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ARTICLE

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A reconnaissance provenance study of Triassic–Jurassic clastic rocks of the Russian Barents Sea

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ABSTRACT

Combined U–Pb detrital zircon dating of 21 samples, along with whole-rock chemical composition and Sm–Nd isotopic studies of 39 samples of Triassic and Jurassic rocks from Franz Josef Land and wells in the southern part of the Russian (eastern) Barents Sea, were analyzed for a reconnaissance provenance study. The similarity of detrital zircon age distributions was statistically assessed using the Kolmogorov–Smirnov (K–S) test and points to a common source area for the clastic material of Triassic to Middle Jurassic age.

Uralian-age detrital zircons predominate in all samples, with a comparably smaller portion of Caledonian- and Timanian-age detrital zircons. The number of Palaeoproterozoic and Archean grains is very small and becomes significant only in a few Jurassic samples. $\varepsilon_{Nd}(t)$ values gradually decrease from −1.5 to +2.5 in Lower Triassic rocks, to −2.0 to −8.2 in Jurassic rocks, suggesting an increasing influence of ancient metamorphic basement erosion in the younger Jurassic rocks. High Co/Th ratios, suggesting the erosion of mafic rocks, were mainly recorded in Lower Triassic rocks, whereas increasing Th/Sc ratios, suggesting the erosion of felsic rocks, were recorded only in some uppermost Triassic and Jurassic rocks.

We identify the Urals and, in addition during the Triassic, the basement of the West Siberian Basin as the main provenance for the studied clastic rocks. By contrast, only a small volume of fine-grained clastic detritus was derived from basement erosion of the East European Craton, which was characterized by a subdued relief during this time.

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Introduction

The Barents Sea region has been the target for extensive geological and geophysical studies over the past few decades and their findings are summarized in a set of papers and maps (e.g. Malyshev 2002; Smelror et al. 2009; Basov et al. 2009; Henriksen et al. 2011; Faleide et al. 2018). Most of the Barents Sea region is covered by a dense grid of seismic profiles used to infer the deep tectonic structure, whereas knowledge and interpretations of the offshore stratigraphy come from the study of wells and onshore outcrops across the Svalbard, Franz Josef Land and Novaya Zemlya archipelagos, as well as the mainland of Arctic Norway and Russia (Fig. 1).

Although provenance studies represent an important tool for the reconstruction of palaeogeographies and depositional systems, U–Pb detrital zircon dating has only been carried out in a few localities mainly in the Norwegian sector of the Barents Sea (Bue & Andresen 2014; Klausen et al. 2017, 2018; Fleming et al. 2016; Flowerdew et al. in press). Within the Russian (eastern) sector, a single detrital zircon study focused on Triassic rocks from the Severnaya well located in the southern part of Franz Josef Land (Soloviev et al. 2015), although preliminary information from a detrital zircon study across the Russian sector was presented by Petrov (2010). In this study, we summarize the U–Pb detrital zircon, whole-rock Sm–Nd isotope and geochemical studies of Triassic and Jurassic samples recovered from 7 deep wells located in the southern part of the Russian Barents Sea and Franz Josef Land (Fig. 1), providing new constraints on clastic provenance regions, sediment transport pathways, and therefore, palaeogeographic reconstructions.

Geological setting

The structure and composition of the Barents Shelf basement and most of the Palaeozoic succession are inferred from seismic data, potential fields data, and the study of onshore outcrops exposed around the perimeter of the shelf. The basement has been interpreted to be of Timanian age (Drachev 2016; Faleide et al. 2018). However, U–Pb dating of pebbles from southern Franz Josef Land and a (U–Th)/He detrital zircon study from Palaeozoic rocks of Severnaya Zemlya suggest the occurrence of Caledonian- and/or Ellesmerian-age magmatic and metamorphic rocks in the northern part of the Barents Sea basement (Ershova et al. 2017, 2018). Palaeozoic sedimentation was interrupted by Devonian rifting, with mafic intrusions and formation of the

