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Tectonostratigraphic development of the Upper Triassic to Middle Jurassic in the Hoop Area, Barents Sea: Implications for understanding ultra-condensed reservoir units

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ABSTRACT

The most prolific reservoir intervals in the Barents Sea are found in the Upper Triassic to Middle Jurassic Realgrunnen Subgroup, deposited during a major change in the structural evolution of the basin which greatly influenced its development and distribution. The effects are evident in one of the petroleum provinces in the SW Barents Sea, the Hoop Area. Due to the condensed nature of the succession, the tectonostratigraphic evolution has been enigmatic.

We use a range of different methods and dataset, including high-resolution P-Cable seismic to determine the tectono-stratigraphic evolution of the succession. Results are important for exploration and production in the Hoop Area and beyond, but also for a broader understanding of how ultra-condensed successions might evolve during long periods of non-deposition and short bursts of deposition.

Seven major phases of deposition and non-deposition/erosion are defined. Stage 1 represents fluvio-deltaic deposition in the Fruholmen Formation (Norian), followed by Stage 2 with significant truncation and non-deposition, lasting up to 35 million years. Deposition resumed with the shallow marine to fluvial Nordmela and Stø formations (Pliensbachian to Bajocian), which both encapsule long periods of erosion and non-deposition (stage 3–6). Stage 7 is represented by transgression and shelf deposition in the Fuglen Formation (Bathonian).

The change from a high-accommodation setting with continuous and relatively high rate of accumulation in the Triassic, to a low-accommodation setting with episodic deposition and extensive sediment cannibalization in the Jurassic, resulted in cleaner sandstones with better reservoir properties. The low-accommodation setting also enabled coarse-graded detritus from hinterlands in Fennoscandia to prograde into distal part of the basin and more amalgamation of the sands during the Jurassic. Adversely, the low accommodation setting also caused a fragmented pattern of deposition and preservation that needs to be carefully considered in subsurface datasets, often with limited resolution.

1. Introduction

The Upper Triassic to Middle Jurassic Realgrunnen Subgroup is a prolific, sandstone-dominated reservoir unit that is widespread throughout the Southwest Barents Sea Basin (Olaussen et al., 1984; Gjelberg et al., 1987; Henriksen et al., 2011). The sedimentary packages were deposited when the Barents Sea experienced a major change in depositional style at the transition from the Triassic to the Jurassic

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(Bergan and Knarud, 1993; Worsley, 2008; Ryseth, 2014; Klausen et al., 2017; Müller et al., 2019). A shallow, rapid subsiding epicontinental basin that characterized the area in the Triassic was inverted during the transition to the Jurassic and resulted in a regional low-accommodation setting with local uplift, erosion and non-deposition (Klausen et al., 2017; Müller et al., 2019). This transition from a high to a low accommodation had a major impact on the basin infill dynamics and the reservoir development, but remain enigmatic due to the condensed nature of the succession.

The temporal and spatial evolution of sedimentary basins are often obscured by subtle but important gaps in the rock record (Sadler, 1981, 1999; Miall, 2015), and this is especially the case for condensed strata such as the Realgrunnen Subgroup. The chance of preservation is small, and the stratigraphic records are better viewed as “frozen accidents” of accumulation. Commonly, only a fraction of time is represented in the stratigraphic record (Crampton et al., 2006; Miall, 2015). In subsurface datasets it is complicated to identify unconformities and important shifts in deposition. The low resolution of conventional seismic and absence of wells often obscures our understanding of the stratigraphic units fragmentary development in the subsurface.

In this study we have used high-quality conventional subsurface datasets, including 2D and 3D seismic, well log and core data in addition to unique high-frequency P-Cable 3D seismic in a cross-disciplinary effort to understand the controlling factors on reservoir distribution and quality within the condensed Upper Triassic to Middle Jurassic Realgrunnen Subgroup in the Hoop Area. To do so, the present study aims to: 1) describe the tectonostratigraphic development of the Upper Triassic to Middle Jurassic succession, 2) evaluate the succession in light of changes in the source to sink dynamics and basin subsidence, and 3) while many studies have emphasized the importance of diagenetic evolution, climate and sedimentary processes (Bjørlykke and Jahren, 2012), this study will investigate how different phases of erosion/non-deposition and accumulation in low accommodation settings influence the petrographic character of the sedimentary succession and their reservoir quality.

1.1. Regional framework

The Barents Sea has undergone several major changes in the basin infill history related to major tectonic events which are characterized by important sequence boundary surfaces. One of these surfaces occur at the Permian-Triassic boundary with a shift from mainly aggrading carbonate or silica deposits to large scale prograding siliciclastic wedges in the Triassic. The Triassic systems are primarily sourced from the

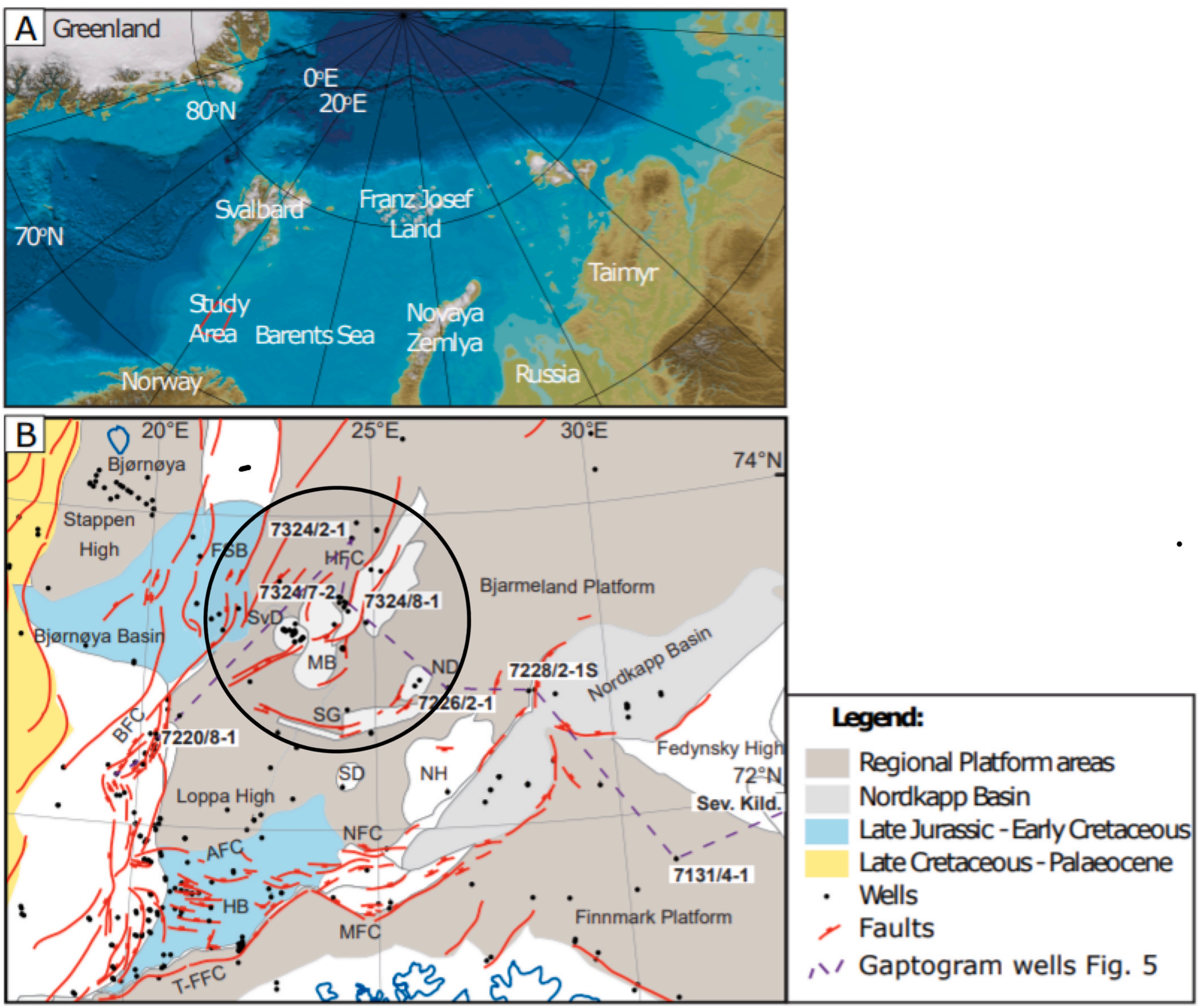

Fig. 1. Basemap showing wells and seismic of the Southwestern Barents Sea and the location of the Greater Hoop Area is marked by the ring.

Uralides and Fennoscandia, which prograded into a subsiding Barents Sea basin (Riis et al., 2008; Høy and Lundschien, 2011; Gilmullina et al., 2021; Klausen et al., 2022 in press). Basin fill is characterized by a series normal regressive delta systems separated by intermittent periods of transgression (van Yperen et al., 2020; Skjold et al., 1998; Glørstad-Clark et al., 2010; Klausen et al., 2015; Gilmullina et al., 2021) throughout the Induan to Early Norian which consists of the Havert, Klappmyss, Kobbe and Snadd formations (Fig. 1).

The Realgrunnen Subgroup is subdivided from below; the Fruholmen, Tubåen, Nordmela and Stø formations (Fig. 2). The lithostratigraphic boundaries are clearly defined by regionally correlative surfaces in the Southwestern Barents Sea (Henriksen et al., 2011). One of these surfaces are seen at the base of the Fruholmen Formation which is a prominent and mappable seismic reflector in the Barents Sea. At the onshore equivalent in Svalbard, the base of Flatsalen Formation is as well easily picked up in outcrops (Lord et al., 2019). The base of Fruholmen Formation coincides with the pan Arctic Norian Flooding (Embry, 1997).

The lowermost part of the Norian to Rhaetian Fruholmen Formation is subdivided into three members, from below: the prodeltaic to offshore marine mudstones of the Akkar Member, followed by the fluvio-deltaic sandstones and floodplain/tidal flat mudstones deposits of the Reke Member and finally the heterolithic Krabbe Member, deposited within a deltaic depositional environment (Fig. 2) (Gjelberg et al., 1987; Klausen et al., 2019; Mendoza et al., 2019).

During the Late Triassic to Early Jurassic, large areas of the Barents Sea including Spitsbergen were uplifted (Müller et al., 2019; Olaussen et al., 2018; Smelror et al., 2009), and the underlying Fruholmen Formation and older Triassic sediments were eroded (e.g. Hoop Area, Fedynsky High, Bjarmeland Platform). The boundary between the Fruholmen and the overlying formations is diachronous and characterized by a subaerial unconformity. Fluvial incisions are seen between the Fruholmen and Tubåen formations in the Hammerfest Basin (Gjelberg et al., 1987). However, most of the platform areas and internal highs on the Barents Shelf were mainly denudated with a few exceptions with thin remnants in parts of the Bjarmeland Platform.

