Linking regional unconformities in the Barents Sea to compression-induced forebulge uplift at the Triassic-Jurassic transition

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ABSTRACT

The Triassic-Jurassic transition marks an important change in the basin configuration of the Greater Barents Sea. A contiguous basin with km-thick sedimentary successions changed into a partitioned basin with uplift in the west and foreland basins in the east with significant implication for the basin infill history. Our study employs a range of different high-resolution datasets from a distal part of the basin which unravels the complex pattern of differential uplift and erosion in the basin during this period.

We record for the first time distinct angular unconformities between Upper Triassic strata and overlying Lower Jurassic strata within the basin, showing that large parts of it formed topographic highs. Our study links these angular unconformities to compression induced by the Novaya Zemlya Fold and Thrust Belt. A heterolithic basement below a thick sedimentary succession where the fold belt developed created a complex uplift pattern in the basin, at the same time similar to but different from typical forebulge areas. Compression caused inversion of older basement rooted faults defining platforms and graben systems throughout western parts of the Barents Sea basin, in addition to salt remobilization that resulted in differential uplift and erosion. These local zones of uplift controlled the sediment distribution pattern to the basin at a time when the most important reservoir units in the basin were deposited. This new understanding of the basin development explains hitherto enigmatic sequence boundaries that has inspired complex paleogeographic models in the past.

1. Introduction

The Upper Triassic to Lower Jurassic succession in the Norwegian sector of the Barents Sea basin (NBSB) is characterised by a pronounced transition from high rate of sedimentation and accommodation in the Triassic, to a condensed succession with limited accommodation, lower rates of sediment supply and bypass in the early Jurassic (Ryseth, 2014; Klausen et al., 2017). This transition was gradual at first, causing changes in river drainage basins (Klausen et al., 2014) but culminated at the Triassic-Jurassic transition causing a major depositional hiatus and changes in regional sediment supply patterns (Klausen et al., 2018). Despite much evidence for this important re-organization throughout the Greater Barents Sea Basin in the late Triassic- early Jurassic, the event itself and its driving mechanism has received relatively little attention and has so far remained poorly understood.

Conversely, the period is traditionally viewed as a period of tectonic quiescence in the Barents Sea (e.g. Faleide et al., 1993; Henriksen et al.,

2011; Glørstad-Clark et al., 2011; Clark et al., 2014; Rojo and Escalona, 2018), and although several studies have noted that the Triassic-Jurassic transition is characterised by a distinct change in the sedimentation pattern (e.g. Smelror et al., 2009; Ryseth, 2014), few discuss the origin and causal mechanism of this change. Other studies have claimed that NBSB experienced a phase of extensional tectonics during the late Triassic to early Jurassic (e.g. Gramberg, 1997; Stoupakova, 2001; Gernigon et al., 2014; Serck et al., 2017). In Ryseth (2014), the transition between the Triassic and Jurassic is thoroughly described, but differences in basin infill between the two periods are mainly attributed to hinterland rejuvenation in Fennoscandia, larger annual precipitation and reduced subsidence rates. This change also coincides with compression in stress regimes set up by the Novaya Zemlya Fold and Thrust Belt which culminated in the late Triassic to early Jurassic (Buiter and Torsvik, 2007; Ritzmann and Faleide, 2009; Faleide et al., 2018), created foreland basins such as the North and South Barents basins in the Russian sector (Scott et al., 2010; Suslova, 2013a, 2013b). The potential

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influence of nearby compressional tectonics at this time has not yet been explored in the Norwegian Barents Sea Basin.

Partially, the lack of knowledge about this important transition is due to the condensed nature of the interval in combination with variable data quality, which makes it difficult to detect important, but subtle, variations on a basin-wide scale. Superficially, the interval appears layer-cake in regional conventional seismic and its thickness does not seem to change much across the basin. From well logs and cores, large internal variations are however apparent (Klausen et al., 2017) and in this study we therefore integrate detailed analysis of well data with regional 2D seismic sections to better understand the timing of the events, and its implications for the basin infill history. In addition, high resolution 2D P-Cable seismic are applied in areas where this is available and offer unprecedented insight into the lateral development of this interval which is normally below seismic resolution in conventional broadband seismic. The subsurface data offshore northern Norway are also considered in context with time-equivalent deposits on Svalbard and in the Russian sector of the Barents Sea.

In the present study, we use novel observations of prominent angular unconformities to investigate the distribution and longevity of pronounced hiatuses near the Triassic-Jurassic transition in the Barents Sea. The stratigraphic relationship is mapped across the basin to constrain the causal mechanism for developing angular unconformities and how these are affected by the protrusion of the Novaya Zemlya Fold and Thrust Belt. It is beyond this study to present a full geodynamic model which explains the detailed impact of the Novaya Zemlya Fold and Thrust Belt on the Greater Barents Sea Basin, but the many important implications of our findings will likely stimulate further research on the topic and explain hitherto enigmatic stratigraphic relationships and salt reactivation across the basin.