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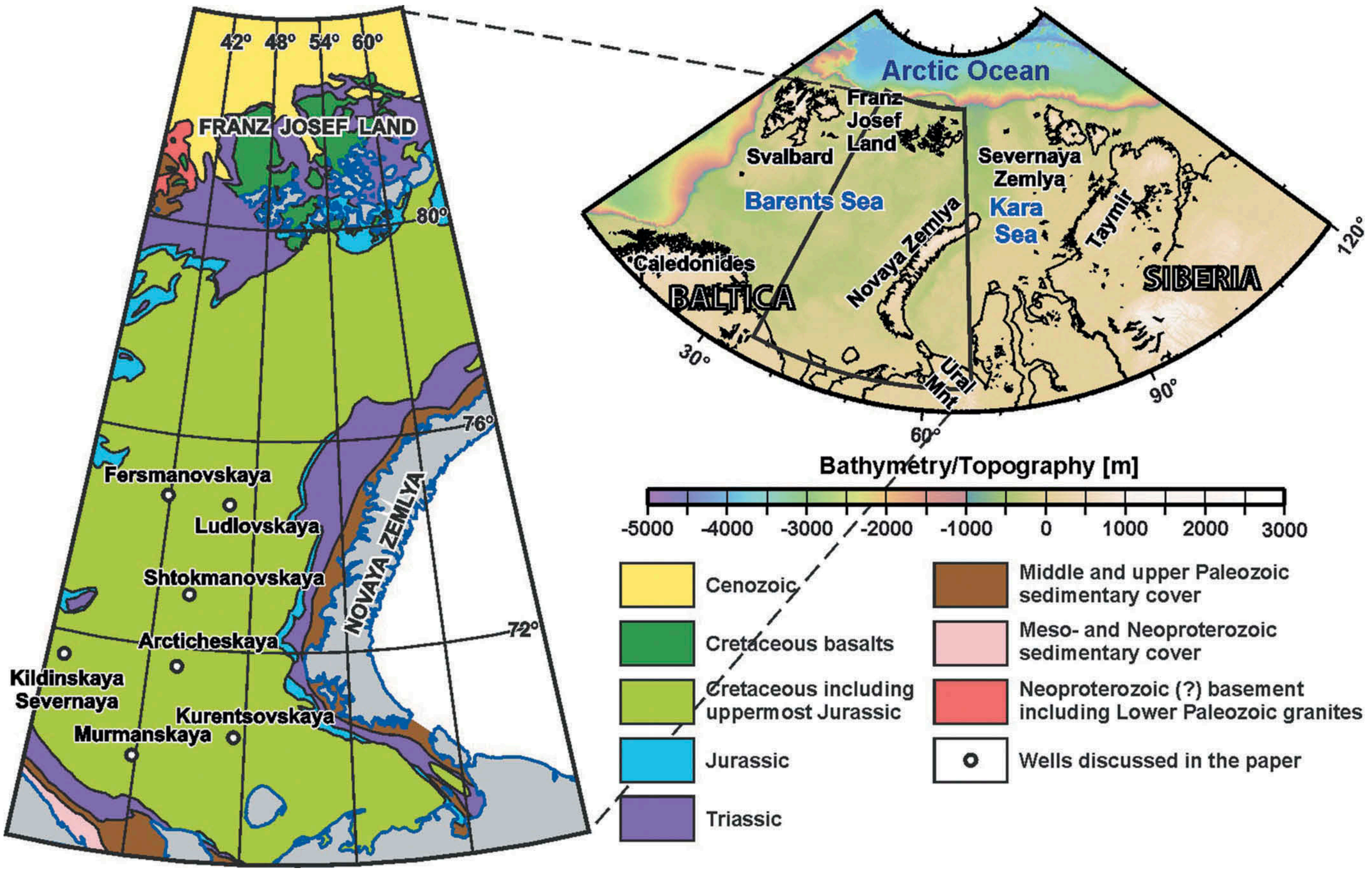

Figure 1. Maps of the Russian Barents Sea region showing location of studied wells. Geology simplified after Petrov (2012).

Ludlov Saddle subdividing the eastern Barents Shelf into two sedimentary basins, the South Barents and North Barents basins (e.g. Drachev et al. 2010; Henriksen et al. 2011; Drachev 2016; Faleide et al. 2018). However, both the South and North Barents basins contain comparable successions of Ordovician to Lower Permian predominantly carbonate rocks, although intercalated clastic units have been inferred as well.

A significant change in the depositional history of the Barents Sea basins commenced in the Wordian (Middle Permian), with a major influx of siliciclastic detritus from the east. Based on a high economic potential for hydrocarbon exploration, the Mesozoic siliciclastic succession has been penetrated by deep wells and seismic interpretation has good stratigraphic control. Rapid subsidence occurred during the Late Permian and Early Triassic, resulting in the formation of a relatively deep-water basin where large volumes of siliciclastic sediment accumulated. The rate of sediment input eventually outpaced the rate of subsidence, largely filling in the accommodation space by the end of the Early Triassic. During the Middle Triassic–Jurassic, depositional environments exhibit a facies transition from lacustrine and fluvial plain, to shallow-water shelf and then deep-water shelf environments in a northward direction from mainland Arctic Russia, and a westward direction from the Novaya Zemlya archipelago, although the detailed distribution of facies varies in different palaeogeographic reconstructions (Basov et al. 2009; Smelror et al. 2009; Henriksen et al. 2011). Several transgressive and regressive stages are also identified, complicating an interpretation of facies distribution.

The Mesozoic was characterized by compressional deformation, documented in the Novaya Zemlya archipelago. Seismic studies in the vicinity of the western coast of Novaya Zemlya show an angular unconformity at approximately the Triassic/Jurassic boundary (Drachev 2016), and recent apatite fission track and (U–Th)/He zircon studies also point to a Late Triassic–Early Jurassic period of deformation (Prokopiev et al. 2016; Zhang et al. 2018).

Samples and approaches

The stratigraphic settings of studied samples from offshore wells and from outcrops on Franz Josef Land are shown in Figure 2 and described in the Electronic Supplementary Data File 1. In total, 21 samples were used for U–Pb detrital zircon dating and 39 samples for whole-rock Sm–Nd isotopic and geochemical studies (Electronic Supplementary Data File 1). All analytical studies were carried out at the Isotopic Centre and Central Laboratory of VSEGEI, St. Petersburg, and related analytical methods and approaches for interpretation are discussed in the Electronic Supplementary Data File 2.

