Evidence for Late Triassic provenance areas and Early Jurassic sediment supply turnover in the Barents Sea Basin of northern Pangea

Tore Grane Klausen1,*, Reidar Müller2,†, Jiri Slama1,§, and William Helland-Hansen1

1DEPARTMENT OF EARTH SCIENCE, UNIVERSITY OF BERGEN, ALLÉGATEN 41, 5007 BERGEN, NORWAY
2TULLOW OIL PLC, TORDENSKJOLDSGATE 6B, 0160 OSLO, NORWAY

ABSTRACT

We used detrital zircon fractions from the Late Triassic to Early Jurassic sedimentary succession in the Norwegian Barents Sea to constrain the role of eastern provenance areas in the basin infill history of the Northern Pangea Boreal basin. Geochronological data from sedimentary rocks in this succession reveal detrital zircon ages that are very close to the biostratigraphically defined maximum depositional age of the two lowermost intervals: The Norian to Rhaetian Fruholmen Formation show U-Pb minimum ages of 208.3 ± 4.2 Ma (discordant by -0.58) and 213.8 ± 5 Ma (discordant by 0.8), and the Rhaetian to Sinemurian Tubåen Formation is 200.6 ± 4.9 Ma (discordant by -3.99) at its minimum. These are the youngest ages thus far documented in the Norwegian Barents Sea, and they demonstrate that a provenance area was magmatically active while, or shortly before, these formations were being deposited. Such protolith ages have not been documented close to the study area, but based on the regional tectonic setting and paleogeography, we argue that the Novaya Zemlya protrusion of the northern Uralian orogen was the most likely provenance area in the region. The Sinemurian to Pliensbachian Nordmela Formation samples yielded, with an exception of a single detrital zircon age of 211 ± 4.3 Ma, a consistent 240–237 Ma minimum detrital zircon age, which suggests that either the magmatic activity or the sediment supply had come to an end by Sinemurian times. This turnover can be explained by a change in the hinterland drainage pattern.

This study documents that eastern provenance areas were actively supplying sediments into the Norwegian Barents Sea Basin later than previously assumed, and our data offer age constraints for tectonic activity in the basin and its hinterland inferred from the changes in sediment supply to the basin.

INTRODUCTION

The Upper Triassic to Lower Jurassic succession in the Norwegian sector of the Barents Sea Basin (NBSB) is characterized by a transition from gradual subsidence with high sediment supply primarily from the east and southeast in the Triassic to a more condensed succession characterized by limited accommodation and bypass in the Early Jurassic (Ryseth, 2014). Because of this decrease in sediment supply and accommodation, the transition also signals a change from a predominantly mudstone-dominated succession into a sandstone-dominated succession, wherein the sedimentary deposits appear more amalgamated, and individual formations are relatively thin. In addition, syn- and postdepositional uplift and erosion have removed parts of the Jurassic succession, and consequently this succession is only partially preserved in some places and is dominated by depositional hiatuses and condensed sections. Accompanying the change from mudstone-dominated Triassic intervals to sandstone-dominated Jurassic intervals, there is a change to more mature sediments in the Jurassic that has been attributed to both climatic and provenance changes at the Triassic Jurassic boundary (Bergan and Knarud, 1993; Ryseth, 2014).

The eastern part of the Barents Sea experienced subhorizontal compression during this period due to the emergence of the Novaya Zemlya protrusion of the northern Uralides (Ritzmann and Faleide, 2009). This fold-and-thrust belt created a foredeep in the Russian part of the Barents Sea that accommodated a relatively thick Jurassic succession in the east (Scott et al., 2010) and is believed to have also influenced the more distal NBSB through forebulge uplift. This tectonic event helps to explain the transition from high- to low-accommodation basin setting in the study area, but its timing and magnitude are not yet fully understood.

Because of its partial preservation and thin nature, no prodeltaic clinoform geometries are seemingly present in the Lower Jurassic succession, and it is, in general, difficult to investigate the succession across the basin using seismic data, which have been routinely used to study the lower part of the Mesozoic succession in the NBSB. As a result, only a few studies have been conducted on the succession (Olausson et al., 1984; Bergan and Knarud, 1993; Ryseth, 2014), with some additional information from regional studies (e.g., Gjelberg et al., 1987; Bugge et al., 2002; Henrik­sen et al., 2011). In order to better understand the drainage patterns and sedimentary routing system, the present study adds to this understanding.
by investigating the detrital zircon signatures from different formations above and below the Triassic-Jurassic boundary.

Detrital zircon age spectra have been used to determine the relative importance of the different provenance areas for the NBSB succession in the underlying and overlying stratigraphic intervals (Omma, 2009; Bue and Andresen, 2013; Fleming et al., 2016; Soloviev et al., 2015), and for the Jurassic interval in the Russian Barents Sea Basin (Suslova, 2013), but no studies have focused especially on the Triassic-Jurassic transition or the effect of the Novaya Zemlya fold-and-thrust belt.

The present study is restricted to the Norwegian sector of the Barents Sea, covering an area of ~300 by 400 km. The study presents U-Pb laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) geochronological data from detrital zircon grains in three different siliciclastic sedimentary formations located above and below the Triassic-Jurassic boundary in the NBSB: the Norian to Rhaetian Fruholmen Formation; the Rhaetian to Sinemurian Tubåen Formation; and the Sinemurian to Pliensbachian Nordmela Formation (Fig. 1). This information constrains the role and longevity of the tectonically active eastern provenance area in the basin infill history, with implications for the regional tectonic evolution along the northern Pangean margin of the Arctic Barents Sea.

