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The New Siberian Islands and evidence for the continuation of the Uralides, Arctic Russia

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U–Pb detrital zircon results from New Siberian Islands sandstones illuminate the long-lived controversy regarding the continuation of the Uralian orogen into the Arctic region. A dominant age peak of *c*. 285 Ma from Permian sandstone requires proximal derivation from Taimyr's Carboniferous–Permian granites, thought to reflect syn- to post-tectonic Uralian magmatism. The provenance of Devonian sandstone has Baltica affinities. The data record a dramatic change in provenance between Devonian and Permian time, from Baltica to a mixed Baltica + Uralian source. Our results confirm that the Uralian foreland basin extended from Taimyr to the New Siberian Islands.

Supplementary material: Sample co-ordinates, sediment petrography and heavy mineral analysis, U–Pb data tables and description of analytical methods associated with detrital zircon and granite analyses are available at http://www.geolsoc.org.uk/SUP18784.

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The Uralian orogen reflects late Palaeozoic collision between the Kazakhstan and Siberian plates and the eastern margin of Euramerica (Laurussia) (Hamilton 1970; Zonenshain *et al*. 1984; Brown *et al*. 2002; and many others). Uralian deformation can be traced over 2000 km, from the Aral Sea in the south to the Polar Urals (Fig. 1) but its inferred continuation northward into the Arctic region is controversial because late Palaeozoic ('Uralian') deformation and magmatism is either not present or not yet well documented (Pease 2011). Within the framework of late Palaeozoic collision, there are significant differences in the timing and geometry of orogeny along this collision zone, as well as in the nature and affinity of accretionary blocks caught between the converging palaeocontinents. This complexity is particularly relevant in the Arctic region, where a scarcity of data has fuelled contradictory interpretations (Fig. 1), such as the orogen (1) terminating at the Polar Urals (Puchkov 1997), (2) trending east from the Polar Urals to Taimyr, without manifestations in Novaya Zemlya owing to an embayment (e.g. Scott *et al*. 2010), or (3) bending west from the Polar Urals along Pai Khoi to Novaya Zemlya, curving dramatically through Taimyr, Severnaya Zemlya, and then back to the Asian mainland (Sengör *et al*. 1993).

Geological similarities suggest a close connection between the New Siberian Islands and Taimyr in Palaeozoic and early Mesozoic times. These geological similarities include lithology and faunal assemblages in the sedimentary succession (Cherkesova 1975; Dumoulin *et al*. 2002; Bogdanov 2004; Cocks & Torsvik 2011; Danukalova *et al*. 2014*b*), the occurrence of Siberian trap flood basalts in the New Siberian Islands (Kuzmichev & Pease 2007), and an inferred Taimyr source for Triassic(?) sandstone on Big Lyakhov island (Miller *et al*. 2013). Zhang *et al*. (2013) documented a distinctive provenance change in late Palaeozoic sediments from Taimyr using heavy mineral and U–Pb detrital zircon analysis; they inferred that uplift and erosion of the Uralian orogen was responsible for the provenance change recorded in the siliciclastic foreland basin deposits of southern Taimyr. We present new U–Pb detrital zircon results from the New Siberian Islands that are consistent with the continuation of the late Palaeozoic synorogenic foreland basin deposits of the Uralian orogen from Taimyr to the New Siberian Islands. This resolves one of the major uncertainties of Arctic tectonics and provides an additional constraint for Arctic tectonic reconstructions.

Geology of Taimyr. The Taimyr Peninsula is composed of the Northern, Central, and Southern domains divided by large-scale thrust faults of SE vergence (Fig. 2; Bezzubtsev *et al*. 1986; Zonenshain *et al*. 1990; Vernikovsky 1996). The Northern Taimyr domain together with the Severnaya Zemlya archipelago constitutes the Kara terrane (for an overview see Pease 2011). The Central domain is a composite terrane accreted to Siberia in the Late Neoproterozoic (Vernikovsky 1996) and the Southern domain represents the Palaeozoic margin of the Siberian platform deformed in the late Mesozoic. A broad belt of Late Carboniferous–Permian granites and high-grade metamorphic rocks marks the boundary between the Northern and Central domains. The oldest foliated syncollisional granites are *c*. 305 Ma (304 ± 5 Ma on zircon, this study; 306 ± 2 Ma on monazite, Vernikovsky *et al*. 1995), whereas undeformed post-collisional granitic plutons are as young as 264 ± 8 Ma (conventional zircon population U–Pb upper-intercept age; Vernikovsky *et al*. 1998) with well-defined contact metamorphic aureoles and late Permian cooling ages (Vernikovsky *et al*.

