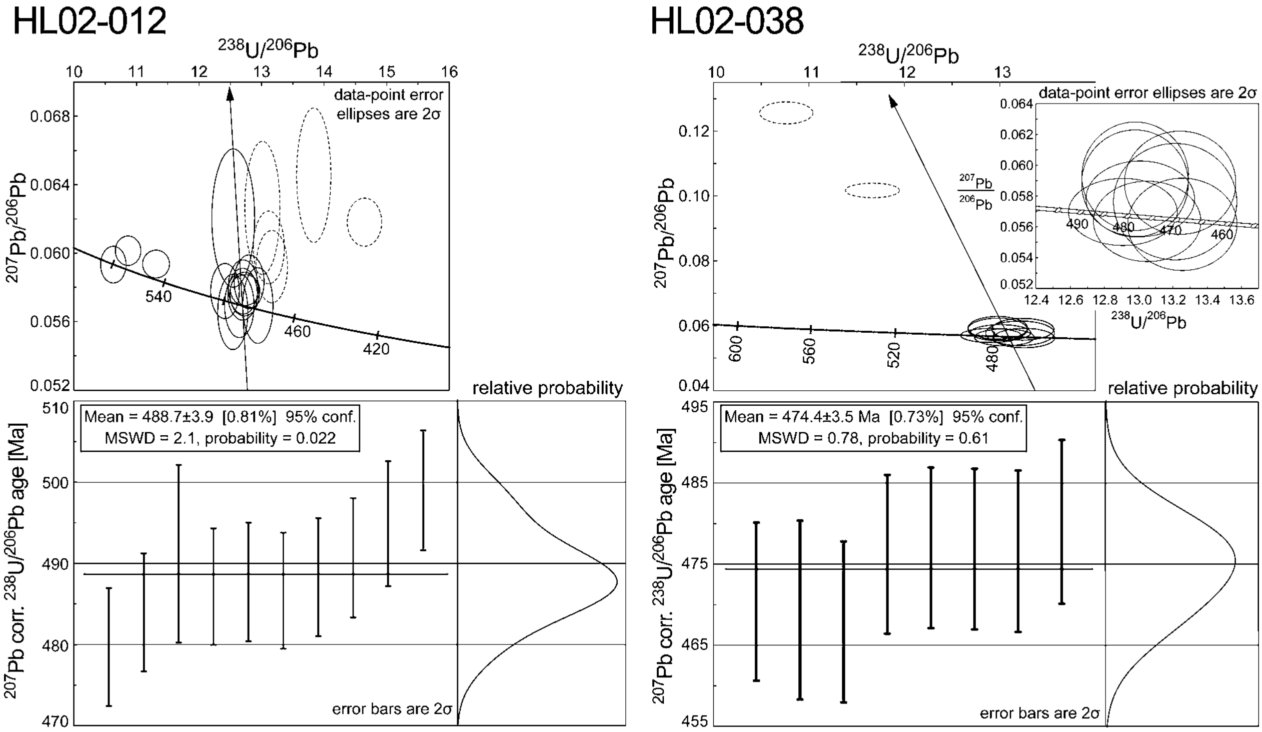

Figure 11. Inverse Concordia plot, calculation of age and relative probability plot for intrusive rocks on October Revolution Island. Analyses whose error ellipses are shown with a broken line in the inverse Concordia plot were excluded from age calculation. The regression lines are plotted for orientation and point towards present-day common Pb (according to the model of Stacey & Kramers, 1975).