GEOLOGICAL BACKGROUND

The Norian to Pliensbachian succession was deposited as a siliciclastic succession during a period when the NBSB underwent a change from regional subsidence in the Norian to uplift in the Hettangian. The thickness of the studied succession, which spans ~45 m.y., ranges from a total of 820 m (well 7219/9–1, western margin) down to 18 m (well 7225/3–2, Bjarmeland Platform). This thickness variation reflects the limited accommodation space on the Bjarmeland Platform, but it also indicates that accommodation was created locally along the western margin of the NBSB during this period (Fig. 1). In contrast, the underlying Snadd Formation reached more than 2000 m in thickness deposited in half the time, i.e., ~20 m.y. (e.g., Klausen et al., 2015).

Significant variation in accommodation space contrasts with the general tectonic quiescence interpreted for the period (Faleide et al., 1993; Clark et al., 2014) but could be explained by two factors. First, the regional uplift that created the low-accommodation setting in the Jurassic NBSB could be attributed to a regional forebulge development in response to the westward protrusion of the Novaya Zemlya fold-and-thrust belt in the Late Triassic to Early Jurassic (Ritzmann and Faleide, 2009). This
is at present the most likely explanation for the inversion of an actively subsiding basin into a low-accommodation area dominated by erosion and depositional hiatuses. Second, the more localized increase in accommodation could have been caused by normal faulting as a precursor to the subsequent Late Jurassic to Cretaceous rifting between Norway and Greenland (Faleide et al., 1993). Small-scale tectonic activity in this period has not been addressed in detail by previous studies in the NBSB and is beyond the scope of the present study, but might correspond to similar rift-onset development in the Sverdrup Basin (Hadlari et al., 2016).

Stratigraphy

The three formations that comprise the Norian to Pliensbachian interval were defined by Dalland et al. (1988) and incorporated in the stratigraphic framework of Mørk et al. (1999) and Vigran et al. (2014). The formations are all dominated by siliciclastic sediment, but because of variable accommodation, they have their own characteristics in terms of facies and sequence stratigraphic development.

The Norian to Rhaetian Fruholmen Formation is up to 573 m thick (well 7219/9–1), but it generally ranges between 100 and 200 m. It follows unconformably above a maximum flooding surface that caps the underlying Ladinian to early Norian Snadd Formation, and it is followed by the overlying Rhaetian to Sinemurian Tubåen Formation above a subaerial unconformity in the study area.

The Rhaetian to Sinemurian Tubåen Formation is up to 261 m thick along the western margin (well 7120/6–1), but it is completely absent in other parts of the study area and is generally only 50–100 m thick. It follows unconformably above the underlying Fruholmen Formation and consists predominantly of well-sorted sandstone, typically deposited in a fluvial braidplain environment (Bugge et al., 2002).

The Tubåen Formation is overlain by more tidally dominated coastal plain deposits of the Sinemurian to Pliensbachian Nordmela Formation (Olaussen et al., 1984). This formation is slightly thicker than the Tubåen Formation (~90 m on average) and is present over a larger area in the NBSB. It is followed stratigraphically by a major transgressive event, which led to deposition of the shallow-marine–dominated Toarcian to Bajocian Stø Formation across the whole study area (Olaussen et al., 1984; Gjelberg et al., 1987). Limited accommodation available for the Stø Formation might have caused some degree of erosion of the underlying formations, especially the Nordmela Formation, as the area was transgressed.

Paleogeography

In the Late Triassic, the study area was located at ~50°N (Golonka, 2007) and likely experienced a slight climatic change toward more humid conditions in the Early Jurassic (Ryseth, 2014). Bergan and Knarud (1993) documented a significant mineralogical change toward coarser and more mature quartz arenites going from the Snadd Formation into the Norian Fruholmen Formation.

At the time of deposition, the study area was surrounded by three distinct provenance areas: (1) the middle to late Paleozoic Uralian orogenic belt to the east and southeast, with a northern continuation that remained active into the Late Triassic and Early Jurassic through the Novaya Zemlya fold-and-thrust belt (Ritzmann and Faleide, 2009); (2) the early to middle Paleozoic Caledonian orogenic belt to the southwest and west; and (3) the Archean to Neoproterozoic Fennoscandia Shield to the south (Fig. 2). Although Mesoproterozoic and Archean protoliths are present in and below the Caledonian nappes (e.g., Harrison et al., 2011; Bergh et al., 2015), this study distinguishes between samples with and without a pronounced Caledonian (i.e., early to middle Paleozoic)
peak. Samples without Caledonian-age grains are here regarded to have a Fennoscandian provenance, which is interpreted to be more likely to occur east of the Caledonian nappes that dominate western Norway and Eastern Greenland (Fig. 2). Caledonian signatures are expected to be relatively more likely and dominant closer to the Caledonian orogen further west. The Fennoscandian provenance region includes protoliths of various ages, including the Neoproterozoic Timanian orogen, Meso- proterozoic Svecnorwegian orogen, and Paleoproterozoic Svecofennian orogen, in addition to Caledonian-age granitoids (Harrison et al., 2011). A feature worth noting is also the fact that protoliths similar to the Fennoscandian provenance are also found in the Greenlandic paleolandmass. In addition to the Uralian orogen, the Siberian Traps represent a magmatic zircon-forming event in western Siberia, east of the study area, at 250 Ma (Reichow et al., 2009).