From each sample, 40 to 67 zircon grains (893 grains in total) were dated by SHRIMP and summarized in Electronic Supplementary Data File 3. $^{207}Pb/^{206}Pb$ ages are reported as the best ages for analyses with $^{206}Pb/^{238}U$ ages >1000 Ma, whilst $^{206}Pb/^{238}U$ ages are reported as the best ages for

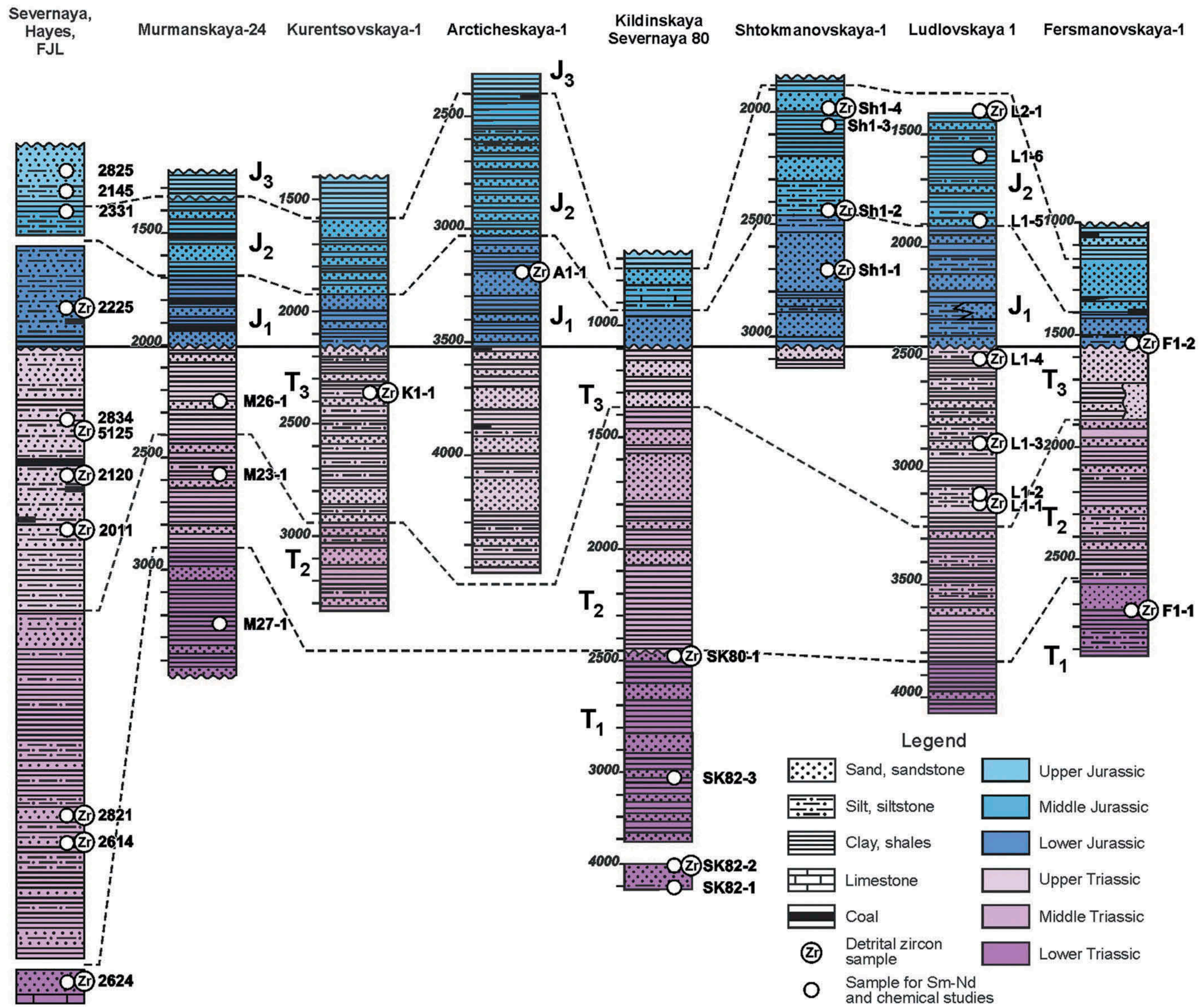

Figure 2. Correlation chart of Triassic–Middle Jurassic rocks of the studied wells and composite section for the south-east part of Franz Josef Land (FJL), Severnaya and Hayes wells (after Shipilov & Tarasov 1998; Malyshev 2002; Petrov 2010; Leonchik 2011; Makariev 2011; Norina 2014; Tkachenko 2014). Lower part of the Severnaya Kildinskaya 80 well below blank belt is for Severnaya Kildinskaya 82 well. Description of samples is in Electronic Supplementary Data File 1.

analyses with $^{206}Pb/^{238}U$ ages ≤1000 Ma. A statistical comparison of the distribution of detrital zircon ages between samples was assessed using the Kolmogorov–Smirnov (K–S) test, which measures the probability that two age distributions have been selected from the same original population (Gehrels 2012).

Whole-rock Sm–Nd isotopic and geochemical studies are very useful for provenance studies. They allow the identification of the chemical composition of the rocks in the source area, the crust/mantle type of eroded magmatic and metamorphic rocks, and sediment reworking processes, as well as being equally applicable to sandstones and fine-grained (i.e., siltstones and shales) clastic sedimentary rocks (Condie 1993; McLennan et al. 1993, 2003). The integration of these three analytical techniques on a set of samples can therefore provide much more robust interpretations of provenance regions comprising a whole suite of different magmatic and metamorphic rocks. The measured concentrations of Sm and Nd isotopes and their ratios, as well as concentrations of major, trace and rare earth elements, are listed in the Electronic Supplementary Data Files 4 and 5.