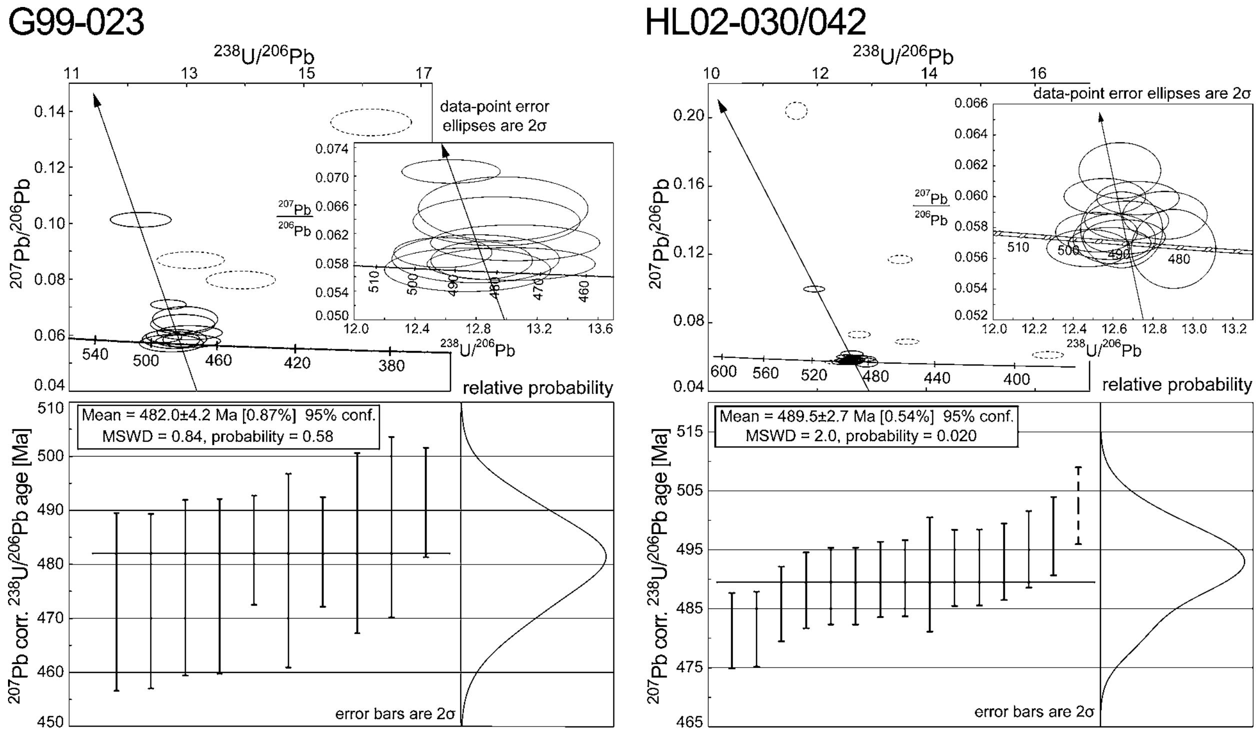

Figure 12. Inverse Concordia plot, calculation of age and relative probability plot for volcanic rocks on October Revolution Island. Analyses whose error ellipses are shown with a broken line in the inverse Concordia plot were excluded from age calculation. Analyses which are shown with a broken line in the age calculation have been statistically rejected during the calculation of the error-weighted average (cf. Ludwig, 2003). The regression lines are plotted for orientation and point towards present-day common Pb (according to the model of Stacey & Kramers, 1975).

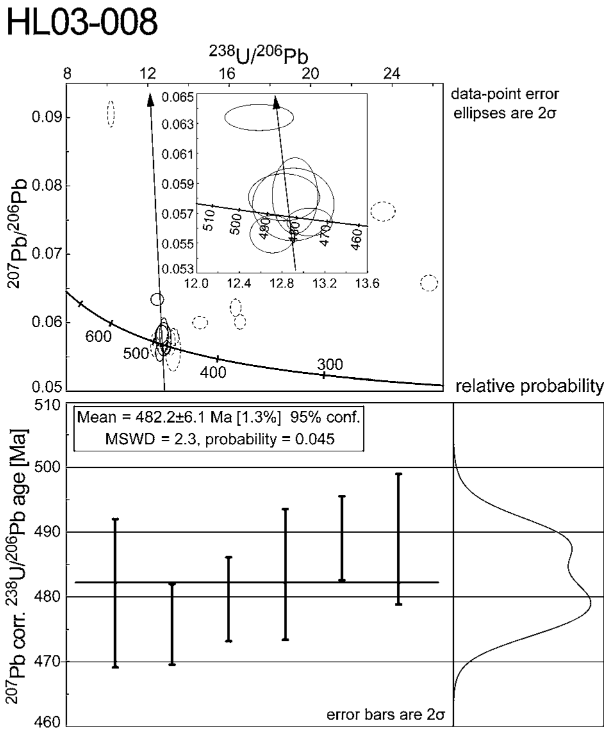

Figure 13. Inverse Concordia plot, calculation of age and relative probability plot for volcanic rocks on October Revolution Island, continued from Figure 12.

Golubkova, 2006), and conodonts (samples K2 and K3, Fig. 7) imply a similar age for the River Bend Formation (T. Tolmacheva, pers. comm.). These data allow the development of the Kan'on River Unconformity during an interval from and including the *Peltura scarabaeoides* zone of the Late Cambrian into the Early Tremadocian.

