NORWEGIAN JOURNAL OF GEOLOGY
https://dx.doi.org/10.1785/njg102-2-1

GEOLOGICAL SOCIETY OF NORWAY

Changing provenance and stratigraphic signatures across the Triassic–Jurassic boundary in eastern Spitsbergen and the subsurface Barents Sea

Tore Grane Klausen[1,2], Bjarte Rismyhr[1,3], Reidar Müller[4] & Snorre Olaussen[3]

[1] University of Bergen, Allégaten 41, 5007 Bergen, Norway
[2] Present address: M Vest Energy AS, Edvard Griegs Vei 3C, 5059 Bergen
[3] The University Centre in Svalbard, 9171 Longyearbyen, Norway
[4] University of Oslo, Sem Sælands vei 1, 0371 Oslo, Norway

E-mail corresponding author (Tore Grane Klausen): tore.klausen@gmail.com

Keywords:
- *Barents Sea*
- *Svalbard*
- *Detrital zircon provenance*
- *Basin uplift*
- *Sediment transport*
- *Condensation*
- *Triassic–Jurassic unconformity*

Electronic supplement 1: Sample list

Electronic supplement 2: LA_ICPMS U-Th-Pb isotopic data

Received: 24. May 2021

Accepted: 25. November 2021

Published online: 3. June 2022

A change to more sandstone dominated deposits and increasing condensation across the Triassic–Jurassic boundary is generally associated with improved reservoir quality in the Barents Sea. However, spatial and temporal changes in reservoir quality in this interval shows that the composition of the sediment source, immature sedimentary rocks supplied from the east or recycled in the basin in contrast to mature arenites to the south and west, affect the reservoir quality. The regional distribution of the different sources is best constrained in the southwestern part of the Barents Sea, and hitherto there has been no direct comparison between the zircon signature in outcrop analogues and their subsurface equivalents. In this study we evaluate the stratigraphic development of formations across the Triassic–Jurassic boundary in the Barents Sea and eastern Spitsbergen to compare their provenance signatures. By coupling outcrop and core data, we tie together the regional tectono-stratigraphic evolution of this important reservoir interval and relate the variable degree of sediment reworking with the relative distribution of immature Triassic sedimentary rocks across the basin. Results show higher degrees of erosion and reworking in Spitsbergen compared to the Barents Sea, consistent with local variations in the forebulge province of Novaya Zemlya observed in the subsurface. Provenance samples from Spitsbergen also record the same change in signature as in the subsurface Barents Sea. However, mature sediments are mixed with immature sediments later in Spitsbergen, indicating a latency in progradation from mature source areas which favour southern provenance areas in Fennoscandia as opposed to Greenland. Presence of young detrital zircon grains with similar Norian ages are recorded in the Upper Triassic strata both in the southernmost Barents Sea and on Spitsbergen, suggesting that a sediment source was active east of the basin and supplied sediment uniformly to the entire basin during the late Triassic.

Klausen, T. G., Rismyhr, B., Müller, R. & Olaussen, S. 2022: Changing provenance and stratigraphic signatures across the Triassic–Jurassic boundary in eastern Spitsbergen and the subsurface Barents Sea. Norwegian Journal of Geology 102, 202205. https://dx.doi.org/10.17850/njg102-2-1

Introduction

The Upper Triassic to Middle Jurassic Realgrunnen Subgroup comprise the most important reservoir in the largest discoveries in the Southwestern part of the Greater Barents Sea Basin (GBSB) to date. However, this reservoir interval varies greatly in thickness across the basin (Klausen et al., 2019) and exploration wells such as for example 7321/4-1 and 7324/2-1 show that the reservoir quality within the interval varies in response to changes in mineral maturity and depositional environment throughout the basin (Klausen et al., 2018). A recent study by Line et al. (2020) document important differences in the mineralogical maturity in this interval across the basin. The maturity of the reservoir rocks has implications for the porosity and permeability, and the potential diagenetic overprint on these parameters. Understanding the distribution of sediment reworked from immature sedimentary rocks is therefore important since their contribution constitute a risk for reservoir quality, compared to sediment derived from mature source areas to the south. Reworking, in addition to a changing climate (Ryseth, 2014; Line et al., 2020) is especially important when considering the frontier areas in the northern part of the basin. These localities are far offset from the mature sediment sources and have experienced pronounced reworking of Triassic and Lower Jurassic strata due to syn- and post-depositional uplift and erosion.

Recent studies have recorded a shift in sedimentation patterns across the Triassic–Jurassic boundary in the GBSB in response to compression along the Novaya Zemlya Fold and Thrust Belt (NZFTB) (Klausen et al., 2017; Müller et al., 2019). This uplift event facilitated a shift in sedimentation from immature sediments sourced from the Uralides in the east, to more mature sediments sourced from the south and west in association with reworked immature sediments (Bergan & Knarud, 1993; Ryseth, 2014; Line et al., 2020). Although the change in mineralogy and provenance across the Triassic–Jurassic boundary has been recorded in previous studies (Klausen et al., 2017, 2018), the lateral and temporal changes between the Barents Sea and Svalbard has not been investigated in detail.

Previous provenance studies in Svalbard have shown that the Upper Triassic is largely derived from eastern source areas, while the Jurassic interval comprise reworked material from this progradational phase (Mørk, 1999, 2013; Omma, 2009; Bue & Andresen, 2014; Fleming et al., 2016). These studies are however not centred around the Triassic–Jurassic boundary, nor are they concentrated in a single locality. In the Barents Sea, focus has either been on provenance differences across the Triassic–Jurassic boundary (Klausen et al., 2017) or temporal and spatial changes within the Pliensbachian to Bajocian aged Stø Formation (Klausen et al., 2018). Regional petrography and provenance studies also offer data on the sediment supply to the basin in different periods (Bergan & Knarud, 1993; Mørk 1999; Omma, 2009; Fleming et al., 2016; Khudoley et al., 2019; Flowerdew et al., 2020; Line et al., 2020), but few with strong stratigraphic control or special focus on certain time intervals that are compared between different locations in the basin.

The aim of this study is to examine potential differences in the basin infill and reworking of reservoir-bearing strata at the Triassic–Jurassic boundary across the Norwegian Barents Sea. This is done by comparing the provenance signatures of samples from the Upper Triassic and Lower Jurassic strata in the southern and central parts of the Barents Sea and Svalbard. Sampling different formations above and below this boundary at given locations allow us to investigate spatial and temporal variations in the sediment supply across the basin. Of particular interest is the rate of change between the different localities in the basin. Analysing provenance data also help understand the tectonostratigraphic evolution across the basin.

Geological setting

Svalbard is an exhumed part of the Barents Sea, and the present-day archipelago in the northwest corner of the GBSB (Fig. 1) was formed during uplift in the Neogene (Nøttvedt et al., 1993; Worsley, 2008; Lasabuda et al., 2021).

During the Triassic to Middle Jurassic, the Barents Sea and Svalbard was part of the same sedimentary basin and experienced the same evolution (Mørk, 1999; Klausen & Mørk, 2014; Lord et al., 2017; Rismyhr et al., 2018; Olaussen et al., 2018; Gilmullina et al., 2021*a*). Local basins and highs in the Barents Sea created during late Permian rifting (Riis et al., 2008; Faleide et al., 2008) were gradually inundated by siliciclastic wedges prograding from the east and southeast during the Triassic (Glørstad-Clark et al., 2010; Høy & Lundschien, 2011; Lord et al., 2017; Gilmullina et al., 2021*a*). In the east, these wedges comprised large-scale deltaic sequences with prodeltaic clinoforms and delta topset characterised by large channel systems that transported immature sediments from the Uralides to the greater Barents Sea basin and towards Svalbard (Riis et al., 2008; Høy & Lundschien, 2011; Klausen et al., 2015; Lord et al., 2017; Haile et al., 2018; Gilmullina et al., 2021*a, b*). Contraction from the NZFTB culminated at the Triassic–Jurassic boundary (Buiter & Torsvik, 2007; Ritzmann & Faleide, 2009; Faleide et al., 2018), and propagation of the foreland bulge to this orogenic event caused an inversion of the sedimentary basin in the Norwegian Barents Sea and Spitsbergen while increasing accommodation in the eastern parts of the Basin (Müller et al., 2019) and in eastern Svalbard (Olaussen et al., 2018). The inception of this compressional event has been used to explain a change to smaller and more frequent channel systems from the early to late Carnian, which suggests a change in the hinterland drainage areas (Klausen et al., 2014).

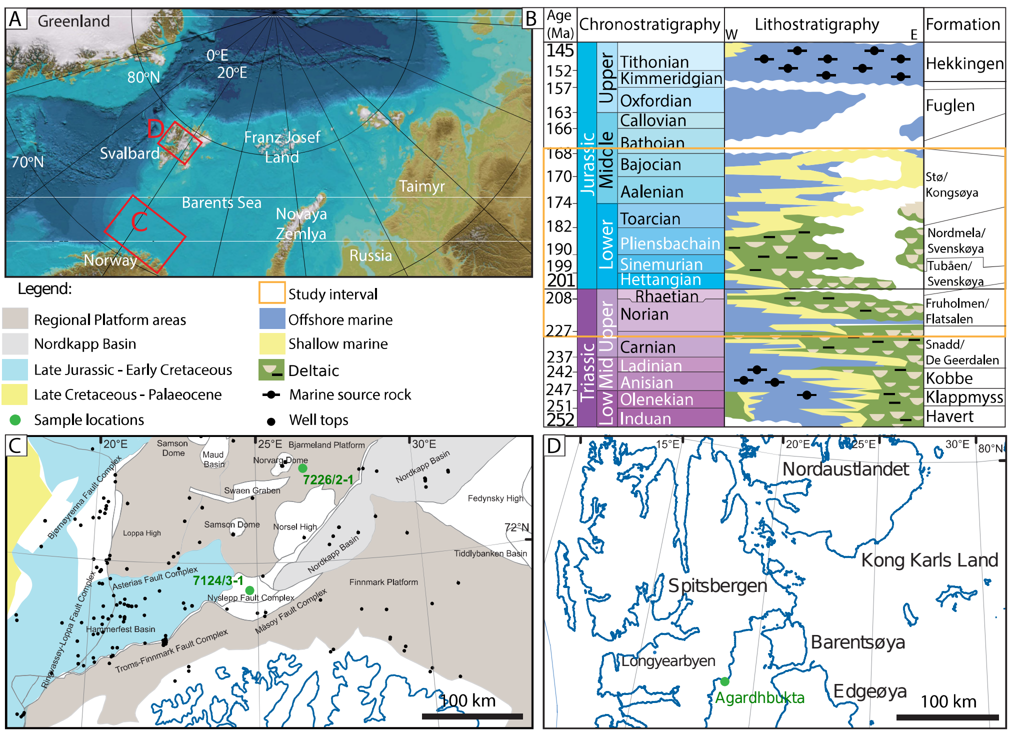

Figure 1. (A) Overview map of the Barents Sea region with the study areas highlighted in red. (B) Stratigraphic chart based on Nøttvedt et al. (1993) which highlights the study interval in the late Triassic to middle Jurassic. (C) Zoomed in overview map of the southern Barents Sea which shows the location of the two exploration wells analysed in the present study and key structural elements. (D) Overview map of Svalbard showing the location of Agardhbukta visited for comparison with the subsurface Barents Sea.

During the uplift and erosion of the sedimentary basin, a pronounced erosional sequence boundary was formed across the Arctic (Gjelberg et al., 1987; Embry, 2011; Müller et al., 2019) while the Rhaetian to early Jurassic Tubåen Formation was deposited as largely fluvial braid-steam deposits in local, incised depocenters (Klausen et al., 2019). These low accommodation deposits were followed by the increasingly marine Nordmela and Stø formations as relative sea-level gradually rose in the basin (Olaussen et al., 1984; Gjelberg et al., 1987; Klausen et al., 2018). In Svalbard, the deposits are observed in outcrop as condensed shallow marine to distal shelf deposits overlying eroded Triassic deposits (Mørk, 1999; Vigran et al., 2014; Rismyhr et al., 2018; Lord et al., 2019). The provenance area for the basin shifted from a sediment transport dominated by eastern provenance areas towards a dominance from mature Caledonian and Svecofennian hinterlands along the southern part of the basin, in combination with reworked Triassic grains derived from intra-basinal highs (Omma, 2009; Fleming et al., 2016; Klausen et al., 2017, 2018).

