Detrital zircon ages and provenance of the Upper Paleozoic successions of Kotel'ny Island (New Siberian Islands archipelago)

Victoria B. Ershova[1,*], Andrei V. Prokopiev[2], Andrei K. Khudoley[1], Nikolay N. Sobolev[3], and Eugeny O. Petrov[3]
[1]INSTITUTE OF EARTH SCIENCE, ST. PETERSBURG STATE UNIVERSITY, UNIVERSITETSKAYA NAB. 7/9, ST. PETERSBURG 199034, RUSSIA
[2]DIAMOND AND PRECIOUS METAL GEOLOGY INSTITUTE, SIBERIAN BRANCH, RUSSIAN ACADEMY OF SCIENCES, LENIN PROSPECT 39, YAKUTSK 677980, RUSSIA
[3]RUSSIAN GEOLOGICAL RESEARCH INSTITUTE (VSEGEI), SREDNIY PROSPECT 74, ST. PETERSBURG 199106, RUSSIA

ABSTRACT

Plate-tectonic models for the Paleozoic evolution of the Arctic are numerous and diverse. Our detrital zircon provenance study of Upper Paleozoic sandstones from Kotel'ny Island (New Siberian Island archipelago) provides new data on the provenance of clastic sediments and crustal affinity of the New Siberian Islands. Upper Devonian–Lower Carboniferous deposits yield detrital zircon populations that are consistent with the age of magmatic and metamorphic rocks within the Grenvillian-Sveconorwegian, Timanian, and Caledonian orogenic belts, but not with the Siberian craton. The Kolmogorov-Smirnov test reveals a strong similarity between detrital zircon populations within Devonian–Permian clastics of the New Siberian Islands, Wrangel Island (and possibly Chukotka), and the Severnaya Zemlya Archipelago. These results suggest that the New Siberian Islands, along with Wrangel Island and the Severnaya Zemlya Archipelago, were located along the northern margin of Laurentia-Baltica in the Late Devonian–Mississippian and possibly made up a single tectonic block. Detrital zircon populations from the Permian clastics record a dramatic shift to a Uralian provenance. The data and results presented here provide vital information to aid Paleozoic tectonic reconstructions of the Arctic region prior to opening of the Mesozoic oceanic basins.

LITHOSPHERE; v. 7; no. 1; p. 40–45; GSA Data Repository Item 2015011 | Published online 31 October 2014 doi:10.1130/L387.1

INTRODUCTION

The number of geological studies and interest in the Arctic region have increased significantly in recent years. The Russian Arctic in particular remains poorly studied. Detrital zircon ages are a useful tool for the construction of paleotectonic restorations, and they represent one of the key data sources for determining the tectonic history of the Arctic realm. As a consequence, the number of provenance studies based on detrital zircon U/Pb ages has risen in past years (Miller et al., 2006, 2010; Lorenz et al., 2008; Amato et al., 2009; Beranek et al., 2010, 2013; Lemieux et al., 2011; Anfinson et al., 2012a, 2012b). However, there are many contrasting models concerning the origins, affinities, and tectonic history of the numerous terranes comprising the present-day Arctic (e.g., Beranek et al., 2010; Miller et al., 2010; Colpron and Nelson, 2011; Anfinson et al., 2012b), with only a limited number of detrital zircon studies carried out on Paleozoic deposits of the eastern Russian Arctic (Lorenz et al., 2008, 2013; Miller et al., 2010; Ershova et al., 2013; Prokopiev et al., 2013). In this paper, we report detrital zircon ages from Upper Devonian to Permian clastic rocks exposed on Kotel'ny Island. It is the largest in the New Siberian Islands archipelago, located in the eastern part of the Russian Arctic. This archipelago forms the eastern border of the Laptev Sea and represents an exposed Paleozoic–Mesozoic crustal fragment. The islands were studied extensively 30–40 yr ago by Kos'ko et al. (1985), when detailed geological maps were constructed. The recent studies have focused on the Mesozoic and Cenozoic deposits of Kotel'ny Island, due to their potential for containing hydrocarbon source rocks and reservoirs on the adjacent Laptev Shelf (Meledina, 1999; Kos'ko and Trufanov, 2002). Several contrasting paleotectonic reconstructions have been compiled, which provide possible models for the affinity of the New Siberian Islands. For example, Kuzmichev (2009) suggested that the New Siberian Islands were attached to the distal northeastern (in present coordinates) margin of the Siberian craton throughout the Paleozoic–Mesozoic, whereas Zonenshain et al. (1990) argued that the New Siberian Islands formed a portion of the Arctida paleocontinent, which shared an affinity with Laurentia until the late Mesozoic. The paleomagnetic study of Vernikovsky et al. (2013) showed the differing apparent polar wander paths of the New Siberian Islands and Siberia. Recent detrital zircon studies of the Paleozoic succession on neighboring Bel'kovsky Island (westernmost island of the New Siberian Islands archipelago) also suggest an affinity with Laurentia or Baltica (V.B. Ershova's data). The new detrital zircon data set from Upper Paleozoic strata of Kotel'ny Island (presented here) helps to further evaluate the affinity of Kotel'ny Island, providing important new insights into the paleogeography of the Arctic during the late Paleozoic.