Few radiometric age estimates of the Late Cambrian trilobite zones exist. Davidek *et al.* (1998) reported an age of 490.9$^{+1.7}_{-0.9}$ Ma from a volcanic ash bed within the lower part of the *Peltura scarabaeoides* zone at Ogof-ddû, Tremadocian Bay, in Wales (Eastern Avalonia). This bed is 2 m above the highest trilobites of the *Peltura minor* zone, 1 m above the lowest trilobites of the *Peltura scarabaeoides* zone, 0.6 m into the second and 3–4 m below the third of four subzones of the *Peltura scarabaeoides* zone. The *Peltura scarabaeoides* zone of Baltica was used for the description of the stratigraphy on October Revolution Island (Bogolepova, Gubanov & Raevskaya, 2001; Rushton, Cocks & Fortey, 2002; Raevskaya & Golubkova, 2006). It is considered to have the same duration as the *Peltura scarabaeoides* zone in Eastern Avalonia (Geyer & Shergold, 2000). It implies that the youngest Cambrian (*Protopeltura praecursor* to *Peltura minor* zones) rocks directly beneath the unconformity, collected in the Kruzhilikha River section, are a little older than Davidek *et al.*'s (1998) age (above). This is the best estimate for a maximum age for the interruption of deposition and beginning of the Kan'on River Deformation.

The age of the base of the Tremadocian is important for the estimation of the time-equivalent of the missing Late Cambrian strata on October Revolution Island. For

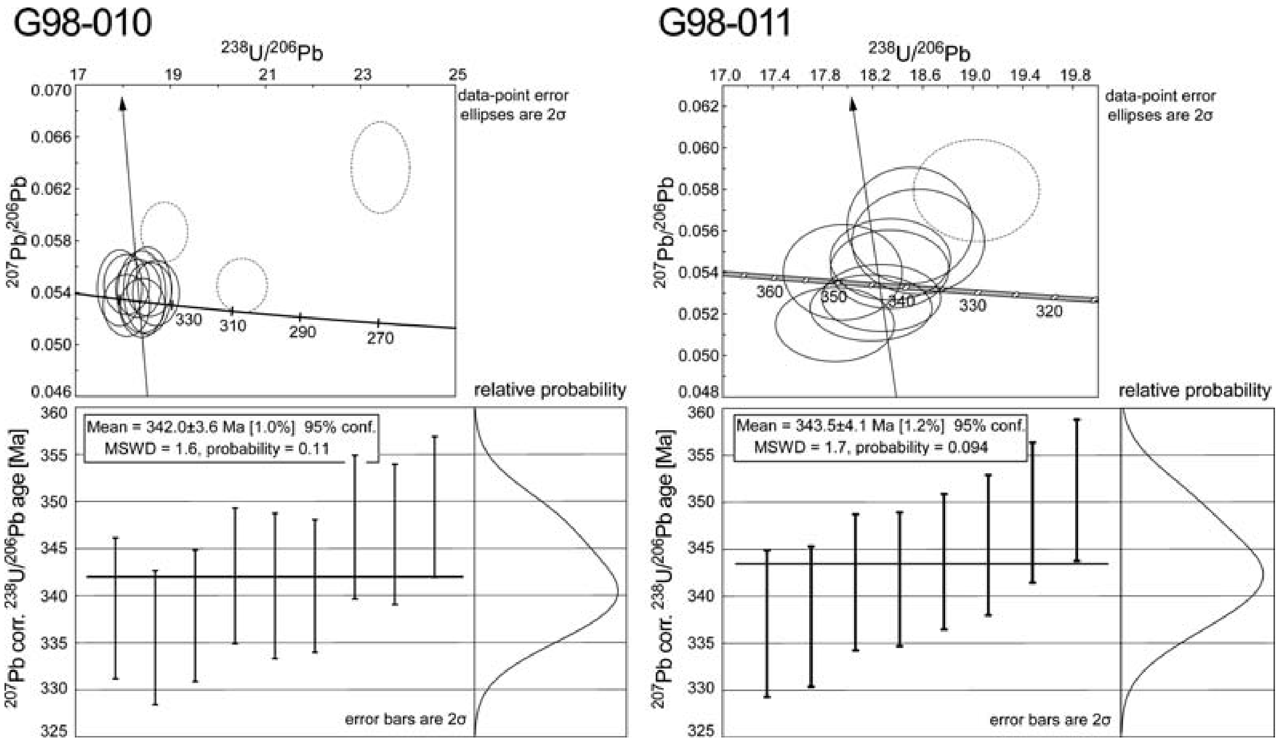

Figure 14. Inverse Concordia plot, calculation of age and relative probability plot for intrusive rocks on Bol'shevik Island. Analyses whose error ellipses were shown with a broken line in the inverse Concordia plot are excluded from age calculation. The regression lines are plotted for orientation and point towards present-day common Pb (according to the model of Stacey & Kramers, 1975).