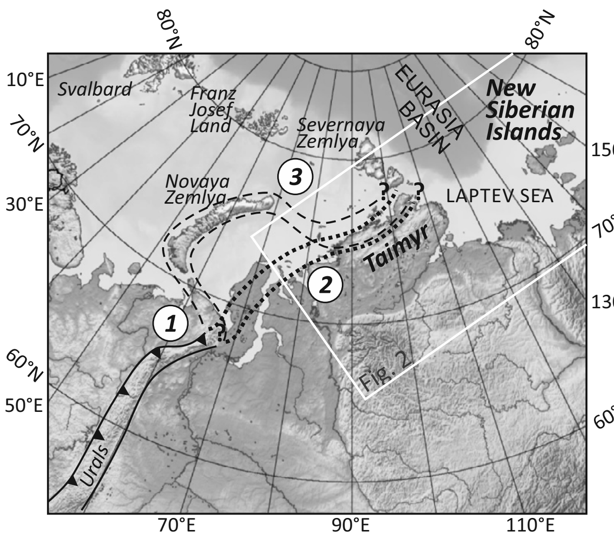

Fig. 1. Possible continuation of the Uralian orogen in the Arctic region (from Pease 2011). Options shown: 1, the orogen ends after the Polar Urals (continuous lines; Puchkov 1997); 2, the orogen heads directly towards Taimyr (dotted lines; Scott *et al*. 2010); 3, the orogen bends circuitously through Novaya Zemlya, Taimyr and ultimately back to Asia (dashed lines; Sengör *et al*. 1993). White rectangle indicates region shown in Figure 2.

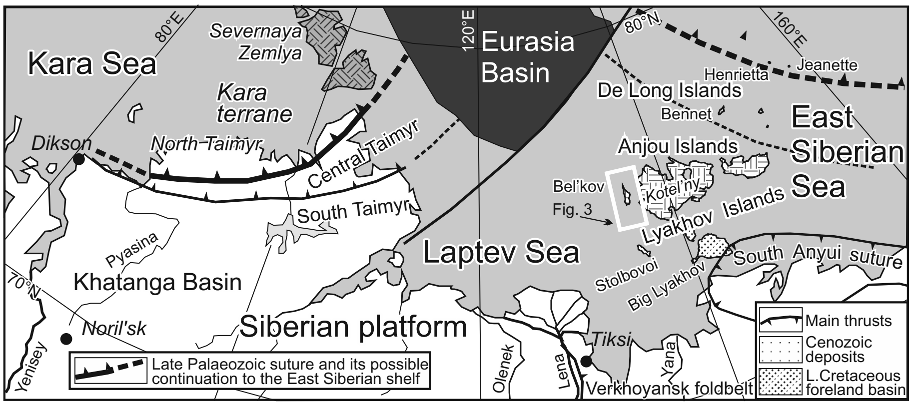

Fig. 2. New Siberian Islands and Taimyr domains. The Late Palaeozoic suture on Taimyr may extend across the Eurasia basin to the East Siberian shelf (dashed line). White rectangle indicates region shown in Figure 3.

1998). This orogenic belt is believed to be a continuation of the Late Palaeozoic Uralian orogen, which in Taimyr was caused by collision of the Kara terrane with Siberia (Zonenshain *et al*., 1990; Vernikovsky 1996). Some workers have argued for a physical link between the Kara terrane and Baltica in Palaeozoic time (e.g. Pease & Scott 2009). It should also be noted that there is little evidence of an ocean (e.g. ophiolitic fragments) separating Kara–Baltica and Central Taimyr prior to their collision and some workers doubt the existence of the northern Taimyr suture (Proskurnin 2013). Despite these controversies, orogenesis across Taimyr is also documented by thick Late Carboniferous and Permian clastic sediments deposited in a foreland basin setting in the Southern Taimyr domain (Bezzubtsev *et al*. 1986; Zhang *et al*. 2013). The structural fabric of Taimyr projects towards the Eurasia basin, which formed only at *c*. 55 Ma (Glebovsky *et al*. 2006), and so may extend to the New Siberian Islands on the other side of this basin (Fig. 2). If so, synorogenic deposits similar to those of the Southern Taimyr domain should be present in the New Siberian Islands, and in particular on Bel'kov island (Kuzmichev & Pease 2007).