Our primary objectives are to: (1) obtain U/Pb age dates of detrital zircons within the Paleozoic clastics; and (2) use the detrital zircon data to examine the crustal affinity of Kotel'ny Island and test the plate-tectonic reconstructions proposed by Zonenshain et al. (1990) and Kuzmichev (2009).

GEOLOGICAL BACKGROUND

Kotel'ny Island is mainly composed of deformed Paleozoic deposits (Fig. 1), whereas Mesozoic and Cenozoic rocks are only locally preserved within synclines and around the periphery of the island (Kos'ko et al., 1985, 2013; Kos'ko and Korago, 2009). The Paleozoic–Mesozoic rocks of Kotel'ny Island are deformed into NW-striking folds, which are

*E-mail: ershovavictoria@gmail.com

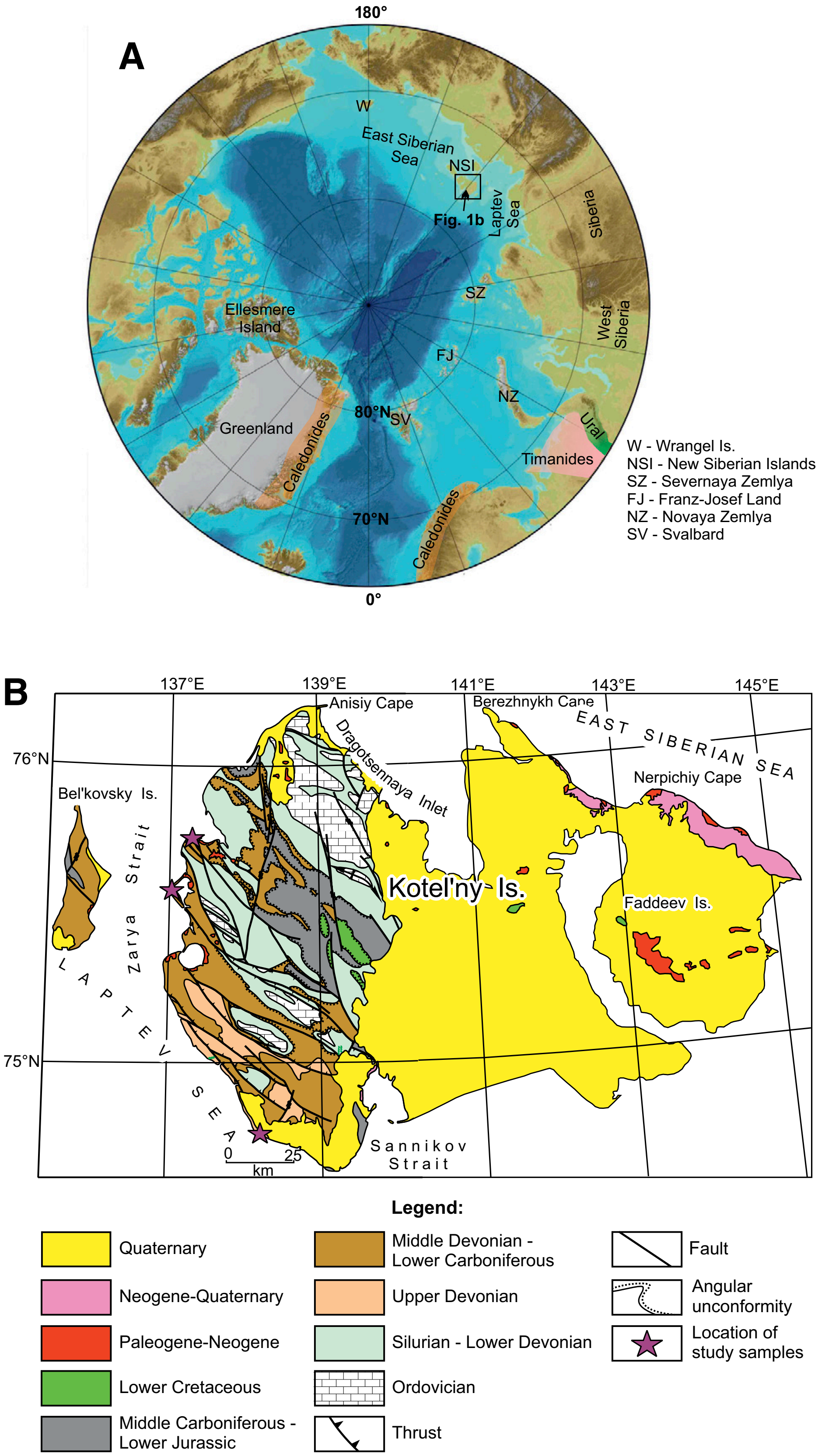

Figure 1. (A) Regional setting of the study area. (B) Geological map of Kotel'ny Island with location of study section (modified from Parfenov and Kuzmin, 2001).

associated with reverse faults and thrusts of SW and NE vergence (Parfenov and Kuzmin, 2001).

The oldest Paleozoic rocks on Kotel'ny Island are Ordovician carbonates that are up to 1.5 km thick (Kos'ko et al., 1985). The thickness of Silurian deposits decreases southwestward across the island from 1200 m to 750 m, with a facies change from predominantly carbonates to interbedded carbonates and cherts in the same direction. Lower Devonian strata are <1 km thick and consist of limestones, dolomites, clayey limestones, and clayey dolomites, with subordinate beds of argillites and siltstones (Kos'ko et al., 1985).