Uplift and erosion during the Cenozoic have exposed the sedimentary strata of the Barents Sea along parts of the western and the northern part of the GBSB (Faleide et al., 1993; Dimakis et al., 1998; Dörr et al., 2012; Lasabuda et al., 2021). Elsewhere in the Barents Sea, this uplift and erosion is evident as the Upper Regional Unconformity with different degrees of erosion in different parts of the basin, for example by eroding into the Snadd Formation in western parts of the Bjarmeland Platform and around the Fedynsky High (Glørstad-Clark et al., 2010; Henriksen et al., 2011; Müller et al., 2019).

Data and methods

For this study, we investigate the provenance signature and stratigraphic evolution in outcrops of late Triassic to middle Jurassic aged strata in Agardhbukta, eastern Spitsbergen, and compared them to time-equivalent strata in exploration wells (7124/3-1 and 7226/2-1) in the southern part of the Barents Sea. Facies and depositional setting for the samples are reported for reference with the regional paleogeography, but not described in detail. Previous publications cover the depositional system in more detail (Klausen & Mørk, 2014; Lord et al., 2017, 2019; Haile et al., 2018; Rismyhr et al., 2018; Olaussen et al., 2018). The Upper Triassic to Middle Jurassic succession is exposed along an up to a 30 m high sea cliff at the northern coast of the Agardhbukta bay. The strata can be followed along the coast for *c*. 9 km and are nearly flat lying or gently dipping to the northeast.

A composite sedimentary log has been recorded across the Triassic–Jurassic boundary and covering the Middle Jurassic strata along the length of this escarpment aided by a Lidar model courtesy of industry sponsors, and photogrammetry which is available online through the Svalbox (https://www.svalbox.no) site courtesy of the University Centre in Svalbard (UNIS).

Detrital zircon analysis was conducted at the ICP-MS lab at the University of Bergen. A Nu AttoM high resolution ICP-MS coupled to a 193 nm ArF excimer laser (Resonetics RESOlutionM-50 LR) was used to measure the Pb/U and Pb isotopic ratios in zircons. No common Pb correction was applied to the data. The concordance-discordance criterion used herein is 10%. Zircon U–Pb ages are presented as histograms and probability density plots (PDP) generated with the ISOPLOT program v. 3.70 (Ludwig, 2008).

Results

This study analyses samples from the Upper Triassic and Lower Jurassic strata in Eastern Svalbard (Agardhbukta) and in the central (Ververis 7226/2-1) and southern (Bamse 7124/3-1) parts of the Norwegian Barents Sea. Below, we focus on describing the deposits which have been sampled and their stratigraphic setting. The stratigraphic signature is correlated across the basin for comparison. Although the distance between localities used for correlation is far and there is considerable variability in the strata between these locations, the overall architecture shows distinct changes that are linked to regional tectonostratigraphic events addressed in the discussion. Within this stratigraphic framework, we describe the provenance signature of the samples analysed herein.

Stratigraphic signature

The stratigraphic architecture and nature of the three sample locations are described from Spitsbergen in the north to the Bamse exploration well, close to the southern margin of the Norwegian Barents Sea (Fig. 1).

Agardhbukta

The samples from Spitsbergen are gathered from fine-grained sandstones deposited as tidal sandbars in the De Geerdalen Formation (Fig. 2A), from condensed shallow marine deposits of the Flatsalen Formation and from shallow marine to shelf deposits of the Svenskøya and Kongsøya formations (Fig. 2B, C).

The upper, early Norian part of the De Geerdalen Formation, equivalent to the Hopen Member (Lord et al., 2014) and the uppermost, transgressive part of the Snadd Formation in the Barents Sea, is missing at this locality. Instead, the lower paralic deltaic, lagoonal and floodplain deposits of the Isfjorden Member are followed unconformably by a hyper-condensed succession of the Flatsalen Formation (c. 2 m, Fig. 2D). The Flatsalen Formation in eastern Svalbard is characterised by a relatively thick (60 to 85 m) prodeltaic to distal deltafront succession (Lord et al., 2017; Rismyhr et al., 2018; Olaussen et al., 2018). This formation is equivalent to the Fruholmen Formation in the subsurface Barents Sea (Klausen et al., 2019). Unlike its subsurface equivalent the Fruholmen Formation, deltaic and floodplain deposits are not preserved anywhere in the Flatsalen Formation in Svalbard. In Agardhbukta, even the prodeltaic part is absent.

The Wilhelmøya Subgroup in Agardhbukta is generally characterised by condensed, shallow marine to inner shelf deposits (e.g., Fig. 2C) developed in an overall transgressive trend that resemble its time-equivalent succession in the Barents Sea; the Realgrunnen Subgroup (Olaussen et al., 1984; Gjelberg et al., 1987; Klausen et al., 2019). The overall sandstone dominated succession is laterally continuous across the 9 km of outcrop in Agardhbukta (Fig. 3B).

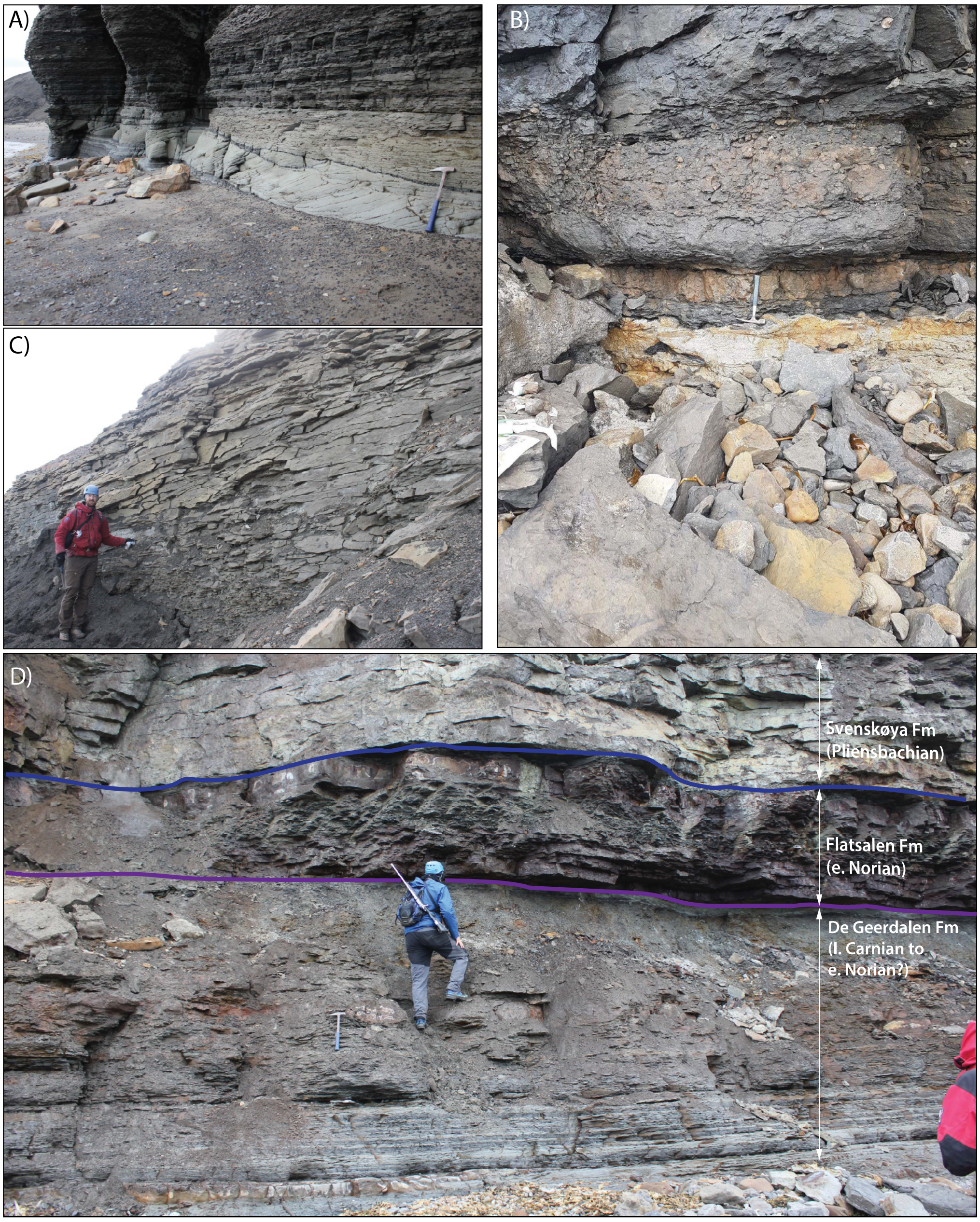

Figure 2. Facies examples and the important stratigraphic break at Agardhbukta. (A) Tidally influenced bay deposits in the uppermost, Carnian to early Norian, part of the De Geerdalen Formation which was sampled for geochronological analysis. (B) Boundary (hiatus) between the late Pliensbachian and late early Toarcian.. The calcite cemented layer behind the hammer comprise numerous ammonites, including Porpoceras polare, Pseudolioceras compactile and Zugodactylioceras braunianus which provides the most reliable dates in the stratigraphic section at Agardhbukta (Rogov and Lutikov, 2022). (C) An example of the Kongsøya Fm in the uppermost part of the studied interval which was sampled for geochronological analysis in the easternmost part of the beach cliff outcrop. Figure is courtesy of Miquel Poyatos-Moré. (D) Significant stratigraphic break along a subaerial unconformity cutting deep into and eroding the early Norian part of the De Geerdalen Formation. The unconformity is followed by a thin (c. 2 m) condensed section of the Flatsalen Formation. This section was sampled for geochronological analysis, but the sampled yielded very few grains from the generally calcite-dominated sample.

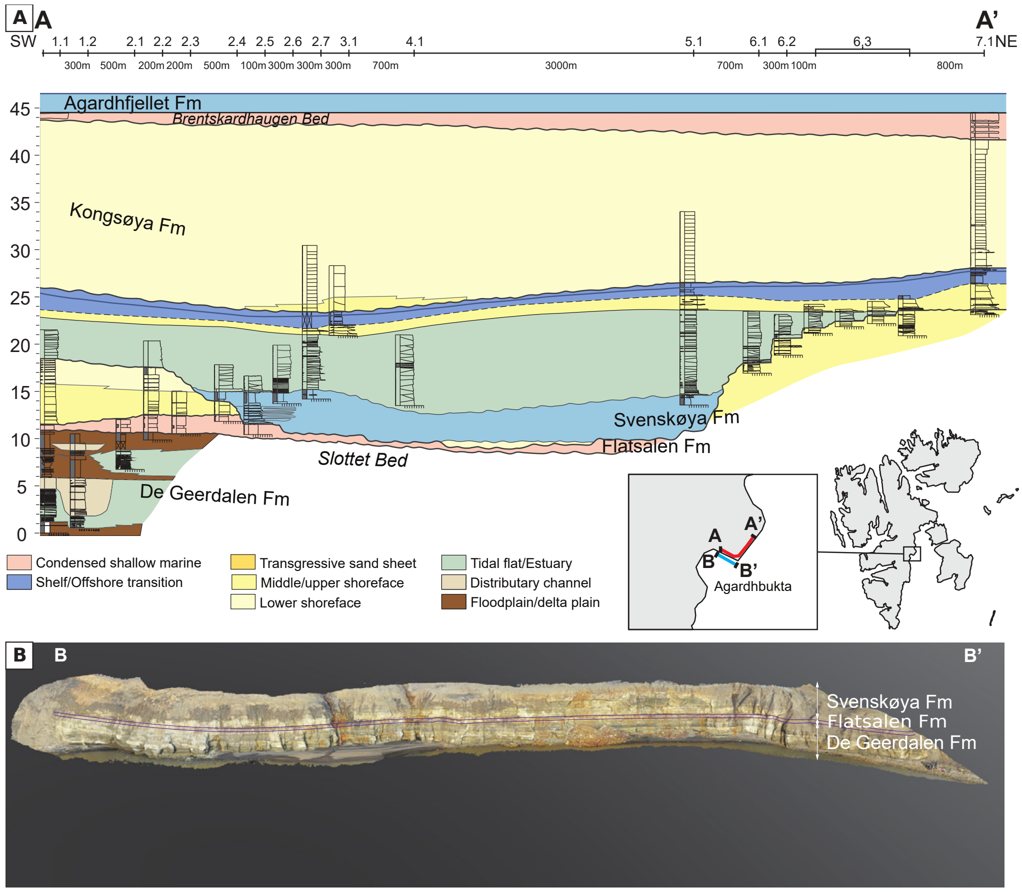

Figure 3. (A)Correlation panel of the Agardhbukta locality showing the lateral variability of the late Triassic to early Jurassic succession and how it has been logged in several shorter logs (labelled 1 to 7 with suffixes in the uppermost line) along the narrow cliff section with stratigraphy gently dipping shallowly to the northeast. These shorter logs are compiled into a representative composite using proprietary lidar models and photomosaic of the beach cliff outcrop (B). The photogrammetric model shown here is available online courtesy of Svalbox (https://www.svalbox.no/). The model is compiled by Peter Betlem and Julian Janocha.