Results

Results of the U–Pb detrital zircon dating are summarized in Figure 3. Grains younger than 700 Ma, mainly of Timanian (c. 640–540 Ma), Caledonian (c. 500–390 Ma), and Uralian (375–250 Ma)-age orogenic events, predominate and constitute 626 out of 893 grains, forming approximately 70% of the whole age population. Grains older than 700 Ma, but younger than 1550 Ma constitute 118 out of 893 (13%) grains, and grains older than 1550 Ma constitute 149 out of 893 (17%) grains. Only 24 out of 893 grains are Archean in age (>2500 Ma, less than 3%). Uralian-age zircon grains predominate in all samples, whereas grains

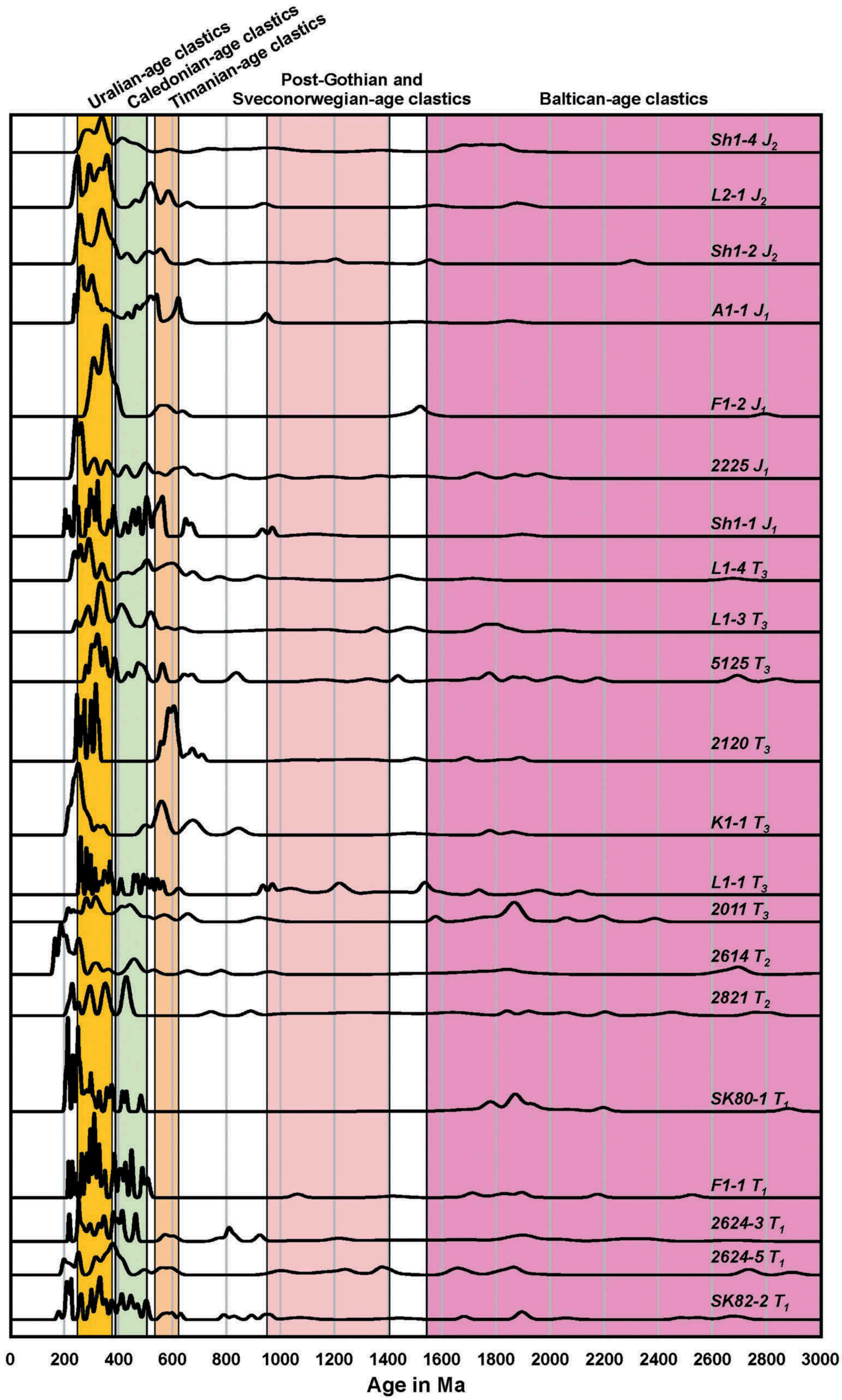

Figure 3. Normalized probability plot for U–Pb detrital zircon age distributions of samples from wells and Franz Josef Land (FJL). See Figures 1 and 2 for location and stratigraphy.

of Baltican ages (older than c. 1550 Ma) are generally not abundant, but are most common in Jurassic sandstones from the northernmost wells (Fersmanovskaya, Ludlovskaya, and Shtokmanovskaya, Fig. 1). Timanian-age zircon grains are distributed fairly uniformly within Triassic and Jurassic samples, but form significant concentrations in samples 2011–10 and 2120–11, both from the Upper Triassic succession of Franz Josef Land.

Approximately half of the zircons have a Th/U ratio of >0.5, which is typical for zircons from magmatic rocks (Hoskin & Schaltegger 2003). However, 27 out of 893 grains have a very low Th/U ratio of <0.1, which suggests these zircons are of metamorphic origin. Zircons with a low Th/U ratio have a predominantly low discordance (D < 10%), with ages ranging from 192 Ma to 2726 Ma.