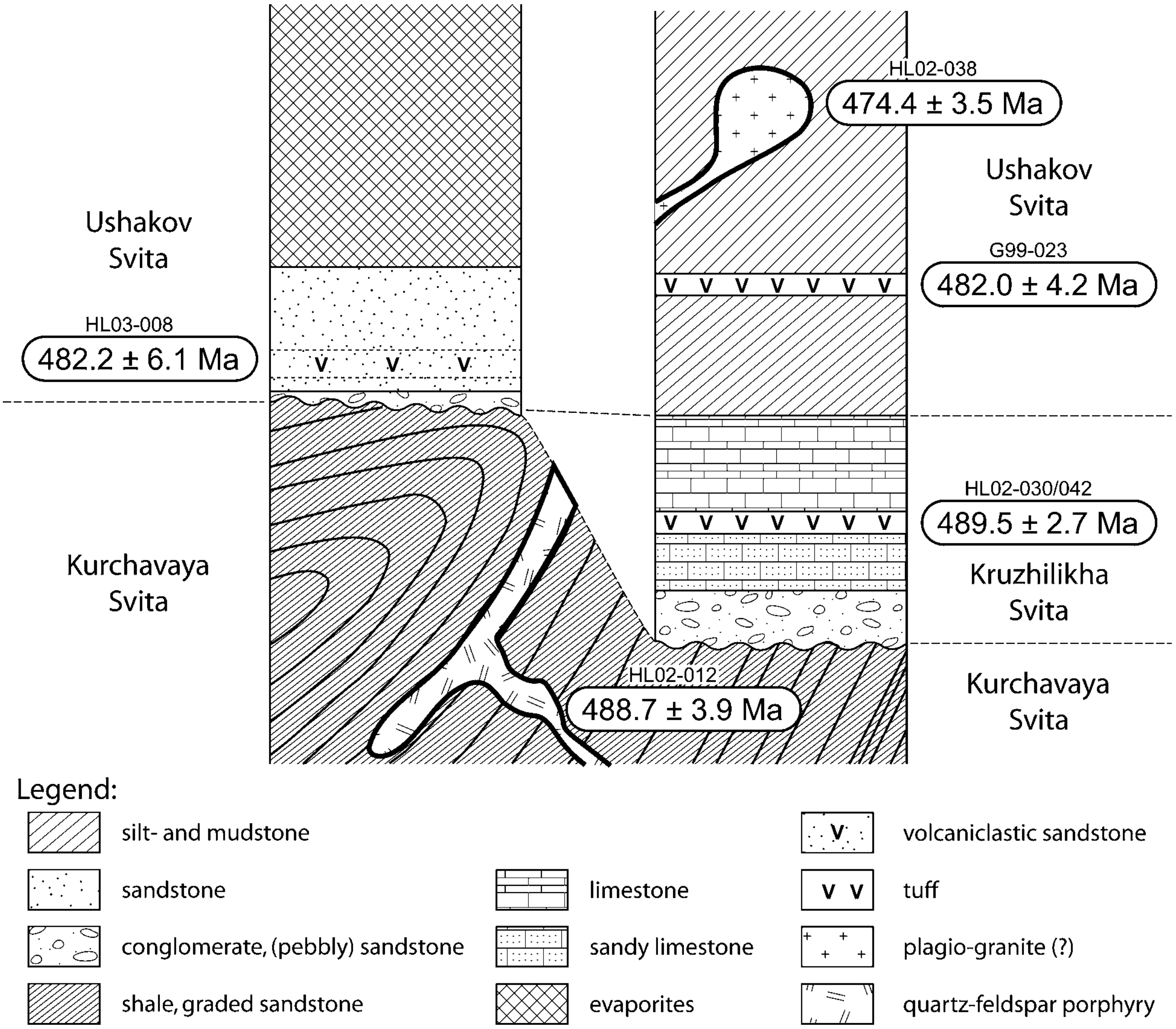

Figure 15. Schematic diagram of the stratigraphic relationships across the Kan'on River Unconformity, including volcanic and intrusive rocks.