The composite log in Fig. 4 shows the stratigraphic development of the Upper Triassic to Middle Jurassic strata in Agardhbukta. It also highlights the condensed nature of this succession in Eastern Spitsbergen. The biggest discrepancy compared to time-equivalent strata from elsewhere in Svalbard (e.g., Worsley, 1973; Vigran et al., 2014; Lord et al., 2017, 2019; Olaussen et al., 2018) is the apparent lack of Norian, Rhaetian and Sinemurian strata. The most reliable data on the relative ages within the Jurassic section in Agardhbukta is provided by numerous ammonites, including *Porpoceras polare, Pseudo-lioceras compactile og Zugodactylioceras braunianus* (Fig. 2B).

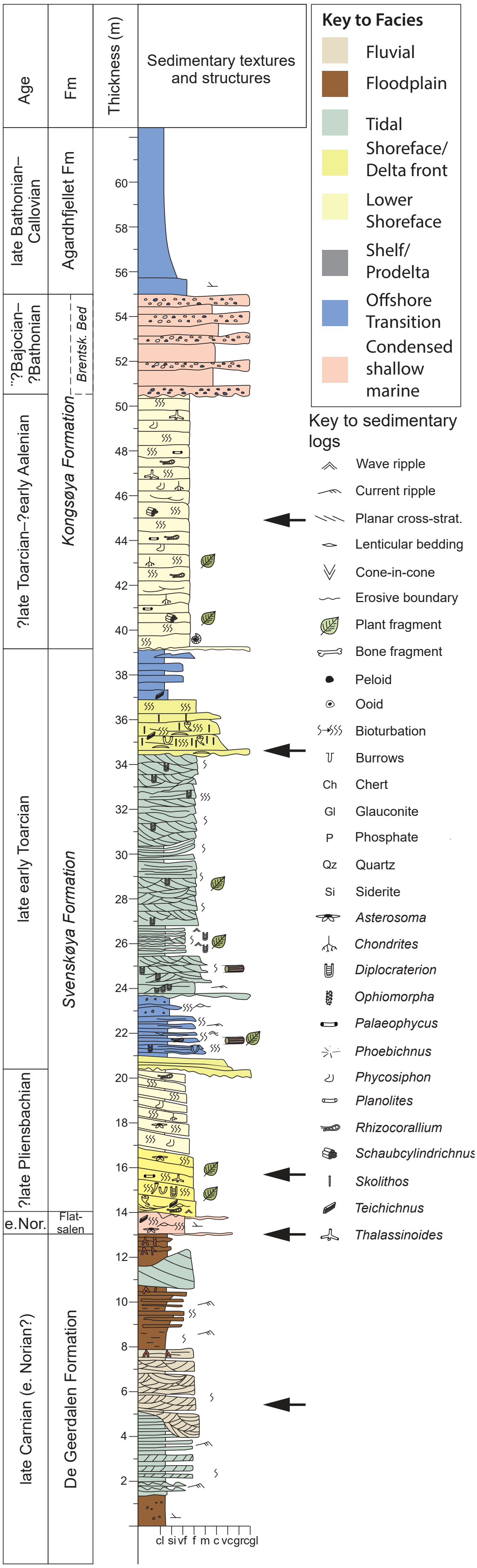

Figure 4. Composite log from Agardhbukta. The composite represents a stacked compilation of the logs collected through the strata that is gently dipping eastward along the beach cliff in northern Agardhbukta (Fig. 3A). The log compilation is assisted by Lidar models and large-scale photomosaic of the outcrop, as exemplified in Fig. 3B. Black arrows indicate the location of samples for geochronological analysis. Log thickness is given as meters above base of log, abbreviated a.b.l.

Ververis (7226/2-1)

The samples from the Ververis well (7226/2-1) represents a medial position in the Norwegian Barents Sea Basin (Fig. 1C), despite being positioned relatively far south compared with the outcrop analogue in eastern Spitsbergen (Fig. 1A). The cored interval comprises a thick succession of the Tubåen Formation and a transgressive Stø Formation. Triassic deposits are only present in the lowermost part of the cored interval and are here represented by the Fruholmen Formation.

The Fruholmen Formation is characterised by lower delta plain deposits, but it has limited core material in this well (Fig. 5). The formation is thinner in this well relative to other wells in the basin interior as it shows a total thickness of *c.* 100 m, as opposed to more than 500 m along the western margin (e.g., in wells southwest of the Loppa High, Fig. 1, see also Klausen et al. [2019]). Another difference is the facies association encountered in this well: The uppermost part of the Fruholmen Formation is here comprised entirely of prodeltaic deposits, as opposed to the typical fluvial nature of the formation in surrounding wells in the basin interior (Klausen et al., 2019). Instead, it is fluvial sandstone deposits of the Tubåen Formation that are resting on the prodeltaic Fruholmen Formation, separated by an erosive surface. This circum-Arctic unconformity starts forming in the Rhaetian and marks the transition from the Triassic to the Jurassic (Gjelberg et al., 1987; Embry, 2011; Müller et al., 2019). The fluvial sandstones at the base of the Tubåen Formation are passing upward to deltaic deposits with distributary channels, floodplain and tidal interfluvial depositional environments (Fig. 5).

The Ververis well shows that there was a period of localised accommodation on the Bjarmeland Platform in the early Jurassic, demonstrated by deposition and preservation of deltaic facies in the Tubåen Formation. However, the Lower to Middle Jurassic succession is also here characterised by a generally highly condensed Jurassic succession and comprises only the upper parts of the Stø Formation above the Tubåen Formation (Fig. 5). The Sinemurian to Toarcian succession is missing at the well location and there is a significant hiatus to the underlying Tubåen Formation. The Stø Formation is characterised by shallow marine to inner shelf deposits formed during an overall transgression.

Bamse (7124/3-1)

The samples from the southernmost part of the Barents Sea are gathered from the Bamse well (7124/3-1) in the southern part of the Hammerfest Basin (Fig. 6). Core from this well covers the late Triassic aged Snadd and Fruholmen formations, and the latest Triassic to early Jurassic Tubåen Formation. Most of the Lower to Middle Jurassic succession is absent at the well location, and the only deposits that could potentially be of early Jurassic age are those assigned to the Tubåen Formation (Fig. 6B) which could potentially be time-transgressive from the Rhaetian and into the Hettangian. In addition, the Norian interval comprising the Fruholmen Formation is highly condensed (*c*. 80 m) compared to its expression in the basin interior (typically exceeding 200 m).

The Upper Triassic Snadd Formation is characterised by tidal, bay and shoreface deposits (Fig. 6D) belonging to the transgressive part of the formation. Overlying the transgressive deposits in the uppermost part of the Snadd Formation are prodeltaic deposits of the Fruholmen Formation. These prodeltaic deposits are followed conformably by deltaic and fluvial deposits (Fig. 6C). This stratigraphic development of the Fruholmen Formation is similar to the development of the formation elsewhere in the basin. Notably however, the thickness of the prodeltaic succession is considerably thinner than the typical 100s of meters observed at more distal positions in the basin. This could suggest that the erosional boundary between the prodeltaic and deltaic to fluvial succession is not autocyclic in nature.

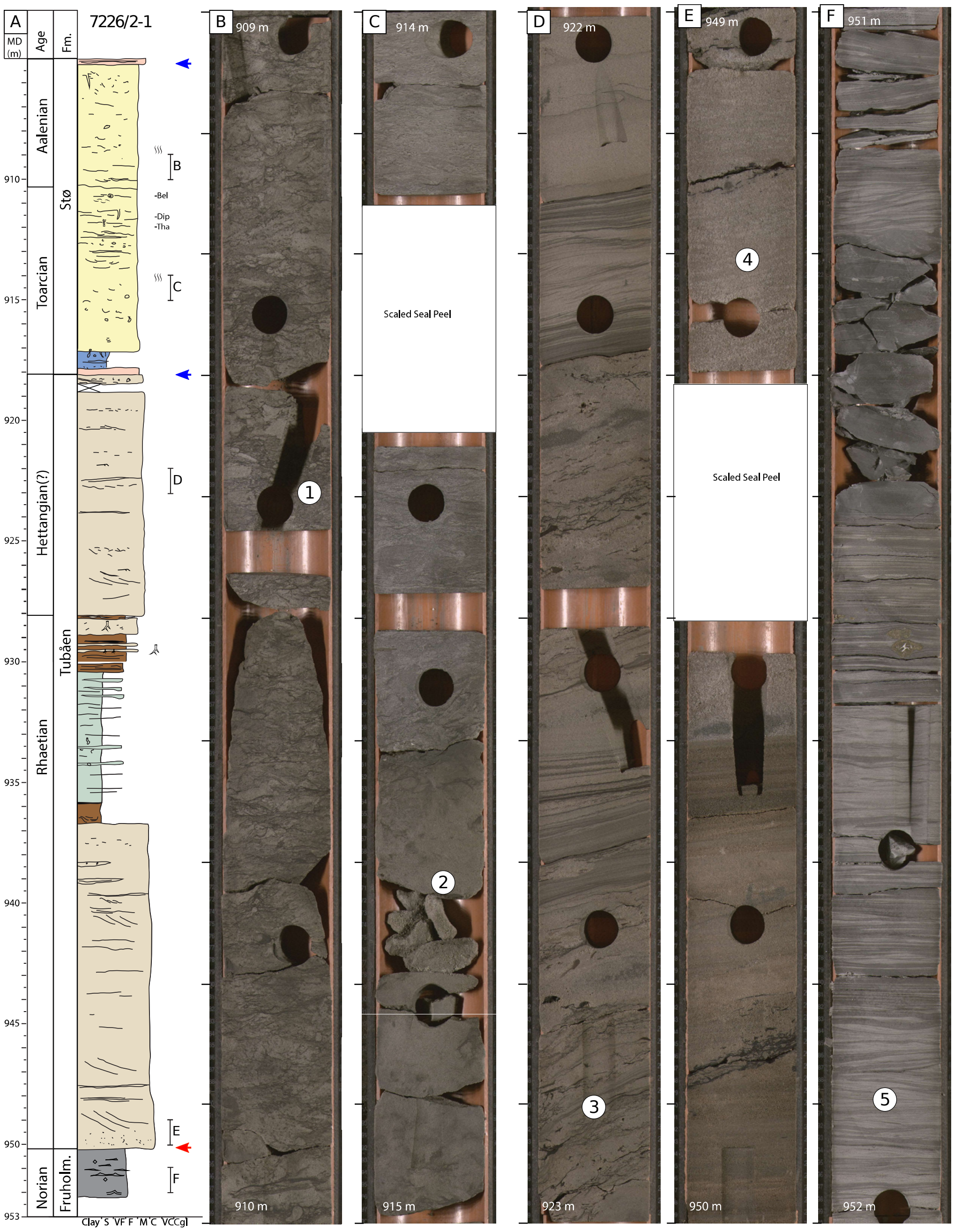

Figure 5. (A) Log of the Upper Triassic to Lower Jurassic interval cored in well 7226/2-1 which sample the succession in the medial part of the Norwegian part of the Barents Sea. Red arrow indicates subaerial unconformity defined by erosion at the base of the Tubåen Formation. Blue arrows indicate maximum flooding surfaces. (B) Bioturbated inner shelf deposits from the Stø Formation dated to be Aalenian which is sampled for geochronological analysis (1). Lines on the left-hand side of figures show decimetre intervals. (C) Similar deposits from the Toarcian part of the Stø Formation sampled for geochronological analysis (2). (D) Fluvial deposits from the younger, possibly Hettangian, part of the Tubåen Formation which is sampled for geochronological analysis (3). (E) Basal part of fluvial deposits in the lowermost, Rhaetian, part of the Tubåen Formation, sampled for geochronological analysis (4). (F) Prodeltaic heteroliths from the Norian Fruholmen Formation sampled for geochronological analysis (5).

The Rhaetian (to possibly early Jurassic) Tubåen Formation has an erosive base to floodplain deposits in the underlying Fruholmen Formation (Fig. 6). The Tubåen Formation is characterised by fluvial deposits in the core and is coarser grained than the underlying Triassic deposits.