The K–S test shows a significant similarity of detrital zircon age distributions between samples (Electronic Supplementary Data File 6). One hundred and eighteen out of 210 tests are characterized by P > 0.05, suggesting that detrital zircon age distributions in samples of a similar age from different parts of the Russian Barents Sea are not statistically different. According to the K–S test, detrital zircon age distributions are similar in 4 out of 5 Lower Triassic samples, both Middle Triassic samples, and all 3 Middle Jurassic samples. In the Upper Triassic samples, 15 out of 21 tests have P > 0.05, suggesting a significant similarity in compared detrital zircon age distributions. The highest variability in the detrital zircon age distribution is recorded for Lower Jurassic samples. For samples of different age, the lowest P values are recorded when Lower Triassic samples are compared with Jurassic and some Upper Triassic samples.

The similarity in Nd model ages estimated with reference to fractionation of Sm and Nd isotopes during sedimentation T_{Nd}(DM-2s), and with no reference to fractionation during any crustal processes T_{Nd}(DM), suggests that the Sm–Nd isotopic system has not been significantly disturbed by the sedimentary processes for 36 out of 39 samples (Electronic Supplementary Data File 4). The highest $\varepsilon_{Nd}(t)$ values ranging mainly from −1.5 to +2.5 were measured in the Lower Triassic samples, whereas the lowest $\varepsilon_{Nd}(t)$ values ranging from −8.2 to −2.0 were documented in the Middle and Upper Jurassic samples, forming a trend of decreasing of $\varepsilon_{Nd}(t)$ values with decreasing sample age (Fig. 4). On the $\varepsilon_{Nd}(t)$ vs. Th/Sc plot (Fig. 4), all samples are located in the field between average compositions of island arc andesite and upper crust, with Lower Triassic samples closer to the former and Jurassic samples closer to the latter.

All measured concentrations of major, trace and rare earth elements are far above detection limits. Specific elements and their ratios (REE, Th, Sc, Zr, Co) are selected in accordance with the approach outlined by McLennan et al. (1993), McLennan et al. (2003).

The Th/Sc ratio is a sensitive indicator of chemical differentiation processes in igneous rocks, because Th is an incompatible element whilst Sc is compatible. The Zr content reflects the abundance of heavy minerals, notably zircon, and therefore is used as a proxy for sediment reworking (McLennan et al. 1993, 2003). In the samples studied here, the Th/Sc ratio varies from 0.11 to 2.76 and most samples follow the source composition trend, whereas a high Zr/Sc ratio (>20) was documented in 10 samples of predominantly Jurassic age (Fig. 5). The La/Sc versus Co/Th diagram (Fig. 5) displays ratios between compatible and incompatible elements, which are sensitive to igneous chemical differentiation processes and represent the composition of igneous rocks in the provenance (Taylor & McLennan 1985). High Co/Th ratios suggest the erosion of mafic rocks, whereas high La/Sc ratios are indicative of the erosion of felsic rocks. In the studied samples, most Triassic rocks have a higher Co/Th ratio, whereas most Jurassic and some Upper Triassic rocks have a higher La/Sc ratio (Fig. 5).

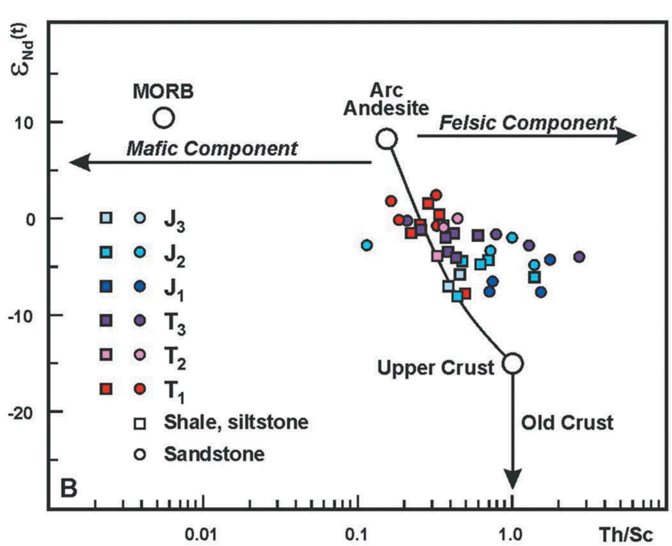

Figure 4. Sm–Nd isotopic characteristic of samples from wells and Franz Josef Land. Diagram $\varepsilon_{Nd}(t)$ vs. Th/Sc after McLennan et al. (1993), McLennan et al. (2003), showing the presence of island arc volcanics in the provenance of Triassic samples, and an increasing influence of ancient crustal erosion during deposition of the Jurassic clastics. See text for discussion.

