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RESEARCH/REVIEW ARTICLE

New data on Upper Carboniferous–Lower Permian deposits of Bol'shevik Island, Severnaya Zemlya Archipelago

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Abstract

We present here a detailed study of the Upper Carboniferous–Lower Permian stratigraphy of Bol'shevik Island in the Severnaya Zemlya Archipelago, consisting of the analysis of sedimentary structures and lithostratigraphy, U/Pb detrital zircon dating and structural studies. The preserved sedimentary structures suggest that the studied strata were deposited in a relatively small meandering fluvial system. U/Pb dating of detrital zircons reveals that the Upper Carboniferous–Lower Permian sandstones contain a primary age population ranging from 450 to 570 millions of years, with a predominance of Early–Middle Ordovician zircons. This detrital zircon distribution indicates that the studied formations were derived locally from the erosion of Lower Ordovician deposits of Bol'shevik Island or elsewhere in the archipelago. Our structural studies suggest that Upper Carboniferous–Lower Permian deposits are deformed into a series of west–north-west verging open asymmetric folds, suggesting a west–north-west direction of tectonic transport and that deformation across the island is post-Early Permian in age.

To access the supplementary material for this article, please see supplementary files under Article Tools online.

As conventional hydrocarbon exploration reaches a mature phase in many parts of the world, increasing attention is being focused on the frontier basins of the Arctic. Paramount amongst the frontier basins in the Russian Arctic is the North Kara Basin, which by analogy with the prolific West Siberian Basin, is considered highly prospective for hydrocarbons. The North Kara Basin is less studied than the Barents Sea basins to the west, with no deep wells drilled offshore to date. Our understanding of its geology is based on seismic data (Drachev et al. 2010) along with the study of onshore outcrop sections exposed along the basin's perimeter on the Severnaya Zemlya Archipelago and Taimyr Peninsula (Gramberg & Ušakov 2000; Lorenz et al. 2007; Lorenz, Mannik et al. 2008; Makar'ev 2013).

The Severnaya Zemlya Archipelago comprises four main islands—Pioneer, October Revolution, Komsomolets and Bol'shevik—along with numerous other small islands, islets and island groups. Pioneer, October Revolution and Komsomolets islands are mainly composed of Cambrian to Upper Devonian deposits, whilst predominantly Cambrian–Ordovician rocks are exposed on Bol'shevik Island, with a few outcrops of Upper Carboniferous–Permian and Mesozoic deposits (Makar'ev 2013). The study area is located in the northern Bol'shevik Island along the coast of Akhmatov Bay (Fig. 1). Bol'shevik Island is the southernmost and second largest island in the group, located across the Shokal'sky Strait from neighbouring October Revolution Island.