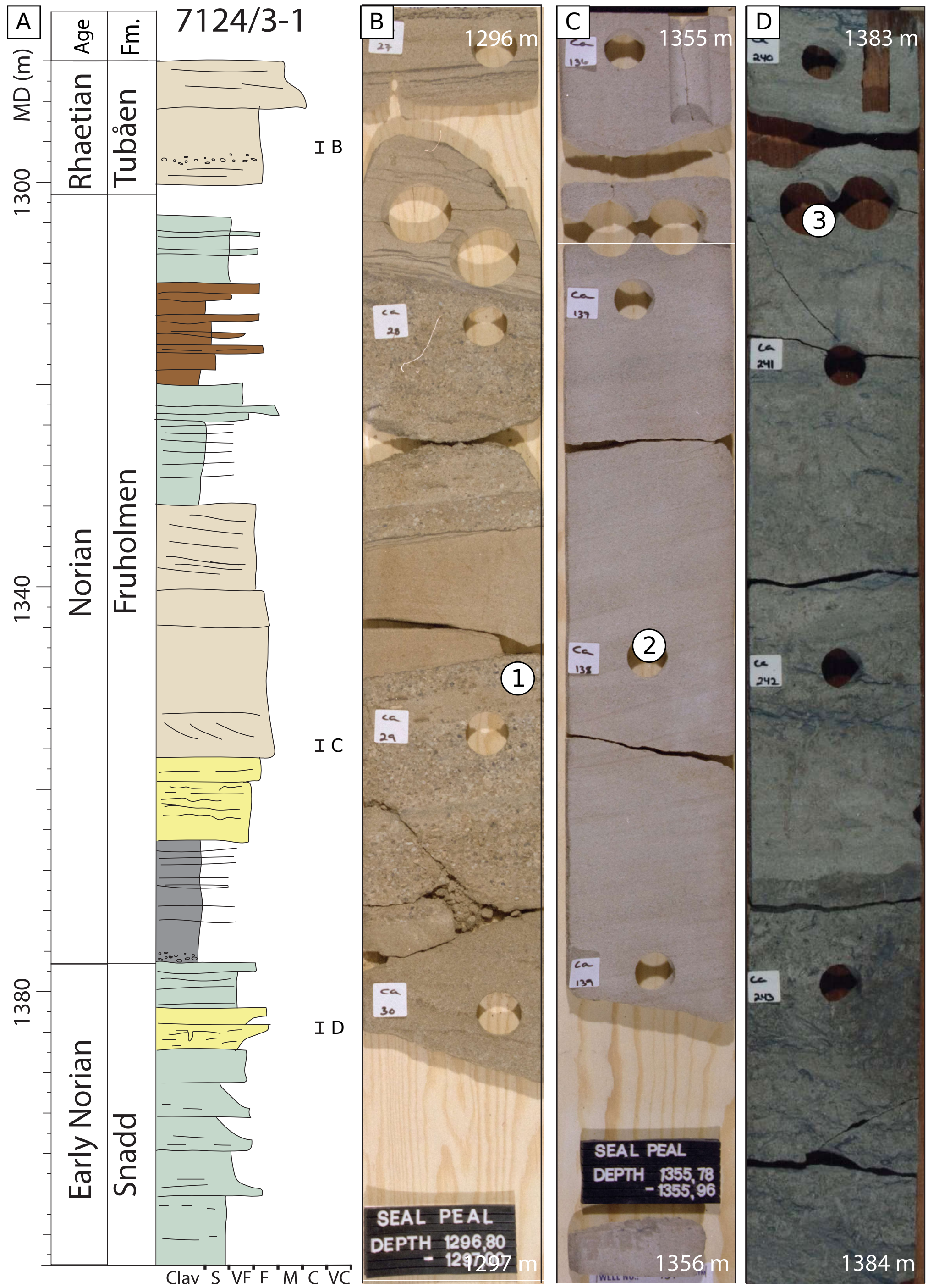

Figure 6. (A) Log of the Upper Triassic to Lower Jurassic interval cored in well 7124/3-1, one of the exploration wells which sample the succession in the southern part of the Norwegian Barents Sea. (B) Shows an example of bimodal grain sizes in fluvial deposits from the Tubåen Formation from which the uppermost sample for geochronological analysis is collected (1). (C) Fluvial deposits from the Fruholmen Formation from which the middle sample for geochronological analysis has been collected (2). (D) Bioturbated shoreface deposits in the uppermost part of the Snadd Formation from which the lowermost samples for geochronological analysis are collected (3).

Regional correlation

The sampled succession at Agardhbukta in eastern Spitsbergen represents some of the northernmost exposures of the Mesozoic succession in the Norwegian Barents Sea (Fig. 1), with the Upper Triassic to Middle Jurassic part being heavily condensed in this area (Fig. 7). The De Geerdalen Formation is dated

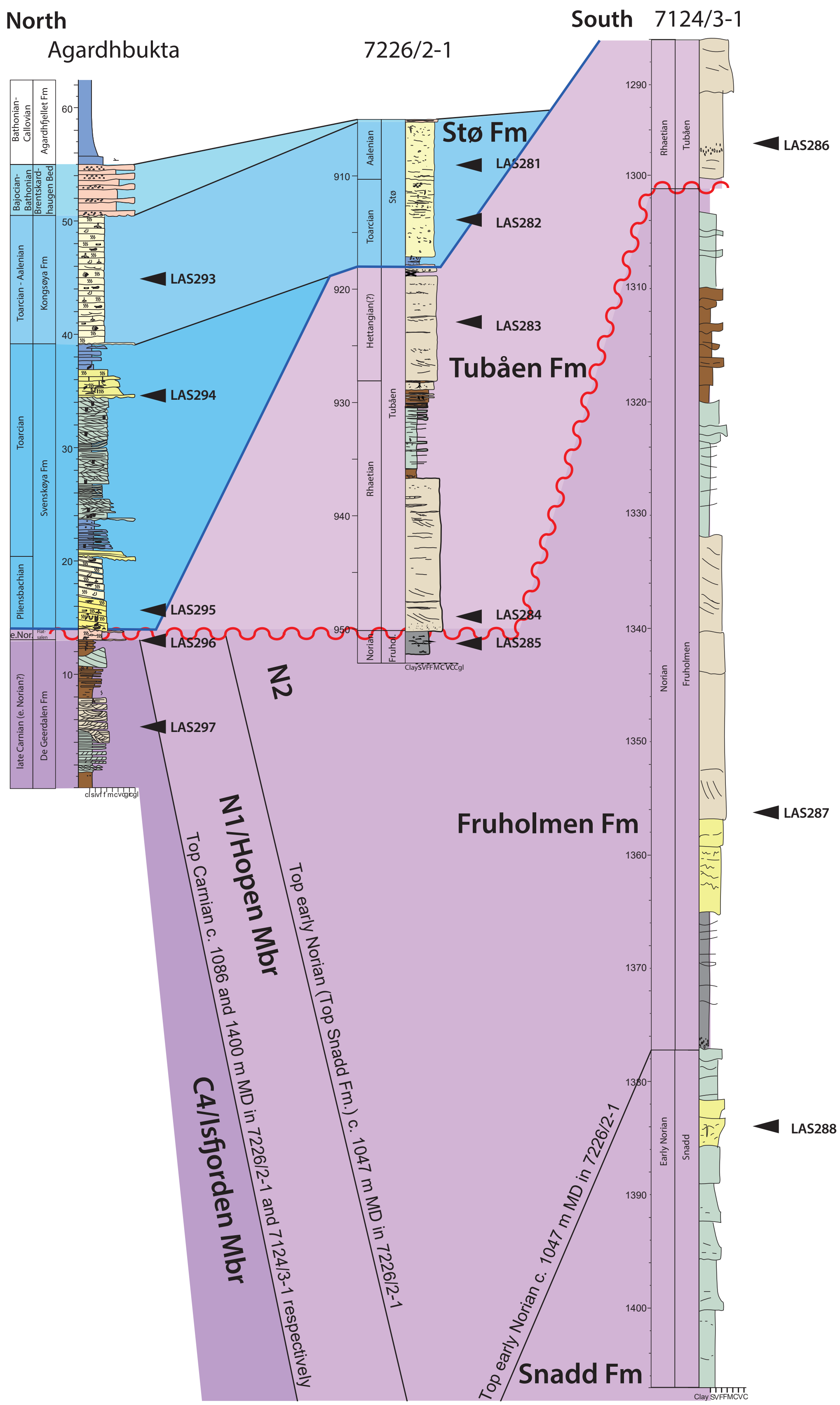

Figure 7. Core correlation panel comparing the Upper Triassic to Lower Jurassic succession across the Norwegian Barents Sea to eastern Spitsbergen described in the present study. Samples for geochronological analysis are marked by black triangles. Note the truncation of Upper Triassic strata in the north, which is also seen locally in the Barents Sea, and the onlap set up by the gradual transgression during the Triassic.

to be late Carnian to early Norian at it youngest (Vigran et al., 2014; Rismyhr et al., 2018), indicating that the youngest part of unit seen in the uppermost part of the De Geerdalen Formation in e.g., Hopen and in its time-equivalent Snadd Formation elsewhere in the basin (Klausen et al., 2015) is completely missing in Agardhbukta. The zircon data suggest however that the De Geerdalen Formation might be younger, likely early Norian, at this location. This will be discussed in more detail below, but regardless: the De Geerdalen Formation does not show the gradual transgressive and progressively more marine upper part that characterise the formation in other parts of Svalbard (e.g., Klausen & Mørk, 2014) and which would be equivalent to the Norian N1 sequence in Klausen et al., (2015) and the Hopen Member in Lord et al. (2014). Above the unconformity that defines the upper boundary of the De Geerdalen Formation, the overlying Norian deposits of the Flatsalen Formation are comprised within a few meters (Fig. 7). This succession is time-equivalent to the lowermost part of the Fruholmen Formation but is extremely condensed in Agardhbukta compared to its subsurface equivalent. In the easternmost parts of the Svalbard archipelago, the Flatsalen Formation typically exceeds many tens of meters (up to more than 80 m) and is characterised by a maximum flooding surface at its base followed conformably by normal regressive prodelta deposits (Lord et al., 2017; Olaussen et al., 2018). The latest Rhaetian to early Jurassic succession comprises the Svenskøya Formation which is equivalent to both the Tubåen and Nordmela formations. In Agardhbukta, the Rhaetian part of the Svenskøya Formation is missing and the fluvial deposits that characterise the lowermost Jurassic is not found. The Svenskøya Formation and Kongsøya Formation comprise condensed shallow marine to inner shelf deposits formed in an overall transgressive setting.

Ververis (7226/2-1) represents a medial position in the basin and here, the Sinemurian (to possibly Pliensbachian) succession is missing. This development differs from eastern Spitsbergen due to the fluvial deposits of Rhaetian age and the missing Sinemurian succession comprising the Nordmela Formation. Also, unlike eastern Spitsbergen, the Norian succession is much better developed (*c.* 100 m as opposed to 2 m) even though the fluvial part of the Fruholmen Formation seems to be completely missing at this location as well, and the Triassic formation is followed unconformably by fluvial deposits of the Tubåen Formation. These observations suggest pronounced erosion of the Fruholmen Formation at the transition to the Jurassic and a significant hiatus after fluvial deposition in the Sinemurian before gradual transgression reached the well location in the later stages of the Stø Formation.

Bamse (7124/3-1) represent the southernmost position in the basin, and here, the Lower to Middle Jurassic except for the fluvial Tubåen Formation is completely missing (Fig. 7). The transgressive phase which followed the Triassic–Jurassic unconformity or fluvial deposits directly overlying this boundary did not reach the well location in the southern part of the basin until the late Jurassic. The southern part of the basin therefore seems to represent a more proximal equivalent with more pronounced, or more sustained uplift compared to the basin interior (e.g., 7226/2-1). The Fruholmen Formation is thin (*c.* 80 m) compared to its equivalent in the basin interior, but demonstrate a complete normal regressive succession ranging from prodeltaic to deltaic and fluvial unlike the more condensed succession we compare with in this study. Its base to the underlying Snadd Formation is notably also not erosive but represented by a maximum flooding surface.

The stratigraphic development described above attests to distinct variability in the degrees of erosion and condensation across the basin during the Triassic–Jurassic transition. The localities studied herein are distributed from the southern part, via approximately medial, to the northern part of the basin. Although local variations certainly exists, as exemplified by several previous studies of the basin interior (Olaussen et al., 1984; Gjelberg et al., 1987; Bergan & Knarud, 1993; Klausen et al., 2017, 2018, 2019; Müller et al., 2019) and in outcrops in Spitsbergen (Rismyhr et al., 2018; Olaussen et al., 2018), the present study records pronounced condensation along the southern part of the basin, erosion in the basin interior and erosion followed by condensation in the northern part of the basin. Both the erosion and condensation are explained by contemporaneous uplift associated with NZFTB (Olaussen et al., 2018; Müller et al., 2019).