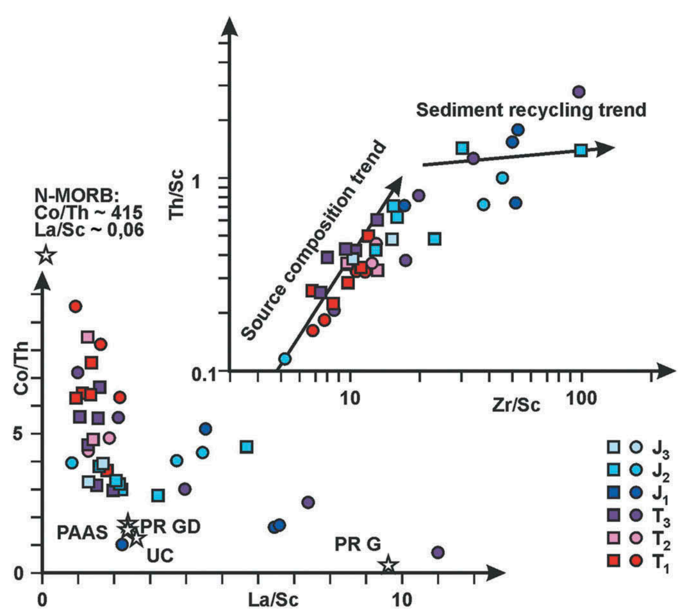

Figure 5. Geochemical characteristics of samples from wells and Franz Josef Land. Diagrams Zr/Sc vs. Th/Sc and Co-Th vs. La/Sc after Taylor and McLennan (1985) and McLennan et al. (1993, 2003). Asterisks show average composition (after Taylor & McLennan 1985; Condie 1993) of normal Mid-Oceanic Ridge Basalt (N-MORB), Post-Archean Australian Shale (PAAS), Upper Crust (UC), Proterozoic granodiorite (PR GD), Proterozoic granite (PR G). See text for discussion.

The Cr/V ratio reflects the enrichment of chromium over other ferromagnesian elements, suggesting the presence of chromite amongst the heavy minerals and therefore the erosion of ultramafic rocks. All studied samples have low Cr/V ratios, ranging from 0.5 to 2.1, as well as low Cr concentrations, ranging from 18.5 to 212 ppm (Electronic Supplementary Data File 5).

Discussion

Based on the interpretation of seismic data and Triassic palaeogeographic reconstructions, most of the Barents Sea including the study area was characterized by subdued topography or marine environments with deposition of clastic sediment, suggesting that significant erosion of local basement highs during this time was unlikely (e.g., Basov et al. 2009; Smelror et al. 2009; Henriksen et al. 2011; Khlebnikov et al. 2011; Leonchik 2011; Tkachenko 2014). The distribution of most Triassic samples along the source composition trend with a low Zr/Sc ratio and variable Th/Sc ratio (Fig. 5) suggests no or very limited sediment reworking (i.e., erosion from older pre-existing clastic sediments). Throughout the study area, the highest Zr/Sc ratios were recorded in Lower and Middle Jurassic and some uppermost Triassic clastic rocks, implying that some minor reworking of older sandstones may have occurred during this time. An erosional basement high of Early Jurassic age is only inferred from the age of granite clasts in conglomerates from the Franz Josef Land archipelago along the northern perimeter of the Barents Sea (Ershova et al. 2017). However, the widespread distribution of feldspar-rich sandstones (Stupakova et al. 2012) suggests that a significant contribution of reworked sediments is unlikely even during the Jurassic, suggesting that the main provenance for Mesozoic clastic rocks was located outside of the eastern Barents Sea region.

Detrital zircon age distributions (Electronic Supplementary Data File 3, Fig. 3) of all samples are dominated by Uralian-age grains. Caledonian- and Timanian-age detrital zircons are much less abundant but, based on the K–S test (Electronic Supplementary Data File 6), all of them seem to have been derived from the same provenance. Some variations in the detrital zircon age distributions between Lower Triassic and uppermost Triassic–Jurassic samples reflect a minor modification of the provenance, including reworking of older clastic material found in Jurassic sandstones.

Very similar detrital zircon age distributions were reported for Triassic rocks from the Severnaya well (Franz Josef Land) by Soloviev et al. (2015). On the Russian mainland, magmatic and metamorphic rocks with similar ages are most typical for Timan and the Urals (e.g. Puchkov 2010), located to the southeast of the study area (Fig. 6). Our interpretation is supported by published palaeogeographic reconstructions, illustrating a facies transition from predominantly deltaic and fluvial environments in the Pechora Sea and southeast Barents Sea, to increasingly marine environments in a northwestward direction across the Barents Shelf (Basov et al. 2009; Smelror et al. 2009; Henriksen et al. 2011).

One of the most significant interpretations from the detrital zircon study is that the East European Craton contributed a negligible volume of clastic detritus to the Russian Barents Sea region during the Triassic and Jurassic. By contrast, the results of the whole-rock Sm–Nd isotopic study suggest an increasing influence of weathering of ancient basement rocks within the younger (Jurassic) sediments (Fig. 4). The whole-rock study involves grains encompassing a broad size range, including grains within the silt and clay size fraction, therefore we suggest that erosion of the subdued relief of the East European Craton only contributed fine-grained clastics containing detrital zircons which are too small to be dated.

Although Uralian-age detrital zircons are also widely distributed in the Norwegian (western) Barents Sea, far to the west of the study area, the provenance of clastic detritus deposited in the Svalbard and Southwestern Barents Sea basin significantly differs from that of the study area (Bue & Andresen 2014; Fleming et al. 2016; Klausen et al. 2017, 2018; Flowerdew et al. in press; Fig. 7). Significant mixing and erosion of different source areas is typical for both Svalbard and the Southwestern Barents Sea basin. Erosional products from the East European Craton are recognized throughout the Triassic and Jurassic sandstone samples, and often predominate. Uralian-age detrital zircons predominate in the Carnian succession, suggesting a major provenance change in the Norwegian Barents Sea (e.g. Fleming et al. 2016). However, the magnitude of this event greatly decreases eastward, and on Franz Josef Land and in offshore wells from the southern part of the Russian Barents Sea, detrital zircon age distributions show only minor variations from Lower Triassic to Jurassic rocks (Fig. 7). Here, some variation in the composition of the provenance is only recorded by a relatively high Co/Th ratio in most Triassic samples, suggesting significant erosion of mafic igneous rocks, whereas Jurassic and some Upper Triassic samples have a higher La/Sc ratio, suggesting increasing erosion of felsic igneous rocks.