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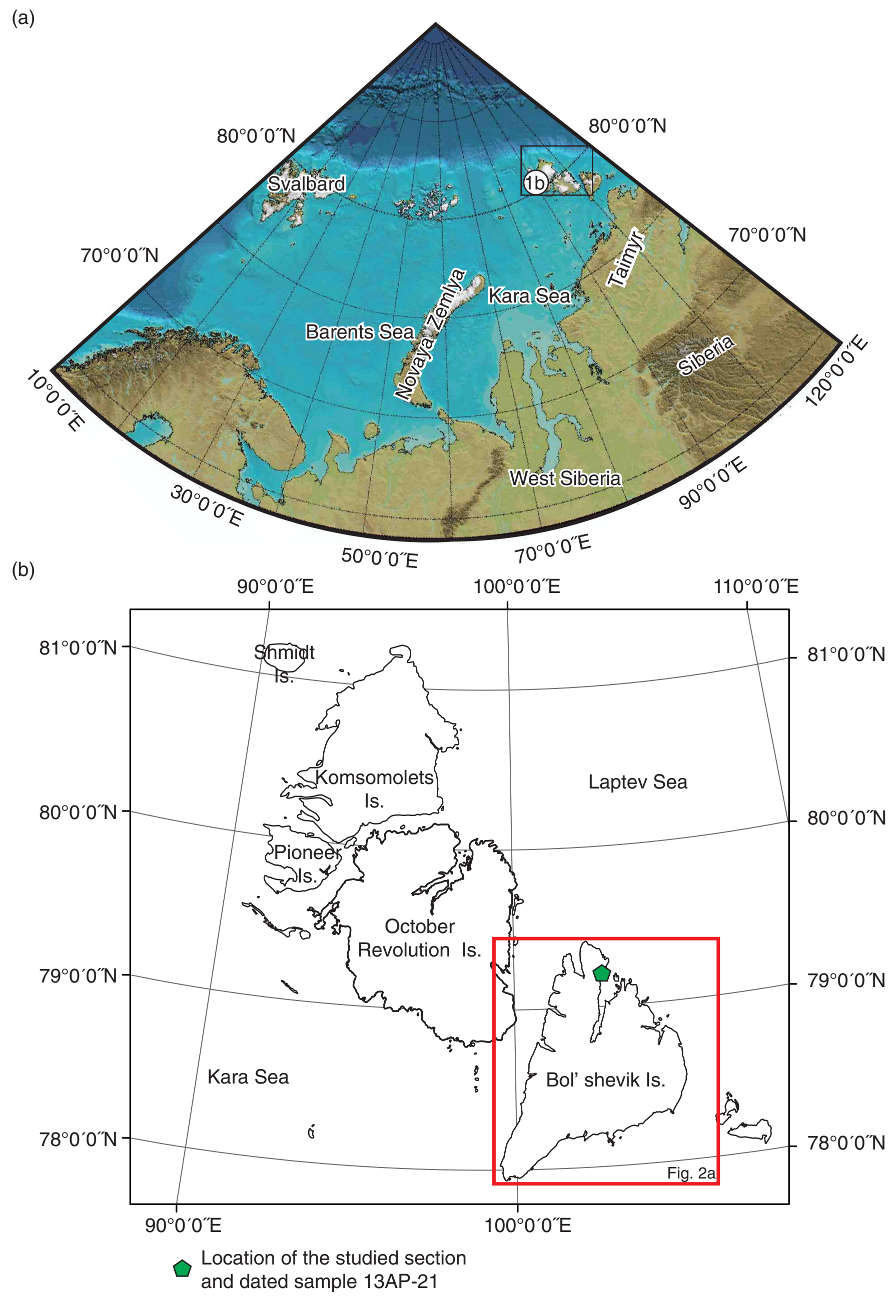

Fig. 1 (a) Regional setting of the study area; (b) map of Severnaya Zemlya Archipelago with location of study sections.

Detrital zircon U/Pb studies have become increasingly popular in recent years, providing new constraints on the tectonic evolution of the Arctic region. U/Pb detrital zircon studies of the Neoproterozoic–Devonian succession of the Severnaya Zemlya Archipelago have been carried out by Lorenz, Gee et al. (2008).

This paper presents new data, derived from the first U/Pb detrital zircon analysis of the Upper Carboniferous–Permian clastic rocks the Upper Carboniferous–Permian succession of Bol'shevik Island. The data presented here provide a new insight into the Late Palaeozoic palaeogeography and tectonics of Severnaya Zemlya and the adjacent offshore North Kara Basin.

Geological background

The Severnaya Zemlya Archipelago, the northern part of the Taimyr Peninsula and the northern Kara Shelf comprise the Kara Terrane. Various models have been proposed for the Palaeozoic history of the Kara Terrane.

Zonenshain et al. (1990) suggested that the terrane was part of a larger continent block called Arctida; Lorenz and co-workers (Lorenz, Gee et al. 2008; Lorenz, Mannik et al. 2008) described it as a marginal part of Baltica, whilst many other researchers suggest it existed as an independent terrane or microcontinent during the Palaeozoic (Bogdanov et al. 1998; Gramberg & Ušakov 2000; Metelkin et al. 2000; Metelkin et al. 2005). In the present tectonic setting, the Kara Terrane is delineated by the continental margin of the Eurasia Basin to the north, whilst the Main Taimyr Thrust separates northern Taimyr (part of the Kara Terrane) from central Taimyr and Siberia to the south (Vernikovskij 1996). The western and eastern offshore boundaries of the Kara Terrane are still being debated. The linear North Siberian basement arch has been identified from seismic data offshore in the Kara Sea, which probably separates the Kara Terrane from the South Kara Basin and West Siberia (Drachev et al. 2010).