While most of the Barents Shelf was denudated, the Tubåen Formation (late Rhaetian-Hettangian) was deposited mainly within the Tromsø, Hammerfest and Nordkapp basins (Klausen et al., 2019). Deposition took place within fluvial channel systems and estuaries. The Tubåen Formation is also present as a thin unit in parts of the Bjarmeland Platform. A prominent flooding surface on top of the Tubåen Formation, led to the deposition of tidally influenced deltas and coastal plains of the Sinemurian-Pliensbachian Nordmela Formation (Olaussen et al., 1984; Gjelberg et al., 1987; Klausen et al., 2019). The Nordmela Formation is only partly present on the Bjarmeland Platform, while it is represented by thick units in other areas of the SW Barents Sea (Olaussen et al., 1984; Gjelberg et al., 1987). The late Pliensbachian to Bajocian Stø Formation is present in almost all the wells in the Barents Sea, which primarily consists of nearshore and inner shelf facies. Multiple hiatuses are observed in this interval, implying a complex interplay between tectonics and relative sea level changes. Particularly on platform areas such as the Bjarmeland platform, the rate of subsidence was low, which resulted in the highly amalgamated and condensed sandstones of the

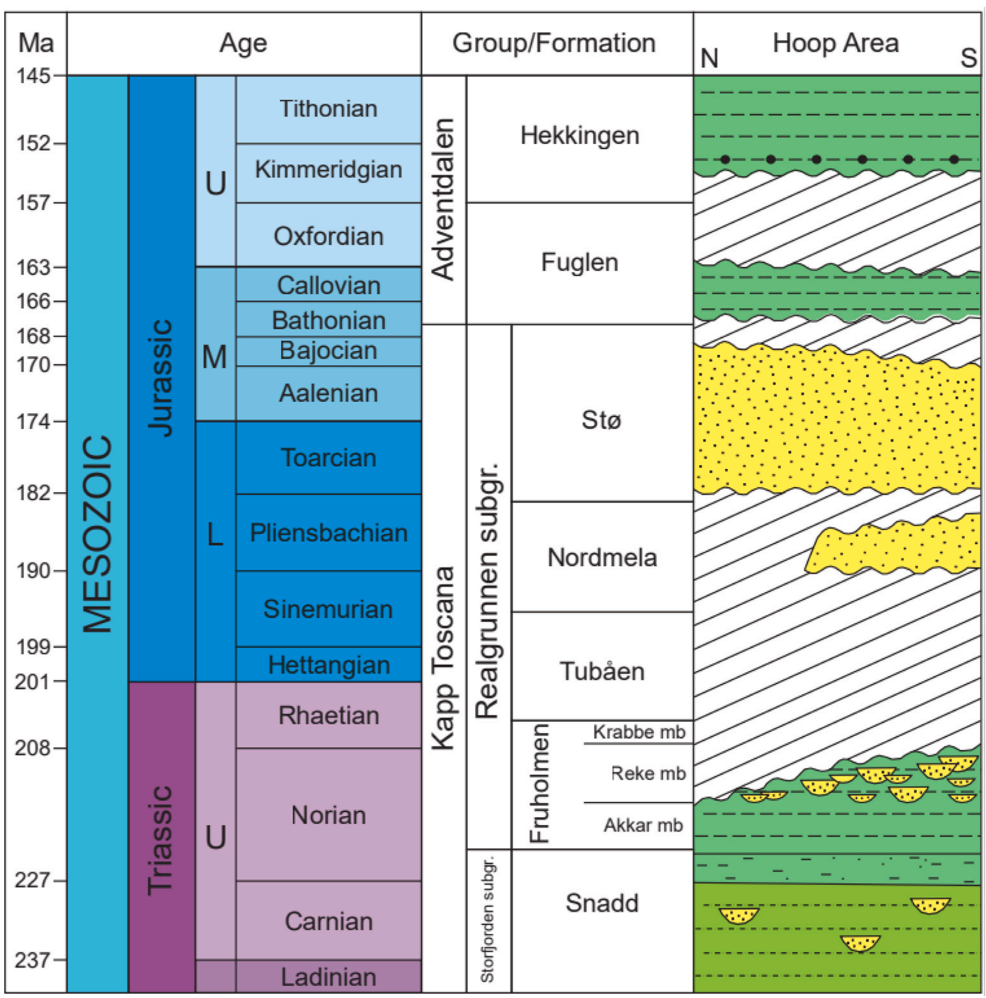

Fig. 2. Stratigraphic column for the Triassic and the Jurassic succession in the Barents Sea.

Lower to Middle Jurassic succession (Ryseth, 2014; Müller et al., 2019).

The initiation of the extensional phase of the Northeast Atlantic rift system is represented by the regional unconformity between the Stø and Fuglen formations in the Bajocian/early Bathonian (Faleide et al., 1993). The Barents Sea was flooded, and the silty mudstone unit of the Bathonian to Callovian Fuglen Formation was deposited, which was later followed by the prolific oil-prone organic rich mudstone of the Oxfordian to Berriasian Hekkingen Formation.

2. Data and methods

2.1. Well data

Eight exploration wells are used in this study, including 7324/8-1, 7324/8-2,7324/7-2, 7324/2-1, 73,251-1, 7324/9-1, 7324/10-1 and 7325/4-1 (Fig. 1). All available core material has been described and correlated. Biostratigraphy is used to constrain relative ages, paleoenviroment and degree of reworking of the strata in the studied wells. The age of sandstone dominated successions such as the Stø Formation is in some of the wells uncertain due to the low number of microfossils, spores and pollen typically recovered from sandstones. Sandstones are on the other hand studied for mineralogy in the various formations and are analysed by XRD-, thin section- and SEM-analysis, providing information about petrography, provenance and reworking.

2.2. Seismic data

The seismic data applied is P-Cable seismic data which includes both 2D wide-azimuth (HR14_2D_HFC and HR15_2D_BS) and 3D-data (HR14_3D) data. These high-resolution data were necessary for interpreting the most important seismic horizons within the condensed Realgrunnen Subgroup. P-Cable seismic data is characterized by short source and receiver distance and very high frequencies compared to conventional seismic data, with very high resolution (down to 1.5 m vertical resolution) above the first sea-floor multiple (Planke and Berndt, 2002). In addition, the TGS Hoop 3D survey from 2011, which is normal polarity broadband was utilized to interpret the key horizons at a more regional scale. See Faleide et al. (2019, 2021) and Corseri et al. (2018) for a more comprehensive description of the resolution and data comparison of conventional and high-resolution data in the study area.

Both the Hoop 3D and the P-Cable data are tied to synthetic seismograms generated from the wells in the area and used to tie the seismic reflectors to the stratigraphic units. Combined with the P-Cable data, well ties provide a very high-resolution regional stratigraphic framework in the Hoop Area (Fig. 3) within which four key horizons of the Upper Triassic to Jurassic interval are interpreted (Table 1). Seismic facies interpretation and horizon attribute analyses were conducted in parallel with the horizon interpretations using Petrel and SMT Kingdom suite software.

3. Results

3.1. Stratigraphy and facies of the Realgrunnen Subgroup

The Realgrunnen Subgroup in the Hoop Area comprise the Fruholmen, Nordmela and Stø formations. The Tubåen Formation is absent (Fig. 2). Results from our investigation of the succession are reported from oldest to youngest formation.

3.2. Fruholmen Formation (Norian-Rhaetian)

The Fruholmen Formation varies in thickness between 25 and 105 m in the Hoop Area (Fig. 3). The mudstone dominated Akkar Member is present in all wells, and is composed of prodeltaic, coarsening upward deposits. The overlying fluvio-deltaic Reke Member is not present in several wells, such as 7324/10-1, 7325/1-1 and 7324/2-1. In wells around the Wisting Field (e.g. 7324/8-1), the Reke Member is present with several thick intervals composed of up to 10–15 m thick tidally influenced fluvial distributary channel sandstones, interbedded with fine-grained and heterolithic tidally influenced bay deposits. The Krabbe Member is not present in any of the investigated wells (Figs. 3 and 5). The thickness of the Fruholmen Formation in the Hoop Area and the Bjarmeland Platform is considerable thinner than in the Fingerdjupet Subbasin (e.g. 7321/8-1), Hammerfest Basin and towards the

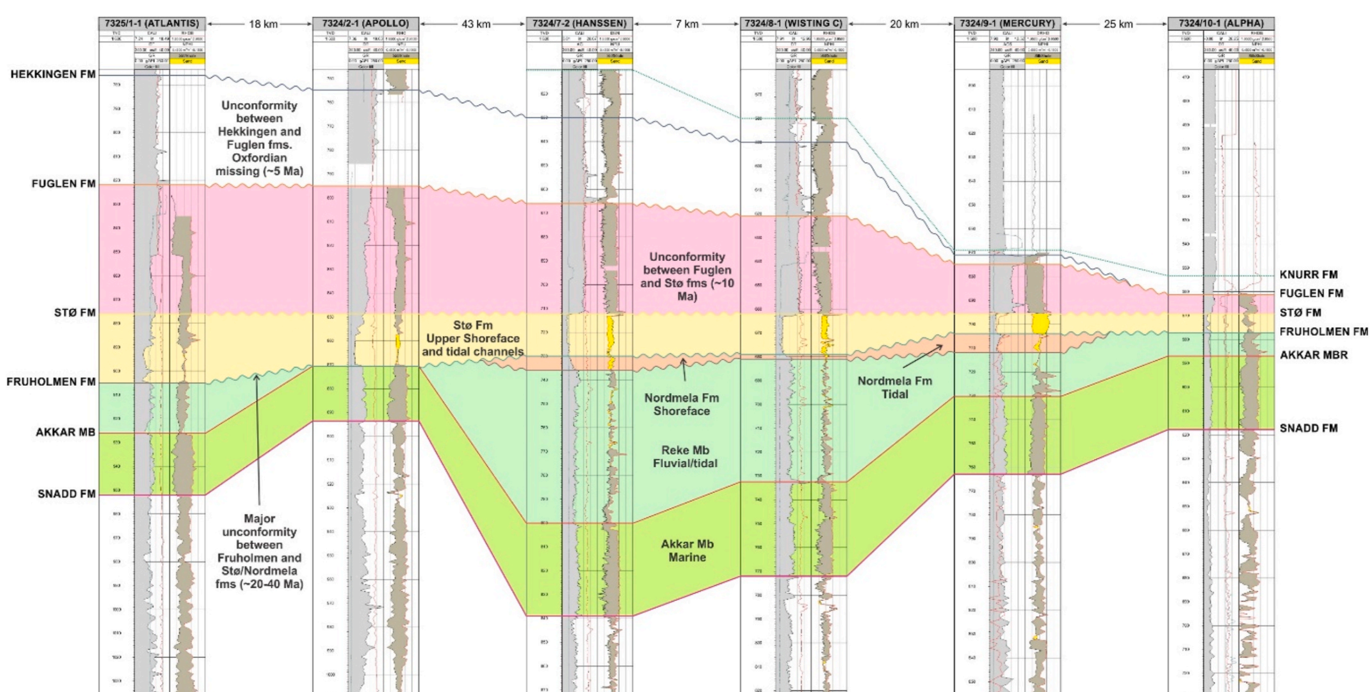

Fig. 3. Well correlation showing thickness variations of Upper Triassic to Jurassic sedimentary facies across the Greater Hoop Area. Note the major unconformities between the reservoir sequences and the large thickness variations across the area indicating active tectonics during the Late Triassic and Jurassic.