The Middle Jurassic paralic to shallow-marine succession was terminated by the onset of the marine Fuglen Formation in the Bajocian. The postdepositional evolution of the study interval includes Late Jurassic rifting along the western margin followed by seafloor spreading, rifting, and shear-margin development in the Paleogene and regional uplift and erosion in the Neogene (Faleide et al., 1996; Clark et al., 2014). During the Cretaceous, the Loppa High was exposed as an intrabasinal high along with the Fyédnsky High (Nøttvedt et al., 1993), and therefore most of the Late Triassic and Early Jurassic strata are missing in these parts of the study area.

DATA AND METHODOLOGY

Available core intervals were logged at the Norwegian Petroleum Directorate, Stavanger, and at Dora, Trondheim. Samples for detrital zircon analysis were collected at specific intervals aimed to check the variability between different stratigraphic intervals and different locations in the basin.

Three samples from the southern part of the study area cover the Tubåen and Nordmela Formations in the Hammerfest Basin (E, G, and I in Fig. 3), whereas one sample represents the Tubåen Formation in the eastern part of the study area (H in Fig. 3). In addition to the two samples in the Hammerfest Basin, three samples from the Nordmela Formation were collected from wells along the western margin and in the north (A, B, and C in Fig. 3). The Nordmela Formation was sampled more frequently than the two underlying formations because it represents a change in depositional environment that is potentially important. The Fruholmen Formation was sampled in the north and northwest (D and F in Fig. 3).

About 20–30 g were collected for each rock sample from these nine sample intervals. In order to prevent loss of sample material, the samples were hand crushed with hammer and agate mill. Hydrocarbon-stained samples were cleaned using a 50/50 mix of dichloromethane and methanol before each sample was loaded into heavy liquids for mineral separation. Individual zircon grains were mounted in 1 in. (2.5 cm) epoxy-filled samples were cleaned using a 50/50 mix of dichloromethane and methanol before each sample was loaded into heavy liquids for mineral separation. Individual zircon grains were mounted in 1 in. (2.5 cm) epoxy-filled blocks and polished to expose surfaces for cathodoluminescence imaging and laser ablation.

A Nu AttoM high-resolution ICP-MS coupled to a 193 nm ArF excimer laser (Resonetics RESOlution M-50 LR) at the University of Bergen, Norway, was used to measure the Pb/U and Pb isotopic ratios in zircons. The laser was fired at a repetition rate of 5 Hz and energy of 80 mJ with 19 or 26 μm spot size. Typical acquisitions consisted of 15 s measurement of blank, followed by measurement of U, Th, and Pb signals from the ablated zircon for another 30 s. The data were acquired in time resolved–peak jumping–pulse counting mode with 1 point measured per peak for masses $^{206}\text{Pb} + ^{176}\text{Hg}$, $^{205}\text{Pb}$, $^{203}\text{Pb}$, $^{208}\text{Pb}$, $^{232}\text{Th}$, $^{235}\text{U}$, and $^{238}\text{U}$. Due to a nonlinear transition between the counting and attenuated (= analog) acquisition modes of the ICP instruments, the raw data were preprocesses using a purpose-made Excel macro. As a result, the intensities of $^{235}\text{U}$ were left unchanged if measured in a counting mode and recalculated from $^{238}\text{U}$ intensities if the $^{235}\text{U}$ was acquired in an attenuated mode. Data reduction was then carried out off-line using the Iolite data reduction package, version 3.0, with VizualAge utility (Petrus and Kamber, 2012). Full details of the data reduction methodology can be found in Paton et al. (2010). The data reduction included correction for gas blank, laser-induced elemental fractionation of Pb and U, and instrument mass bias. For the data presented here, blank intensities and instrumental bias were interpolated using an automatic spline function, while down-hole interelement fractionation was corrected using an exponential function. No common Pb correction was applied to the data, but the low concentrations of common Pb were controlled by observing the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio during measurements. Residual elemental fractionation and instrumental mass bias were corrected by normalization to the natural zircon reference material Plešovice (Sláma et al., 2008). Zircon reference materials GJ-1 (nr. 63) (Jackson et al., 2004) and 91500 (Wiedenbeck et al., 1995) were periodically analyzed during the measurement for quality control, and the obtained mean values of $600 \pm 4$ (2σ) Ma and $1086.0 \pm 9$ (2σ) Ma are accurate within 2% to the published reference values (600.5 ± 0.4 Ma—Schaltegger et al., 2015; 1065 Ma—Wiedenbeck et al., 1995, respectively). The zircon U-Pb ages are presented as histograms and probability density plots generated with the Isoplot program v. 3.70 (Ludwig, 2008).

DESCRIPTION OF SAMPLES AND RESULTS OF U-Pb ZIRCON DATING

Fruholmen Formation Samples

Two samples (D and F; Figs. 3, 4, and 5) were collected from a sandstone-dominated interval interpreted to be deposited by tidally influenced fluvial channels (Fig. 4). These deposits are characterized by sedimentary structures indicative of fluvial deposition such as trough cross-stratification and unidirectional current ripples, but they include minor occurrences of marine bioturbation and mud drapes. Tidal influence is interpreted to reflect a shallow-gradient lower delta plain. The samples were both gathered from the northern wells 7321/8–1 and 7324/8–1 (Fig. 3).