Differential accommodation affects the sediment supply patterns to the basin and thus the distribution of its most important reservoir interval. The composition of the sediment source area determines the nature of its sedimentary product. The mineralogically more mature southern source areas are better candidates for forming quality reservoir rocks, than immature Triassic rocks reworked in the basin interior. The supply directions and extent of different sediment provenance areas can be assessed by analysing the provenance signatures of the different formations across the basin (e.g., Gilmullina et al., 2021a).

Provenance signature

Agardhbukta (Outcrop Eastern Spitsbergen)

The sample from the De Geerdalen Formation shows detrital zircon U–Pb data with little variation. This sample is dominated by Permian to Triassic ages (Fig. 8E), with few occurrences indicating Precambrian ages. The youngest detected zircon is dated as being 220 ± 6.5 Ma in age (Norian), with the oldest being Archean in age.

Samples from the Flatsalen Formation had low recovery of detrital zircons, reflecting the condensed marine composition of the sediment with a high concentration of limestone and relatively few sand-stone grains, compared to the over- and under-lying formations. Nevertheless, a uniform distribution of Triassic to Paleozoic detrital zircon ages is present, with the youngest grain dated to 224.9 ± 6.5 Ma (Fig. 8D).

Samples from the Svenskøya Formation both show a distinct Triassic peak and different magnitude of Mesoproterozoic age signatures. The youngest grains in the two samples are 215.6 ± 5.7 Ma and 221.6 ± 6.7 Ma respectively (Fig. 8C, B).

The sample from the Kongsøya Formation also did not contain abundant zircons, but the analysed grains show a signature which is distinct from the underlying formations by having no Triassic age grains and a more pronounced Mesoproterozoic age spectrum (Fig. 8A). The youngest grain in this sample is early Permian in age 297.6 ± 10 Ma.

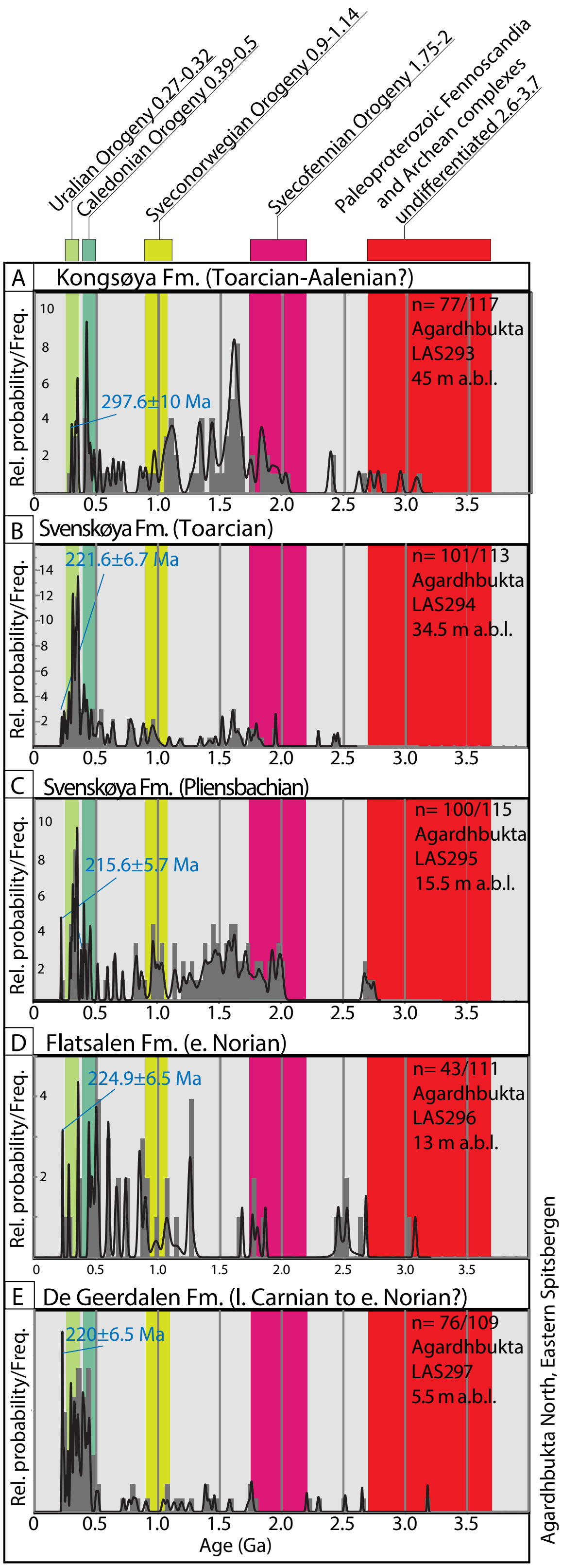

Figure 8. Detrital zircon age spectrum for samples from the late Triassic to middle Jurassic strata in Agardhbukta, Eastern Spitsbergen. The De Geerdalen Formation records an influx of sediment grains with crystallisation age close to maximum depositional age (E). The remaining samples show age spectra consistent with a reworked Triassic sediment source (D–B). Note the very low recovery in samples from the Norian Flatsalen Formation which are dominated by carbonate cement (D). The sample from the youngest strata show the oldest grains (A), with Permian/Carboniferous, Caledonian and Svecofennian grains dominating the spectrum.

Ververis (7226/2-1)

Because of the limited core material available for the Fruholmen Formation, the sample is gathered from the sandstone directly below the Tubåen Formation (Fig. 9H). Alternatively, the sample might be interpreted to belong to the Lower Jurassic interval, but nevertheless it shows a dominant Triassic age signature, with youngest grain dated to be 225.1 ± 5.1 Ma (Fig. 9H).

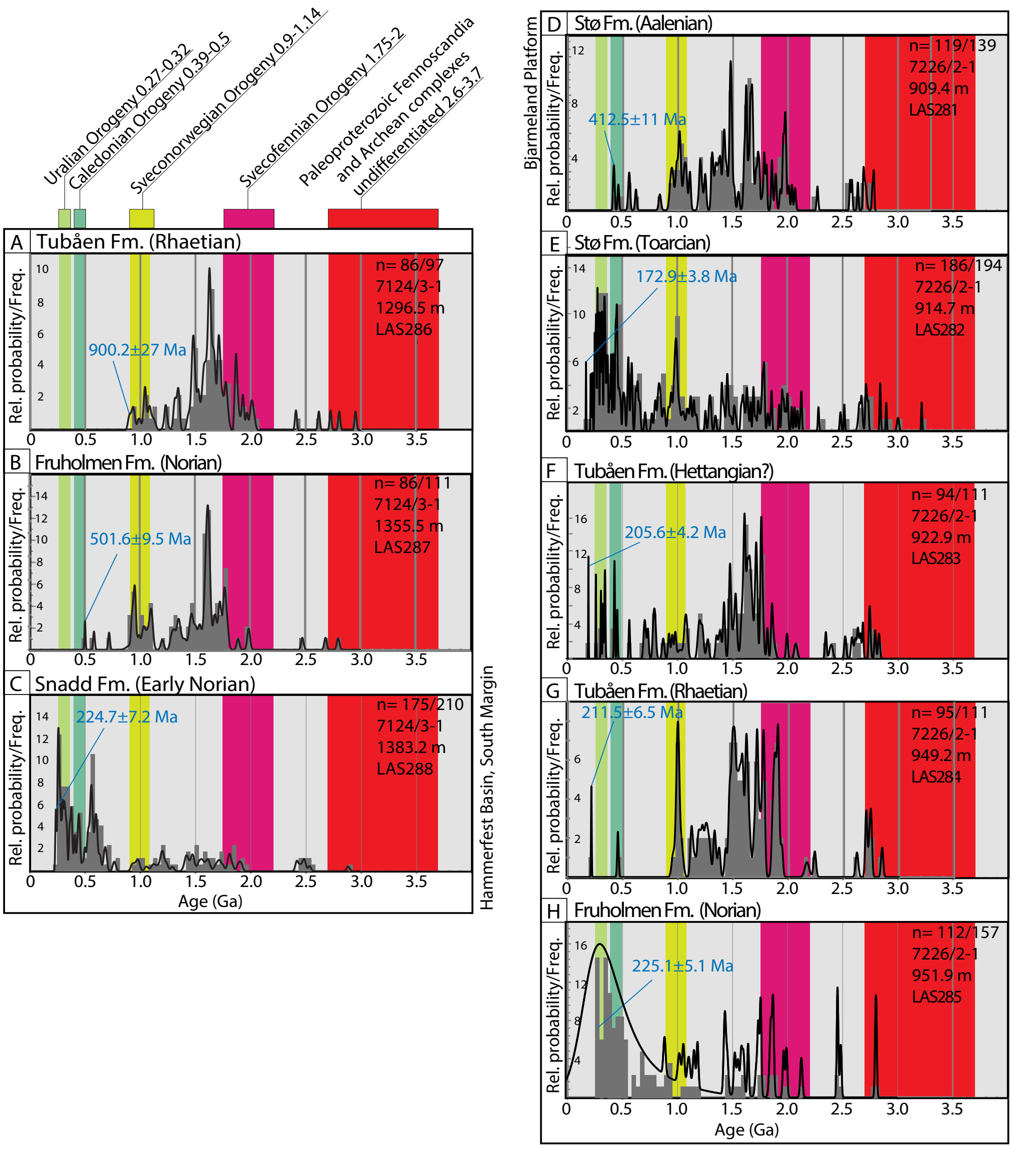

Figure 9. Detrital zircon age spectrum for samples from the Triassic to early/middle Jurassic strata in exploration wells from the Barents Sea. (A) Tubåen Fm from the southernmost well (7124/3-1) show a dominant Svecofennian age signature, similar to Fruholmen Fm sample in the same well (B). (C) The Snadd Fm in this well show a detrital zircon age spectre dominated by young grains consistent with a young and active sediment source in the East. (D) The Stø Fm from a medial position in the Barents Sea basin (7226/2-1) is dominated by a Svecofennian age signature with some minor contribution from a Caledonian age provenance area. (E) The Toarcian Stø Fm sample in this well is anomalous compared to detrital zircon age spectrum from time-equivalent deposits in other studies (Klausen et al., 2017, 2018, 2019; Line et al., 2020) for two reasons: i) it records the youngest detrital zircon grain from these strata in the Norwegian Barents Sea so far, and ii) it is dominated by young detrital zircon grains consistent with an Eastern source. (F) The two samples from the Tubåen Fm show dominantly Svecofennian ages with minor reworked Triassic grains. Note however the pronounced Sveconorwegian peak around 1 Ga in the sample from the oldest strata (G). (H) The sample from the Fruholmen Fm show a dominance of Eastern provenance areas that typically characterise the formation in the basin interior.

The sample from the base of the formally defined Tubåen Formation does not show the same dominant Triassic peak, but has a few notably young grains of Triassic (youngest is 211.5 ± 6.5 Ma) and Paleozoic age but is dominantly Mesoproterozoic (Fig. 9G).

The sample from the upper part of the Tubåen Formation is also dominated by a Mesoproterozoic to Archean age spectrum (Fig. 9F). This sample has more Triassic and Paleozoic grains in comparison to the sample from the lower part of the Tubåen Formation and a younger minimum age on the Triassic grains (205.6 ± 4.2 Ma).

Samples from the Stø Formation also show a distinct difference in the detrital zircon age spectrum between the lowermost and uppermost part of the formation (Fig. 9E, D). The lowermost Stø Formation sample, dated to be of Toarcian age, is dominated by Triassic to Paleozoic grains but has a notable Aalenian age grain as the youngest grain in the sample (172.9 ± 3.8 Ma). This is younger than the age defined by biostratigraphy, but the span on the error margin overlaps with the Toarcian age defined for the interval. The uppermost part of the Stø Formation is distinctly different in having no Triassic age grains and is dominated by Mesoproterozoic to Archean age grains with the youngest grains being Devonian (412.5 ± 11 Ma).

Bamse (7124/3-1)

The sample from the Snadd Formation show detrital zircon ages with slightly larger variations in their distribution compared to the sample from Agardhbukta. The sample from the Snadd Formation in the Bamse well is dominated by Permian to Triassic ages (Fig. 9C), with few occurrences of Precambrian ages as in the previous sample but contains a prominent 510–540 Ma peak. The age of the youngest detected zircon is 224.7 ± 7.2 Ma, and the oldest is Archean in age.