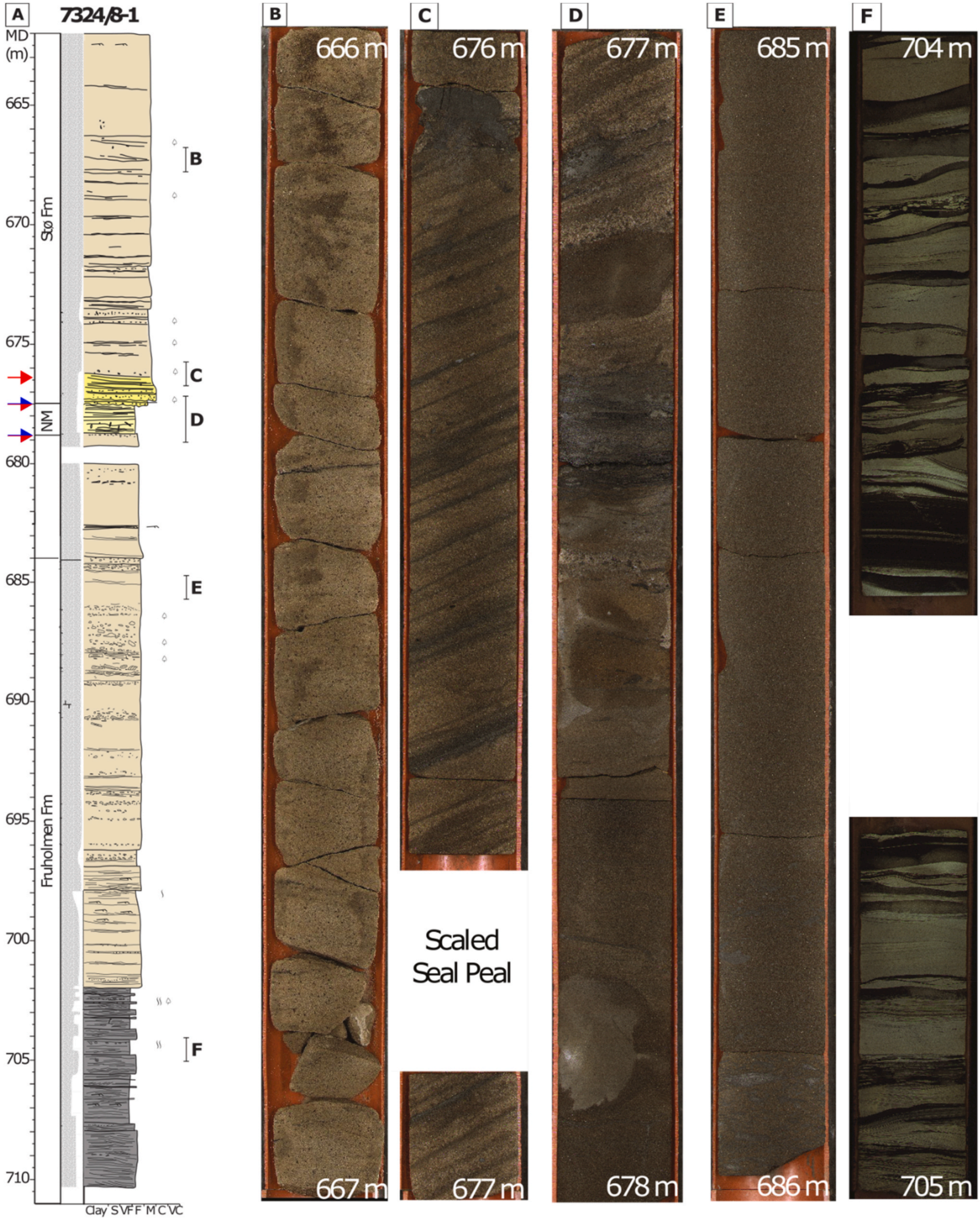

Fig. 4. A) Logged core section from well 7324/8-1 (Wisting) which shows example of typical facies for the different formations encountered in the Hoop Area: B) Fluvial. C) Tidally influence transgressive shoreface. D) Inner Shelf deposits unconformably followed by a transgressive lag. E) Fluvial deposits. F) Prodeltaic turbidites. See Klausen et al. (2018) and Klausen et al. (2019), for more details on the deposits and their facies associations. Red and blue arrows in A) indicate subaerial unconformities and flooding surfaces. Combinations are common: long periods with subaerial erosion and hiatus followed by transgressions, such surfaces are indicated by split red and blue arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
List of key seismic horizons (see appendix for more details).

Seismic horizon	Description
Basal Cretaceous Unconformity	The basal Cretaceous Unconformity (BCU) is picked as a high amplitude (trough) reflection which is continuous, regular and generally smooth.
Top Stø	Characterized by low amplitude, irregular and faulted reflection (trough).
Top Akkar	Picked as a high amplitude, regular, smooth and faulted reflection (peak).
Top Snadd	Characterized by a low amplitude, discontinuous and faulted reflection (trough).

Bjørnøyrenna Fault Zone (e.g. well 7220/8-1). For example, in the Johan Castberg Area, it can reach up to 600 m (e.g 7220/8-1).

The sandstones of the Fruholmen Formation in the Hoop Area classify mostly as sub-arkoses to lithic sub-arkoses (Fig. 6). This contrasts the lithic arenites which characterize the underlying Triassic formations (Line et al., 2020). In addition, some intervals in 7324/9-1 classify as sublitharenites. The porosity of these moderate-to well-sorted sandstones ranges from 3 to 29%, but with low to moderate permeabilities (Fig. 6). The Reke Member in the Hoop Area also holds the first documented occurrence of recycled quartz grains recorded in the basin, which has been interpreted to be derived from an extrabasinal provenance terrain in the east that consisted of consolidated and uplifted Triassic strata (Haile et al., 2020).

Zircon-analysis of the Fruholmen Formation in the Hoop Area indicate mainly a Uralide/Novaya Zemlya origin (Klausen et al., 2017), and that the Fruholmen Formation was part of a large-scale system prograding towards the NW, following the same depositional trends as the underlying Snadd Formation (Klausen et al., 2019). Zircon grains as young as 215 Ma (Early Norian age) in well 7324/8-1 suggest that the eastern provenance areas continued to contribute sediments to the western Barents Sea, although input of older material, likely derived from the Caledonides in Fennoscandia, was also recorded in these studies.

3.3. *Tubåen Formation (Rhaetian to Hettangian)*

As in the terraces and internal basin highs in southwestern Barents Sea, the Tubåen Formation is not encountered in the Hoop Area. In surrounding basins such as the Hammerfest, Tromsø and Nordkapp basins, the Tubåen Formation is composed of up to 140 m thick coarse grained multistorey fluvial channelized unit with a high sand/shale ratio (Klausen et al., 2019), (Fig. 5). In the Hoop Area, the Tubåen Formation is missing, and its coeval hiatus represent a considerable gap in the rock record.

3.4. *Nordmela Formation (Sinemurian to Pliensbachian)*

The Nordmela Formation is absent or only seen as thin (1–7 m) unit unconformably overlying the Norian Fruholmen Formation in wells 7324/7-2, 7324/8-1, 7324/9-1 and 7325/4-1 in the Hoop Area

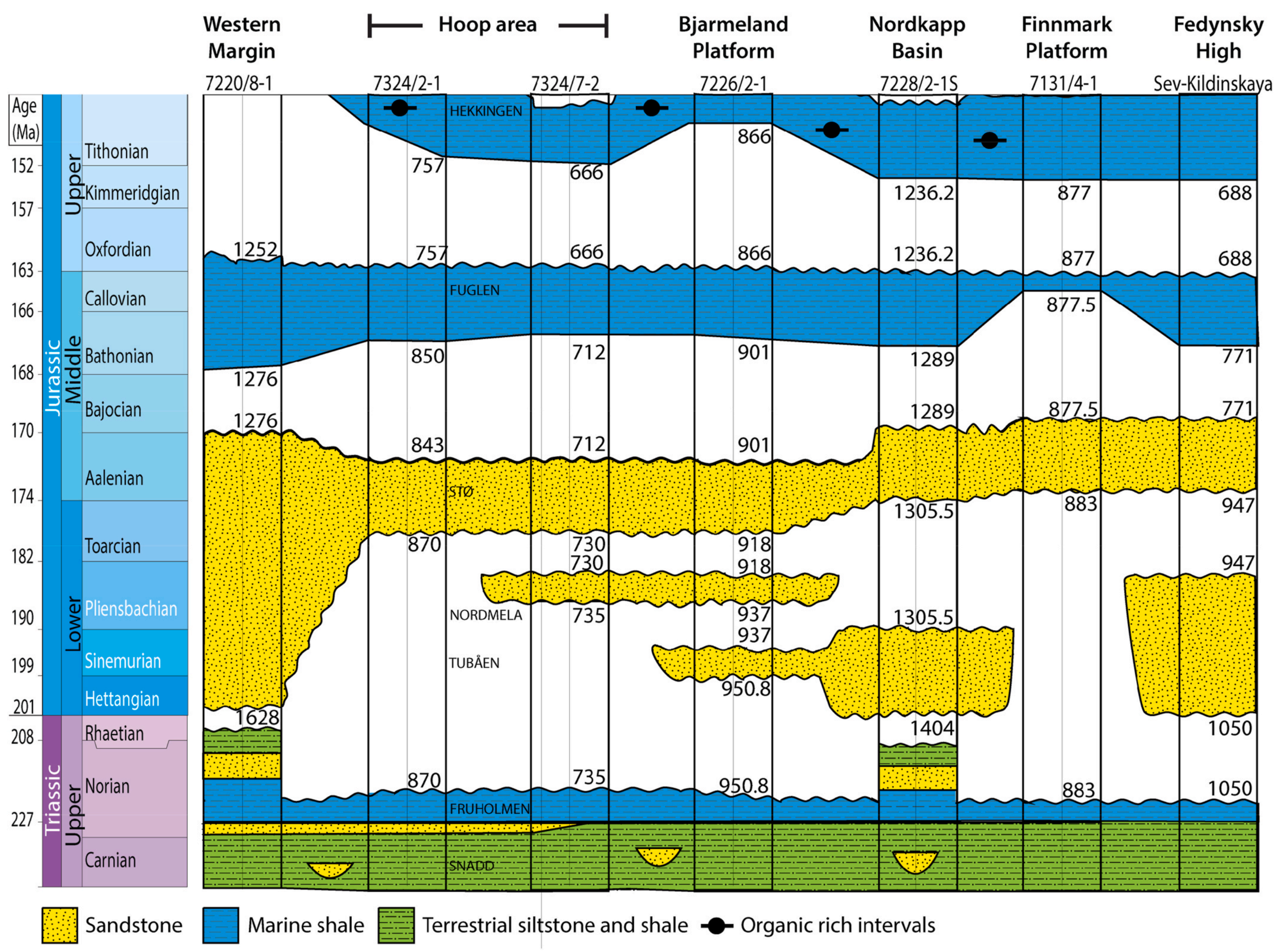

Fig. 5. A gaptogram showing the most important hiatus in the Hoop Area compared with wells in other parts of the Barents Sea basin.

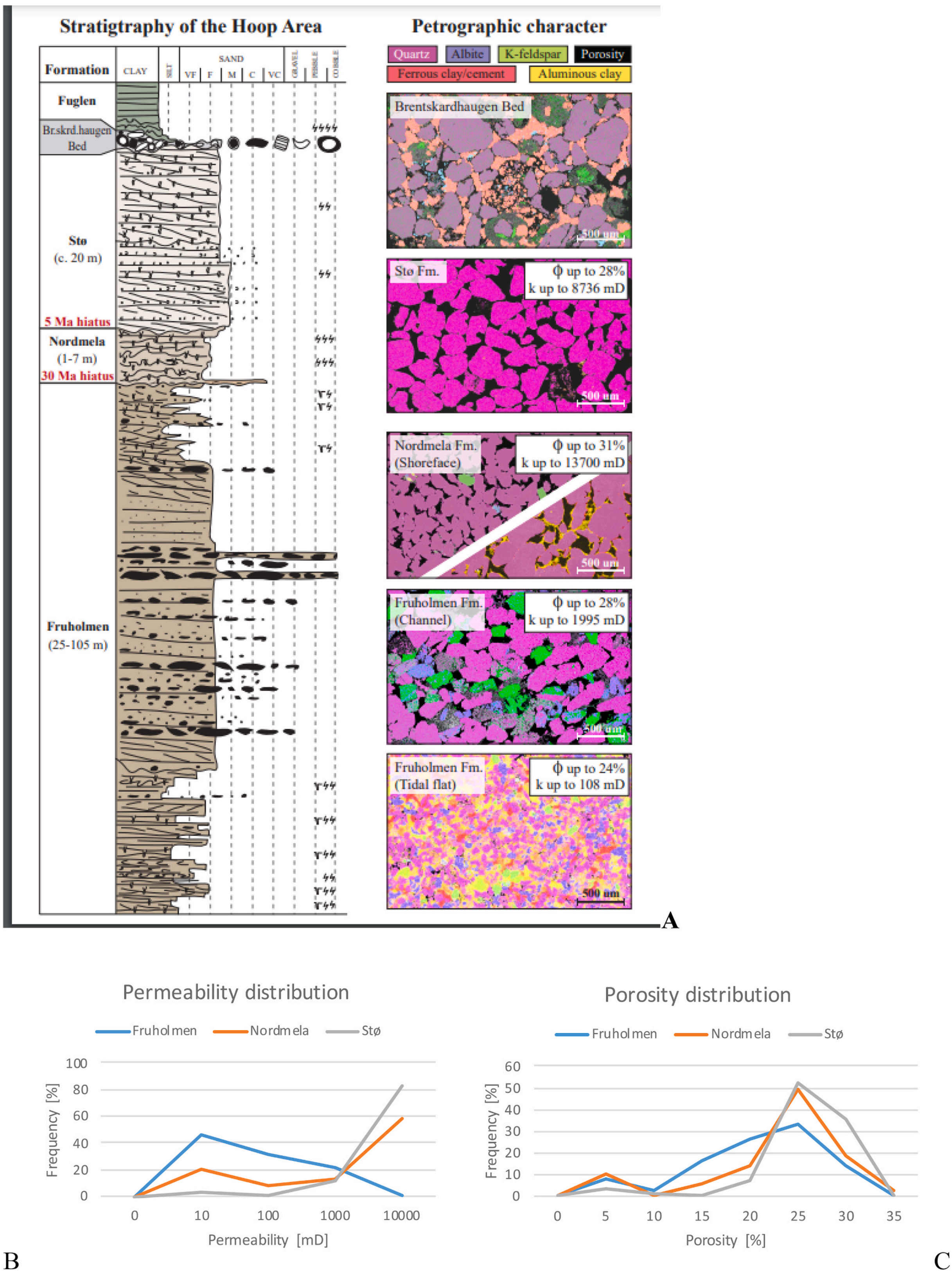

Fig. 6. Schematic core description showing the petrographic development of the Fruholmen, Nordmela, Stø and Fuglen formations. Note the increase in grain size and sorting of the Stø and Nordmela formations compared to the Fruholmen Formation.