Detrital zircon ages show signatures characterized by a Triassic peak and minimum ages of 213.8 ± 5 Ma and 208.3 ± 4.2 Ma (Figs. 5D and 5F). These values are relatively well constrained, having discordance of 0.8 and ~0.58, respectively (see GSA Data Repository Item). The samples also contain smaller amounts of Caledonian and Fennoscandian detrital zircon grains.

Tubåen Formation Samples

Two samples (I and H; Figs. 3, 4, and 5) were gathered from sandstone-dominated siliciclastic deposits interpreted to have been deposited by fluvial channels (Fig. 4). The deposits are characterized by medium-grained sandstone with scattered organic material and very limited marine bioturbation. The samples came from cores in the easternmost (7230/5-U-3) and southernmost (7122/6–1) part of the study area (Fig. 3).

The two samples show diachronously different detrital zircon signatures. The southernmost sample is characterized by Fennoscandian signatures, with a minimum age of 857 ± 14 Ma (Fig. 5I), whereas the easternmost

---

1GSA Data Repository Item 2016358, raw data results from the detrital zircon U-Pb LA-ICP-MS analyses, is available at www.geosociety.org/pubs/f2016.htm, or on request from editing@geosociety.org.
Figure 3. Correlation panel of the wells and the stratigraphic intervals from which the different samples were gathered. The samples are concentrated around the Triassic-Jurassic boundary and are labeled according to how they are grouped for comparison in Figure 5: D and F are from the Norian to Rhaetian Fruholmen Formation; I and H are from the Rhaetian to Sinemurian Tubåen Formation; and A, B, C, E, and G are from the Sinemurian to Pliensbachian Nordmela Formation. Note the unconformable relation between the Fruholmen and Nordmela Formations to the northwest. The locations of the wells and correlation panel are given in Figure 1.
Figure 4. Representative core examples from the north, south, and east show the depositional facies from which the sample intervals were gathered and the stratigraphic relationship between the different formations. Note the thin interval of the Nordmela Formation resting unconformably on deposits from the Fruholmen Formation in well 7324/8-1. Letters show the positions of the different samples, labeled according to Figure 5.
Figure 5. Probability density plots of the detrital zircon ages recorded in the different samples. Minimum ages are given for each respective sample.
Late Triassic provenance areas and Early Jurassic sediment supply turnover | RESEARCH

sample shows pronounced Triassic signatures and a minimum age of 200.6 ± 4.9 Ma (Fig. 5H). This young age, however, has a relatively high degree of discordance (−3.99; GSA Data Repository Item) and should consequently be treated with care, as discussed further in the following discussion. The Triassic peak in this sample is nevertheless prominent. Evidence for an eastern provenance in the sample from 7230/5-U-3 is particularly important because it shows that the deposits that are dated as Early Jurassic with reworked Triassic palynomorphs (Vigran et al., 2014) do not contain significant amounts of Fennoscandian detrital zircon grains, which are characteristic for the Early Jurassic samples. The sample interval is therefore assigned to the Tubåen Formation in the present study.

Nordmela Formation Samples

Five Nordmela Formation samples (A, B, C, E, and G; Figs. 3, 4, and 5) were gathered from siliciclastic sedimentary deposits interpreted to reflect tidal channels, tidal sandflats, and inner shelf deposits (Fig. 4). These depositional environments are characteristically dominated by mixed heterolithic sandstone and siltstone with mud drapes and marine bioturbation. The wells from which the samples were gathered are spread from south to north across the study area, following the western margin of the NBSB (Fig. 3).

Detrital zircon U-Pb data show significant variations in the Nordmela Formation samples, ranging from mixed Caledonian and Triassic ages (Figs. 5A, 5B, and 5C) through predominantly Caledonian (Fig. 5E) to predominantly Fennoscandian ages (Fig. 5G). This change is reflected in the relative positions of the samples in the basin, becoming gradually more dominated by Caledonian or Fennoscandian signatures toward the southern basin margin. Similarly, the age of the youngest detected zircon increases in this direction, going from a minimum of 211 ± 4.1 Ma, 237.9 ± 6.7 Ma, and 244.9 ± 6.5 Ma in the north (Figs. 5A, 5B, and 5C) to 373 ± 13 Ma and 434 ± 15 Ma in the south (Figs. 5E and 5G).

Characteristics of Detrital Zircon Grains

Cathodoluminescence images of the studied samples reveal both prismatic and oscillatory-zoned detrital zircon grains and grains with sector-zoned inner domains and inherited cores, indicating an igneous source (Fig. 6). U-Th ratios lower than 3 indicate that the youngest zircon grains were formed by magmatism (Fig. 7; Hoskin and Schaltegger, 2003; Miller et al., 2006). Most of the metamorphic activity seems to be related to Proterozoic orogenies and the Caledonian orogen. Detrital zircon grains show varying degrees of abrasion, and there are no qualitative differences in abrasion between young and old detrital zircon grains. The youngest age recorded in the study (200.6 ± 4.9 Ma) was recorded in a particularly bright outer zone of a detrital zircon grain (Fig. 6B) with high concentrations of both U and Th, which might indicate that the value is anomalous, i.e., slightly discordant due to a higher degree of crystal lattice damage and partial Pb loss.