several decades, the Cambrian–Ordovician boundary has been the subject of discussion (Cooper, Nowland & Williams, 2001). The global stratotype section is now accepted to be at Green Point, Newfoundland (Western Avalonia), and an age 'no older than, and close to, 490 Ma' has been suggested by Cooper, Nowland & Williams (2001, p. 26). According to the International Commission on Stratigraphy, the boundary age is between 490.0 and 486.6 Ma (488.3 ± 1.7 Ma: Gradstein, Ogg & Smith, 2004). At the Bryn-llin-fawr road, Harlech Dome, Wales, Landing *et al.* (2000) reported a boundary age between 489.6 and 488.4 Ma (489 ± 0.6 Ma) from two reworked tuff beds. They suggest, on the basis of trilobites, that the stratigraphic position of the tuff beds can be closely correlated to the boundary at Green Point, Newfoundland; however, they suggested that a more precise correlation could be based on conodonts and olenid trilobites.

According to these data, the time-equivalent of the missing strata on Severnaya Zemlya is *c.* 3 to 4 Ma; considering the larger error of Davidek *et al.*'s (1998) age towards old ages and the younger estimate of the Cambrian–Ordovician boundary of Gradstein, Ogg & Smith (2004), the time-gap may be up to 6 Ma. On October Revolution Island, it has not yet been possible to determine how much of the Tremadocian is missing.

In the Kan'on River area, the bright green tuff dated in this study is located about 60 m above the Kan'on River Unconformity within the Tremadocian Kruzhilikha Svita (Lorenz, Gee & Bogolepova, in press), and it has been observed both at Vos'merka Hill and southwards from Kan'on River to the locality of the River Bend Formation (Figs 6, 7). Its age of 489.5 ± 2.7 Ma (492.2 to 486.8 Ma), determined from combined samples HL02-030/042 (Figs 12, 15), is slightly older than both Gradstein, Ogg & Smith's (2004) and Landing *et al.*'s (2000) age estimates

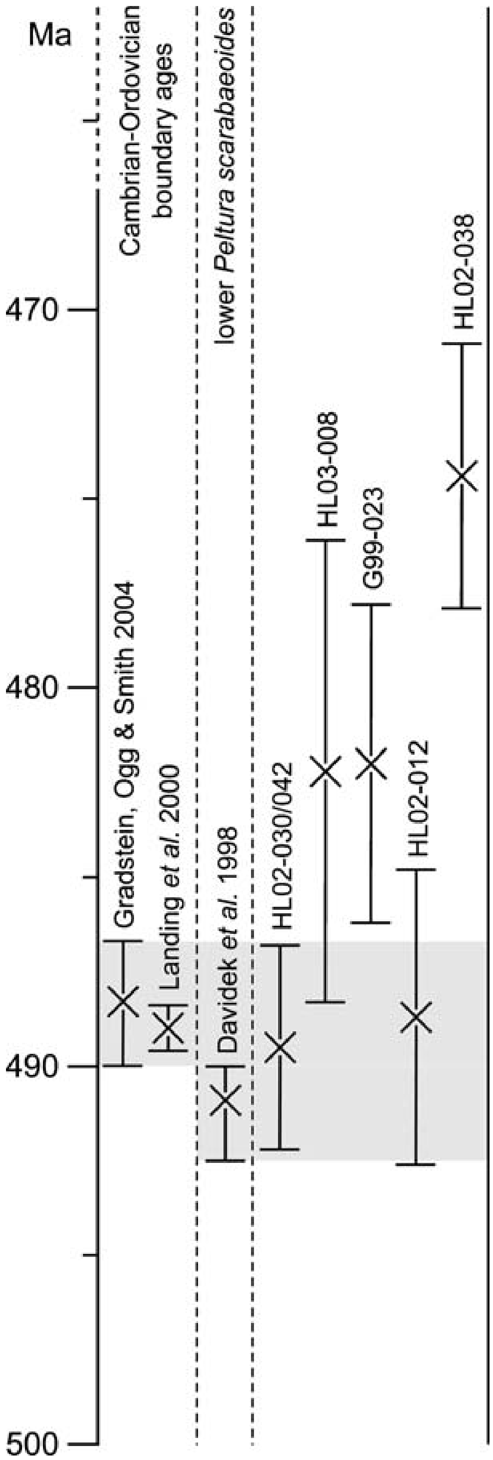

Figure 16. Comparison chart of published geochronological reference ages for the Cambrian–Ordovician boundary, the uppermost Cambrian and ages obtained in this study.