(Figs. 2–4). It is composed of mainly sand-rich fluvio-deltaic to shallow marine deposits (Fig. 4). Biostratigraphic analyses show that only the late Pliensbachian part of the formation is preserved. This suggests either an erosional remnant or non-deposition (lacuna) in the early stages of the formation. The hiatus between the Fruholmen and Nordmela formations is roughly estimated to be c. 30 Ma (Fig. 5). Due to the thin nature of the formation, it has not been possible to define any trends in the facies belts. As for the Fruholmen Formation, the Nordmela Formation is very thin in the Hoop Area compared to the thicknesses in the Bjørnøyrenna Fault Zone and Hammerfest Basin, where it can reach up to 160 m.

The presence of reworked Triassic spores and pollen suggest reworking of the underlying Triassic successions, which is further substantiated by detrital zircon age signatures in the Jurassic that closely resemble the geochronological character of the Triassic strata in the Hoop Area (Klausen et al., 2017). A reworked origin is also supported by petrographic data, where the sub-litharenitic and quartz arenites in Nordmela Formation contains a large portion of similar-sized grains as the underlying substrate, although being significantly more quartz-dominated than the Fruholmen Formation (Fig. 6). At moderate burial depths, the Nordmela Formation exhibit excellent reservoir properties (Klausen et al., 2019) with up to 30% porosity and high permeability (Fig. 6).

3.5. *Stø Formation (Toarcian to Bathonian)*

The Stø Formation is encountered in almost all the exploration wells in the Barents Sea, including the Hoop Area, reflecting its overall transgressive nature and the culmination of sandstone deposition of the Lower and Middle Jurassic succession of the Realgrunnen Subgroup. As for the underlying formations in the Realgrunnen Subgroup, the Stø Formation is much thicker and reaches more than 150 m in thickness in the Hammerfest Basin and Bjørnøyrenna Fault Zone, respectively, while it is considerable thinner in the Hoop Area and further to the east on the Bjarmeland Platform. In the Hoop Area, the thickness of the Stø Formation varies regionally from c. 10 m in 7324/10-1 to 22 m in 7324/2-1 (Figs. 3–5).

The Stø Formation represent predominantly a shoreline depositional environment, which also includes tidally influenced tidal bars and fluvial channels. The lowermost boundary of the Stø Formation in the Hoop Area is defined by a transgressive lag following a rise in relative sea level, which is unconformably overlying the Nordmela Formation (e.g. wells 7324/7-2, 7324/8-1, 7324/9-1, 7325/4-1) and the Fruholmen Formation (7324/8-2, 7325/1-1, 7324/2-1) (Figs. 3 and 4). The erosional surface between the Norian Fruholmen Formation and the base of the Stø Formation, dated to late Toarcian, spans nearly 40 Ma and represent a prolonged phase of non-deposition and erosion in the Hoop Area, However, where the Pliensbachian Nordmela formation is present, the hiatus between the Nordmela and Stø formations is limited to up to 5 Ma (Fig. 5).

Dating of the internal units within the Stø Formation in the Hoop Area is poorly constrained but a late Toarcian to early Bajocian age is defined for formation. This is due to barren samples and few diagnostic age markers from the biostratigraphic analysis. Because of relatively poor resolution, the exact temporal and spatial relationship between the internal units in the Stø Formation are not resolved. However, the Stø Formation is apparently – at least – composed of two units: The lower unit comprises transgressive lag deposits which is superimposed by a relatively thick upper unit consisting of homogenous cross-bedded fluvio-tidal sandstones, as observed in cores from wells 7324/7-2, 7324/8-1 and well 7324/9-1 (e.g. Fig. 4d) (Klausen et al., 2018). The boundary between these two units is erosional. Further north, in wells 7324/2-1 and 7325/1-1, a possible third unit in the upper part of the Stø Formation is characterized by mud-to silt-dominated beds which appear to be absent in the wells to the south (7324/7-2,7324/8-1, 7324/9-1).

Detrital zircon-analyses of the Stø Formation in the wells from the Hoop Area show that it includes similar Uralide/Novaya Zemlya-ages as observed for the Fruholmen Formation (Klausen et al., 2017, 2018), but importantly the upper part of the Stø Formation comprise samples with a dominant Caledonian age peak along with higher abundances of older grains suggesting sediment input from the southern margin without reworked Triassic strata (Klausen et al., 2019). This distinct change corresponds to the facies change between the two units observed in the Stø Formation from the Hoop wells mentioned above: An upper massive fluvial sandstone that erodes into a basal transgressive lag for example at c. 676,1 m MD in 7324/8-1 (Fig. 4c).

Most sandstone samples from the Stø Formation are clean quartz arenites (Fig. 6). Compared to the underlying Nordmela Formation, increased mineralogical maturity in the Stø Formation is coupled with an overall increase in sorting and grain roundness. The Stø Formation sandstones are also associated with thin, pebble-graded conglomerate horizons that occur more frequently than in the Nordmela Formation below. The porosity in non-cemented intervals ranges generally from 22 to 28%, while permeability ranges from 200 to 9000 mD (Fig. 6).

The massive Stø Formation sandstones in well 7324/2-1, located c. 40 km to the north, has smaller grain size and higher mud content (Vclay: 16%) than the wells in the Wisting Area. This could be attributed to a more distal position to the marginal marine system that characterizes the Stø Formation in the Hoop Area. A more distal facies is also encountered in the nearby wells in the Fingerdjupet Subbasin (e.g. 7321/8-1). These observations might suggest that the very well-developed channel sandstones encountered in the 7324/8-1 and 7324/7-2 can be relatively local.

In the transition to the Fuglen Formation and assigned to the uppermost Stø Formation is the Bathonian Brentskardhaugen Bed Equivalent. This is a remanié polymict conglomerate is in some wells. These conglomerates are characterized by an up to 1 m thick conglomerate layer, consisting of pebble-sized, intraformational clasts and cm-sized belemnites in some of the Hoop Area wells. In most wells, the matrix of the lag has similar lithology as the substrate, reflecting erosion of the underlying sediments simultaneously with the deposition of the pebbles.

The matrix-loaded conglomerate contains a diverse clast assembly, including chert, quartz, phosphate and carbonate nodules, pyrite concretions, glauconite peloids and fossil fragments. Mono- and polycrystalline pebbles are typically well-rounded, whereas the other clast components are sub-angular (Fig. 6). Deposition of this condensed unit is caused by subaqueous precipitation in a sediment-starved marine environment following a rise in relative sea-level and defines the flooding at the base of the Fuglen Formation which overlay the Realgrunnen Subgroup.

3.6. *Fuglen Formation (Bathonian-Callovian)*

The Stø Formation is unconformably succeeded by the Fuglen Formation which varies in thickness from c. 20 m (e.g., 7324/8-1) in the south to c. 100 m in the north (e.g., 7325/1-1). The transition between these formations is represented by a long hiatus (at least c. 2 Ma; Fig. 5).

The plane-parallel laminated mudstone of the Fuglen Formation consists of predominantly clay-graded quartz, illite and kaolin clay minerals, with local variations in mineral fractions. Siderite occasionally account for 25–50% of the bulk, whereas ankerite, pyrite, glauconite and apatite occur in minor portions (1–10%).

In well 7324/7-2 the basal part of Fuglen Formation 50 cm very fine-grained calcareous sandstone with burrows linked to the Skolithos ichnofacies with glauconite, ooids and pyrite (Bjørnebye, 2019). This part is comparable or spot on with the Marhøgda Bed at the base of the Agardhfjellet Formation in Svalbard (c.f., Bäckstrøm and Nagy, 1985; Krajewski et al., 2001; Rismyhr et al., 2018). The ooids are here ferruginous. Marhøgda bed was her interpreted as a condensed sallow marine deposit (Krajewski et al., 2001).

The remaining part of the Fuglen Formation consist of mudstone with scarce glauconite gains and thin siltstone beds probably deposited

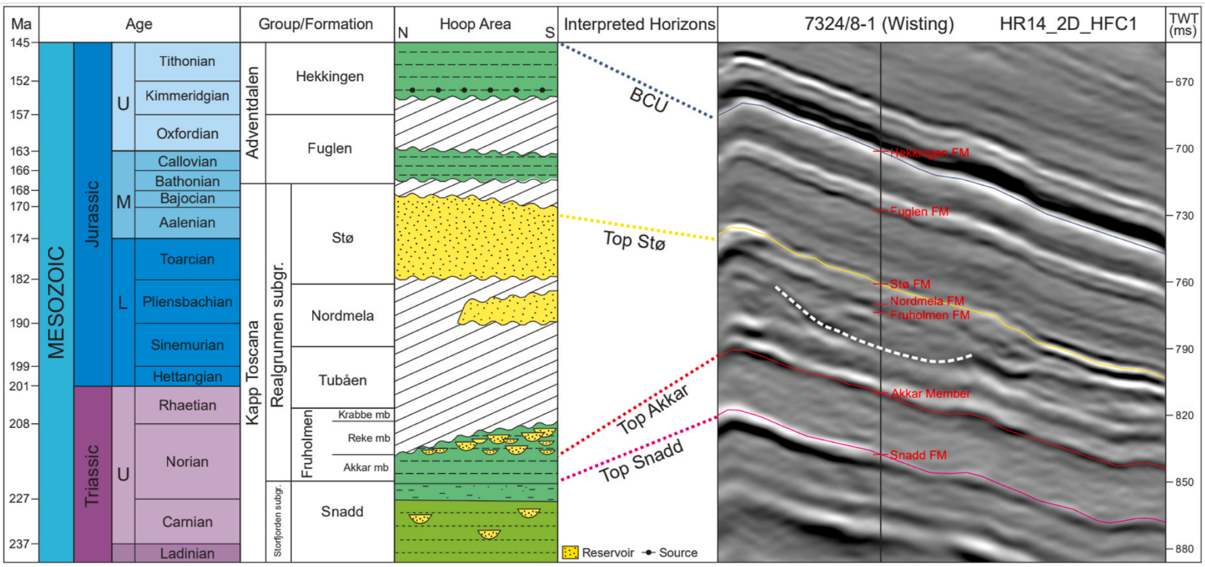

Fig. 7. Stratigraphic framework of the Hoop Area with seismic tie from 7324/8-1 (Wisting well).

in marine shelf environment, but probably under a slow sedimentation rate (Bjørnebye, 2019).

3.7. Seismic stratigraphy

The high-resolution P-Cable data reveal details about thickness variations, unconformities and seismic stratigraphy of the Realgrunnen Subgroup which is not resolved in conventional seismic data (Fig. 7) (e. g., Faleide et al., 2019, 2021).

3.8. Fruholmen Formation (Upper Triassic)

The P-Cable data shows a pronounced angular unconformity that characterize the boundary between the Fruholmen and Snadd formations and the overlying Stø and Fuglen formations towards the Svalis Dome (Figs. 8 and 9).

In the Hoop Area, the lowermost Akkar Member is easily identified on the seismic sections as a continuous, uniform and transparent package, while the seismic facies of the Reke Member is characterized by discontinuous high amplitude troughs, which suggest the presence of channelized features (Fig. 10). P-Cable 3D attribute maps show geometries resembling interdistributary channels, and in conventional 3D from Hoop at least 5 km wide channel deposits of highly sinuous character, representing scroll bars within a trunk channel can be interpreted (Athmer et al., 2016). Channel orientation show autocyclic variations and sinuosity with an overall transport direction to the NW, ranging from E to N similar to the underlying Snadd Formation (Klausen et al., 2014).

The high-resolution P-Cable seismic data show the regional extent of how the Fruholmen Formation varies considerably in thickness within the Hoop Area, being more complete in the Maud Basin while it thins towards north where both the Reke and Krabbe members are truncated.