Pooled ages of the youngest detrital zircons detected in the samples reveal a near-concordant age of 210.4 ± 1.9 Ma for the youngest zircon-forming event (Fig. 8). They also show that the youngest detrital zircon age is anomalously low, as it falls outside the concordia age ellipse.

DISCUSSION

Correlation of Samples and Relative Importance of Different Provenance Areas

The results show that there is large variability in detrital zircon age signatures between individual samples (Fig. 9). This variability reflects
the relative importance of the different provenance areas that supplied sediments during the Late Triassic to Early Jurassic, and the results are naturally dependent on the proximity of the samples to the provenance area. The closer the samples are to the southern margin of the basin, the more the detrital zircon signature is dominated by Fennoscandian ages (Fig. 5), with one prominent Caledonian peak (Fig. 5E). In the central and northern parts of the NBSB, the Triassic signature dominates until the Sinemurian to Pliensbachian, when the influx of southerly derived sediment gradually caused older zircon grains to appear in samples from the northernmost part of the study area. This gradual north-south change is reflected in the cumulative density plots (Fig. 9).

A similar trend is likely also the case for both the Fruholmen and Tubåen Formations. These formations are, however, relatively more dominated by young detrital zircon grains. The cumulative density plot shows a very close match between the curves of the Fruholmen Formation samples and the easternmost Tubåen Formation sample, which is dominated by young detrital zircon grains. The difference between the two Fruholmen Formation samples is the timing of the first rise of the curve and the relative proportion of Caledonian and older grains (Fig. 9). Since the two Fruholmen Formation samples are closely spaced, the higher proportion of older grains in the stratigraphically lowest Fruholmen Formation (7324/8–1; Fig. 5F) likely reflects temporal differences in the sedimentary environment. The closer the samples are to the southern margin of the basin, the higher proportion of older grains in the stratigraphically lowest Fruholmen Formation (7324/8–1; Fig. 5F) is relatively more dominated by older, southerly derived sediments as compared to the sample with a higher stratigraphic position (7321/8–1; Fig. 5D).

Similar to the cumulative density plot in Figure 8, the Kolmogorov-Smirnov (K-S) statistical test shows that there is, in general, little correlation between the analyzed samples (Table 1). The most significant similarities exist between the Tubåen and Nordmela samples from 7122/6–1 (Figs. 5G and 5I), suggesting that a predominantly Fennoscandian provenance area was active along the southern margin of the NBSB during deposition of both formations. It is therefore interesting to note the pronounced input of Caledonian sediments in the uppermost sample in the Nordmela Formation (E in Fig. 5), making the detrital zircon age spectrum slightly dissimilar from the stratigraphically lower samples from well 7122/6–1 (Figs. 5G and 5I). It is possible that the narrow and high-amplitude peak in Figure 5E could represent a Caledonian granitoid in the Fennoscandian Shield (Harrison et al., 2011), but the western sample location implies proximity to the Caledonides. Although the sample fractions are relatively small, the sample in Figure 5E might represent an increased influx of Caledonian sediments that were distributed basinward during deposition of the Nordmela Formation, as reflected in the relatively higher Caledonian peaks in the Nordmela Formation compared with the Fruholmen and Tubåen Formations.

Another sample that does not correlate very well with the other samples is the Nordmela Formation sample from well 7220/8–1 (Figs. 5G and 5I). Lack of correlation is caused by a mix between the three end-member detrital zircon age signatures (Triassic, Caledonian, and Fennoscandian). This mix of different provenance areas is interpreted to reflect the intermediate position of the sample in the basin, where sediments from both Fennoscandian and Caledonian provenance areas were deposited along with reworked underlying strata originally derived from the Uralides.
The second best correlation is found between the Fruholmen and Tubåen Formation samples (7321/8–1 and 7230/5-U-3; Figs. 5D and 5H), located in the westernmost and easternmost parts of the study area, respectively. The relatively small difference in detrital zircon age signatures is difficult to see in the probability density plots and cumulative density plots plots (Figs. 5 and 9), but the K-S test reveals a P value for correlation of 0.673 (Table 1), which is due to a larger fraction of older Caledonian grains in the sample from the Fruholmen Formation. Their similarity is interpreted to represent a continuation of the Triassic provenance area from the Fruholmen Formation into the Tubåen Formation, while the subtle difference between their signatures reflects the influx of southerly derived Fennoscandian sediments with increasing importance in more distal, western positions in the basin.

Because of the high discordance in the youngest grains from the Tubåen Formation sample in 7230/5-U-3, there is also an alternative explanation for the similarity to the Fruholmen Formation sample. Instead of being directly derived from an active magmatic provenance, the Tubåen Formation sample might represent deposits that were eroded from the underlying Fruholmen Formation. Because the minimum detrital zircon age of the Nordmela Formation samples (211 ± 4.1 Ma) is not younger than the bio-stratigraphically defined end of the Fruholmen Formation, it is possible that this sample represents reworking of the underlying Fruholmen Formation. A reworked sediment source for the northern Nordmela Formation is in line with the pronounced erosion in the northern part of the study area, where the entire Tubåen Formation is missing, along with significant parts of the Fruholmen Formation (Fig. 3). However, the distinct change from minimum zircon ages that closely match the depositional age to minimum ages that are significantly older than the depositional age, which occurs in the Nordmela Formation in the NBSB (Fig. 10), could also be due to a lack of zircon-forming events after 210 Ma, while sediments were still being supplied from the eastern provenance area into the Pliensbachian. This is discussed in more detail in the following.