Previous studies led to the assumption that Bol'shevik Island was mainly composed of deformed Proterozoic rocks, intruded by Early Carboniferous granites (Markovskij et al. 1999; Lorenz, Mannik et al. 2008; Fig. 2a). However, more recent U/Pb studies have revealed that the folded rocks on Bol'shevik Island are mostly of Cambrian–Ordovician age (Lorenz, Gee et al. 2008; Makar'ev & Makar'eva 2012; Makar'ev 2013). The stratigraphic subdivision recently proposed by Makar'ev (2013) is mainly based on the youngest populations of detrital zircons, along with the relationship between different stratigraphic units identified during geological mapping on Bol'shevik Island. Nonetheless, the lack of modern biostratigraphic studies has left the stratigraphic succession of the highly

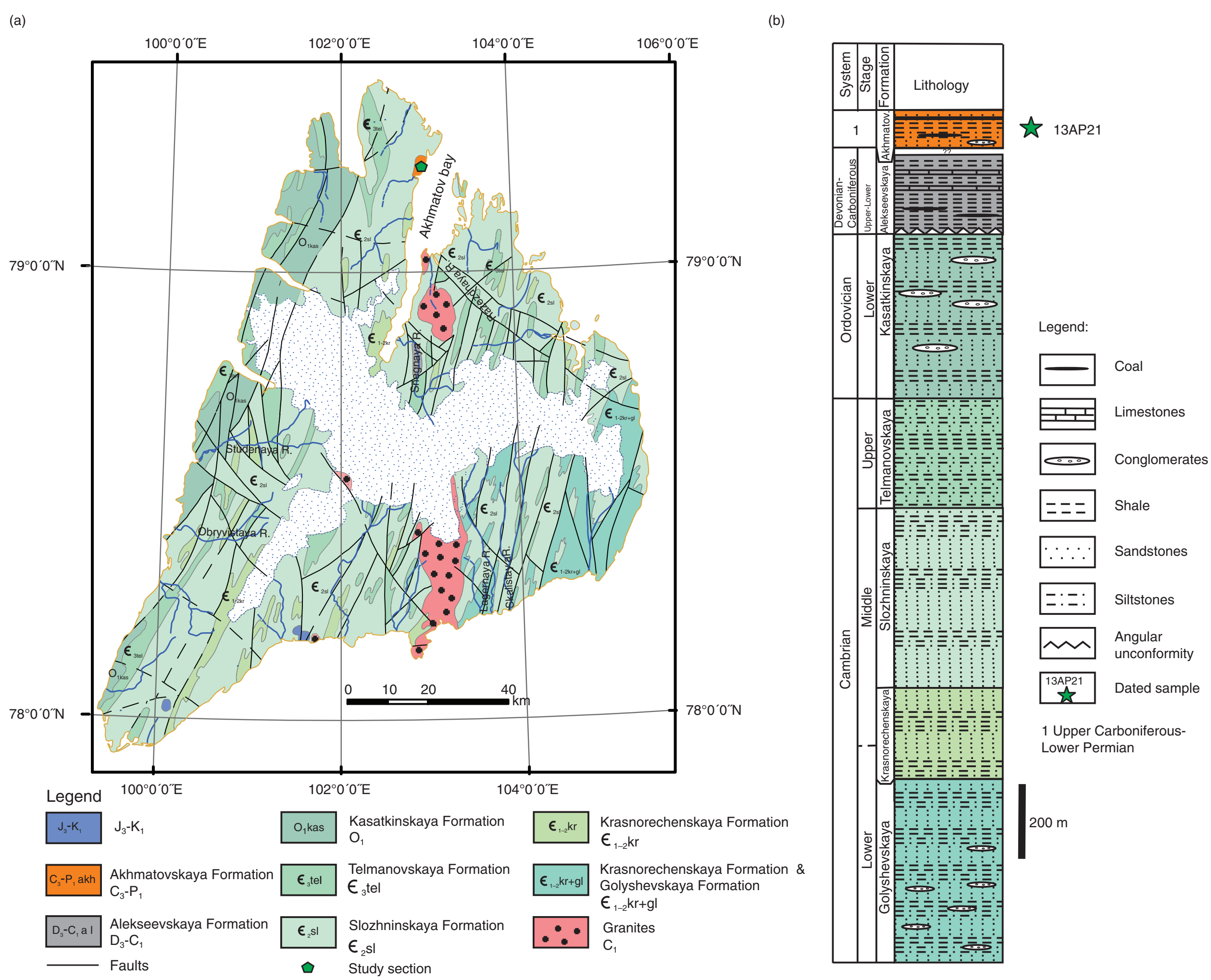

Fig. 2 (a) Simplified geological map of Bol'shevik Island (modified after Makar'ev 2013); (b) composite stratigraphic section of Palaeozoic rocks of Bol'shevik Island. (For a larger version of this figure, see Supplementary File 3.)

deformed outcrops on Bol'shevik Island unclear. Five Lower Palaeozoic formations have been described from Bol'shevik Island: Golyshevskaya, Krasnorechenskaya, Telmanovskaya, Slozhninskaya and Kasatkinskaya (Makar'ev 2013; Fig. 2b).