The sample from the Fruholmen Formation show a Mesoproterozoic age signature with no Triassic age grains (Fig. 9B). The youngest grain in the sample is Paleozoic in age (501.6 ± 9.5 Ma).

The sample from the Tubåen Formation show a similar signature (Fig. 9A) as the Fruholmen Formation below with no grains of Triassic age. The detrital zircon age signature is dominated by Mesoproterozoic grains, but the youngest grain in this sample is considerably older than the sample from the Fruholmen Formation being here Neoproterozoic in age (900.2 ± 27 Ma).

Discussion

This study documents the same trends in detrital zircon age signatures recorded across the Triassic–Jurassic boundary as previous studies (Omma, 2009; Bue & Andresen, 2014; Klausen et al., 2017, 2018) but show the variability across the basin from its northernmost to southernmost extreme, along with previously undocumented well locations in the medial part of the basin interior. The samples analysed in the present study record the youngest grains hitherto documented from the Lower to Middle Jurassic succession in the Norwegian part of the Barents Sea. They also place the detrital zircon age signatures in a stratigraphic context that highlight important stratigraphic breaks and differences across the basin that have so far received limited attention. The results corroborate previous studies of the basin development at the Triassic–Jurassic boundary (Müller et al., 2019), but the early Norian age recorded in the De Geerdalen Formation might have implications for the timing of previously assigned sequences (Klausen et al., 2015) and the sediment distribution across the basin in the late Triassic. Here we discuss the results presented above, and their implications for how to assess the potential impact on reservoir properties in the Barents Sea.

Stratigraphic signature

The succession in Agardhbukta is consistent with the pronounced uplift and erosion at the Triassic–Jurassic boundary in north-western part of the Svalbard Archipelago (Steel & Worsley, 1984; Rismyhr et al., 2018; Olaussen et al., 2018; Müller et al., 2019). The present study shows that the uppermost part of the De Geerdalen Formation (Hopen Member sensu Lord et al., 2014) is completely missing, and deltaic deposits of late Carnian age (lower to middle parts of the Isfjorden Member sensu Rismyhr et al., 2018) is followed unconformably by condensed offshore marine deposits of a very thin Flatsalen Formation. However, detrital zircon ages in the present study suggest that these deposits might have been deposited as late as early Norian, which means that there is a fluvial depositional environment in Svalbard shortly before the onset of basinwide transgression in the uppermost part of the De Geerdalen and Snadd formations (Klausen et al., 2015). This implies that the N1 sequence proposed by Klausen et al. (2015) to cover the early Norian transgressive part of the Snadd Formation in the Barents Sea and Svalbard (e.g., Figs. 6 & 7), potentially should be expanded into the upper part of the fluvial succession in the De Geerdalen Formation, as exemplified in Agardhbukta, which potentially could be dated to early Norian based on detrital zircon data analysed for the present study (Fig. 8E). In this case, the succession likely formed the at the onset of a gradual turnover to more marine conditions in the beginning of the Norian. It should however be noted that although several grains analysed in the present study are Norian in age (Fig. 8C), their error margin verges on the limit of the late Carnian (*c.* 227 Ma), and we therefore regard the early Norian age as tentative for the De Geerdalen Formation in Agardhbukta and favour that the N1, and its Hopen Member equivalent in Svalbard, are used to define the marine flooding and transgressive deposits in the uppermost part of the formations.

Apart from this possible fluvial component in the earliest Norian, the lithological transgressive part belonging to the Hopen Member or its N1 equivalent in the subsurface, is eroded and absent in Agardhabukta. Furthermore, the Flatsalen Formation is elsewhere in Svalbard characterised by a maximum flooding surface at its base and a thick prodeltaic succession that is normal regressive into deltaic and fluvial (Worsley, 1973; Mørk, 1999, 2013; Olaussen et al., 2018; Lord et al., 2019). This succession has been eroded together with the uppermost part of the De Geerdalen Formation and highlights that the variable uplift and erosion that has been documented in the Norwegian Barents Sea (Müller et al., 2019) is also evident in Svalbard (Olaussen et al., 2018; Hounslow et al., 2022), and likely also adjacent areas. Previous studies have not fully understood the pronounced erosion at the Triassic–Jurassic transition in eastern Spitsbergen, partially because it is highly differential across the Archipelago. The unconformity between the Upper Triassic and the Jurassic is noted from a few localities in Svalbard by Vigran et al. (2014) and Hounslow et al. (2022), but not put in context with the basin development. Rismyhr et al. (2018) linked the condensation at the Triassic–Jurassic boundary to forebulge uplift in response to NZFTB (Klausen et al., 2017; Müller et al., 2019), and the stratigraphic development in Agardhbukta reflects the same pattern with pronounced erosion of the Flatsalen and De Geerdalen formations, followed by a prolonged period of non-deposition. The fluvial succession that characterises the Tubåen Formation in the Barents Sea, and in the Svenskøya Formation in Hopen (Lord et al., 2019), is missing from the outcrop locality and this supports that there was limited accommodation in the area at the Triassic–Jurassic transition, consistent with a low-accommodation basin configuration with local incisions. Later flooding facilitated deposition of distal marine Svenskøya and Kongsøya formations in Agardhbukta (equivalent to the Nordmela and Stø formations respectively).

Erosion of the Upper Triassic formations is also evident in the subsurface Barents Sea (Müller et al., 2019), but as in Svalbard the degree of erosion varies significantly in different parts of the basin. In Ververis (7226/2-1), the Tubåen Formation seems to have incised into the prodeltaic deposits of the Fruholmen Formation. Although there might be local variations in the original thickness of Fruholmen Formation due to contemporaneous tectonic activity in the hinterland (Klausen et al., 2014; Zhang et al., 2018; Müller et al., 2019), this has yet to be proven and the prodeltaic part of the formation seems to be consistent in thickness (*c.* 70 m) when comparing the first upwards coarsening sequence in for example wells 7220/8-1 and 7324/8-1 (Klausen et al., 2019). If we assume original thicknesses of the Fruholmen Formation was nearly up to the maximum thickness recorded along the western margin of the Barents Sea (e.g., 7220/8-1), as much as 400 m of fluvial to deltaic deposits might have been eroded during uplift at the Triassic–Jurassic boundary. It is reasonable to assume that at the very least a few hundred meters has been removed. Following the fluvial deposits of the Tubåen Formation there is a pronounced hiatus where Sinemurian to Toarcian strata is completely missing, suggesting that the Tubåen Formation was deposited in a terrestrial highland, possibly experiencing continued uplift, where the following marine transgression did not reach until late in the development of the Stø Formation (Figs. 5 & 7).

In the southernmost well investigated for this study, Bamse (7124/3-1), the Fruholmen Formation is also condensed compared to the thickness it displays in the basin interior, although not nearly as condensed as in eastern Spitsbergen. Despite its relatively condensed nature, the formation is rather well-developed showing a normal regressive trend from prodeltaic to deltaic and fluvial deposits. It is followed stratigraphically by coarse grained fluvial deposits of the Tubåen Formation, but the depositional environment but without dramatic change in the depositional environment, which may indicate that the boundary here is entirely autogenic. The Tubåen Formation is followed by an Upper Jurassic to Lower Cretaceous succession, meaning that the Nordmela and Stø formations are absent at the well location. This suggests the presence of an elevated highland throughout the Jurassic and was one of the last areas to be inundated by the progressive flooding that occurred throughout the early to middle Jurassic time. The limited thickness of the succession attest to limited accommodation, but the lack of clear subaerial unconformities suggests the area was gradually subsiding until the early Jurassic.

Provenance

The Triassic samples from Agardhbukta comprise ages that closely match their depositional age. The detrital zircon age spectrum for the Jurassic samples is broadly similar to the Triassic samples, with the exception of a sample from the uppermost part of the Kongsøya Formation. The youngest grains are Norian in age and the appearance of such grains suggest their source is volcanic since there is little time between grain crystallisation and deposition (Sharman & Malkowski, 2020). This trend is similar to what has been recorded in the Barents Sea by previous studies (Klausen et al., 2017; 2018; Line et al., 2020). Note that the youngest grain in the Flatsalen Formation is older than the youngest grain in the De Geerdalen Formation (Fig. 8), in addition to considerable overlap in detrital zircon ages this indicates that the former might be the reworked product of the latter.

The detrital zircon age signature of the Jurassic samples from Agardhbukta continue the trend from the Triassic samples below, similar to the trend recorded by Bue & Andresen (2014), but it is recognised herein that the youngest grains are not matching the depositional age of the deposits from which they have been recovered (Fig. 8). This suggest the original sediment source ceased and the young grains are sourced from reworked Triassic strata. However, in the sample from the upper part of the Kongsøya Formation, only ages older than Triassic are recorded (Fig. 8A). The influx of grains with an older provenance signature indicates that the intrabasinal highs from which the Triassic grains are reworked have been inundated by the late stages of the Kongsøya Formation, likely due to a gradual transgression, with intermittent periods of regression, filling the inverted basin. It also indicates that mature source areas are supplying sediments all the way to Svalbard in the late stages of the Lower Jurassic. The mature detrital zircon age spectrum from this sample could be derived from Greenland or sources north of Svalbard (e.g., Dörr et al., 2012), which at that time was located close to Svalbard. However, it is important to note that the similar zircon ages are also derived from Fennoscandia which bordered the Barents Sea area to the south (Klausen et al., 2018).

Detrital zircon age spectrums from samples in the Ververis well (7226/2-1) show a similar development with young grains closely matching depositional age in the Triassic, with reworked Triassic age signatures in the Lower Jurassic section. It is however worth noting that although the sample from the Tubåen Formation comprise Norian age grains, the overall character of the spectrum indicates provenance from a mature province in Fennoscandia, south of the Barents Sea. Also, the sample from the Toarcian part of the Stø Formation shows the youngest detrital zircon age yet recovered in the Jurassic succession from the Norwegian part of the Barents Sea. This demonstrates a similarity with young detrital zircon grains sourced from the east recovered by Suslova (2013) from time equivalent deposits in the Russian sector of the Barents Sea. Suggesting that these grains were also partially supplied to certain areas of the Norwegian Sector, deposited in regressive shoreface to shelf systems, despite this region being an uplifted forebulge in the early Jurassic. This sediment supply, driven predominantly by prograding shallow marine system, did not however reach far into the Norwegian Barents Sea, as there is no record of similar grains in Svalbard, or along the southern margin during this time. In the uppermost part of the Stø Formation, the mature source area to the south again becomes dominant at the well location and its central part in the basin.

The detrital zircon age spectrum from samples in the Bamse well (7124/3-1), in the southern part of the basin, show young detrital zircon age spectrum in the Triassic Snadd Formation. However, in the Norian sample (Fruholmen Formation) and onwards, the provenance signature is that of the southern, mature source areas. Klausen et al. (2018) proposed two distinct provenance areas in the southern hinterland, one characterised by Caledonian age zircons and one characterised by Archean age zircons, both comprising various amounts of grains from the Nappe Complexes found in both provenance areas. The two source areas in northern Norway and Fennoscandia have later been reaffirmed by Flowerdew et al. (2020), and it appears that the sample from 7124/3-1 consists of sediment derived from the easternmost of these two southern provenance areas. Thus, lacking grains of Caledonian age. The sample from the Fruholmen Formation differs from samples in the basin interior, by not having any young grains that closely match the maximum depositional age. This is a natural response due to the location of the well being closer to the mature source areas that became increasingly dominant relative to the eastern provenance areas, as the Norwegian part of the Barents Sea was inverted at the Triassic–Jurassic boundary.

It is important to note that the young detrital zircon grains recorded in the upper parts of the De Geerdalen Formation and its subsurface the equivalent Snadd Formation show the same trend with minimum crystallisation age closely matching the maximum depositional age. Despite this occurring at the northern and southernmost extremes in the basin (Agardhbukta and Bamse well, 7124/3-1). The relative age of the strata might be subject to more scrutiny as the De Geerdalen Formation in central Spitsbergen is dated to late Carnian based on palynological data (Rismyhr et al., 2018), whereas the Snadd Formation in Bamse (7124/3-1) is early Norian, but the detrital zircon grain with crystallisation age of 220 Ma from Agardhbukta suggest that even with an uncertainty range of 6.5 Ma the sampled outcrop interval could also be early Norian in age. Since the sampled intervals are then broadly time-equivalent, although not in the same lithological unit, there was a common, active sediment source supplying the two locations. This is in line with previous interpretations of sediment supply from eastern provenance areas during the late Triassic to early Jurassic (Klausen et al., 2014, 2017; Gilmullina et al., 2021a), but strongly contrast the proposed Taimyr source to the northeast of the basin by Fleming et al. (2016). Sediment transport from Taimyr to the southern margin of the Barents Sea would trend perpendicular to the multiple fluvial systems documented from the southwest during the Carnian (Klausen et al., 2014) and be directed away from the contemporaneous Boreal basin to the north and northwest. Naturally, this is hard to reconcile with sedimentological evidence, thus a common sediment source active in the east supplying sediment north-westward to the entire Barents Sea basin is by far the more rational explanation (Klausen et al., 2015, 2017; Gilmullina et al., 2021a), and the provenance data documented in the present study (Fig. 9) support this conclusion.