for the Cambrian–Ordovician boundary and slightly younger than Davidek *et al.*'s (1998) estimate for the lower subdivision of the *Peltura scarabaeoides* zone (Fig. 16). Proposing a Late Cambrian age for the lower Kruzhilikha Svita is unreasonable, because several workers (Markovsky & Makar'ev, 1982; Bogolepova, Gubanov & Raevskaya, 2001; Raevskaya & Golubkova, 2006) have provided faunal evidence for its Tremadocian age. Similarly, compelling evidence is preserved in the River Bend Formation, whose age is demonstrated by four conodont genera (*Cordylodus sp.*, *Drepanoistodus sp.*, *Semiacontiodus sp.*, *Variabiliconus cf. V. bassleri (Furnish)*) from samples K2 and K3 (Fig. 7) to be not older than Tremadocian (T. Tolmacheva, pers. comm.).

Taking into account the error limits of Landing *et al.*'s (2000) age for the Cambrian–Ordovician boundary and the age of sample HL02-030/042, a time-span of at most 3 Ma is available for the deposition of the sediments below the green tuff, and, in the case of the River Bend Formation, above sample location K3. Additionally, in the latter location, at least 250 m of terrigenous and carbonate rocks have to be accommodated between the unconformable upper boundary of the Kurchavaya Svita and sample location K3 (Fig. 7).

Three factors influence the evaluation of the period of time available for the Kan'on River Deformation: uplift, erosion and the deposition of the rocks beneath the bright green tuff. It is possible that sample HL02-030/042 ranges in the younger half of its error interval. Nevertheless, the Cambrian–Ordovician boundary age of Landing *et al.* (2000), the small error interval of which leaves little room for adjustment, seems to be too young to accommodate the Tremadocian strata. The largest uncertainty may be the exact correlation of palaeontological markers for the Cambrian–Ordovician boundary between the different palaeo-continents and, perhaps, our knowledge about and interpretation of faunal migration.

The stratigraphic thickness between the Kan'on River Unconformity and the dated tuff from the Ushakov Svita (G99-023) in the Kruzhilikha River area (Fig. 6) is thought to be in the order of 300 m. The age of 482.0 ± 4.2 Ma (Figs 12, 15), probably Late Tremadocian, is as expected, significantly younger than the age of the green tuff of the Kruzhilikha Svita (sample HL02-030/042). Another Tremadocian age, 488.7 ± 3.9 Ma (sample HL02-012; Figs 11, 15), has been obtained from the subvolcanic quartz-feldspar porphyry of the Sopka Suite at Snezhnaya Bay (Fig. 6), southeasternmost October Revolution Island. These intrusions are likely related to the green tuff and various volcanic rocks of the Smutnoe igneous suite (Lorenz, Gee & Bogolepova, in press; Figs 2, 6).

Sample HL03-008 (Fig. 6), from the red volcaniclastic sandstone approximately 15 m above the Kan'on River Unconformity in the Lake Fiordovoe area, supports the field evidence that the unconformity in this area is directly overlain by younger sediments than are found in the areas to the south and east. Zircons are rounded and witnessed transport and resedimentation. Their age of 482.2 ± 6.1 Ma (Figs 13, 15) is a maximum age for the base of the Ushakov Svita and is, as expected, younger than the bright green tuff bed (sample HL02-030/042) in the Kruzhilikha Svita and similar to the white tuff (sample G99-023) in the Ushakov Svita in the Kruzhilikha River area (Fig. 16). Similar white tuff beds have been observed within and above the overlying evaporite section at Lake Fiordovoe.

4.b. Timing of the Severnaya Zemlya Unconformity

Folded and thrust strata of Ordovician to Late Devonian age occur on October Revolution Island, Komsomolets Island, Pioneer Island and the Sedov Archipelago. It is likely that this deformation is of latest Devonian to Early Carboniferous age. On October Revolution Island, the deformed Famennian clastic sediments (Shul'ga, 2000) are unconformably overlain by Late Carboniferous, undeformed strata (Dibner, 1982). Similar undeformed sandstones on Bol'shevik Island are of Early Carboniferous age (Dibner, 1982).