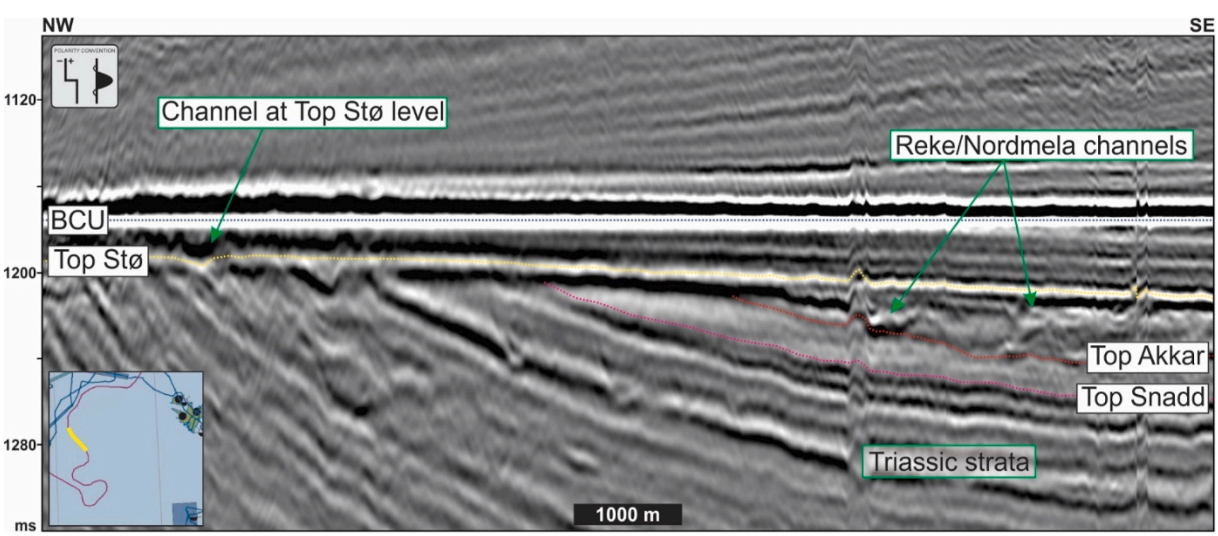

Fig. 8. Seismic section (HR15_2D_IKU1) showing angular unconformity between Fruholmen/Snadd formations and overlying Stø/Fuglen formations adjacent to Svalis Dome area (seismic section flattened at Top Stø level). Seismic data courtesy of TGS and VBPR.

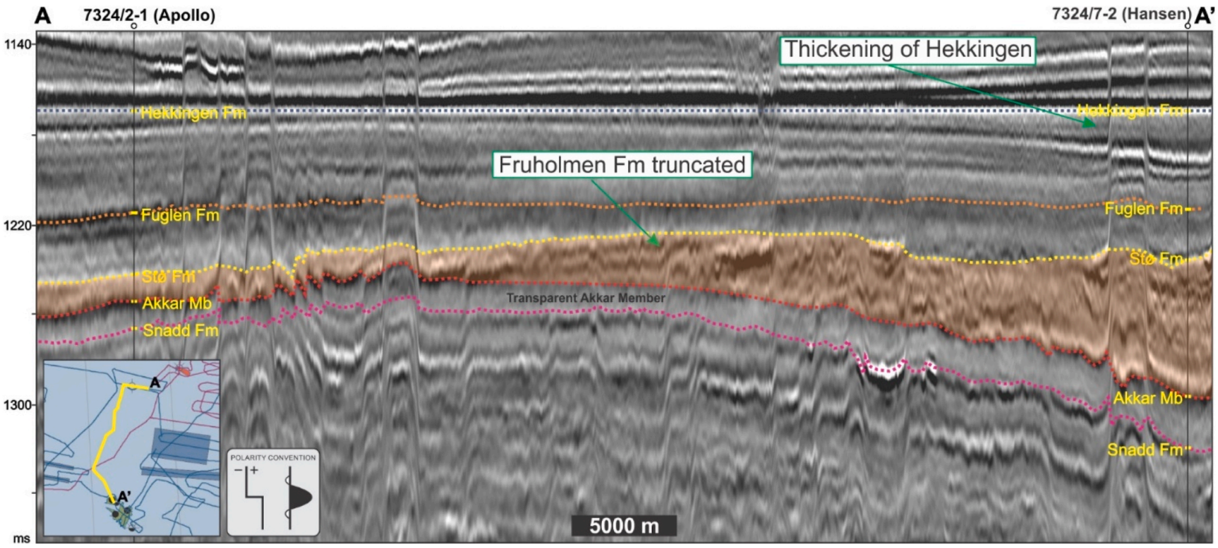

Fig. 9. Seismic profile (HR14_2D_HFC3) showing thickening of Fruholmen Formation and thinning of Fuglen Formation from well 7324/2-1 towards the south, Wisting/Hansen area (seismic section flattened at BCU level). Seismic data courtesy of TGS, WGP and VBPR.

In the north, only the lowermost part of the Fruholmen Formation is preserved, as also documented by the wells in the area (Figs. 3 and 8).

Within the Fruholmen Formation, NNE-SSW trending faults are observed in parts of the Hoop Area. The Fruholmen Formation is more completely preserved in the hanging-wall and grabens and thus thinner reservoir units are expected at the crests of the rotated fault blocks (Fig. 11).

3.9. *Stø/Nordmela/Tubåen formations (Lower to Middle Jurassic)*

The Stø and Nordmela formations are not possible to separate from each other on seismic data, not even on high resolution P-Cable seismic. The relatively thin (max 25 m thick) and homogenous, sandstone-dominated Stø Formation with little internal contrast in acoustic impedance exhibits a diffuse, low amplitude trough.

The most remarkable observations made in the P-Cable data is the

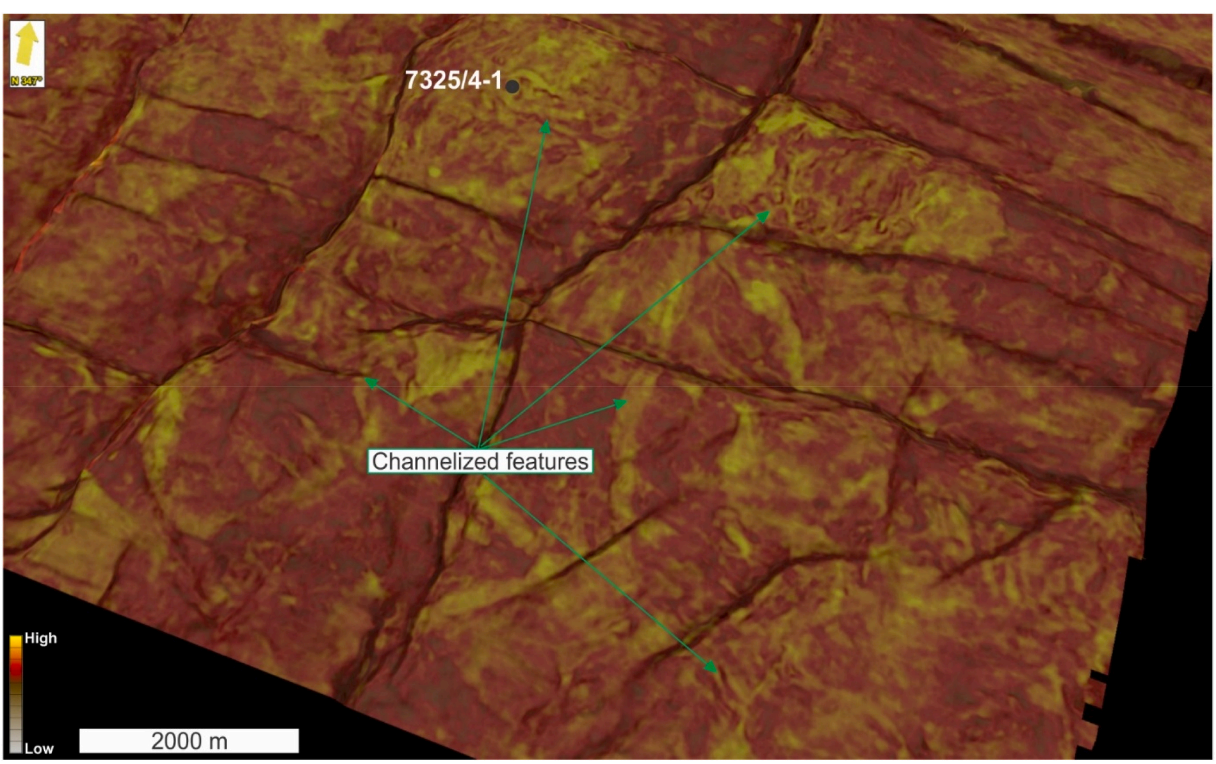

Fig. 10. (a) 5 ms shifted downward Top Stø RMS10 (window 0 above and 10 ms below) co-blended with incoherence showing Reke interdistributary channels. (b, c) Zoom in views of yellow and blue wide and 3 km long. Seismic data courtesy of TGS, WGP and VBPR. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

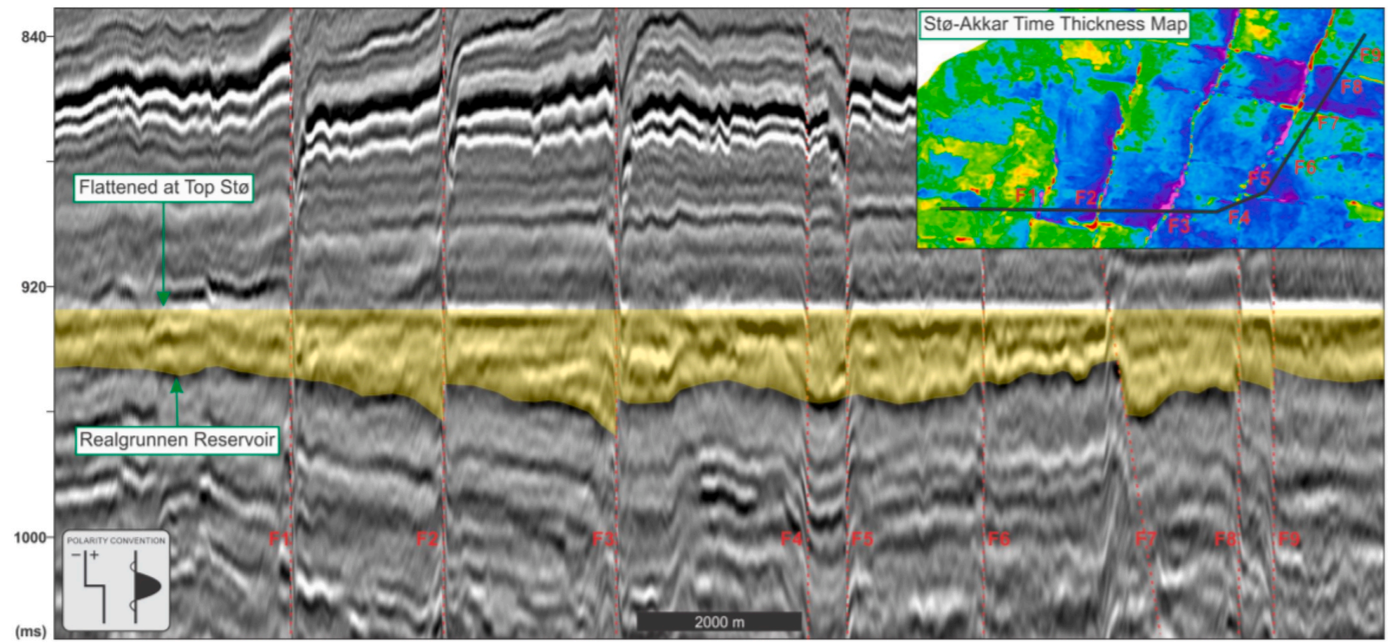

Fig. 11. Seismic section (HFCE1) showing thickness variations of the Fruholmen Formation (yellow color), showing NNE-SSV orientated rotated fault blocks (seismic section flattened at Top Stø level). Map showing thickness map between top Stø Formation and top Akker Member which display thickness increase towards the faults. Seismic data courtesy of TGS, WGP and VBPR. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

distinct erosional nature of the boundary between the Stø/Nordmela Formation and the underlying Fruholmen Formation, as seen in seismic section HR_15_2D_IKU, located west of the present Maud Basin: A 30 m deep incision or channel into the Akkar Member is observed, probably filled with sandy material of the Nordmela Formation (Fig. 12). The Nordmela Formation varies in thickness which is confirmed by well 7324/7-3 S, and it is thicker here than in the other exploration wells in the Hoop Area (Krathus-Larsen, 2017).

Attribute maps near the top Stø Formation in the P-Cable seismic has revealed geomorphological features in map view that might be interpreted as strand plain deposits or beach ridges (Fig. 13). These strand plain deposits trending WNW-ESE, opposite to the direction of the coastline during the deposition of both the Fruholmen and Snadd formations (Klausen et al., 2016).