The Middle Devonian strata (Sokolov Formation) rest on different stratigraphic levels of the Lower Devonian carbonates with disconformity, with thicknesses varying from 270 m to 600 m across the island. They consist of interbedded dolomites and limestones, with beds of carbonate breccias containing angular clasts of pebble and boulder size (up to 1 m diameter) in the lower part of the formation. The upper part is composed of limestones (Fig. 2A).

The Frasnian deposits (Nerpalakh Formation) mainly consist of gray argillites and siltstones, with subordinate beds of limestone and sandstone (Fig. 2A). The formation does not exceed several hundred meters in the southwestern part of Kotel'ny Island (our field observation), but according to Kos'ko et al. (1985), the thickness of the Nerpalakh Formation can reach up to 7 km across Kotel'ny Island. Such a large thickness is likely to be an overestimation due to tectonic-induced repetition.

The Famennian–Tournaisian deposits of Chekur Formation are up to 1200 m thick. The formation is composed of gray and red sandstones with interbeds of greenish gray and red siltstones, with rare beds of bioclastic limestones in the lower part of the formation. The upper part of the formation is composed of interbedded gray and red quartz and polymictic sandstones, with interbeds of gravelly to pebbly polymictic conglomerates (Kos'ko et al., 1985).

The Visean–Serpukhovian strata (Taas-Ary Formation) are mainly represented by up to 1100 m of bioclastic limestones and argillites, with subordinate beds of dolomite, siltstone, sandstone, and occasional thin lenses and beds of pebbly conglomerate.

The Carboniferous succession of Kotel'ny Island is capped by an Upper Carboniferous (undivided) succession, consisting of up to 30 m of alternating bioclastic limestone, sandy and silty limestone, dolomite, carbonate breccias, and polymictic conglomerates.