Although both Fruholmen Formation samples and one Tubåen Formation sample are characterized by Triassic dominance and show similar detrital zircon age signatures (Figs. 5A and 5H), the best correlation exists between the Fruholmen Formation sample from well 7321/8–1 and the easternmost Tubåen Formation sample (Table 1). This trend signals variations in the depositional age of different stratigraphic intervals within the Fruholmen Formation. The stratigraphically younger Fruholmen Formation sample in 7321/8–1 was deposited later and with a correspondingly younger detrital zircon peak than the stratigraphically lower Fruholmen Formation sample in well 7324/8–1 (Fig. 10). The upper part of the Fruholmen Formation has been eroded, and the Tubåen Formation is absent in this area, suggesting that this part of the basin was exposed and eroded in the Hettangian. The erosional product is seen in the Nordmela Formation samples, as discussed already.

Progressively younger detrital zircon ages upward in the stratigraphy until onset of the Nordmela Formation suggest magmatically active provenance areas when sediments were deposited in the NBSB, and that detrital zircon grains were formed and shed basinward shortly before deposition. The Novaya Zemlya fold-and-thrust belt along the eastern margin of the Barents Sea is suggested to be Late Triassic to Early Jurassic in age (Ritzmann and Faleide, 2009), and it represents the closest tectonically active region to the NBSB in the northward continuation.
of the Uralian orogen. This uplift was a likely driver for the sediments derived from the east and the subsequent uplift of the Norwegian part of the Barents Sea, at which point input of zircons with ages close to the depositional age ceased. However, there are no recorded igneous rocks of this age in the thrust belt, and the magmatic source for the detrital zircons (Fig. 7) could therefore be attributed a more northern provenance area instead (Anfinson et al., 2016).

Comparison to Previous Studies

Previous studies have documented similar detrital zircon ages from the Barents Sea and Svalbard (Omma, 2009; Bue and Andresen, 2013; Suslova, 2013; Fleming et al., 2016; Soloviev et al., 2015; Anfinson et al., 2016). With some variation related to different study aims and areas, the common result for most of these studies is a dominance of Caledonian and Fennoscandian (or Laurentian) detrital zircon signatures in the Lower Triassic, followed by the characteristic Triassic detrital zircon signatures of the Middle to Upper Triassic strata, whereas the Jurassic interval consists of mixed detrital zircon signatures interpreted to reflect a reworking of underlying strata and rejuvenation of southern and western provenance areas (Bue and Andresen, 2013). Detrital zircon grains as young as those found in the present study have only been recorded in the Russian part of the Barents Sea (Suslova, 2013), and it has therefore been natural to conclude that there was a depositional hiatus in the NBSB in the latest Triassic, with a subsequent reworking of underlying strata mixed with more sediment influx from mature provenance areas in the Jurassic.

Bue and Andresen (2013) and Fleming et al. (2016) recorded detrital zircons with ages of 230 Ma and ca. 235 Ma, respectively, in Upper Triassic Snadd Formation equivalents on Spitsbergen, Svalbard. These minimum ages probably reflect deposition shortly after the grains were formed, because they match the maximum depositional ages of the formations closely. Similarly, the minimum detrital zircon age of 218 Ma recorded by Soloviev et al. (2015) from the Norian succession offshore the Franz Josef Land Archipelago in the Severnaya well (undifferentiated Snadd and Fruholmen Formation equivalents) probably indicates that the zircon formed relatively shortly before deposition.

The young detrital zircon grains documented in the present study are interpreted to reflect sediment supply from eastern provenance areas that continued into the Norian to Rhaetian Fruholmen Formation and the Rhaetian to Sinemurian Tubåen Formation. Although the present data set also shows that southern provenance areas existed along the southern margin of the NBSB from at least the Rhaetian, and became increasingly more important upward in the stratigraphy, the eastern provenance area was not terminated until the Sinemurian. The influx of southerly derived sediments documented herein corresponds to the Late Triassic to Early Jurassic denudation trend documented onshore in mainland Norway (Hendriks and Andriessen, 2002), and it is likely also related to the increased maturity seen in previous mineralogical studies (Bergan and Knarud, 1993; Ryseth, 2014).

The turnover from detrital zircon ages that closely match the depositional age to deposits dominated by grains much older than the depositional age of any of the formations studied here has been linked to significant reworking of underlying strata in the Sinemurian to Pliensbachian
Nordmela Formation. As mentioned already, this change in the detrital zircon signatures could simply be due to an absence of zircon-forming events and denudation in the provenance area that still supplied sediment to the NBSB. Although this argument is valid for the Nordmela Formation sample in 7324/7-2 (Fig. 5A), it is hard to reconcile with the distinct lack of detrital zircon grains younger than the Ladinian in the remaining Nordmela Formation samples (Figs. 5B, 5C, 5E, and 5G). Supply of young detrital zircon grains to the NBSB from the east had ended by the Sinemurian, but whether this change in detrital zircon ages was due to a cessation in hinterland tectonics or changes in the drainage network could still be debated. However, Suslova (2013) documented even younger detrital zircon ages than those recorded in the present study in the Russian part of the Barents Sea. Significant detrital zircon peaks from Early Jurassic samples in the Shtokman well were dated to be ca. 190 Ma (Fig. 10X), at the Sinemurian–Priabonian boundary. These ages show that magmatic activity continued well into the Early Jurassic, and that contemporaneous deposits in the NBSB without similar ages should be considered to have been reworked from underlying strata.