3.10. *Stratigraphic equivalents on svalbard*

The Upper Triassic to Middle Jurassic outcrops (Wilhelmøya Subgroup) on Svalbard are analogues to the time equivalent deposits in the Hoop Area (Fig. 14). The Wilhelmøya Subgroup is subdivided into three formations. The lower formation is the offshore to distal delta front deposits of the Norian Flatsalen Formation, corresponding to the offshore Fruholmen Formation. The coastal plain/tidal flat deposition of the Sjøgrenfjellet Member of the Svenskøya Formation (Hettangian-Pliensbachian), as seen in south, north and east, are the onshore equivalent the Tubåen and Nordmela formations. The shoreline deposited Mohnhøgda Member of the Svenskøya Formation (late Pliensbachian/early Toarcian) and the inner shelf deposited Kongsøya Formation (late Toarcian/early Aalenian) represent lower and upper part of Stø Formation respectively (Fig. 14). The uppermost part of the Kongsøya Formation occasionally consists of an up to 4 m thick polymict phosphatic and glauconitic conglomerate which is the Brentskardhaugen Bed equivalent of Bathonian age (Bäckstrøm and Nagy, 1985). An equivalent to the Brentskardhaugen Bed is also seen below the base of the Fuglen Formation in the Hoop area as well in the Fingerdjupet Subbasin.

As for the Realgrunnen Subgroup in the Hoop Area, the Wilhelmøya Subgroup is defined at the base by a key sequence stratigraphic surface; the pan Arctic Norian Flooding surface, which also is an important mappable seismic reflector in the Southwestern Barents Sea. Onshore it is seen as a polymict phosphatic glauconitic conglomerate interpreted as transgressive lag deposits (Rismyhr et al., 2018). Besides, the important stratigraphic hiatus recorded between the Fruholmen (Norian) and the Nordmela formations (Pliensbachian) in the Hoop area is also observed between the Flatsalen Bed and the Svenskeøya Formation on Svalbard (Fig. 14). This suggests that an important superregional event influenced this part of the Arctic in the latest Triassic and into the early Jurassic and resulted in erosion and non-deposition. The two areas were in comparable structural settings and probably responded similarly to larger scale forcing factors such as eustatic sea-level changes and regional tectonics, as the Novaya Zemlya protrusion in the late Triassic to early Jurassic (Klausen et al., 2022 in press).

4. Discussion

4.1. *Temporal and spatial development of the basin infill*

In this study we have divided the Realgrunnen Subgroup in the Hoop Area into seven distinct stages, including periods of non-deposition and erosion (Fig. 15). Below we discuss the tectonostratigraphic evolution for these seven stages and its influence on petrography and rates of accumulation.

4.1.1. *Stage 1: basin infill of Fruholmen Formation (Norian-Rhaetian?)*

The Fruholmen Formation, deposited above the early Norian pan Arctic flooding (unconformity), represent an overall progradation of a large-scale deltaic system over the Barents Sea margin and Svalbard (Fig. 15) (Gjelberg et al., 1987; Klausen et al., 2019). As for the Snadd Formation, the Fruholmen Formation represented deposition within a high accommodation setting (Klausen et al., 2017). The stacked fluvio-deltaic deposits of the Reke Member might also suggest that rate of accommodation and sediment supply was relatively balanced, as for the underlying Snadd Formation, with no major episodes of erosion and non-deposition.

If we assume that the Fruholmen Formation had a more or less

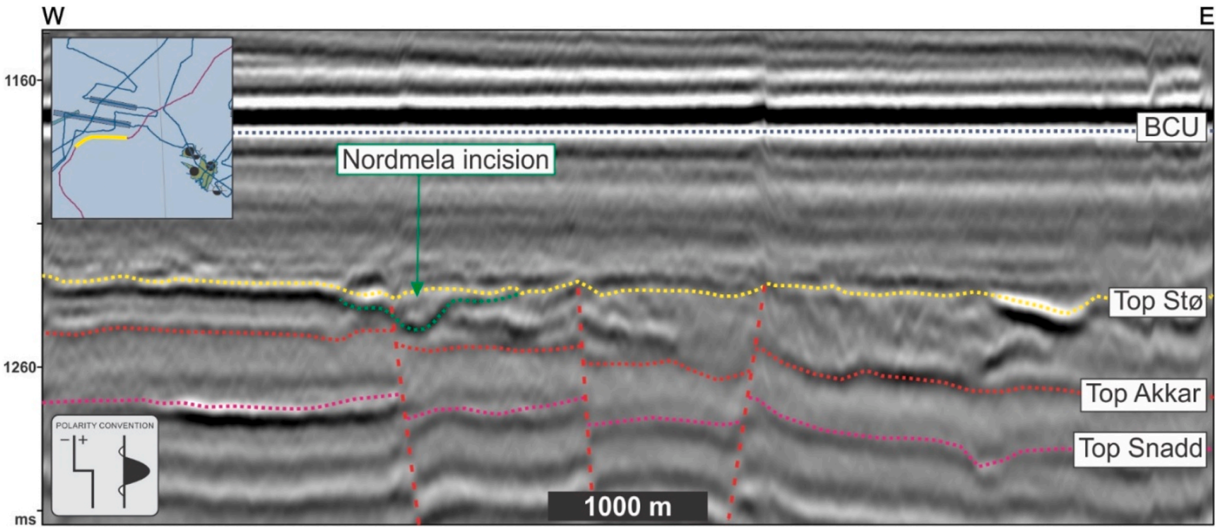

Fig. 12. Seismic section (HR15_2D_IKU1) showing incisions of Nordmela Formation (seismic section flattened at Top Stø level). Seismic data courtesy of TGS and VBPR.

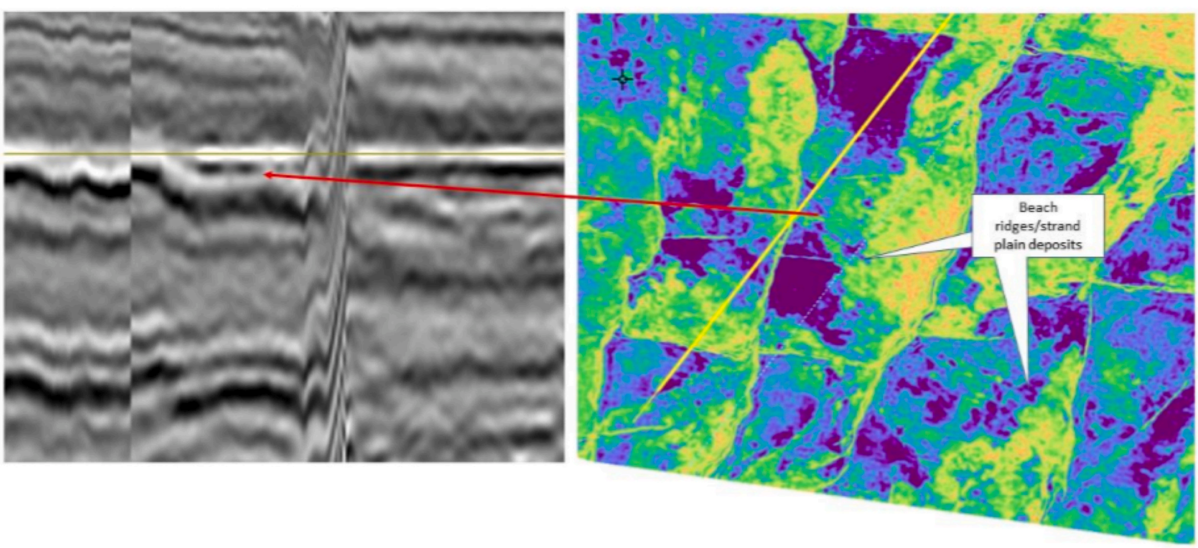

Fig. 13. Strandplain/beach ridges orientated WNW-ESE in the Stø Formation shown on a RMS-amplitude map flattened on top Stø. Seismic section to the left shows the seismic expression of the beach ridges. Seismic data courtesy of TGS, WGP and VBPR.

uniform distribution across the basin similar to the underlying Triassic formations and scaling to the more complete successions of the formation in for example the Hammerfest Basin, the actual accumulation rates have been considerable higher for the Fruholmen Formation in the Hoop Area than what can be estimated based on the preserved succession. Under these assumptions, the accumulation rates could range from 10 m to 30 m per Ma, dependent on uncertainties regarding thickness and age of the Fruholmen Formation.

Sediments were primarily sourced from the Uralides and Novaya Zemlya (Klausen et al., 2017) in the Triassic, but higher compositional maturity and the occurrence of recycled quartz grains in the Fruholmen Formation distinguish it from underlying Triassic successions (Line et al., 2020; Haile et al., 2020). A significant maturation trend is also observed at the Carnian-Norian boundary along the southern margins of the basin, but these occurred in association with a change in provenance (Bergan and Knarud, 1993; Ryseth, 2014). The more subtle maturation trend for the Fruholmen Formation in the Hoop Area is better explained by recycling of older, consolidated Triassic successions that were exposed during uplift of the Novaya Zemlya Fold and Thrust Belt (Line et al., 2020).

4.1.2. *Stage 2: erosion and non-deposition (Rhaetian to early Pliensbachian)*

The base of the Nordmela (Pliensbachian) and the Stø (Toarcian) formations are developed over a major diachronous unconformity that can be traced regionally across the Barents Sea and Svalbard. Depending on which formation is found above the unconformity, the hiatus it represents locally spans from 35 to 40 Ma in the Hoop Area (Fig. 5). This major hiatus is explained by forebulge uplift related to the Novaya Zemlya protrusion of the Uralide-Taimyr fold and thrust belt in the late Triassic (Müller et al., 2019). In response to these compressional forces, the whole Bjarmeland Platform and the Fedynsky High were uplifted in the Late Triassic-Early Jurassic, and Permian salts in the SW Barents Sea were remobilized (Fig. 15).

As a result of the salt remobilization, the Svalis Dome was uplifted resulting in tilting and differential truncation of the Fruholmen

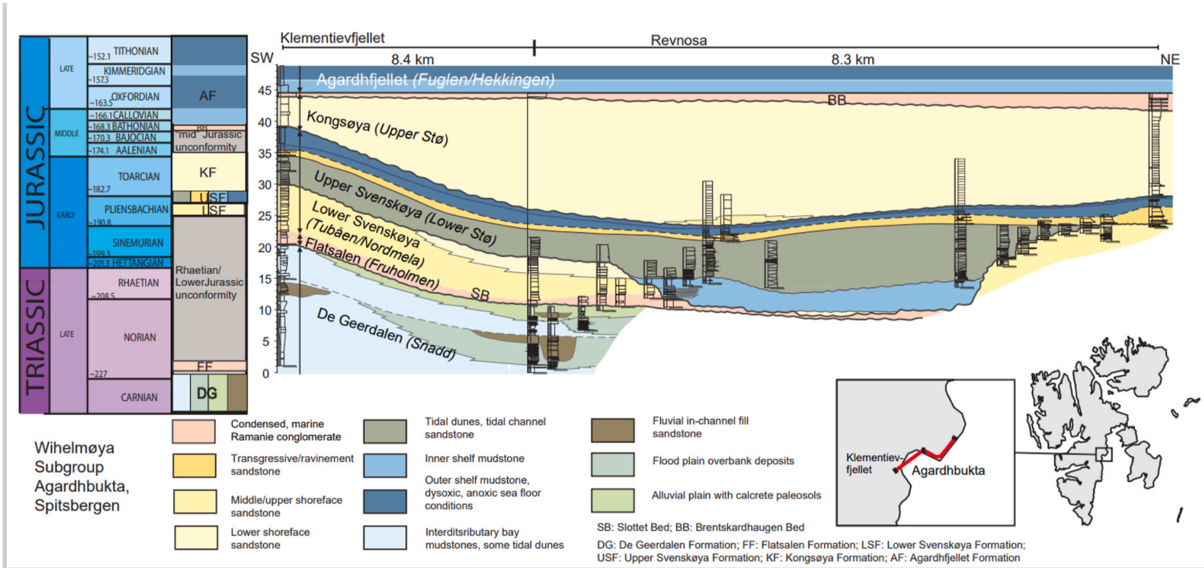

Fig. 14. The Upper Triassic to Middle Jurassic outcrops on Svalbard as in the Agardh Bay are analogues to the time equivalent succession in the Hoop area. Note the considerable hiatus between the Flatsalen Member (Norian) and the Lower Svenskeøya (Pliensbachian).