The Permian (undivided) succession is represented by 180 m of argillite with subordinate beds of siltstone, sandstone, and limestone in

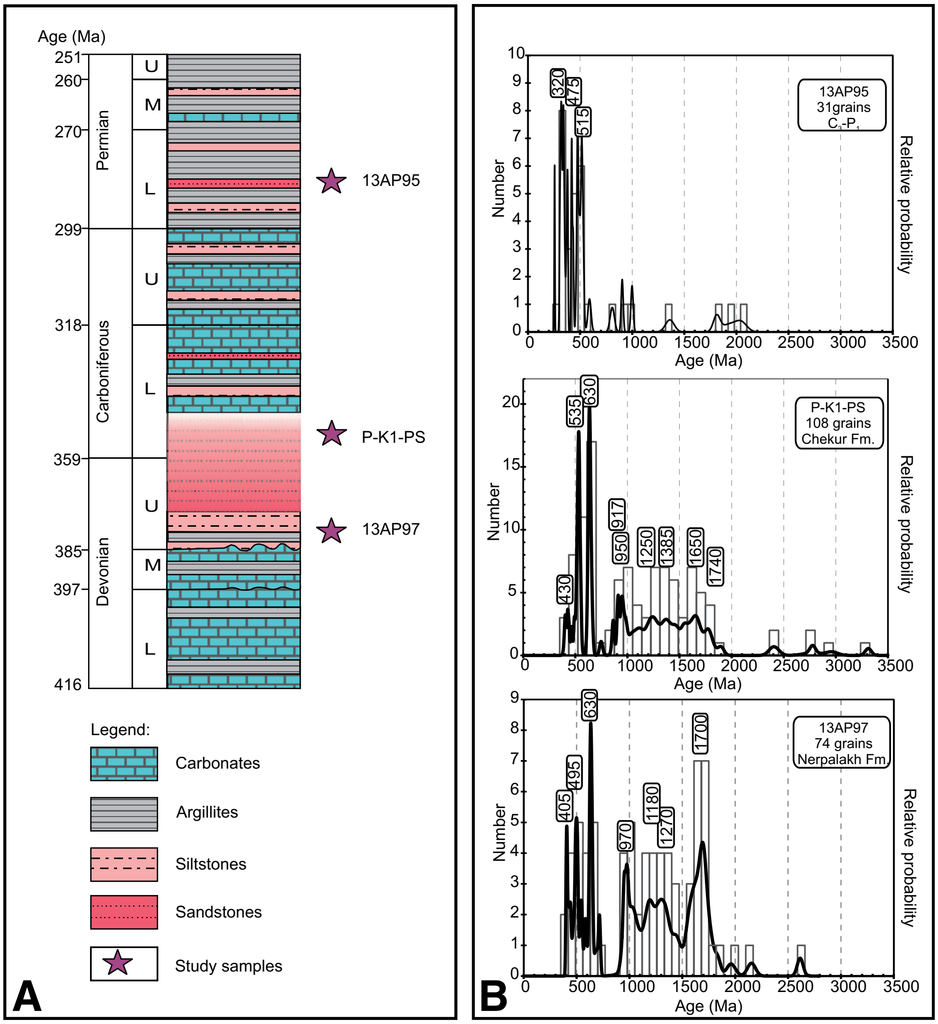

Figure 2. (A) Generalized stratigraphic columns of the of Devonian–Permian strata of Kotel'ny Island (compiled from Kos'ko et al., 1985). U—Upper; M—Middle; L—Lower. (B) Probability density diagram with superimposed histogram of detrital zircon U-Pb ages from Paleozoic rocks of Kotel'ny Island.

the northwest of Kotel'ny Island. Clayey limestone and limy argillite beds, 10–15 m in thickness, have been described from the central part of the island (Kos'ko et al., 1985).