2. Geologic setting and stratigraphy

The Barents Sea basin is characterised by a highly complex basement structure, affected by the Timanian, Caledonian and Uralian orogenies (Gernigon et al., 2014), but generally experienced regional sag subsidence during the Triassic period (Glørstad-Clark et al., 2010; Clark et al., 2014) which accommodated kilometre-thick successions of siliciclastic deltaic deposits characterised by platform-scale clinoforms sourced primarily from the southeast (Mørk, 1999; Riis et al., 2008; Glørstad-Clark et al., 2010; Bue and Andresen, 2014). In the late Triassic, the basin infill pattern started to change due to uplift of the Novaya Zemlya fold and thrust belt, which altered drainage patterns that controlled sediment supply in the Carnian (Klausen et al., 2014). This fold and thrust belt culminated with a pronounced turnover in sediment supply at the transition from the late Triassic to the early Jurassic (Klausen et al., 2018).

The Realgrunnen Subgroup comprises the normal regressive offshore to deltaic Fruholmen Formation (Norian-Rhaetian), the forced regressive Tubåen Formation (Rhaetian-Sinemurian), and the overall transgressive Nordmela (Sinemurian-Pliensbachian) and Stø (Pliensbachian - Bajocian) formations (Fig. 1B; Olaussen et al., 1984; Gjelberg et al., 1987; Mørk et al., 1999; Klausen et al., 2017; Klausen et al., 2018; Mulrooney et al., 2018). The Fruholmen Formation is furthermore subdivided into three members: the prodeltaic Akkar, the fluvio-tidal Reke and the deltaic Krabbe members (Dalland et al., 1988), and is predominantly supplied with immature and fine-grained sediments from the east whereas the sandstone-dominated Tubåen, Nordmela and Stø formations comprise reworked and predominantly southerly derived coarser sediments in the NBSB (Klausen et al., 2017).

The stratigraphic onshore equivalent to the Realgrunnen Subgroup is the Wilhelmøya Subgroup in Svalbard. While the Wilhelmøya Subgroup is up to 300 m thick with almost complete early Norian to Aalenian stratigraphic succession in Kong Karls Land, only 5 to 20 m thick condensed or eroded units with several hiatuses are preserved on the western and central Spitsbergen (Bäckstrøm and Nagy, 1985; Nagy

and Berge, 2008) making the offshore-onshore link problematic. As for the Realgrunnen Subgroup in the Barents Sea, the base and top are defined by the early Norian flooding and the Bathonian flooding respectively (Mørk et al., 1999; Worsley, 2008; Henriksen et al., 2011; Koevoets et al., 2018) (Table 1).

The post-depositional history of the succession involves late Jurassic and Cretaceous rifting (Serck et al., 2017), and transpression between the Barents Sea and eastern Greenland in the Eocene (Faleide et al., 1993; Faleide et al., 1996; Faleide et al., 2008; Clark et al., 2014). The effects of these events are most pronounced along the western margin of the NBSB (Fig. 1c). These events therefore had relatively little impact on the present study area, but repeated regional glaciations in the Pleistocene (Vorren et al., 1989) resulted in pronounced erosion referred to as the Upper Regional Unconformity (URU) - a composite erosional feature seen across most of the study area.

3. Data and methods

Coverage and quality of seismic data, in addition to the amount of well data, varies across the study area. Data coverage is extensive in areas with ongoing hydrocarbon exploration and field development such as the Hoop Fault Complex area, where regional 2D seismic data is accompanied by conventional 3D and P-Cable seismic data combined with several recently drilled exploration wells with cores that provide high-resolution biostratigraphy (Vigran et al., 2014). Other parts of the basin remain frontier areas where interpretations have to be extrapolated from observations in areas with dense data coverage. For example, the Fingerdjupet Subbasin in the northwestern parts of the study area is characterised by a deterioration in 2D seismic quality westward, partly due to hard sea floor above and larger burial depths. Data coverage and quality decrease north of the study area, and insight into the nature of the stratigraphic boundary in areas to the north are therefore best offered by outcrop exposures and we present one example from Agardhbukta on eastern Spitsbergen (Fig. 1a).

3.1. Well data and outcrop studies

A database of 95 exploration wells (Fig. 1) from both the Norwegian and Russian sectors of the Barents Sea has been studied. Gamma ray (GR), neutron density (NEU) and density (RHO) log signals are coupled with core data to guide interpretations of changes in gross depositional environment. In addition to standard stratigraphic information available from the Norwegian Petroleum Directorate, key wells are reviewed in terms of biostratigraphic information.