Implications for basin development during the Triassic–Jurassic transition

The stratigraphic development observed from different localities spread across the Barents Sea and Svalbard together with the detrital zircon provenance data reveal how the sediment transport changed through time and space. It also tells us which sediment source was dominant in different parts of the basin throughout the period, and in which areas there was most erosion — which in turn relates to the sediment source as reworked clastic material.

The stratigraphy investigated in eastern Spitsbergen when compared to the Barents Sea, shows the variable magnitude of uplift and erosion at the Triassic–Jurassic boundary. It seems reasonable to assume that the De Geerdalen and Flatsalen formations originally had similar development as elsewhere in the western part of the Svalbard Platform, Svalbard and the Barents Sea, and that many hundreds of meters of strata is missing below the Jurassic unconformity (Müller et al., 2019; Gilmullina et al., 2021b). This erosion is the source for sediments with young detrital zircon age spectrum in the Jurassic succession. Although this reworking is associated with an increase in mineralogical maturity (Line et al., 2020) and better reservoir properties relative to the underlying Triassic sediments, it is worth noting that these sediments were originally relatively immature and clay rich. Thus, constitute an inferior mineralogical composition relative to arenites from mature source areas around the basin (e.g., Ryseth, 2014).

In the middle part of the basin, the Norian succession also seems to be partly eroded below the Tubåen Formation (Fig. 5) and does not show a well-developed fluvial succession which characterise the formation along the western margin of basin (Klausen et al., 2019). The differential uplift and erosion across the basin attest to a complex forebulge development and sediment dispersal pattern in the Norwegian parts of the Barents Sea in response to NZFTB (Müller et al., 2019). Early Jurassic erosion as far down into the Triassic as the Snadd and De Geerdalen formations as recorded in Agardhbukta in the present study (Fig. 2D). An observation that is also made in the western parts of the Norwegian Barents Sea and around local highs, such as the Fedynsky High (Klausen et al., 2017).

Reworked Triassic sediments were deposited along with sediments supplied from mature source areas to the south while the basin was uplifted and eroded in the Jurassic. There is a clear spatial and temporal component to the magnitude of mature sediments deposited along with reworked immature material: the closer to the mature source area, naturally the earlier the mature sediment source becomes dominant (as shown with the comparison of samples from the Bamse well (7124/3-1), to the Agardhbukta outcrop). The temporal component, with less young grains in the upper part of the Lower Jurassic succession, suggest; 1) that the source for young detrital zircon grains becomes inundated and 2) that sediments from mature source areas to the south require time to prograde to the distal parts of the basin. Given that the latter factor is partially controlling the detrital zircon age spectrum, it is evident that the source areas along the southern margin of the basin might be more important than potential sediment sources west of Svalbard. If there was a source for mature sediments immediately west of Svalbard at the time of uplift and erosion, it would be natural to have influx of sediments from this provenance in the earliest Jurassic, similar to the development along the southern margin of the basin (e.g., the Bamse well 7124/3-1, Figs. 6 & 7).

The seaway between Greenland and the Barents Sea, which was tentatively placed east of Svalbard in a regional study of the Stø Formation based mostly on subsurface well data (Klausen et al., 2018) should be updated in light of the observed provenance trend, interpreted herein. Literature sources were originally used to constrain the facies distribution in Svalbard (Vigran et al., 2014; Lord et al., 2017; Rismyhr et al., 2018; Olaussen et al., 2018) and the seaway was tentatively placed southeast of Svalbard in relation to these observations (Klausen et al., 2018).

In Agardhbukta, the present study shows that it is only in the later stages of the Kongsøya Formation that Caledonian and Svecofennian grains become prominent in the detrital zircon age spectrum. The oldest sample from the Svenskøya Formation carry some Proterozoic grains that might be linked to such a source, but these signatures are also well documented from Fennoscandia, contributing to the overall age spectrum observed in Triassic strata throughout the basin (e.g., Fig. 9H). Thus, there is a lack of a clear transition to a potential sediment source in the west, similar to that observed along the southern margin of the basin in the Bamse well (7124/3-1, Fig. 9A–C). Instead, a rather pronounced latency in the arrival of non-reworked sediments is evident, suggest that it was primarily the southern margin of the basin that supplied sediments to areas as far north as Svalbard in the Middle Jurassic. With this in mind it is likely that the western source was negligible if at all contributing. This also suggests that the seaway between the Barents Sea and Greenland was located further west of Svalbard, as opposed to the east as hypothesised in previous studies (e.g., Klausen et al., 2018), with Svalbard Archipelago being connected with the sediment system in the Barents Sea region throughout the Triassic and early to middle Jurassic.

Samples from the middle part of the Stø Formation (Toarcian) in the Ververis well (7226/2-1) feature the youngest grains recorded in the Norwegian Barents Sea (Fig. 9E). At the time of deposition, the Norwegian part of the Barents Sea has been interpreted as being completely cut-off from the eastern part by the forebulge uplift developing west of the foreland basin for NZFTB (Klausen et al., 2017; Müller et al., 2019). Although there are relatively few grains analysed, the young grains in Ververis (7226/2-1), with crystallisation age close to depositional age, indicates that sediments are supplied from volcanically active source areas in the east as late as in the Toarcian, while most of the Norwegian Barents Sea was uplifted and eroded (e.g., Müller et al., 2019). These ages are similar to ages recorded from time-equivalent strata in the Shtokman well in the Russian part of the Barents Sea (Suslova, 2013). Their presence in the Norwegian Barents Sea, as recorded for the first time in this study, both: 1) support the existence of a young source area being active east of the Barents Sea close to depositional age for the formations deposited here as late as the earliest Jurassic (?Hettangian and Toarcian), and 2) implies that supply from the east persisted into the Jurassic with intermittent hiatuses (inferred from the absence of the Sinermurian to Pliensbachian Nordmela Formation) while the Norwegian Barents Sea in general formed an uplifted forebulge distal to the NZFTB (Müller et al., 2019).

Conclusions

Details of the pronounced Triassic–Jurassic unconformity in Svalbard and the Barents Sea has been investigated in both core and outcrop, aided by provenance data and palynology, to reveal the different degrees of erosion and sediment transport that characterise the interval in proximal, medial and distal parts of the basin relative to mainland Norway. Differential uplift and erosion likely reflect the different positions each area occupied within the basin relative to the forebulge uplift generated in front of the Novaya Zemlya Fold and Thrust Belt. This differential uplift affected rates of erosion and areas of deposition in the basin, with effect on the distribution of sediment more prone to form quality reservoir rocks. Several hundreds of meters of sediments seem to have been eroded in eastern Spitsbergen, and the area experienced a pronounced hiatus while sediments were deposited on the Bjarmeland and Finnmark platforms. The basin was gradually transgressed, with flooding and deposition of marine sediments occurring earlier in eastern Spitsbergen than on the Finnmark Platform in the south.

The youngest detrital zircon ages recorded in the samples closely follows the maximum depositional age of the samples they are recorded from, until the Fruholmen Formation. This shows that there is a provenance area active to the east of the basin well into the Norian. The fact that Norian age zircons are found in the Hammerfest Basin as well as Western parts of the Svalbard Archipelago shows that the active sediment source in the east was not unique to one restricted part of the basin, but rather uniformly distributed across the basin in the late Triassic. This has important implications for constraining the sediment supply fairways to the basin, and our results support conclusions in recent sedimentological studies that a common sediment source in the east to southeast supply the entire Greater Barents Sea basin uniformly during the late Triassic. The young Jurassic aged grains recorded in the Stø Formation however show that the easternmost part of the Norwegian Barents Sea is not completely cut off from the Russian part in the Jurassic.

Samples with detrital zircon age spectrums associated with more mature sediment sources are typically found in the youngest samples, or in samples geographically closer to the southern source. This suggests both that the reworking of Triassic sedimentary rocks ceased with their inundation during gradual transgression and that the sediments from the southern provenance area needed time to prograde the basin. The further from the hinterland, the more reworked Triassic material dominate the age spectrum. This development has implications for how to assess reservoir quality across the Barents Sea: reworking of immature sediments is more important away from the mature southern source areas. The amount of uplift and erosion seems to be similar and heterogenous across the basin, but in general it seems the De Geerdalen Formation and its time-equivalent Snadd Formation is eroded mainly in the west and northwest, although local variations are pronounced even within a restricted geographical area such as Svalbard. It also suggests that the source for mature sediments in Svalbard is located along the southern margin of the Barents Sea as opposed to Greenland.

Acknowledgements. We appreciate support from the Research Council of Norway through the PETROMAKS2 ISBAR project, grant number 267689. Support from Eni Norge (now: Vår Energi), which facilitated the field work, is much appreciated. Siv Hjorth Dundas, Martina Suppersberger Hamre, Irina Maria Dumitru, Leif-Erik Rydland Pedersen and Rolf-Birger Pedersen are thanked for help with the detrital zircon analysis, and Miquel Poyatos-Moré for valuable discussions in the field. Mai Britt E. Mørk and Gareth Steven Lord are gratefully thanked for their thoughtful comments and suggestions which improved the quality of the manuscript.

References

Bergan, M. & Knarud, R. 1993: Apparent changes in clastic mineralogy of the Triassic–Jurassic succession, Norwegian Barents Sea: possible implications for palaeodrainage and subsidence. *Norwegian Petroleum Society Special Publications 2*, 481–493. https://doi.org/10.1016/B978-0-444-88943-0.50034-4.

Bue, E.P. & Andresen, A. 2014: Constraining depositional models in the Barents Sea region using detrital zircon U–Pb data from Mesozoic sediments in Svalbard. *Geological Society, London, Special Publications 386,* 261–279. https://doi.org/10.1144/SP386.14.

Buiter, S.J. & Torsvik, T.H. 2007: Horizontal movements in the eastern Barents Sea constrained by numerical models and plate reconstructions. *Geophysical Journal International 171*, 1376–1389. https://doi.org/10.1111/j.1365-246X.2007.03595.x.

Dimakis, P., Braathen, B.I., Faleide, J.I., Elverhøi, A. & Gudlaugsson, S.T. 1998: Cenozoic erosion and the preglacial uplift of the Svalbard–Barents Sea region. *Tectonophysics 300*, 311–327. https://doi.org/10.1016/S0040-1951(98)00245-5.

Dörr, N., Lisker, F., Clift, P.D., Carter, A., Gee, D.G., Tebenkov, A.M. & Spiegel, C. 2012: Late Mesozoic–Cenozoic exhumation history of northern Svalbard and its regional significance: Constraints from apatite fission track analysis. *Tectonophysics 514,* 81–92. https://doi.org/10.1016/j.tecto.2011.10.007.

Embry, A. 2011: Petroleum prospectivity of the Triassic–Jurassic succession of Sverdrup Basin, Canadian Arctic Archipelago. *Geological Society, London, Memoirs 35,* 545–558. https://doi.org/10.1144/M35.36.

Faleide, J.I., Vågnes, E. & Gudlaugsson, S.T. 1993: Late Mesozoic-Cenozoic evolution of the south-western Barents Sea in a regional rift-shear tectonic setting. *Marine and Petroleum Geology 10,* 186–214. https://doi.org/10.1016/0264-8172(93)90104-Z.

Faleide, J.I., Pease, V., Curtis, M., Klitzke, P., Minakov, A., Scheck-Wenderoth, M., Kostyuchenko, S. & Zayonchek, A. 2018: Tectonic implications of the lithospheric structure across the Barents and Kara shelves. *Geological Society, London, Special Publications 460,* 285–314. https://doi.org/10.1144/SP460.18.

Fleming, E.J., Flowerdew, M.J., Smyth, H.R., Scott, R.A., Morton, A.C., Omma, J.E., Frei, D. & Whitehouse, M.J. 2016: Provenance of Triassic sandstones on the southwest Barents Shelf and the implication for sediment dispersal patterns in northwest Pangaea. *Marine and Petroleum Geology 78*, 516–535. https://doi.org/10.1016/j.marpetgeo.2016.10.005.