DETRITAL ZIRCON GEOCHRONOLOGY

This study presents U/Pb geochronological results for three samples from the Upper Devonian–Permian clastic succession on Kotel'ny Island. Sample locations are shown in Figure 1. Samples were crushed, and the heavy minerals were concentrated using standard techniques at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences. 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 (LA-ICP-MS). A description of the analytical procedures is provided in Table DR1.[1] The $^{207}Pb/^{206}Pb$ ages are reported for grains older than 1.0 Ga, and the $^{206}Pb/^{238}U$ ages are reported for grains equal to or younger than 1.0 Ga. Following Gehrels (2012), analyses with greater than 30% discordance and 10% reverse discordance were excluded. A full breakdown of the results of the U-Pb study is illustrated in Figure 2B.

Sample 13AP97 (Frasnian, Nerpalakh Formation)

In total, 79 zircons extracted from very fine-grained sandstone were analyzed, of which 74 were considered (Fig. 2B). A significant number of zircons yielded ages between 1900 and 1000 Ma (n = 47), with peaks evident at 1700, 1270, and 1180 Ma. Fifteen zircons yielded Neoproterozoic dates, with the most dominant peaks at 970 and 630 Ma, whereas only one zircon yielded an Archean age (2615 Ma). The sample yielded 10 Paleozoic grains with dominant age peaks at 405 and 495 Ma.

Sample P-K1-PS (Famennian–Tournaisian, Chekur Formation)

In total, 119 zircons extracted from the medium-grained red sandstones were analyzed, of which 108 were considered. The sample yielded four Archean zircons dated at 2767, 2778, 2961, and 3312 Ma. The Paleoproterozoic grains (n = 17) formed a dominant peak at 1650 Ma, with subordinate age group at ca. 1740 Ma (Fig. 2B). Thirty-one zircons fall in the Neoproterozoic interval, with dominant age peaks at 950, 917, and 630 Ma and subordinate peaks at 1250 and 1385 Ma. The 19 Paleozoic grains formed a prominent peak at 535 Ma and a subordinate one at 430 Ma.

Sample 13AP95 (Upper Carboniferous–Permian)

In total, 51 zircons were analyzed from fine-grained silty sandstone, of which 31 were considered. Eight zircons of Precambrian age were identified but did not form significant peaks. The Paleozoic grains (n = 23) formed peaks at 515, 475, and 320 Ma (Fig. 2B).

DISCUSSION AND CONCLUSION

Based on the obtained detrital zircon data, we can test several extant paleotectonic models (Zonenshain et al., 1990; Kuzmichev, 2009) and therefore better constrain the Paleozoic paleogeography of the New Siberian Islands archipelago within the Arctic realm. So far, there are two models regarding the position of the archipelago in the Paleozoic: (1) along the margin of Laurentia (Zonenshain et al., 1990); and (2) along the margin of Siberia (Kuzmichev, 2009).

Our detrital zircon data reveal a major shift in the provenance of clastic sediment between Late Devonian–Mississippian and Pennsylvanian–Permian time. The Upper Devonian–Lower Carboniferous clastics illustrate prominent peaks within the age range of 630–1700 Ma. The abundant 1090–940 Ma zircons suggest a significant sediment contribution from the Grenvillian-Sveconorwegian orogen (Bingen et al., 2008; Rivers, 2008). These orogens stretched from the eastern seaboard of North America to

[1]GSA Data Repository Item 2015011, Analytical technique and Result of U/Pb dating of detrital zircon, is available at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

southwestern Scandinavia, possibly continuing northwards to the edge of the Eurasia basin (Lorenz et al., 2013). The 2.0–1.3 Ga detrital zircon population could be attributed to the early evolution of the Grenville Province (McLelland et al., 2010), and are correlative to the ages of Mesoproterozoic to latest Paleoproterozoic terranes in the Sveconorwegian orogen (Bingen et al., 2008). Reported Mesoproterozoic and latest Paleoproterozoic ages are limited across the Siberian craton basement (Rozen, 2003; Smelov and Timofeev, 2007, and references therein). The ages of most Siberian craton basement blocks are predominantly Archean, while the age of assembly of the Siberian craton has been defined as 1800–1950 Ma. However, only a few zircons close to this age were identified in the studied samples.