The Golyshevskaya Formation (Lower Cambrian) is widespread in the eastern part of Bol'shevik Island. It is composed of alternating sandstones, siltstones and shales with subordinate lenses and layers of conglomerates, reaching a typical thickness of 490–500 m.

The Krasnorechenskaya Formation (Lower–Middle Cambrian) consists of greyish quartzose and feldspathic fine-grained sandstones, with beds of dark grey siltstones and shales. These deposits conformably overlie the Golyshevskaya Formation, with a typical thickness of 250–260 m.

The Slozhninskaya Formation (Middle Cambrian) lies conformably on the Lower–Middle Cambrian Krasnorechenskaya Formation and comprises 600 m of green sandstones interbedded with greenish grey siltstones and shales.

The Telmanovskaya Formation (Upper Cambrian) is composed of 300–450 m of varicoloured sandstones, interbedded with shale and siltstone. Sandstones are predominant in the lower part of the formation.

The Kasatkinskaya Formation (Lower Ordovician) conformably overlies the Cambrian strata and comprises 450–600 m of green-coloured sandstones interbedded with greenish shales. Sandstones are prevalent in the lower part of the formation and contain numerous layers and lenses of gravelly and pebbly conglomerates.

These Cambrian–Lower Ordovician rocks are highly deformed into a series of north–north-east striking anticlines and synclines, which are crosscut by numerous north–north-east-trending faults.

Middle–Upper Palaeozoic strata have a very patchy distribution across the island. The Upper Devonian–Lower Carboniferous Alekseevskaya Formation has only been described from small exposures along the middle reaches of the Snezhnaya River in the northern part of the island. The formation is composed of 220–260 m of black shales and siltstones with rare beds of limestone and coalified plant detritus, with a prominent angular unconformity at its base.

The studied Akhmatovskaya Formation (Late Carboniferous–Lower Permian) is only exposed in the northern part of the island, along the coast of Akhmatov Bay. The formation overlies folded Middle Cambrian deposits of the Slozhninskaya Formation, with a significant angular unconformity and hiatus. The Akhmatovskaya Formation has been dated by plant fragments, spores and pollen as spanning the Late Carboniferous and Early Permian periods (Dibner 1982; Gramberg & Ušakov 2000; Makar'ev 2013; Sobolev et al. 2013). The studied succession in Akhmatov Bay comprises an alternation of poorly cemented fine-grained sandstones, siltstones and shales, with lenses and layers of coal and numerous beds of coalified plant detritus (Fig. 3). Sandstone beds (3–5 m thick) have been observed within the succession, which is generally much finer grained. The sandstones are medium- to coarse-grained and composed of quartz, with subordinate lenses of gravelly to pebbly quartz conglomerates. The thickness of the formation has been estimated at up to