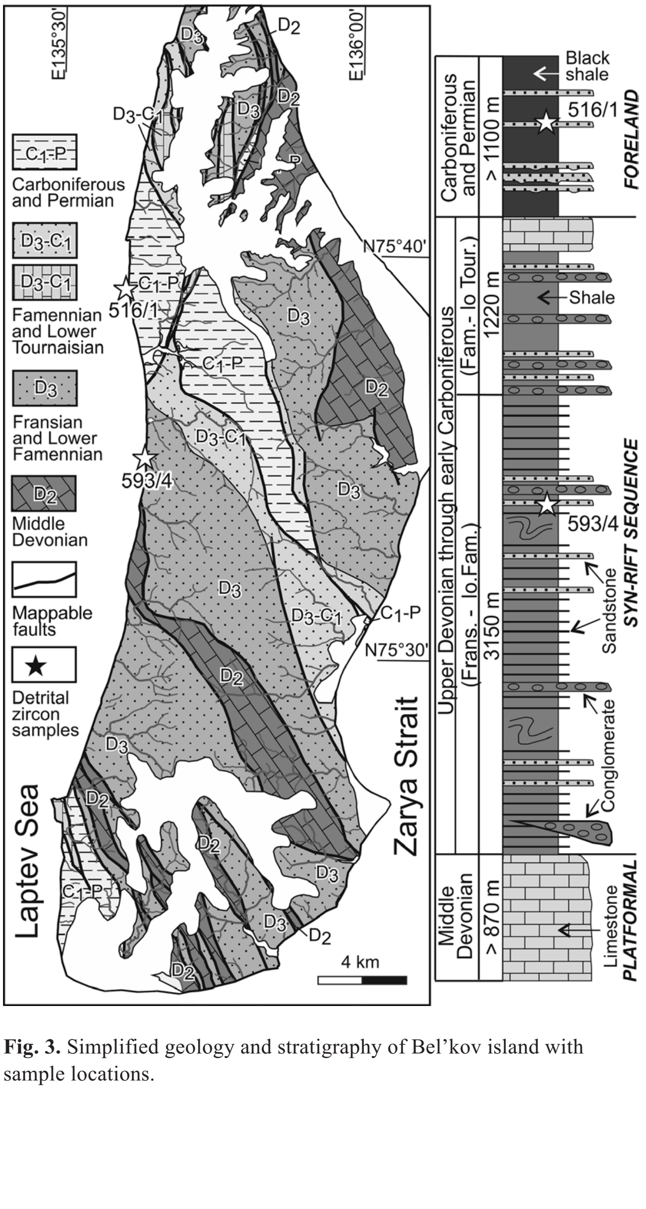

Fig. 3. Simplified geology and stratigraphy of Bel'kov island with sample locations.

Geology of the New Siberian Islands and Bel'kov island. The New Siberian archipelago includes the Lyakhov, Anjou and De Long islands (Fig. 2). Their general geology (summarized by Kos'ko & Korago 2009; Kuzmichev 2009; Pease 2011) comprises a Lower Ordovician–Middle Devonian sequence dominated by platform carbonates (Fig. 3). The Upper Devonian–Permian section is composed of shale, sandstone and minor limestone that are covered by Triassic–Jurassic marine clay-rich sediments. Post-orogenic Aptian–Tertiary deposits lie unconformably on earlier Mesozoic strata. The main deformation occurred in Early Cretaceous (pre-Aptian) time (Kos'ko & Korago 2009; Kuzmichev 2009).

Palaeozoic and Mesozoic rocks equivalent to those of the Southern Taimyr domain occur on the Anjou islands of Bel'kov and Kotel'ny. In the late Middle Devonian platform carbonate sedimentation ceased on the islands when rifting affected Eastern Siberia. NE Kotel'ny was uplifted whereas its SW portion and Bel'kov became a trough filled with several kilometres of Late Devonian clay-rich and clastic sediments. The Late Devonian rocks on Bel'kov island were deposited by gravity-driven mass movement including slumps, debris flows and turbidity currents, as well as along-slope bottom currents. Fossiliferous limestones typical of Kotel'ny are scarce on Bel'kov and occur only at the top of the Devonian section (Fig. 3; Danukalova *et al*. 2014*a*).