**Implications of Young Detrital Zircon Ages**

The present study and data from the Russian Barents Sea (Suslova, 2013) document a provenance area that was active during the Norian to Sinemurian period. However, no protolith with such ages has been recorded in the hinterland areas close to the study area (Fig. 2). The youngest protoliths recorded close to the study area are the 230–220 Ma intrusive rocks in south Taimyr dated by Walderhaug et al. (2005) using Ar-Ar geochronology. Their study also suggested an Early Jurassic fold-and-thrust belt in Novaya Zemlya, which likely was active during this period (Ritzmann and Faleide, 2009; Scott et al., 2010) and offers a potential candidate for a gradually evolving, local provenance area. This fold-and-thrust belt could also explain the relatively short distance to the basin and the short time between zircon formation and deposition. The present study therefore favors a magmatic provenance area closely related and linked to the Novaya Zemlya fold-and-thrust belt in the northern continuation of the Uralides, but we recognize that this interpretation is controversial since no igneous protolith has been dated in the Novaya Zemlya archipelago. However, Lopatin et al. (2001) indicates the possible presence of Late Triassic to Early Jurassic igneous suites on the island.

Anfinson et al. (2016) and Midwinter et al. (2016) recorded similar young detrital zircon ages in the contemporaneous Sverdrup Basin and also related these ages to sediment transport from the Uralides. This interpretation substantiates the Uralide source interpreted in the present study, but the results of the present study furthermore suggest that sediment transport from the northern Urals to the Sverdrup Basin must have been more important than previously thought (Nordmela Formation, but this youngest age in the Nordmela Formation is considered to have been reworked from underlying strata).

Miller et al. (2008) documented Late Triassic and Jurassic island-arc magmatism in eastern Russia, and although zircon grains might be transported by windblown tuffs (e.g., Rasmussen and Fletcher, 2010), such an explanation is hard to reconcile with the absence of Jurassic-aged zircons in the study area. If ash-fall events were the source for young zircon ages, similar ages as in the Russian part of the Barents Sea (Suslova, 2013) should also be expected in the Norwegian sector. Although the Jurassic interval was most extensively tested, no Jurassic ages were documented in the present study.

Zhang et al. (2016) also debated the enigmatic Early Jurassic zircons and, amongst other sources, pointed to the south (Donskaya et al., 2013; Parfenov et al., 2009) as a possible explanation for young detrital zircon grains in Taimyr. There might have existed sedimentary pathways from Taimyr to the Barents Sea during this period, but this route had to be oriented across or to either side of the uplift in Novaya Zemlya, which likely represented a significant barrier to sediment transport in the Late Triassic. Related to the fold-and-thrust belt in Novaya Zemlya, there was also rifting in the Kara Sea (Nikishin et al., 2002), and minor magmatism could have resulted from this event or could have been related to the tectonic activity in the thrust belt.

Although some of the young detrital zircon grains in the present study could possibly be explained by a northeastern Taimyr magmatic source (Siberian Traps) or simply intraplate magmatism, it seems less likely that multiple and progressively young detrital zircon peaks associated with the stratigraphically younger sample intervals seen in the present study and previous studies (Omma, 2009; Bue and Andresen, 2013; Suslova, 2013; Fleming et al., 2016; Soloviev et al., 2015) could be explained by the Siberian Traps alone. The progressively younging peaks instead suggest a dynamic provenance area with some igneous activity at least from deposition of the Middle Triassic Snadd Formation until the Sinemurian to Priabonian Tubåen Formation. The Novaya Zemlya protrusion of the Northern Uralian orogenic belt was active during this period (Ritzmann and Faleide, 2009; Scott et al., 2010) and offers a potential candidate for a gradually evolving, local provenance area. This fold-and-thrust belt could also explain the relatively short distance to the basin and the short time between zircon formation and deposition. The present study therefore favors a magmatic provenance area closely related and linked to the Novaya Zemlya fold-and-thrust belt in the northern continuation of the Uralides, but we recognize that this interpretation is controversial since no igneous protolith has been dated in the Novaya Zemlya archipelago. However, Lopatin et al. (2001) indicates the possible presence of Late Triassic to Early Jurassic igneous suites on the island.

**Basin Margin Evolution and Infill History**

This study records a turnover in sediment supply from a magmatically active, eastern basin margin to sediment supply sourced primarily from a tectonically inactive basin margin in the Hettangian to Sinemurian NBSB. This turnover was most likely related to the evolution of the Novaya Zemlya protrusion of the Northern Uralian orogenic. The data presented herein put a lower time constraint on the sediment supply to the NBSB from this eastern provenance area and question the notion that detrital zircons grains were transported across the Arctic Basin by winds.

An active tectonic basin margin explains the progressively younging Triassic detrital zircon peak in the stratigraphically younger samples (Fig. 10). It also explains why the youngest detrital zircon grains have ages that closely match the depositional age. Cawood et al. (2012) showed that basins fed by an active tectonic margin are characterized by multiple, but not necessarily prominent, detrital zircon ages that closely match the age of deposition. This is the case for the underlying Snadd Formation equivalents (Bue and Andresen, 2013; Fleming et al., 2016), Fruholmen or Snadd equivalents (Soloviev et al., 2015), and the deposits studied herein, until the onset of the Nordmela Formation, further substantiating the interpreted link to the Novaya Zemlya fold-and-thrust belt.