Abundant late Neoproterozoic to Early Cambrian zircons in the Upper Devonian–Lower Carboniferous sediments suggest a significant sediment contribution from granitoids associated with the Timanian orogeny (Kuznetsov et al., 2007, and references therein). The Timan fold belt formed as the result of terrane accretion in the late Neoproterozoic–earliest Cambrian onto the northeastern margin of Baltica, currently located in the northwest portion of the European part of Russia.

Ordovician–Silurian zircon ages support a sediment contribution from the Caledonian orogeny, the remains of which are located across northern Scandinavia, eastern Greenland, and northern Britain (McKerrow et al., 2000). Both the late Neoproterozoic–Early Cambrian and Ordovician zircon ages are rare in rocks on the Siberian craton (Parfenov and Kuzmin, 2001). Therefore, the detrital zircon population from the Upper Devonian–Lower Carboniferous clastics does not support a Siberian crustal affinity for Kotel'ny Island, but it is suggestive of a Laurentia-Baltica affinity.

We constructed cumulative age probability plots (Fig. 3A) for numerous localities across the Arctic and further compared the data using a Kolmogorov-Smirnov test (K-S test; Table 1), which measures the probability of similarities of age distributions (Guynn and Gehrels, 2010). The data displayed in Figure 3A suggest that the Upper Devonian–Lower Carboniferous clastic rocks of Bel'kovsky and Kotel'ny Islands (the New Siberian Islands) were derived from the same provenance. A comparison of detrital zircon signatures from coeval strata across the wider Arctic reveals that Upper Devonian–Permian clastics deposited on the Severnaya Zemlya Archipelago, Wrangel Island, and New Siberian Islands were all possibly sourced from the same provenance. Consequently, we suggest that these Arctic regions potentially formed a single tectonic domain located along the northern margin of Laurentia-Baltica during the Late Devonian–Mississippian (Fig. 4).