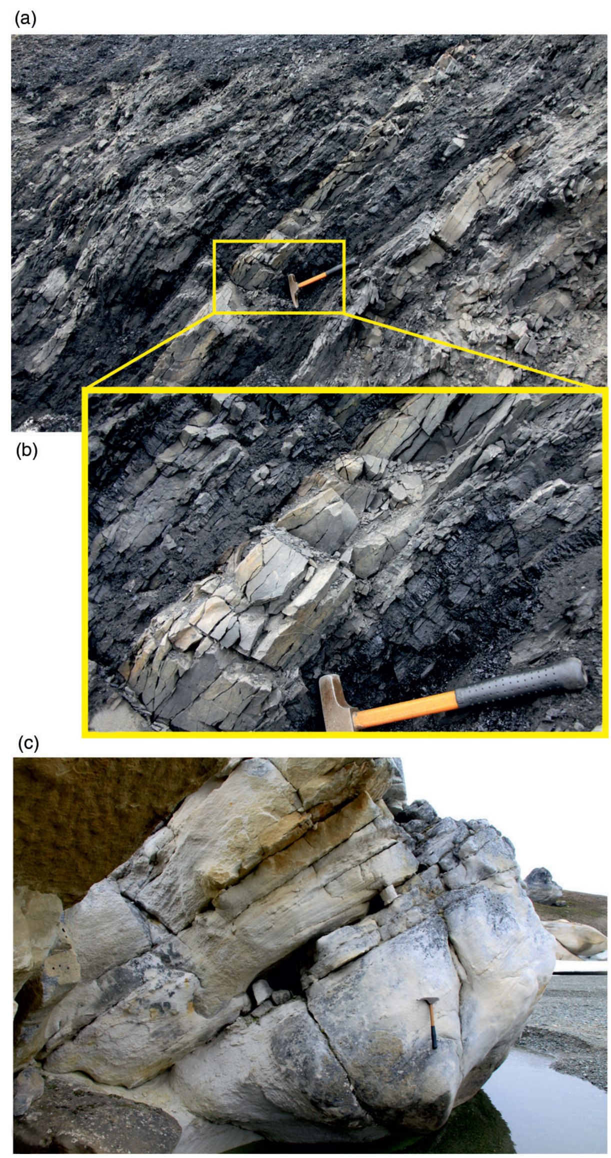

Fig. 3 Photographs of the studied Upper Carboniferous–Permian deposits: (a) general view of outcrop intercalation of siltstones, sandstones and coals (flood plain environments); (b) close-up view of outcrop; (c) trough-cross bedded sandstone (filling in channel).

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100 m by Gramberg & Ušakov (2000) and up to 250 m by Makar'ev (2013). The fine-grained non-marine sedimentary facies and presence of coal beds are characteristic of deposition on a low gradient flood plain, bordering a meandering fluvial system. Trough and planar cross-bedding have been observed from the medium- to coarse-grained sandstone beds which are likely to have been deposited within the main axis of the river channel as it migrated across the flood plain. The small thickness of the sandstone beds suggests that this Late Carboniferous–Early Permian fluvial system within the study area was relatively small.

Structural studies show that rocks of the Akhmatovskaya Formation dip west–north-westward at 55°–60°, as well as east–south-eastward at 20° to 40° (Figs. 3, 4a, b). We therefore assume that Upper Carboniferous–Lower Permian clastics of the Akhmatovskaya Formation have been subsequently deformed into open asymmetric folds with a west–north-west vergence. The width of the folds varies from a few tens to a few hundred metres and the hinges plunge in a north–north-eastern direction. Unfortunately, the cores of these folds are covered by scree and have not been observed at outcrop in the field. The north–north-east plunge of these folds was therefore determined by plotting the structural data obtained from these folds on a stereonet (Fig. 4c), and our data are consistent with data obtained during recent geological mapping by other researchers (Markovskij et al. 1999; Makar'ev 2013; Fig. 4). The direct contact of the Akhmatovskaya Formation with the underlying Middle Cambrian rocks has not been observed in onshore outcrops. However, the Middle Cambrian rocks have been observed to dip almost vertically close to the studied Akhmatovskaya Formation outcrops (Fig. 4a). This observation indicates an angular unconformity between these stratigraphic units (Markovskij et al. 1999; Makar'ev 2013).

Methods

The U/Pb dating of detrital zircons was done on one sample collected from a medium-grained quartz sandstone (Fig. 2). The sample was crushed and the heavy minerals were concentrated using standard techniques at the Institute of Precambrian Geology and Geochronology, Russian Academy of Science. The U/Pb detrital zircon dating was done by Apatite to Zircon, Inc., using the Washington State University laser-ablation–inductively coupled plasma–mass spectrometer. $^{207}Pb/^{206}Pb$ ages are reported for >1.0 Gy grains and $^{206}Pb/^{238}U$ ages for ≤ 1.0 Gy grains. Following Gehrels (2012), analyses with $>30\%$ discordance and 10% reverse discordance were excluded.

Results

Data tables and a detailed description of analytical procedures are provided in the Supplementary Files 1 and 2. The complete results of the U/Pb study are illustrated in Fig. 5.