With regard to the relationships on Bol'shevik Island, it remains possible that the folding of the Neoproterozoic strata occurred in the latest Cambrian, related to the Kan'on River Deformation, and that this eastern part of the Severnaya Zemlya Archipelago existed as a stable foreland in relation to the Severnaya Zemlya Deformation further west. The ages of undeformed granites (Fig. 14), which cut the folds on Bol'shevik Island, are Early Carboniferous (Tournaisian; 342.0 ± 3.6 Ma and 343.5 ± 4.1 Ma) and more precise than previous K/Ar dates, ranging between 292 ± 10 Ma and 439 ± 37 Ma (Proskurnin & Shul'ga, 2000). These new zircon ages thus suggest that the time of deformation on Bol'shevik Island was earliest Carboniferous or older and must have occurred at least 40 to 50 Ma earlier than in northern Tajmyr. There, Vernikovsky *et al.* (1995; U–Pb zircon multigrain analyses) and Pease (2001; Pb/Pb single zircon evaporation method) report ages of 306 ± 2 Ma and 304 ± 5 Ma, respectively, from granites (Fig. 3) which they interpret as syntectonic to the collision between the North Kara Terrane and Siberia.

4.c. Tectonic evolution and terrane affinities

Based on recent work on Severnaya Zemlya, Gee & Bogolepova (in press) and Lorenz, Gee & Bogolepova (in press) have argued in favour of the North Kara Terrane being a part of Baltica at least from the Late Neoproterozoic to Early Carboniferous time. Pease (2001) presented a provenance age study of two greywacke samples from northernmost Tajmyr, from rocks that were thought to be of late Neoproterozoic to Cambrian age and belong to Tajmyr's northern belt (Zonenshain, Kuzmin & Natapov, 1990, their North Tajmyr Zone), a part of the North Kara Terrane. The samples have a dominant peak in the cumulative frequency curve at 556 Ma and 567 Ma, respectively, and Pease (2001) inferred a Baltica provenance. Similar ages between *c.* 540 Ma and 560 Ma have been obtained from inherited cores of sample HL02-012 (Fig. 11) and a grain from sample HL03-008 (Fig. 13), which suggest that the source of these igneous rocks, deeper in the crust beneath October Revolution Island, comprises rocks of this age, possibly a continuation of basement influenced by the Timanian Orogeny beneath Severnaya Zemlya. An unpublished Ar/Ar age (V. Vernikovsky) of 543.9 ± 2.0 Ma from detrital muscovite in a Late Cambrian sandstone on October Revolution Island reflects the same age. These detrital ages are not characteristic of Siberia, but typical for the Timanide Orogen of the northeastern margin of Baltica (Gee *et al.* 2000; Gee & Pease, 2004, and references therein).

The link to Baltica is further supported by the age of the deformation periods which are recorded in Severnaya Zemlya and which may be related to the early and late Caledonian orogenic episodes in Baltica. An early Tremadocian deformation episode, the Finnmarkian orogeny (Ramsay & Sturt, 1976), has been described in the northern Scandinavian Caledonides (Gee, 1987). These observations, together with the Kan'on River Unconformity on October Revolution Island, suggest short but pronounced orogenic activity at the Cambrian–Ordovician boundary in the northern Scandinavian and Arctic Caledonides.

Two tectonic scenarios may be considered for the Severnaya Zemlya Deformation in the Severnaya Zemlya Archipelago. One involves Uralian collision between Siberia and the North Kara Terrane, and the other the eastwards migration of the Caledonian deformation front across the Old Red Sandstone foreland basin into the area of Severnaya Zemlya. Both imply considerable diachroneity.

If the deformation on Severnaya Zemlya was related to uralian collision of the North Kara Terrane with Siberia, as inferred by all previous authors, this would imply diachronous progression of orogeny which began in the NW the Early Carboniferous (perhaps latest Devonian) and reached northern Tajmyr in Late Carboniferous time. Simultaneously, Uralian orogeny began in mid-Carboniferous time in the southern Urals (Puchkov, 2002) and advanced westwards and also northwards (e.g. mid-Triassic on Novaya Zemlya: Korago *et al.* 1992). Post-tectonic intrusions from the area south of Cape Chelyushkin, approximately 150 km south of the intrusions on Bol'shevik Island, have been dated to 258 ± 28 Ma and 258 ± 73 Ma by the Rb/Sr method and to 264 ± 8 Ma by the U–Pb method (zircon multigrain: Vernikovsky *et al.* 1998; Fig. 3), which would imply a surprisingly long-lasting (*c.* 75 Ma) magmatic activity within the Tajmyr orogen. It should be noted that the Uralian tectonic scenario does not account for the E-vergent structures on Severnaya Zemlya; expected W-vergent structures have not been reported from Severnaya Zemlya and northern Tajmyr.