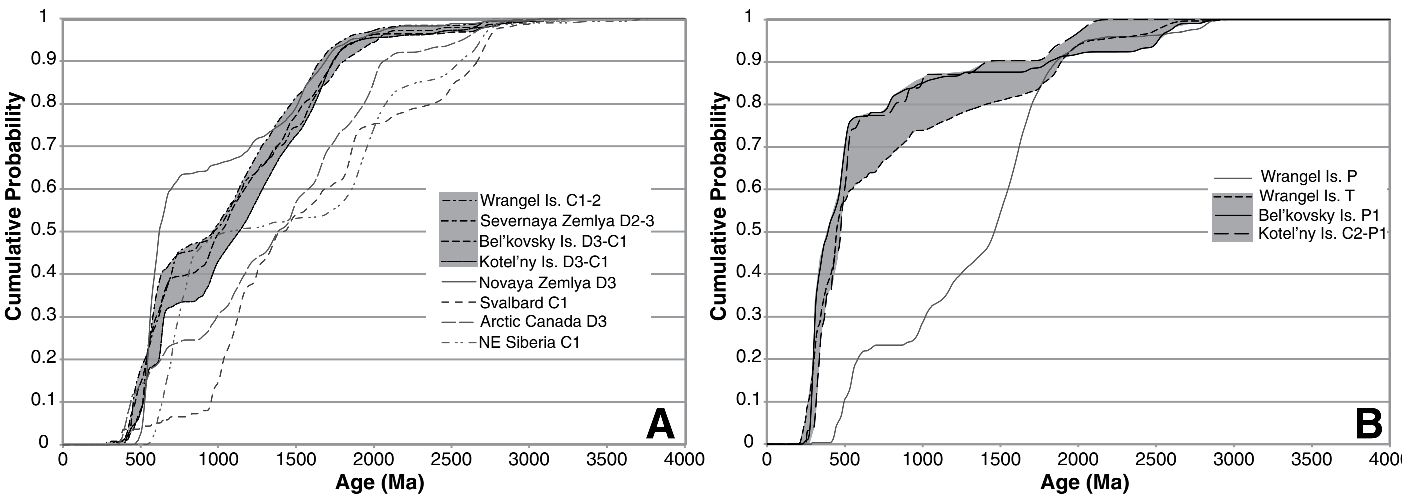

Figure 3. (A) Cumulative probability diagram for Upper Devonian–Lower Carboniferous of Kotel'ny Island (this study) and Devonian samples from Severnaya Zemlya (Lorenz et al., 2008), Upper Devonian–Lower Carboniferous samples from Bel'kovsky Island (V.B. Ershova's data), Carboniferous samples from Wrangel Island, Upper Devonian samples of Arctic Canada (Anfinson et al., 2012a), Carboniferous samples of Svalbard (Gasser and Andresen, 2013), Upper Devonian–Lower Carboniferous samples of Novaya Zemlya (Lorenz et al., 2013), and Lower Carboniferous NE Siberia (Ershova et al., 2013; Prokopiev et al., 2013). (B) Cumulative probability diagram for Upper Carboniferous–Permian samples of Kotel'ny Island (this study), Permian samples of Bel'kovsky Island (V.B. Ershova's data), and Permian and Triassic samples of Wrangel Island (Miller et al., 2010).

TABLE.1 RESULTS OF KOLMOGOROV-SMIRNOV TEST OF DETRITAL ZIRCON AGE SPECTRA SIMILARITY FOR DEVONIAN–CARBONIFEROUS SAMPLES

	Wrangel Island C1-2	Severnaya Zemlya D3-C1	Bel'kovsky Island D3-C1	Kotel'ny Island D3-C1	Novaya Zemlya D3-C1	Svalbard C	Arctic Canada D3	NE Siberia C1
Wrangel Island C1-2		**0.305**	**0.516**	0.021	0.000	0.000	0.000	0.000
Severnaya Zemlya D3-C1	**0.305**		**0.815**	0.013	0.011	0.000	0.000	0.000
Bel'kovsky Island D3-C1	**0.516**	**0.815**		**0.145**	0.000	0.000	0.000	0.000
Kotel'ny Island D3-C1	0.021	0.013	**0.145**		0.000	0.000	0.000	0.000
Novaya Zemlya D3-C1	0.000	0.011	0.000	0.000		0.000	0.000	0.000
Svalbard C	0.000	0.000	0.000	0.000	0.000		0.002	0.000
Arctic Canada D3	0.000	0.000	0.000	0.000	0.000	0.002		0.000
NE Siberia C1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

Values that pass the test for a 95% confidence level are bold.

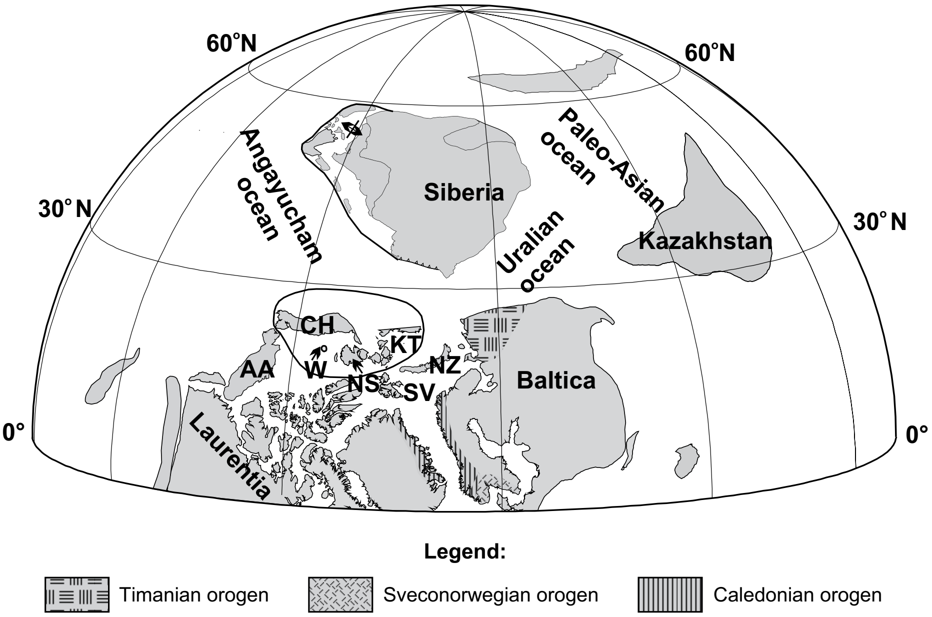

Figure 4. Paleogeographic restoration for Late Devonian-Mississipian (modified from Lawver et al., 2002; Miller et al., 2010). AA—Arctic Alaska, CH—Chukotka, W—Wrangel Island, SV—Svalbard, KT—Kara terrane, NZ—Novaya Zemlya, NS—New Siberian Islands.