The studied sandstones contain a primary age population ranging from 450 to 570 millions of years (My), forming 80% of the dated grains. Five Palaeoproterozoic grains range from 1640 to 1880 millions of years ago (Mya), whilst the few Mesoproterozoic ages ($N = 4$) range from 1115 to 1550 My and do not form significant peaks. Neoproterozoic zircons comprise 20% of the population and form a significant peak at 550 Mya. Ordovician zircons comprise 60% of the total dated grains and form the major peak at 465 Mya, whilst only two grains are of Early Carboniferous age and close to the time of sedimentation.

Discussion

Previous U/Pb detrital zircon studies by Lorenz, Gee et al. (2008) illustrated that the Cambrian and Devonian clastics of neighbouring October Revolution Island contain predominantly Meso–Palaeoproterozoic zircons and very few zircons of Ordovician age. In complete contrast, our data reveal that the main zircon population in Upper Carboniferous–Lower Permian clastics from Bol'shevik Island is Ordovician in age, with very few Meso-Palaeoproterozoic grains. Our data would therefore indicate that the Upper Carboniferous–Lower Permian clastics derived mainly from eroding Ordovician rocks on Bol'shevik Island or elsewhere in the Severnaya Zemlya Archipelago. The predominance of Early–Middle Ordovician zircons matches well with the age of well-dated Ordovician volcanic rocks exposed on October Revolution Island (Lorenz et al. 2007) and the findings of detrital zircon in Ordovician clastics (Lorenz, Gee et al. 2008). This interpretation matches the interpreted depositional environment of the Late Carboniferous–Early Permian clastics within a relatively small meandering fluvial system which is likely to have sourced clastics from a local provenance.

Geological maps of Bol'shevik Island (Makar'ev 2013; Fig. 2a) suggest that the Upper Carboniferous–Lower Permian sediments of the Akhmatovskaya Formation unconformably overlie poorly dated sediments interpreted as Middle Cambrian in age, whilst Ordovician rocks have only been studied in the westernmost part of the island, far away from the study area. The virtual absence of Meso-Palaeoproterozoic zircons suggests that the Akhmatovskaya Formation overlies Ordovician and not Cambrian deposits. We can therefore assume that Cambrian strata are not as widely distributed across northern Bol'shevik Island as shown in published geological maps and that some of the sediments interpreted as Cambrian