Carboniferous–Permian deposits form a continuous succession on Bel'kov island that conformably covers the underlying rocks (Fig. 3). The dark shale has abundant siderite and phosphatic concretions, with scarce siltstone and sandstone layers and rare packages of turbiditic sandstone, and is characterized by slump folding and faulting. Some sediment is highly bioturbated. The sequence lacks carbonate beds and lacks fossils. Its lower age limit is defined by conformably overlying early Tournaisian rocks (Danukalova *et al*. 2014*a*) of the synrift sequence. The presence of Permian detrital zircon in the sequence (see below) provides a maximum age for the upper third of the succession of ≤280 Ma. The upper part of the sequence should be Permian in age as it was non-lithified and water-saturated when intruded by 252 Ma basaltic magma (Kuzmichev & Goldyrev 2007).

Detrital zircon populations and provenance. Petrographic descriptions and heavy mineral analyses were performed at the

Russian Academy of Sciences. Zircon U–Pb detrital dating was performed by secondary ion-microprobe mass spectrometry (SIMS) at the NordSIM facility, Stockholm, Sweden. A syntectonic granite from Northern Taimyr was dated by the Kober method at the Swedish Museum of Natural History.

A feldspathic litharenite (sample 516/1) was collected from the upper third of the Carboniferous–Permian succession (Fig. 3), inferred to be comparable in age with synorogenic deposits of southern Taimyr. This sample represents the first input of angular detritus and indicates the transition to first-cycle sedimentation and short-distance transport. The sample is dominated by Palaeozoic zircon, with minor (12%) Precambrian ages present (Fig. 4). The most significant age-peak (40%) is Late Carboniferous to Early Permian (300–280 Ma). The sample also has significant Devonian–Early Carboniferous (400–310 Ma) and Early Palaeozoic (550–450 Ma) populations.

A Late Devonian (late Frasnian) litharenite (sample 593/4) was sampled from the synrift sequence (Fig. 3) and analysed for comparative purposes. The Devonian sample is dominated by a Silurian–Early Devonian age-peak (445–410 Ma) (Fig. 4). Other notable peaks include Late Cambrian–Early Ordovician (510–480 Ma), Ediacaran–earliest Cambrian (560–535 Ma), Late Neoproterozoic (660–600 Ma), Meso-Neoproterozoic (1400 Ma and 1180–950 Ma) and late Palaeoproterozoic (1740–1620 Ma) ages (Fig. 4).

The detrital zircon ages, consistent with the petrographic and heavy mineral analysis, indicate a drastic change in sediment provenance by Permian time most plausibly associated with orogenesis of Carboniferous–Permian age. The Permian first-cycle sandstone contains detrital zircons that can be confidently attributed to granitoids (305–260 Ma) of the Northern Taimyr domain (this study; Vernikovsky 1996; Vernikovsky *et al*. 1998). Peak ages of 390–330 and 540–450 Ma may be derived from Severnaya Zemlya (Lorenz *et al*. 2007). This age spectrum is very similar to that defined in coeval sediment of Southern Taimyr (Fig. 4; Zhang *et al*. 2013) and we conclude that a foreland basin extended from Taimyr to the New Siberian Islands in the Permian.

The Devonian sample is dominated by Baltica-derived zircon detritus. Distinct Caledonian (Silurian and Early Devonian), Timanian (latest Ediacarian), and Grenvillian (*sensu lato*; Tonian) zircon ages are usually regarded as representing a Baltica signature (e.g. Pease *et al*. 2008) and are not present in Siberian sources (including the Central Taimyr domain). Baltica is a source for Meso-Neoproterozic to Ediacaran ages (Bingen & Solli 2009) and is also a potential source for late Palaeoproterozoic ages (from Laurentian fragments incorporated during Caledonian thrusting; e.g. Kirkland *et al*. 2008). The Kara terrane was probably a part of Baltica in the Devonian (Pease & Scott 2009) and is a likely source for the Early Ordovician zircons (Lorenz *et al*. 2007).