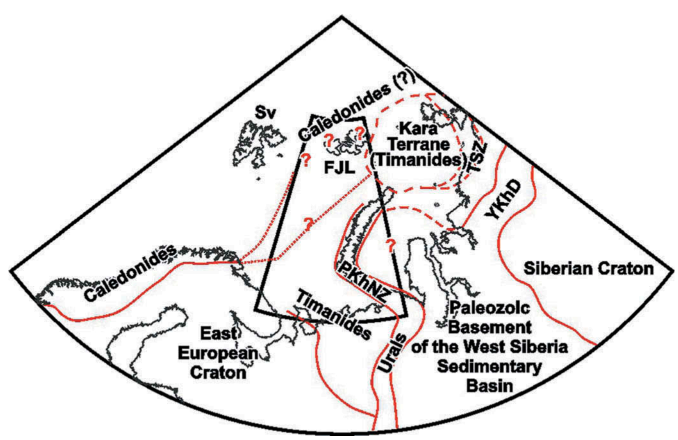

Figure 6. The main provenance areas for the east Barents Sea Triassic and Jurassic clastic rocks. Sv Svalbard, FJL Franz Josef Land; Fold and thrust belts: PKhNZ Pai-Khoi – Novaya Zemlya, TSZ Taimyr–Severnaya Zemlya; Sedimentary Basins: YKhD Yenisey-Khatanga Depression. Dash lines are proposed boundaries of the Kara terrane and Taimyr–Severnaya Zemlya fold and thrust belt, whereas dot lines are proposed limits of the Caledonian rocks in the Barents Sea basement (after Drachev et al. 2010; Drachev 2016; Ershova et al. 2018; Faleide et al. 2018). Location of Figure 1 is shown.