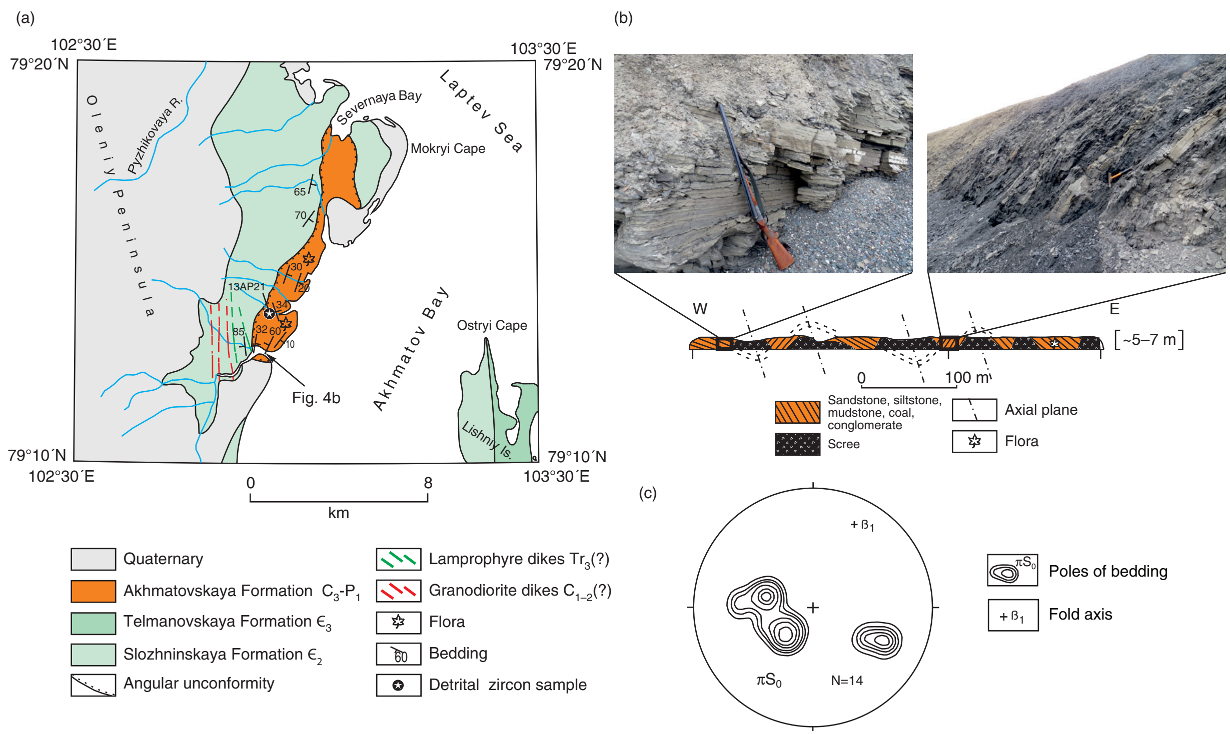

Fig. 4 (a) Geological map of north-western part of Akhmatov Bay, Oleniy Peninsula, Bol'shevik Island; (b) geological cross-section across the Akhmatovskaya Formation; (c) stereographic projections of bedding poles of the Akhmatovskaya Formation.

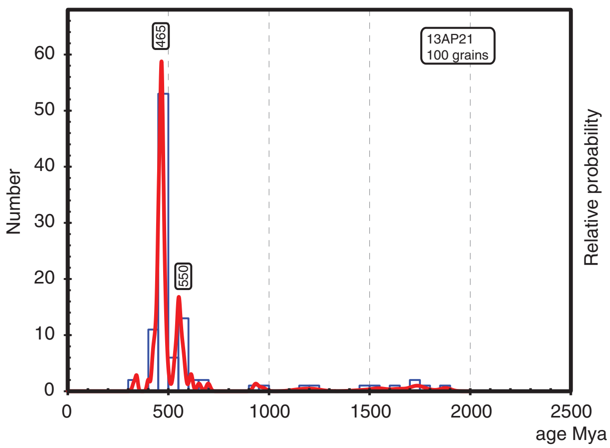

Fig. 5 Probability distribution plot of zircon U/Pb ages of the studied sample.

age may in fact be Ordovician. The few Carboniferous zircon grains are comparable with the ages of granites intruded into the Lower Palaeozoic deposits of Bol'shevik Island, and can be explained by local uplift and erosion of these granite plutons (Lorenz et al. 2007).

Two episodes of deformation have been previously identified across the Severnaya Zemlya Archipelago; the first at the Cambrian–Ordovician boundary and the second during the Late Devonian and/or Early Carboniferous (Lorenz, Mannik et al. 2008; Makar'ev 2013). Previous researchers have assumed that the Late Palaeozoic strata are undeformed and have concluded that the tectonic structures of Severnaya Zemlya were formed prior to the deposition of Late Palaeozoic (Carboniferous and Permian) strata (Lorenz, Mannik et al. 2008; Drachev et al. 2010). In contrast to these opinions, evidence of post-Permian deformation on Bol'shevik Island was noted by Makar'ev (2013). Our field observations and data also suggest that a relatively intense period of post-Early Permian deformation occurred on Bol'shevik Island. The structural style of deformation of Carboniferous to Permian deposits suggests a west–north-west direction of tectonic transport.

A number of previous studies have concluded that collision between the Kara Terrane and Siberian Craton occurred during Late Carboniferous–Permian time (Metelkin et al. 2005; Cocks & Torsvik 2007). However, Early Carboniferous granites (342–343 My in age) have been studied on Bol'shevik Island (Lorenz et al. 2007) and reported from northern Taimyr and adjacent islands (ages range from 317 to 344 My; Makar'ev 2013). One of the deformation episodes reported from October Revolution Island was dated as Late Devonian/Early Carboniferous (Lorenz, Mannik et al. 2008). Taking into account the distribution of detrital zircon data from Carboniferous strata of north-eastern Siberia (Ershova et al. 2013; Prokopiev et al. 2013), we suggest that collision between the Kara Terrane and Siberian Craton may have occurred much earlier than previously assumed, during the Visean stage of the Early Carboniferous. If Kara accreted to Siberia during the Early Carboniferous, then the interpreted post-Early Permian deformation is unlikely to be connected to the Kara–Siberia collision. This deformation may be associated with a Mesozoic compression event documented within Taimyr (Zonenshain et al. 1990; Verzhbitsky & Khudoley 2010). Further studies of the structural geology are required to explain how this youngest deformation event affected the structural style of Bol'shevik Island and the larger Severnaya Zemlya Archipelago.

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