3.2. Seismic data

Regional 2D seismic data, tied to well logs (Fig. 1), are used to map the study interval across the basin. These seismic lines are spaced between 5 and 10 km, and the seismic resolution varies across the study area depending on burial depth. Limits of visibility is typically around 10 m whereas limits of separability are roughly 20 m (cf. Brown, 2011).

The formation boundaries within the Realgrunnen Subgroup are difficult to connect to and trace in seismic because the formations are thin and lithologically similar, which lead to small contrast in acoustic impedance and poor visibility in seismic data imaging. Nine seismic horizons are interpreted on a regional scale and used as a framework for evaluating the basin evolution across the Triassic-Jurassic boundary, including Lower Triassic to Upper Jurassic strata: Top of the Havert Formation, Top of the Klappmyss Formation, Top of the Kobbe Formation, Top of the Snadd Formation, Top of the Realgrunnen Subgroup, Top of the Fuglen Formation, and the Base Cretaceous Unconformity (BCU) (Fig. 1B). Horizon flattening is a powerful tool that help unravel the stratigraphic relationships between strata of different ages relative to a datum. In most of the seismic profiles presented herein, we use the Top of the Relagrunnen Subgroup as a flat datum.
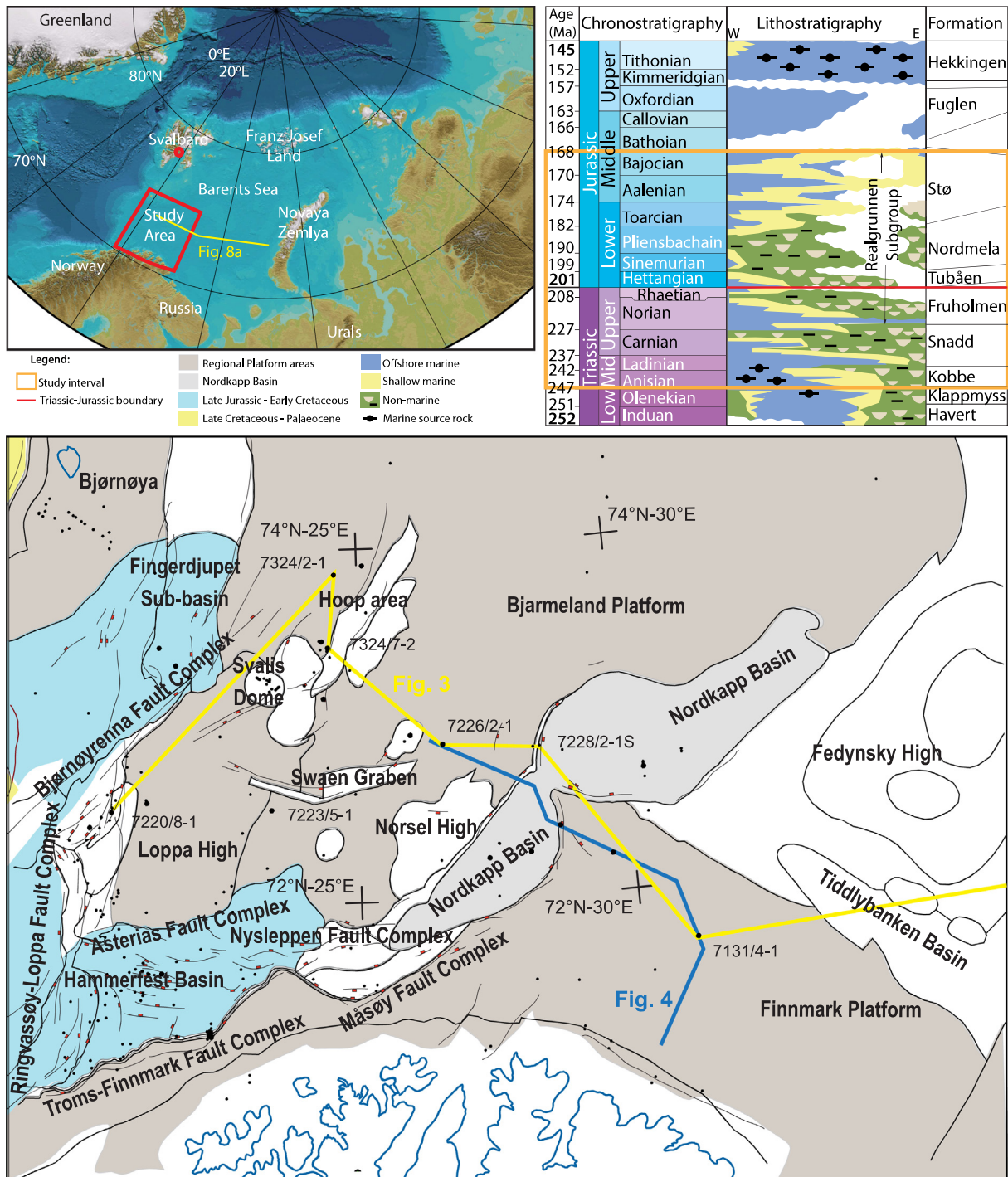
Fig. 1. A) Regional setting of the study area. B) The study interval is the Realgrunnen Subgroup that spans the Triassic-Jurassic transition. The tectonic event occurring at this transition also affects Triassic formations, and the study has therefore also considered formations above and below the study interval. C) Structural setting and exploration wells drilled in the study area.