The youngest age found in one of the five Nordmela Formation samples (211 ± 4.3 Ma) postdates the youngest grain found in the Fruholmen Formation, but this youngest age in the Nordmela Formation is found within a highly condensed marine deposit that probably represents...
reworking of the underlying strata (Fig. 4), whereas the minimum zircon ages in remaining Nordmela Formation samples are older (Fig. 5). The reversal in detrital zircon ages and signatures from the Fruholmen and Tubåen Formations to the Nordmela Formation is therefore striking and could be explained by a change from an active orogen to a tectonically inactive basin margin. However, the young ages in the Russian sector (ca. 190 Ma; Suslova, 2013) suggest that the turnaround seen in detrital zircon age signatures in the study area was instead caused by changes in the drainage networks. Specifically, a shift in sediment transport toward the north, facilitated by accommodation created in the Novaya Zemlya foredeep, is a plausible explanation (Fig. 11). This would explain continued sediment supply from the Novaya Zemlya fold-and-thrust belt during the Sinemurian while sediment transport to the western NBSB and the study area was prohibited.

Forebulge uplift in the Fedynsky High area could have been caused by the Novaya Zemlya fold-and-thrust belt and would form a likely barrier for sediment transport from the east (Fig. 11). Although accommodation existed to the north and south of this high during the Rhaetian to Sinemurian, and potentially facilitated sediment transport to the NBSB from Novaya Zemlya, exposure of the Fedynsky High could explain the erosion of the underlying Fruholmen Formation and thus represent an alternative年轻的sediment source for the Tubåen Formation deposits in the sample from 7230/5-U-3. Granted that the Fedynsky High contributed all the sediments with Triassic signatures to the Jurassic NBSB by erosion of the Fruholmen Formation, the turnover in sediment supply would have predated the Tubåen Formation and should be considered directly related to the uplift of the NBSB and loss of accommodation during deposition of the Tubåen Formation at the Triassic-Jurassic boundary.

**CONCLUSION**

Detrital zircon grains with a pooled U-Pb age of 210.4 ± 1.9 Ma attest to input of sediments formed shortly before deposition of the Norian to Sinemurian Fruholmen and Tubåen Formations in the NBSB. This proves a dynamic and magmatically active eastern provenance area until Early Jurassic times. Cathodoluminescence images and U/Th ratios suggest a predominantly igneous origin for the detrital zircon grains characterized by young ages. The detrital zircon age spectra show multiple, but not necessarily prominent, young ages, a signature that is often associated with sediments fed from an active tectonic margin.

---

Figure 11. Schematic overview of the Barents Sea Basin in the northern, Boreal part of Pangea. Paleogeographic reconstruction of the Greenland paleo-landmass is based on Faleide et al. (2010). The extent of regional highs is only known from the study area, restricted to the southwestern part of the Barents Sea. The potential contribution of Triassic sediments from the Fedynsky High is indicated in the map for the Tubåen Formation.
The Nordmela Formation was most extensively tested, but it failed to yield detrital zircon ages younger than the Fruholmen Formation, and thus it represents the first stratigraphic interval where the youngest detrital zircon peak is not contemporaneous with deposition. This suggests a turnover in sediment supply to the study area in the Sinemurian. Sediment supply from Fennoscandia became more prominent and was deposited along with reworked Triassic sediments in the NBSB. However, data from the Russian part of the Barents Sea suggest continued formation of zircons in the eastern provenance area after the Rhaetian to Sinemurian Tubien Formation. Since sediments with such young ages never reached the study area, it is reasonable to assume that there was a sedimentary sink or change in drainage facilitated by the Novaya Zemlya foredeep, which presented a barrier to sediment transport in the later stages of basin evolution. The absence of young ages in the NBSB also suggests that the detrital zircon grains were not derived from windblown volcanic ash.

Results from the present study thus suggest a young, Late Triassic to Early Jurassic magmatic provenance area interpreted to be located to the east of the study area. In addition, a distinct turnover in detrital zircon ages suggests a lower temporal constraint on sediment supply. This young, magmatic provenance area is enigmatic, since there has so far not been any documented protoliths with similar young ages, and more work is needed to constrain this source. However, a progressively younger detrital zircon peak upwards in the stratigraphy, coupled with a tectonically driven sediment supply, favors a provenance area related to the Novaya Zemlya promontory of the Northern Uralian orogen. An interpretation where the protolith instead was related to late magmatism in Taimyr cannot be ruled out, but sediments from these eastern areas would in that case have to navigate across or to either side of the contemporaneous uplift in Novaya Zemlya.

ACKNOWLEDGMENTS

We would like to thank the Research Council of Norway for funding through the Triassic North project, in addition to project sponsors, Tullow Oil Norway, Statoil, Lundin, Edison and DEA Norway AS, and the Norwegian Petroleum Directorate. Siv Hjorth Dundes, Aide Mark, Inna Maria Dunse, and Andrea Sundberg, Norwegian University of Science and Technology are thanked for valuable assistance in the laboratory. Freydís Eide is thanked for her input on palynological data, and Elizabeth Miller is gratefully thanked for commenting on an earlier version of the manuscript. Thomas Hadiari and one anonymous reviewer are kindly thanked for thoughtful comments that improved the quality of the manuscript.

REFERENCES CITED


Published in the USA