The Uralian orogen in the Arctic. Major sources for detrital zircon signatures of northern Baltica were Grenvillian, Timanian and Caledonian granitoids and are consistent with similar aged zircons found in our Late Devonian sample. This implies that the New Siberian Islands received clastic detritus from Baltica in Devonian time because either it was attached to Baltica (not Siberia) or it was proximal to Baltica (i.e. there was no Uralian ocean between Kara and Siberia in Devonian time). Given the lack of Siberian-derived detritus in our Devonian sample, the former seems more plausible and is consistent with the inferred dynamics of Uralian collision discussed below.

Late Carboniferous–Permian Uralian collision between Baltica and Siberia best explains the mixed Baltica plus Uralian signatures found in our Permian sample. By Permian time, Uralian collision between northern Baltica–Kara (including the New Siberian Islands?) and northern Siberia resulted in uplift and erosion of northern Taimyr's syn- to post-tectonic granitoids and the deposition of detritus (zircon) derived from them. The provenance match between the Permian samples from the New Siberian Islands and Southern Taimyr suggests that both locations received similar detritus from the Uralian orogen and that synorogenic Uralian foreland basin(s) extended from Taimyr to the New Siberian Islands.

These results favour the model of Scott *et al*. (2010) (option 2 in Fig. 1). Uralian orogeny extended from the Ural Mountains to Taimyr and beyond to the New Siberian Islands. This is consistent with the diachronous Uralian orogen younging from south to north, the lack of Carboniferous–Permian (Uralian) deformation and magmatism on Novaya Zemlya, and the dramatic change in sediment provenance by Permian time in both Taimyr and the New Siberian Islands, as well as the similarity in sediment provenance of Permian sandstones from both locations.

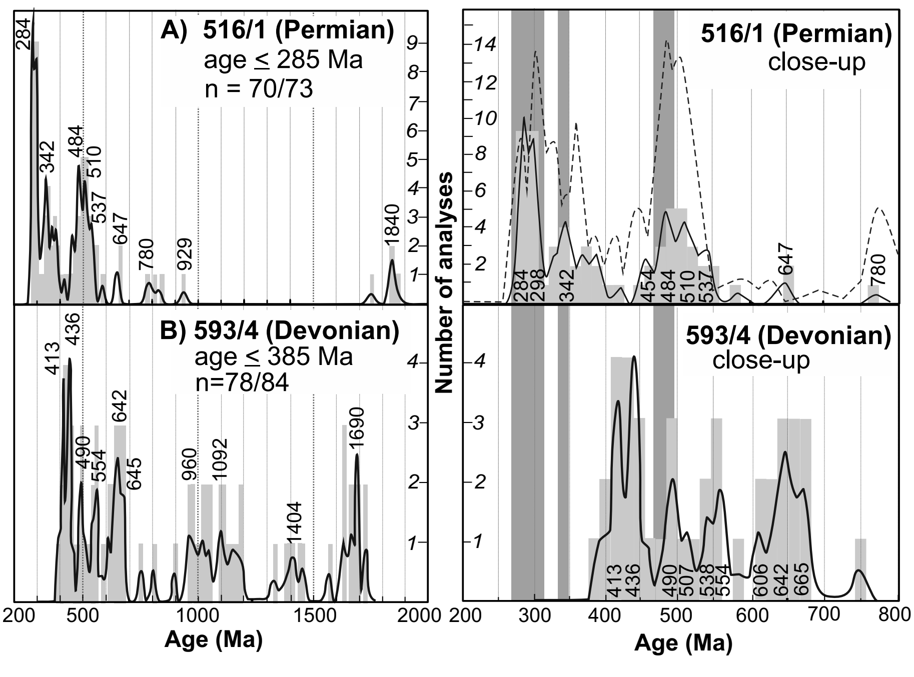

Fig. 4. Summary of U–Pb detrital zircon analyses. Relative age probability curves show (1) distinct differences between Permian and Devonian samples, indicating a dramatic change in provenance, and (2) strong similarities to equivalent strata from Taimyr (dashed probability curve in Permian close-up; from Zhang *et al*. 2013). Fields of syn- to post-tectonic granites of Taimyr and Severnaya Zemlya are indicated by bars. It should be noted that minor populations with ages >2 Ga are not plotted.

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