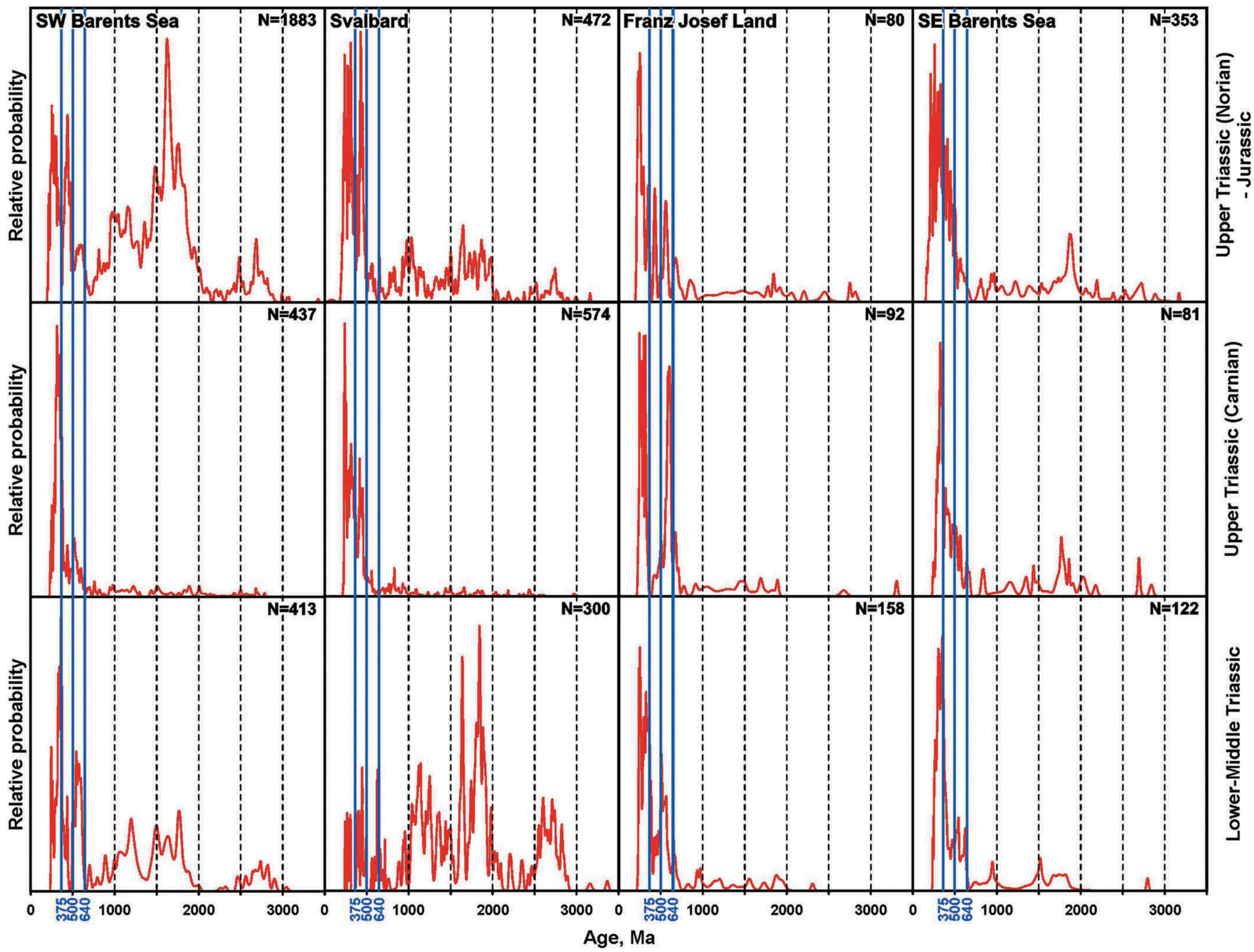

Figure 7. Relative probability curves for detrital zircons, comparing data from this study on Franz Josef Land and the eastern Barents Shelf, with the southwestern Barents Sea basin (Klausen et al. 2017; Fleming et al. 2016; Flowerdew et al. in press) and Svalbard (Bue & Andresen 2014). Solid lines (375, 500 and 640 Ma) show approximate limits for estimating the number of Uralian-, Caledonian-, and Timanian-age detrital zircon grains. N – number of dated grains. All databases were reformatted to show $^{207}Pb/^{206}Pb$ ages for analyses with $^{206}Pb/^{238}U$ ages >1000 Ma, and $^{206}Pb/^{238}U$ ages for analyses with $^{206}Pb/^{238}U$ ages ≤1000 Ma.

The immense volume of Triassic clastic rocks deposited in the eastern Barents Sea and Southwestern Barents Sea sedimentary basins requires erosion of not only the Urals, but of an additional provenance as well. The primary candidate for an additional provenance of Triassic clastics is the basement of the West Siberian sedimentary basin, which comprises a wide distribution of Uralian-age orogenic belts. The other proposed provenance for the eastern Barents Sea and Svalbard Triassic clastics is the Taimyr–Severnaya Zemlya fold and thrust belt (e.g. Hastard 2016; Startseva et al. 2017). The Taimyr–Severnaya Zemlya fold and thrust belt, along with the Kara Terrane and surrounding areas, contain numerous Uralian-, Timanian- and, probably, Caledonian-age intrusions and metamorphic rocks (Vernikovsky 1996; Pease & Scott 2009; Ershova et al. 2015, 2018; Kurapov et al. 2018), representing a conceivable provenance for the studied clastic rocks. However, regional seismic data do not provide evidence for significant progradation of deltaic facies to the Russian Barents Sea from a northeastward direction (Smelror et al. 2009; Henriksen et al. 2011), suggesting that Taimyr and the Kara terrane are unlikely to represent a significant provenance for Triassic clastic sediments of the Russian Barents Sea. By contrast, northwesterly prograding Triassic clinoforms are recognized throughout the Barents Sea, supporting the Urals and West Siberian basin basement as the main provenances (e.g., Anell et al. 2014; Lundschien et al. 2014; Norina 2014).

The Late Triassic–Early Jurassic deformation event produced significant uplift within the Novaya Zemlya segment of the Pai-Khoi-Novaya Zemlya fold-and-thrust belt (Prokopiev et al. 2016; Zhang et al. 2018). Erosion of the Novaya Zemlya area, discussed by Klausen et al. (2017), probably supplied the Russian Barents Sea basins with reworked clastics, locally recognized in the uppermost Triassic and Jurassic samples. However, the Novaya Zemlya area contains an insufficient volume of granite intrusions to source enough clastics to fill the Barents Sea sedimentary basins, without invoking a significant additional contribution from reworked sediments, which is unsupported by our data. Recent studies (e.g. Curtis et al. 2018; Khudoley et al. 2018; Zhang et al.

2018) support the embayment model of the Pai-Khoi-Novaya Zemlya fold-and-thrust belt formation proposed by Drachev et al. (2010) and Scott et al. (2010). This model implies that after the main deformation event occurred in Novaya Zemlya in the Late Triassic–Early Jurassic, a deep marine basin trapping clastic detritus sourced from the south existed in the Kara Sea area between the proposed sedimentary source region of the West Siberian basin basement and sedimentary basins of the eastern Barents Shelf. As a result, the Urals became the single main provenance for clastic detritus deposited across the Russian Barents Sea during the Jurassic, although some reworking of older sediments likely occurred as well.

Conclusions

Our reconnaissance provenance study that used U–Pb detrital zircon dating and whole-rock chemical and Sm–Nd isotopic studies has the main outcomes:

(1) The main provenance for Triassic and Jurassic clastic rocks within the Russian (eastern) Barents Sea, including Franz Josef Land, was located in the Urals and, during the Triassic, the basement of the West Siberian Basin as well. Due to a subdued relief, erosion of the East European Craton only contributed a small volume of fine-grained clastics to the eastern Barents Sea basins during the latest Triassic and Jurassic.
(2) Minor modification of the provenance reflected in detrital zircon ages distribution as well as in the chemical composition of clastic rocks occurred in latest Triassic and is likely to correlate with a distinct provenance change recorded in Late Triassic (early Norian) in the Norwegian Barents Sea.
(3) All studied samples were derived from erosion of primary igneous and metamorphic rocks in the provenance, with limited evidence for sediment reworking. Evidence for minor sediment reworking is only found in some uppermost Triassic and Jurassic samples, and may be derived from erosion of the Novaya Zemlya archipelago.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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