Alternatively, the Severnaya Zemlya Deformation is related to Caledonian orogeny, as favoured here. It was preceded by deposition of thick clastic sediments of Old Red Sandstone facies (Kuršs, 1982; Gee & Bogolepova, in press), thought to be derived from the Caledonide Orogen, a source which complies well with Kuršs' (1982) determination of the Devonian sedimentation directions from W to NW. This requires the development of a Caledonian foreland basin in the area of Severnaya Zemlya, extending westwards to the Caledonian (Scandian) deformation front (Fig. 1). Unpublished Ar/Ar ages (V. Vernikovsky) on detrital muscovite from Early Devonian sandstones of 453.1 ± 3.9 Ma and 451.9 ± 3.9 Ma support this interpretation. This evidence favours the development of the Late Palaeozoic E-vergent structures as the result of an eastward-migrating Caledonian deformation front, successively overriding the foreland basin. If this interpretation is correct, it strongly supports the interpretation of the North Kara Terrane as having been a part of Baltica at least since the Neoproterozoic, possibly a prong (but of unknown prolongation) pointing northwards towards the contemporary palaeo-equator in Early and Mid-Ordovician time, allowing the deposition of October Revolution Island's Ordovician evaporitic sequences.

As noted above, Uralian W- or NW-vergent structures have not been reported from the North Kara Terrane, nor have rock types indicative of a suture. This difference in tectonic style between the Urals and Tajmyr/Severnaya Zemlya is difficult to explain with a plate tectonic model which separates Laurussia and Siberia completely by the Uralian ocean until the onset of the Uralian orogeny (e.g. Torsvik *et al.* 1992). However, an alternative plate tectonic model by Golonka *et al.* (2003) places northeastern Laurussia and northwestern Siberia (present coordinates) alongside each other. In Golonka's model the Palaeoasian and Uralian oceans were embraced by these two palaeocontinents and were closed by the approach of the Kazakhstan collage of microcontinents combined with a clockwise rotation of Siberia. The absence of Uralian suture rocks in Tajmyr would result from the absence of the Uralian ocean in the high Arctic. It also provides an explanation for rifting on the eastern Barents Shelf and strike-slip displacement during Uralian deformation in Tajmyr, as reported by Bezzubtsev *et al.* (1983), Bezzubtzev, Zalyaleyev & Sakovich (1986) and Inger, Scott & Golionko (1999).

5. Conclusions

Deformation of Severnaya Zemlya's Cambrian and Neoproterozoic successions started in the Late Cambrian *Peltura scarabaeoides* zone or immediately thereafter (dated elsewhere to $490.9^{+1.7}_{-0.9}$ Ma by Davidek *et al.* 1998). A tuff with Tremadocian acritarchs and conodonts in unconformably overlying strata yields a new isotope age of 489.5 ± 2.7 Ma. These ages overlap, and the shortness of time for the formation of the unconformity and the deposition of the sediments below the tuff suggest that problems may exist with the correlation of faunal markers across the palaeocontinents and the interpretation of faunal migration. The age of the deformation is comparable to that of the Finnmarkian orogeny in the northern Scandinavian Caledonides (Gee, 1987). The shortening on Severnaya Zemlya may be a far-field effect of deformation within this orogen.

The existence of the River Bend Formation to the south of the Kan'on River and its low-angle unconformable contact to the Early Ordovician Kruzhilikha Svita imply that the formation also overlies the Kan'on River Unconformity. Together with the younger age (482.2 ± 6.1 Ma) of the Ushakov Svita, which is overlying the unconformity in the Lake Fiordovoe Area, this indicates that the Kan'on River Unconformity probably transgressed from the SE to the NW.

Dating of other igneous rocks from October Revolution Island demonstrates that the Tremadocian was characterized by intrusive and extrusive igneous activity, which extended on through the Early Ordovician to *c.* 475 Ma.

Xenocrysts (*c.* 540–560 Ma) in the igneous rocks of October Revolution Island indicate a Timanian component in the crust beneath the North Kara Terrane. Together with sediment provenance studies, it suggests that the North Kara Terrane was attached to the East European Craton during or before the Timanian Orogeny. It formed an apron which pointed northwards towards the palaeo-equator during Ordovician time, allowing evaporite deposition as observed on October Revolution Island. In the latest Silurian, Severnaya Zemlya became a part of the Caledonian foreland basin, with westerly derived Old Red Sandstone deposition throughout the Devonian. The eastwards-migrating Caledonian deformation front reached the archipelago in the latest Devonian or very early in the Carboniferous. This deformation ceased before the deposition of unconformably overlying sediments in the late Early Carboniferous, some fifty million years prior to the start of Late Palaeozoic deformation further southest in the Tajmyr orogen.

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