In sharp contrast to the older samples, the predominantly Paleozoic zircon population of the Pennsylvanian–Permian deposits on Kotel'ny Island can be correlated to a different magmatic episode reported from the Urals (Brown et al., 2008). Therefore, we interpret a major clastic provenance shift on Kotel'ny Island from Laurentia-Baltica to the Uralian orogeny during the Pennsylvanian. The detrital zircon ages obtained from the studied Upper Carboniferous–Lower Permian sandstones of Kotel'ny Island are also very similar to those from the Lower Permian of neighboring Bel'kovsky Island (Fig. 3B; Table 2) and to Triassic deposits of Wrangel Island. The Uralian orogeny has also been proposed as the main source area for Lower Permian deposits of Bel'kovsky Island (V.B. Ershova's data), while Miller et al. (2013) interpreted the Urals as the source location for Triassic clastic strata on Wrangel Island, Chukotka, and the New Siberian Islands. The K-S test reveals a high probability of similar age distribution and therefore suggests a similar provenance for Permian clastics of the New Siberian Islands and Triassic deposits of Wrangel Island (Triassic grains were excluded from the test; Table 2). Therefore, we interpret that the New Siberian Islands and Wrangel Island were probably located fairly close to each other, with clastics derived from a Uralian provenance from the Pennsylvanian until the early Mesozoic.

The Devonian–Carboniferous rifting event, well documented throughout the Arctic area (Nikishin et al., 1996; Dewey and Strachan, 2003; Miller et al., 2011), may have resulted in separation of the New Siberian Islands, Wrangel Island (with Chukotka), and Severnaya Zemlya, followed by an eastward (in present coordinates) drift of these continental blocks. An alternative possibility includes rifting of all of these terranes from the Laurentian margin during opening of the Arctic Ocean in the Mesozoic.

The data presented here provide new information to aid Paleozoic tectonic reconstructions of the Arctic region prior to opening of the Mesozoic oceanic basins. In summary, our data reveal that Middle–Upper Paleozoic clastic strata on the New Siberian Islands, Severnaya Zemlya Archipelago, Wrangel Island, and possibly Chukotka were likely derived from the same provenance—from Laurentia-Baltica during the Late Devonian–Mississippian and the Uralian orogeny during the Pennsylvanian–Permian.

TABLE 2. RESULTS OF KOLMOGOROV-SMIRNOV TEST OF DETRITAL ZIRCON AGE SPECTRA SIMILARITY FOR PERMIAN SAMPLES

	Wrangel Island, P	Wrangel Island, T	Bel'kovsky Island, P1	Kotel'ny Island, C2-P1
Wrangel Island, P		0.000	0.000	0.000
Wrangel Island, T	0.000		0.006	**0.331**
Bel'kovsky Island, P1	0.000	0.006		**0.118**
Kotel'ny, C2-P1	0.000	**0.331**	**0.118**	

Values that pass the test for a 95% confidence level are bold

ACKNOWLEDGMENTS

This research was supported by RFBR (Russian Foundation for Basic Research) grants N 13-05-00700, 13-05-00943, Grant of the President of Russia for Young Scientist MK-2902.2013.5, research grant of St. Petersburg State University 3.38.137.2014, in accordance with research program DPMGI SB RAS N 66.1.4, Integration Project SB RAS N 68, and Project N 53 (program of Russian Academy of Sciences N 2). We are grateful to James Barnet for useful comments on a first draft of this paper and correcting the English. We are very grateful to the crew of the *Somov* icebreaker for assistance in the field and hospitality. Reviews by Andrew Leier, Luke Beranek, and Lawrence Lawver greatly improved the figures and the text.

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MANUSCRIPT RECEIVED 24 APRIL 2014
REVISED MANUSCRIPT RECEIVED 24 JULY 2014
MANUSCRIPT ACCEPTED 13 OCTOBER 2014

Printed in the USA