Formation and even the Snadd Formation. This resulted in NNE-SSW orientated rotated faults blocks where erosion took place on the crests of the uplifted footwalls. The development of the Svalis Dome is previously assigned to be of Late Jurassic-Early Cretaceous age (Mørk and Elvebakk, 1999), but the high-resolution P-Cable data shows that the movement was of Late Triassic to Early Jurassic age, time-equivalent to the Novaya Zemlya tectonic event (Figs. 8 and 14).

The uplift of the Svalis Dome also resulted in the formation of several rotated fault blocks as identified to the east of the Maud Basin, and a highly variable thickness of the Fruholmen Formation (Fig. 11). The thickness of this stratigraphic interval reaches up to 600 m elsewhere in the SW Barents Sea, and the 20–100 m thickness in the Hoop Area suggest that the erosion was immense in this area, at least several hundreds of meters. Consequently, the Krabbe and Reke members, which defines the uppermost parts of the Fruholmen Formation, are completely absent in the northern part of the Hoop Area. Furthermore, the salt movement beneath the Svalis Dome resulted in the formation of a rim syncline to the north due to the salt withdrawal and played an important role to preserve the Fruholmen Formation, and especially the reservoir units of the Reke Member (Fig. 15). Such basin-scale uplift events often result in massive reorganization of the basins, and the formation of considerable hiatuses, and the time embodied in these hiatuses is up to 10 or even 100-fold that of the time represented in the deposits (Miall, 2015).

4.1.3. Stage 3: deposition of Nordmela Formation (late Pliensbachian)

The Nordmela Formation reach several hundreds of meters in the Hammerfest Basin and the Bjørnøyrenna Fault Zone (Olaussen et al., 1984; Gjelberg et al., 1987), but is present only as a thin blanket of sandstones in the Hoop Area (Klausen et al., 2019). The reason for the contrasting development along the western margin and the Bjarmeland Platform (Fig. 5) is attributed to the fact that this part of the Bjarmeland Platform was a structural high throughout most of the Early Jurassic following contraction associated with uplift in Novaya Zemlya.

The long duration of non-deposition and erosion, spanning tens of millions of years, transformed the landscape by periods of river incision forming wide valleys (Fig. 15). Such erosional features are identified at the transition between the Fruholmen Formation and the Nordmela Formation. This, together with partial preservation of the following transgressive tidal deposits, can explain the variable thickness of the Nordmela Formation in the Hoop Area (typically 1–7 m), such as the somewhat thicker deposits reported by Krathus-Larsen (2017) in well 7324/7-3 S.

The source area of the Nordmela Formation is enigmatic, but detrital zircon analysis suggests that the Caledonian and Fennoscandian hinterlands started to act as an important contributor of sediments (Klausen et al., 2017), while the presence of reworked Triassic spores and pollen in the lowermost part of the Nordmela Formation, indicate that reworking of Triassic rocks was an important contributor of sediment as well. Reworking of underlying Triassic sediments, in combination with supply of medium- and coarse-grained sediments from the south, is supported by the moderate sorting and grain size distributions documented from the Nordmela Formation in the Hoop Area. Local provenance areas, such as the Svalis Dome, probably acted as a source for reworked Triassic sediment to the Nordmela Formation.

4.1.4. Stage 4: uplift and non-deposition/erosion (early Pliensbachian - early Toarcian?)

A renewed period of non-deposition and erosion occurred after the deposition of Nordmela Formation, which probably lasted at least 5 million years (Fig. 14). This hiatus is not as pronounced in adjacent areas such as the Hammerfest Basin and the Bjørnøyarenna Fault Complex (Olaussen et al., 1984; Klausen et al., 2019). Although it is difficult to evaluate the cause for this episode due to the condensed nature of the accumulated deposits, the non-deposition can be related to a regional uplift of the Bjarmeland Platform. Alternatively, it can be speculated upon if renewed salt halokinesis in the Svalis Dome contributed to a local uplift of parts of the Hoop Area.

The unconformity between the Nordmela and Stø formations might be locally overprinted and entirely masked, but at the same time it is impossible to discriminate whether Nordmela Formation was deposited there or not. The upper boundary of both the Nordmela and Fruholmen formations is defined by a subaerial unconformity prior to the flooding surface that defines base Stø Formation.

We cannot rule out the possibility that the nearshore deposits were influenced by the major fall in the eustatic sea level in the early Toarcian (Haq et al., 1987), which resulted in the erosion of the underlying Nordmela Formation, represented by a wave ravinement surface, and potentially also further truncation of the Fruholmen Formation. The Nordmela Formation seems elsewhere in the Barents Sea to passively fill accommodation between local highs developed during the Tubåen Formation as part of a gradual transgression that culminated with the

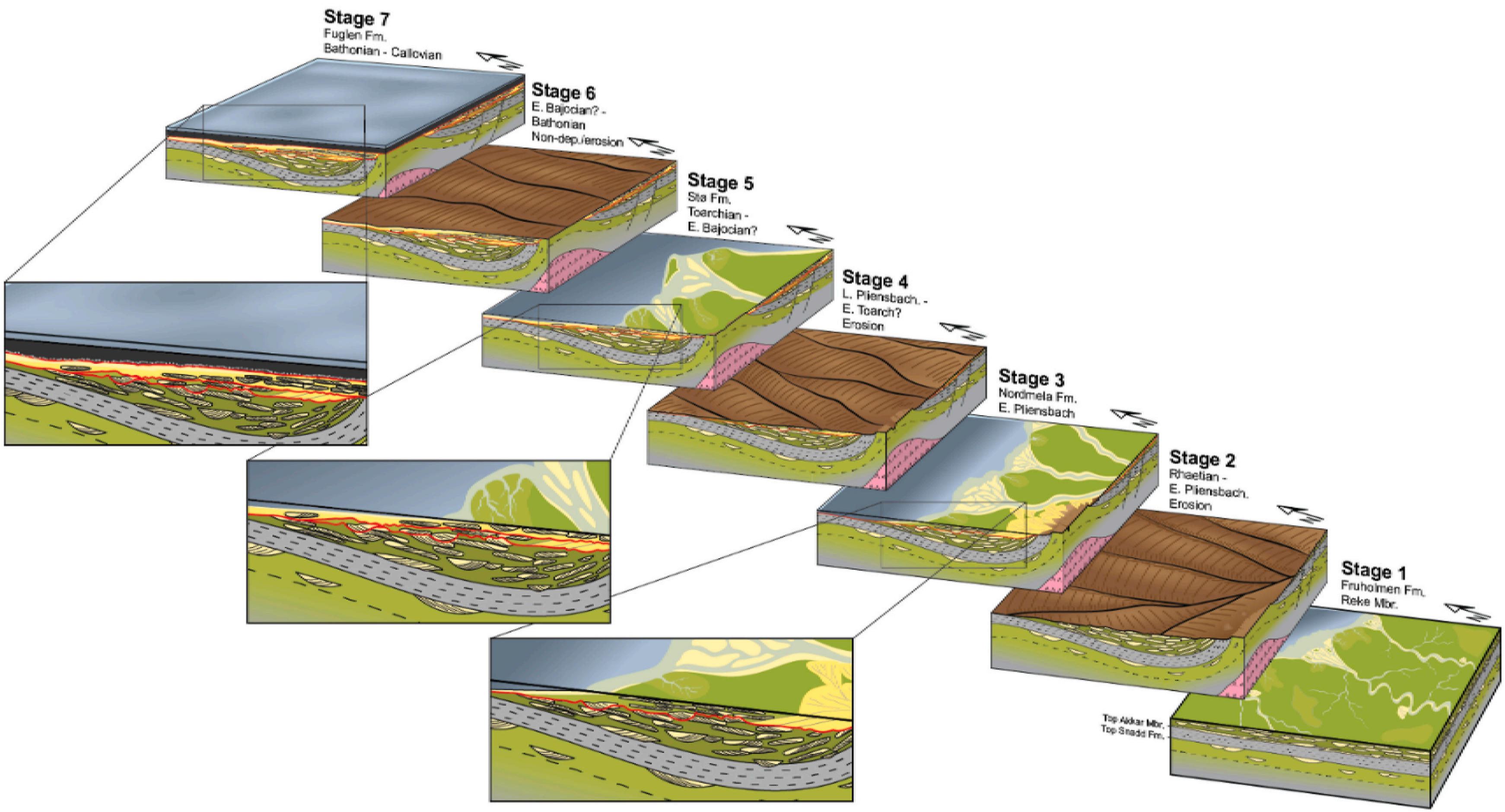

Fig. 15. Block diagrams showing basin infill history of the Hoop Area through seven different stages: Stage 1: Normal regressive delta progradation in Norian Fruholmen Formation; Stage 2: Uplift and subaerial erosion during early Jurassic Tubåen Formation; Stage 3: Flooding and deposition of tidally influenced shallow marine to inner shelf Nordmela Formation; Stage 4: Subaerial erosion due to fall in relative sea level in the late Pliensbachian to early Toarcian; Stage 5: Rise in relative sea level and deposition of shallow marine transgressive lag at the base of the Stø Formation which is followed unconformably by an erosive boundary to overlying fluival deposits in the upper part of the Stø Formation (e.g. Fig. 4); Stage 6: Hiatus and non-deposition following the fluvial deposits in the uppermost part of the Stø Formation; and Stage 7: Rise in relative sea level and flooding of the Triassic-Jurassic succession of the Realgrunnen Subgroup.

deposition of the Stø Formation (Klausen et al., 2019).

The limited thickness of the Nordmela Formation (1–7 m) suggests that only a fraction of the time is represented by deposition. The Nordmela Formation is considerably thicker 200 km to the east on the Bjarmeland Platform where it comprises up to 75 m thick, multistorey channel sandstones. It can be speculated that the Nordmela Formation in the Hoop Area was much thicker and what is preserved today is just what is left after erosion and wave ravinement at the transgressive base of the Stø Formation.

4.1.5. Stage 5: deposition of the Stø Formation (Toarcian-Aalenian)

Deposits in the Stø Formation of the Hoop Area suggest that an increase in relative sea-level took place probably during the late Toarcian, which resulted in the deposition of nearshore to inner shelf deposits across the Barents Sea (Fig. 15). Multiple stratigraphic boundaries with unconformable facies changes or prominent wave ravinement surfaces marked by polymict conglomerates, often with phosphatic, are seen throughout the formation (Gjelberg et al., 1987; Klausen et al., 2018). An example of an abrupt facies change is a regressive pulse characterized by fluvial channel and mouth bar sandstones in the Stø Formation in 7324/8-1 (Fig. 15). Above this regressive wedge there is another transgressive conglomeratic lag deposits, probably of Bathonian age, which characterize the transition to the Fuglen Formation in some of the wells in the Hoop Area (Fig. 6A). Apart from the major hiatuses at the base and upper part of the formation, several stratigraphic breaks within the Stø Formation are also evident (Figs. 4 and 6).

For the Stø Formation in the Hoop Area, the c. 20 m thick succession represent a period of 15 million years (Toarcian to Bathonian). This could, very simplified, suggest that the rate of accumulation was very low – only 1 m per Ma. This support the conclusions in Ryseth (2014) and Klausen et al. (2017) that the rate of accumulations for the whole Lower to Middle Jurassic succession in the Hoop area was considerably lower than for the Triassic. The Stø Formation was however probably deposited by a series of depositional events, each spanning much shorter time. In for example wells 7324/8-1 and 7324/7-2, the transgressive lag at the base of the Stø Formation is followed unconformably by fluvial and tidal inlet to barrier deposits (e.g. Fig. 15).

In comparison to the 1–2.5 m thick transgressive lag at the base of the Stø Formation in 7324/8-1 and 7324/9-1 respectively, the Galveston Island barrier is 12 m thick, and 3.5 ka old at it is base (Bernard et al., 1962; Miall, 2015), which indicate an average rate of sedimentation of 3.4 m/ka. If we assume the same rate of sedimentation of the Stø Formation in the Hoop Area, the 2.5 m thick sandstone unit was deposited in a period of c. 700 years. Fluvial deposits in the middle or upper part of the formation are up to 14.5 m thick (e.g. 7324/8-1 in Klausen et al. (2018)). Stouthamer et al. (2011) showed that the aggradation rate of fluvial deposits in the Rhine-Meuse delta range between 0.4 and 4 m/kyr depending on the position relative to the main channel axis and its shoreline position, and from this range Miall (2015) used a local aggradation rate of 2.8 m/kyr as an approximate channel aggradation rate. Assuming the same rate for the Stø Formation in the Hoop Area, the 14.5 m thick fluvial sandstone that is preserved was potentially deposited in a period of c. 5000 years.