Flowerdew, M.J., Fleming, E.J., Morton, A.C., Frei, D., Chew, D.M., & Daly, J.S. 2020: Assessing mineral fertility and bias in sedimentary provenance studies: examples from the Barents Shelf. *Geological Society, London, Special Publications 484*, 255–274. https://doi.org/10.1144/SP484.11.

Gilmullina, A., Klausen, T.G., Paterson, N.W., Suslova, A. & Eide, C.H. 2021a: Regional correlation and seismic stratigraphy of Triassic Strata in the Greater Barents Sea: Implications for sediment transport in Arctic basins. *Basin Research 33,* 1546–1579. https://doi.org/10.1111/bre.12526.

Gilmullina, A., Klausen, T.G., Doré, A., Rossi, V., Suslova, A. & Eide, C.H. 2021b: Linking sediment supply variations and tectonic evolution in deep-time source-to-sink systems - The Triassic Greater Barents Sea Basin. *Geological Society of America Bulletin*, B36090. https://doi.org/10.1130/B36090.1.

Gjelberg, J., Dreyer, T., Hoie, A., Tjelland, T. & Lilleng, T. 1987: Late Triassic to Mid-Jurassic sandbody development on the Barents and Mid-Norwegian shelf. *Conference on petroleum geology of North West Europe. 3,* 1105–1129.

Glørstad-Clark, E., Faleide, J.I., Lundschien, B.A. & Nystuen, J.P. 2010: Triassic seismic sequence stratigraphy and paleogeography of the western Barents Sea area. *Marine and Petroleum geology 27*, 1448–1475. https://doi.org/10.1016/j.marpetgeo.2010.02.008.

Haile, B.G., Klausen, T.G., Czarniecka, U., Xi, K., Jahren, J. & Hellevang, H. 2018: How are diagenesis and reservoir quality linked to depositional facies? A deltaic succession, Edgeøya, Svalbard. *Marine and Petroleum Geology 92*, 519–546. https://doi.org/10.1016/j.marpetgeo.2017.11.019.

Henriksen, E., Ryseth, A.E., Larssen, G.B., Heide, T., Rønning, K., Sollid, K. & Stoupakova, A.V. 2011: Tectonostratigraphy of the greater Barents Sea: implications for petroleum systems. Geological Society, *London, Memoirs 35*, 163–195. https://doi.org/10.1144/M35.10.

Hounslow, M. W., Harris, S. E., Karloukovski, V. & Mørk, A. 2022: Geomagnetic polarity and carbon isotopic stratigraphic assessment of the late Carnian -earliest Norian in Svalbard: evidence for a major hiatus and improved Boreal to Tethyan correlation. *Norwegian Journal of Geology 102,* 202204. https://dx.doi.org/10.17850/njg102-1-4.

Høy, T. & Lundschien, B.A. 2011: Triassic deltaic sequences in the northern Barents Sea. *Geological Society, London, Memoirs 35*, 249–260. https://doi.org/10.1144/M35.15.

Khudoley, A.K., Sobolev, N.N., Petrov, E.O., Ershova, V.B., Makariev, A.A., Makarieva, E.V., Gaina, C. & Sobolev, P.O. 2019: A reconnaissance provenance study of Triassic–Jurassic clastic rocks of the Russian Barents Sea. *Geologiska Föreningen i Stockholm Förhandlingar 141,* 263–271. https://doi.org/10.1080/11035897.2019.1621372.

Klausen, T.G. & Mørk, A. 2014: The Upper Triassic paralic deposits of the De Geerdalen Formation on Hopen: outcrop analog to the subsurface Snadd Formation in the Barents Sea. *American Association of Petroleum Geologists Bulletin 98*, 1911–1941. https://doi.org/10.1306/02191413064.

Klausen, T.G., Ryseth, A.E., Helland-Hansen, W., Gawthorpe, R. & Laursen, I. 2014: Spatial and temporal changes in geometries of fluvial channel bodies from the Triassic Snadd Formation of offshore Norway. *Journal of Sedimentary Research 84,* 567–585. https://doi.org/10.2110/jsr.2014.47.

Klausen, T.G., Ryseth, A.E., Helland-Hansen, W., Gawthorpe, R. & Laursen, I. 2015: Regional development and sequence stratigraphy of the Middle to Late Triassic Snadd Formation, Norwegian Barents Sea. *Marine and Petroleum Geology 62,* 102–122. https://doi.org/10.1016/j.marpetgeo.2015.02.004.

Klausen, T.G., Müller, R., Slama, J. & Helland-Hansen, W. 2017: Evidence for Late Triassic provenance areas and Early Jurassic sediment supply turnover in the Barents Sea Basin of northern Pangea. *Lithosphere 9,* 14–28. https://doi.org/10.1130/L556.1.

Klausen, T.G., Müller, R., Sláma, J., Olaussen, S., Rismyhr, B. & Helland-Hansen, W. 2018: Depositional history of a condensed shallow marine reservoir succession: stratigraphy and detrital zircon geochronology of the Jurassic Stø Formation, Barents Sea. Journal of the Geological Society 175, 130–145. https://doi.org/10.1144/jgs2017-024.

Klausen, T.G., Müller, R., Poyatos-Moré, M., Olaussen, S. & Stueland, E. 2019: Tectonic, provenance and sedimentological controls on reservoir characteristics in the Upper Triassic–Middle Jurassic Realgrunnen Subgroup, SW Barents Sea. *Geological Society, London, Special Publications 495.* https://doi.org/10.1144/SP495-2018-165.

Lasabuda, A.P., Johansen, N.S., Laberg, J.S., Faleide, J.I., Senger, K., Rydningen, T.A., Patton, H., Knutsen, S.M. & Hanssen, A. 2021: Cenozoic uplift and erosion on the Norwegian Barents Shelf–A review. *Earth-Science Reviews 217,* 103609. https://doi.org/10.1016/j.earscirev.2021.103609.

Line, L.H., Müller, R., Klausen, T.G., Jahren, J. & Hellevang, H. 2020: Distinct petrographic responses to basin reorganization across the Triassic–Jurassic boundary in the southwestern Barents Sea. *Basin Research 32,* 1463–1484. https://doi.org/10.1111/bre.12437.

Lord, G., Solvi, K.H., Ask, M., Mørk, A., Hounslow, M. & Paterson, N.W. 2014: The Hopen member: a new member of the Triassic de Geerdalen formation. *Norwegian petroleum directorate Bulletin 11*, 81–96.

Lord, G.S., Johansen, S.K., Støen, S.J. & Mørk, A. 2017: Facies development of the Upper Triassic succession on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard. *Norwegian Journal of Geology 97*, 33–62. https://doi.org/10.17850/njg97-1-03.

Lord, G.S., Mørk, M.B.E., Mørk, A. & Olaussen, S. 2019: Sedimentology and petrography of the Svenskøya Formation on Hopen, Svalbard: an analogue to sandstone reservoirs in the Realgrunnen Subgroup. *Polar Research 38,* 3523. https://doi.org/10.33265/polar.v38.3523.

Ludwig, K.R. 2008: Isoplot 3.7: Berkeley Geochronology Center Special Publication.

Müller, R., Klausen, T.G., Faleide, J.I., Olaussen, S., Eide, C.H. & Suslova, A. 2019: Linking regional unconformities in the Barents Sea to compression-induced forebulge uplift at the Triassic-Jurassic transition. *Tectonophysics 765*, 35–51. https://doi.org/10.1016/j.tecto.2019.04.006.

Mørk, M.B.E. 1999: Compositional variations and provenance of Triassic sandstones from the Barents Shelf. *Journal of Sedimentary Research 69*, 690–710. https://doi.org/10.2110/jsr.69.690.

Mørk, M.B.E. 2013: Diagenesis and quartz cement distribution of low-permeability Upper Triassic–Middle Jurassic reservoir sandstones, Longyearbyen CO2 lab well site in Svalbard, Norway. *American Association of Petroleum Geologists bulletin 97,* 577–596. https://doi.org/10.1306/10031211193.

Nøttvedt, A., Cecchi, M., Gjelberg, J.G., Kristensen, S.E., Lønøy, A., Rasmussen, A., Rasmussen, E., Skott, P.H. & Van Veen, P.M. 1993: Svalbard-Barents Sea correlation: a short review. *Norwegian Petroleum Society Special Publications 2,* 363–375. https://doi.org/10.1016/B978-0-444-88943-0.50027-7.

Olaussen, S., Dalland, A., Gloppen, T.G. & Johannessen, E. 1984: Depositional environment and diagenesis of Jurassic reservoir sandstones in the eastern part of Troms I area. *In* Spencer, A.M. (ed.): *Petroleum Geology of the North European Margin*, Springer, Dordrecht, pp. 61–79. https://doi.org/10.1007/978-94-009-5626-1_6.

Olaussen, S., Larssen, G.B., Helland-Hansen, W., Johannessen, E.P., Nøttvedt, A., Riis, F., Rismyhr, B., Smelror, M. & Worsley, D. 2018: Mesozoic strata of Kong Karls Land, Svalbard, Norway; a link to the northern Barents Sea basins and platforms. *Norwegian Journal of Geology 98,* 1–69. https://doi.org/10.17850/njg98-4-06.

Omma, J.E. 2009: *Provenance of Late Paleozoic and Mesozoic sediment to key Arctic basins: implications for the opening of the Arctic Ocean*. PhD thesis, University of Cambridge, 222 pp.

Riis, F., Lundschien, B.A., Høy, T., Mørk, A. & Mørk, M.B.E. 2008: Evolution of the Triassic shelf in the northern Barents Sea region. *Polar Research 27,* 318–338. https://doi.org/10.1111/j.1751-8369.2008.00086.x.

Rismyhr, B., Bjærke, T., Olaussen, S., Mulrooney, M.J. & Senger, K. 2018: Facies, palynostratigraphy and sequence stratigraphy of the Wilhelmøya Subgroup (Upper Triassic–Middle Jurassic) in western central Spitsbergen, Svalbard. *Norwegian Journal of Geology 99*, 35–64. https://doi.org/10.17850/njg001.

Ritzmann, O. & Faleide, J.I. 2009: The crust and mantle lithosphere in the Barents Sea/Kara Sea region. *Tectonophysics 470,* 89–104. https://doi.org/10.1016/j.tecto.2008.06.018.

Rogov, Mikhail A. & Lutikov, Oleg A. 2022: A Dactylioceras – Meleagrinella (Clathrolima) assemblage from the Agardhbukta (eastern coast of Spitsbergen): a first in situ Toarcian molluscan occurrence from Svalbard providing interregional correlation. Norwegian Journal of Geology 102. https://dx.doi.org/10.17850/njg102-1-2

Ryseth, A. 2014: Sedimentation at the Jurassic–Triassic boundary, south-west Barents Sea: indication of climate change. *International Association of Sedimentologists Special Publication 46*, 187–214. https://doi.org/10.1002/9781118920435.ch9.

Sharman, G.R. & Malkowski, M.A. 2020: Needles in a haystack: Detrital zircon UPb ages and the maximum depositional age of modern global sediment. *Earth-Science Reviews 203,* 103109. https://doi.org/10.1016/j.earscirev.2020.103109.

Steel, R.J. & Worsley, D. 1984: Svalbard's post-Caledonian strata—an atlas of sedimentational patterns and palaeogeographic evolution. *In* Spencer, A.M. (ed.): *Petroleum geology of the North European margin*, Springer, Dordrecht, pp. 109–135. https://doi.org/10.1007/978-94-009-5626-1_9.

Suslova, A.A. 2013: Seismostratigraphic complex of Jurassic deposits, Barents Sea shelf. *Moscow University geology bulletin 68*, 207–209. https://doi.org/10.3103/S0145875213030071.

Vigran, J.O., Mangerud, G., Mørk, A., Worsley, D. & Hochuli, P.A. 2014: *Palynology and geology of the Triassic succession of Svalbard and the Barents Sea.* Geological Survey of Norway Special Publication 14, 270 pp.

Worsley, D. 1973: The Wilhelmoya Formation – a new lithostratigraphical unit from the Mesozoic of eastern Svalbard. *Norsk Polarinstitutt Årbok 1971*, 7–16.

Worsley, D. 2008: The post-Caledonian development of Svalbard and the western Barents Sea. *Polar research 27,* 298–317. https://doi.org/10.1111/j.1751-8369.2008.00085.x.

Zhang, X., Pease, V., Carter, A. & Scott, R. 2018: Reconstructing Palaeozoic and Mesozoic tectonic evolution of Novaya Zemlya: combing geochronology and thermochronology. *Geological Society, London, Special Publications 460,* 335–353. https://doi.org/10.1144/SP460.13.