In a similar exercise, de Natris and Helland-Hansen (2012) used rates of sedimentation derived from modern depositional environments to calculate elapsed time in the Tarbert formation in the North Sea, and they concluded that rate versus thickness for each facies explained only 7% of the 2.8 Ma elapsed. For the Stø Formation we find that the time of deposition only embody below one per mille (0,04%) of the total time of the chronostratigraphy which the formation represents. This emphasize the fact that this ultra-condensed section is characterized by extremely long periods of non-deposition, abrupted by short, frozen accidents of accumulation which is preserved. The order of magnitude that separates the time accounted for by deposition in the two studies scale to the different time spans over which the entire Stø Formation (c. 15 Ma) was deposited over compared to the significantly shorter period over which the Tarbert Formation was deposited (c. 2.8 Ma) (de Natris, 2012). Naturally, more time gaps are captured in the Stø Formation relative to the Tarbert Formation. Adding to this difference in longevity and potential frequency of hiatuses, is the fact that the Tarbert Formation is one order of magnitude thicker (more than 200 m) compared to the Stø Formation (c. 20 m).

The main sediment source for the Stø Formation was local reworking of the Nordmela and Fruholmen formations, or older Triassic sediments in the basal part of the formation (Klausen et al., 2018), and Fennoscandian in the upper parts (Klausen et al., 2019). This is reconcilable with considerable erosion of the Fruholmen Formation in nearby areas during Late Triassic-Early Jurassic, and the presence of reworked Late Triassic spores and pollen in the Stø Formation in the Hoop Area. Periodic uplift of local source areas, such as the Svalis Dome, was also important for the clastic input of sand into the basin during deposition of the lower part of the Stø Formation. Within the formation, there are large variations in the reservoir quality, as exemplified by exploration wells 7321/8-1 in the Fingerdjupet Basin and 7325/1-1 (Klausen et al., 2018). Poorer reservoir in the latter is directly linked to higher mud content, and the deposition took place in a more distal position relative to time-equivalent fluvial deposits in the Wisting area. This suggests that proximal-distal trends in the depositional system, such as distance to the Fennoscandian margin and uplifted local high such as the Svalis Dome, controlled reservoir quality.

4.1.6. Stage 6: Bajocian-Bathonian: erosional event

The deposition of the Stø Formation in the Hoop Area was followed by a renewed phase of erosion, representing a hiatus of at least c. 2 Ma (Fig. 15). This erosion resulted in an uneven distribution of the Stø Formation. A regional tilting opposite to that imposed by the earlier uplift event in the Rhaetian, can explain why the uppermost part of the Stø Formation was eroded or not deposited in the area around 7324/8-1, while it was preserved in the 7325/1-1 and 7324/2-1.

4.1.7. Stage 7: Bathonian-Callovian: deposition of the Fuglen Formation

During the relative sea-level rise that took place in the Bathonian, a transgressive conglomerate, mainly composed of phosphate nodules and pebble-sized clast assemblages, was deposited regionally in a shelfal setting in the Barents Sea and towards Svalbard (Fig. 15). The mixture of well-rounded and sub-angular clasts suggests an incorporation of long-lived and more recent sediment input. As such, the conglomerate represents a lag of mixed origins, where erosion and reworking over time have concentrated both extrabasinal and intrabasinal clast components of various ages. The prolonged sediment starvation and high concentration of organic matter required to form pyrite, phosphate and glauconite (Burnett, 1977; Odin and Matter, 1981; Baldermann et al., 2012) suggest that these lag constituents are remnants of former marine shelf sediments. Pebble-sized quartz and chert represent extrabasinal sediment input delivered to the basin.

The overlying, homogeneous calcareous silty mudstone with glauconite in the Fuglen Formation implies low depositional energy typical of distal marine and starved basin fill. While the deposition of the underlying formations, such as Stø and Nordmela, was abrupt and episodic separated by numerous hiatuses, the deposition of the Fuglen Formation was probably more continuous and could have formed over 100s of thousands of years without significant breaks in sedimentation in the distal shelf. However, the condensed unit at the base of the Fuglen Formation, e.g. the Brentskardhaugen Bed Equivalent analogue, required considerable time to form and might be associated with a significant hiatus before distal shelf deposits started to accumulate.

4.2. Mind the gap: implications for understanding reservoir potential in ultra-condensed sections

The multiple hiatuses that characterize ultra-condensed sections impose a major control on the distribution of reservoir properties.

Prolonged surface exposure and reworking associated with non-deposition and erosion yield a high potential for sedimentary particles to react with various components of the hydro-, bio- and atmosphere. Sandstones deposited in ultra-condensed sections are therefore highly susceptible to textural and compositional alteration processes which often lead to increased reservoir quality. In this study, we have documented how a major inversion of the Barents Sea Basin changed the tectonic configuration in the Hoop Area from a high-accommodation basin with balanced sediment accumulation and -supply rates, to a low-accommodation setting with episodic deposition, erosion and extensive sediment cannibalization. This tectonic rearrangement is accompanied by a shift from poor to moderate reservoir quality in the Triassic Snadd and Fruholmen formations, to extremely well-developed and prolific reservoirs in the Jurassic Nordmela and Stø formations.

The better reservoir quality recorded in the Jurassic sandstones is mainly attributed to a significant increase in permeability (Fig. 6B–C) and suggest that the best reservoir units in the Barents Sea Basin can be linked to conditions that suppress accumulation of argillaceous material in the pore space. As opposed to periods with high rate of accommodation, where coarse-graded sediments are trapped in the most proximal part of the system, low-accommodation settings enable coarse-graded detritus to migrate further into the basin (Paola and Angevinet, 1992). This trend is observed across the Triassic-Jurassic boundary on the Barents Shelf. Medium-grained sandstone reservoirs of the Fruholmen Formation occur exclusively in proximity to the Caledonian and Fennoscandian provenance terrains in the south, whereas time-equivalent strata in the distal Hoop Area is dominated by very fine-to fine--grained sandstones sourced primarily from the Urals and Novaya Zemlya (Line et al., 2020). During the Pliensbachian, however, medium-to coarse-grained sandstones and pebble to cobble-sized clasts from the quartz-rich Caledonian and Fennoscandian provenance areas were introduced to the Hoop Area during the deposition of the Nordmela Formation. Consequently, lower rates of accommodation improved the reservoir quality in distal positions by displacing the gravel-sand transition out into the basin and thereby facilitated the influx of quartz-rich sand from more mature provenance areas.

The architectural style (e.g. sandbody geometry/facies, stacking pattern and interconnectedness) associated with condensed sections and low-accommodation settings also promote high sand:mud ratio and suppress the potential for incorporating argillaceous material into sandy intervals. During the high-accommodation basin configuration in the Triassic, sand accumulated in confined channels enclosed by floodplain clays (Klausen et al., 2014). The high preservation of argillaceous deposits allowed floodplain clays to be incorporated into the sand during channel erosion and riverbank collapse, thereby reducing the reservoir permeability in these reservoirs (Line et al., 2020). By contrast, lower rates of accommodation are linked to increased amalgamation (Bridge et al., 1993), which promote sandstone amalgamation and low preservation of fine-graded and argillaceous sediment in the system (van Yperen et al., 2020). Prolonged sediment cannibalization in the Hoop Area during the Early-Middle Jurassic acted as a discrimination agent separating silt- and clay-graded material from the sand- and gravel fractions and suppressed incorporation of clays into the sandy reservoir units. Clay- and silt-sized particle fractions appear to have accumulated in the more distal, low-energetic parts of the system, which explains the poor reservoir quality in wells drilled in distal parts of the Stø Formation (e.g. 7325/1-1 and 7324/2-1) and the Fuglen Formation.

The evolution of reservoir properties with depth is also closely linked to the mineralogical composition of the sediment (Bjørlykke, 2014), which changes abruptly across the Triassic-Jurassic boundary in the Barents Sea Basin (Line et al., 2020). In addition to a well-documented provenance shift in the Early Norian (Bergan and Knarud, 1993; Mørk, 1999; Ryseth, 2014; Fleming et al., 2016), uplift-induced reworking has previously been considered amongst the main factors driving the Upper Triassic subarkosic sandstones in the Hoop Area towards quartz arenitic compositions in the Jurassic (Line et al., 2020). However, reworked sediments do not mature compositionally during physical wear but are instead monotonously quartz-rich because their parent sandstones have undergone prolonged diagenetic dissolution and chemical weathering (Garzanti, 2017). Hiatuses and erosional unconformities are important in this context because the potential for sediments to change their bulk composition is much higher at shallow depths due to mass transfer constraints at greater burial (Bjørlykke and Jahren, 2012). Long periods of non-deposition in uplifted areas on the Barents Shelf during the early Pliensbachian (Stage 2) and Early Toarcian (Stage 4) allowed fine-graded litharenites and subarkosic sediments of exposed Triassic strata to be leached by meteoric water (Fig. 15). The condensed nature of the Lower Jurassic units likely promoted extensive kaolinization of labile silicate grains (e.g. feldspars, micas and Fe-bearing rock fragments) across the Barents Sea basin. However, as erosion rates probably exceeded the propagation rate of the dissolution front in the sandstones (Bjørkum et al., 1990), accumulation of diagenetic kaolin in the intergranular pore space was efficiently suppressed by subsequent sediment cannibalization. Diagenetic dissolution and subsequent removal of argillaceous precipitation products through multiple regressive-transgressive cycles over the course of 35 Ma therefore skewed the Lower to Middle Jurassic sandstones of the Nordmela and Stø formations toward higher mineralogical maturity (Fig. 6), adding to the effect of increased sediment supply from more mature provenance areas.

The Stø Formation contains both fine-graded particles inherited from reworking of Triassic strata and coarse-graded extrabasinal particles derived directly from the Norwegian mainland and indirectly through reworking of underlying Early Jurassic units (Nordmela and possibly Tubåen formations). Higher compositional maturity, degree of sorting and grain roundness indicate more extensive meteoric leaching, amalgamation and cannibalization of the sands deposited in the Toarcian Stø Formation compared to the preserved parts of the Pliensbachian Nordmela Formation in the Hoop Area. The Stø Formation would thus represent the extreme endmember in the Early-Middle Jurassic condensation cycle, which resulted in cleaner sandstones with better sorting, less clay, and hence, better reservoir properties. However, our study also shows that local variations exist within the overall condensed succession: lithological variations are linked to proximal-distal facies trends in the overall distribution of reservoir rocks and it shows that the results of individual accidents of deposition are important when these are preserved in the rock record.

5. Conclusion

Upper Triassic to Lower Jurassic tectonostratigraphic development in the Hoop Area is distinct from other areas in the Barents Sea. This is due to a complex interplay between regional forebulge uplift with local uplift and erosion of reactivated salt structures. This resulted in seven stages of basin infill and erosion, including the deposition of Fruholmen, Nordmela, Stø and Fuglen formations, which were interrupted by major phases of non-deposition and truncation. Especially the ultra-condensed Stø Formation is separated into several discrete depositional episodes, where the estimated rate of accumulation for the preserved unit only represents a fragment of the total time which the unit represent.

The impact of the condensation is that the Hoop Area developed its most prolific reservoir interval, especially within the Nordmela and Stø formations. The low accommodation setting was favorable for the sandstone amalgamation and the uplift caused erosion and reworking of sediments, improving the reservoir quality. In addition to the important sediment input of clean, quartz-rich sands from Fennoscandia, proximity to local source areas such as the Svalis Dome, favored the access of lithologically mature reworked clastics. The deposition in the more distal, low-energetic parts of the system, however, seems to have promoted mudstone and silt even within the overall condensed succession, while the more proximal parts of the system, as in the rim around the Svalis Dome, was favored by a high-energetic system that promoted both better sorting and fractionation of mud and silt from sand.

This study attributes major improvements in reservoir quality is to lower rate of accommodation and condensation. The interplay between episodic deposition, erosion and prolonged periods of non-deposition that characterize ultra-condensed sections like the Lower Jurassic formations in the Barents Sea promoted high-quality, prolific reservoir units.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Reidar Muller reports financial support was provided by University of Oslo.

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