This surface represents a close-to paleohorizontal surface formed at a maximum transgressive stage in the late Middle Jurassic and is of regional extent. In a few areas, e.g. where the Upper Regional Unconformity (URU) is truncating the Upper Jurassic or where the Realgrunnen Subgroup cannot be mapped with confidence, flattening does not work, and the seismic profiles are consequently distorted in these areas.

P-Cable seismic data is available in the Hoop area (Fig. 1c). These datasets have higher frequencies but shallower penetration depth than conventional seismic, and typically has a vertical resolution of about

5 m at the studied intervals. This high-resolution dataset provides detailed information about the Realgrunnen Subgroup, where the strata are not too deeply buried to be imaged with this method and add important knowledge about the age relationships and stratigraphic evolution of the study interval.

4. Results

Results reveal distinct thickness variations and angular unconformities that are directly tied to prolonged periods of non-

Table 1
Overview of relative ages and stratigraphic relationships in the Norwegian and Russian Barents Sea and Svalbard.

Age[a]	Stage	Barents Sea Stratigraphy	Svalbard Stratigraphy	Russian Zonation
168.3	Bathonian	Fuglen Fm	Agardhfjellet Fm	Bajocian-
170.3	Bajocian	Stø Fm		Bathonian
			Hiatus[b]	Aalenian-
174.1	Aalenian			Bajocian
182.7	Toarcian		Kongsøya Fm	Lower
190.8	Pliensbachian	Nordmela Fm	Svenskøya Fm	Jurassic
199.3	Sinemurian	Tubåen Fm		
201.3	Hettangian			
208.5	Rhaetian	Fruholmen Fm		
227	Norian		Flatsalen Fm	T3
237	Carnian	Snadd Fm	De Geerdalen Fm	T2
242	Ladinian		Tschermakfjellet Fm	
247.2	Anisian	Kobbe Fm	Botneheia Fm	T1
251.2	Olenekian	Klappmyss Fm		
251.9	Induan	Havert Fm	Vikinghøgda Fm	

[a] Numerical age as defined at the base of the interval by the ICS per 2019.
[b] Svalbard Hiatus (Smelror et al., 2019).

deposition and reworking, evident in exploration wells, within the Realgrunnen Subgroup (Fig. 2). In this section, we show the results from the different datasets, and how these are used to map truncation patterns throughout the study area.

### 4.1. Stratigraphic information from wells

The Realgrunnen Subgroup exhibits large temporal and spatial variations in thickness and provides important information relevant for this study about time of deposition and periods of non-deposition and erosion. Biostratigraphic analyses have revealed the presence of a considerable hiatus between the Norian-Rhaetian (Fruholmen Formation) and the uppermost Triassic to Middle Jurassic, Rhaetian-Bajocian (Tubåen, Nordmela and Stø formations) (Fig. 2).

In the northwestern and northern parts of NBSB, the Toarcian (Stø Formation) is unconformable overlying directly on the Norian (Fruholmen Formation) (e.g. wells 7324/2-1, 7325/1-1, 7324/10-1). The hiatus in these wells is considerable, and spans to over 40 m.y. In other wells, a thin late Pliensbachian package (Nordmela Formation) is present in between the Fruholmen and Stø formations (e.g. wells 7324/8-1, 7324/7-2), while in other parts of the platform areas, also Hettangian-Sinemurian (Tubåen Formation) is present although relatively thin, as evident in for example well 7226/2-1.

The thickness of the Norian (Fruholmen Formation) varies from c. 27 to 120 m in the northwestern and northern NBSB, which suggests, together with the biostratigraphic analysis, pronounced truncation and erosion in the late Triassic and early Jurassic (e.g. 7324/7-2; Fig. 3). The unconformity is covered by thin units of dominantly Middle Jurassic Stø Formation (maximum 27 m) and occasionally thin Lower Jurassic Tubåen and Nordmela formations are present (Fig. 3). Review of the biostratigraphic information of the wells in the northwest NBSB also reveal that reworked Triassic taxa (e.g. *Kyrtomisporis gracilis*, *P. amicus* and *Cavatosporites obvius*) are present in both the Nordmela and
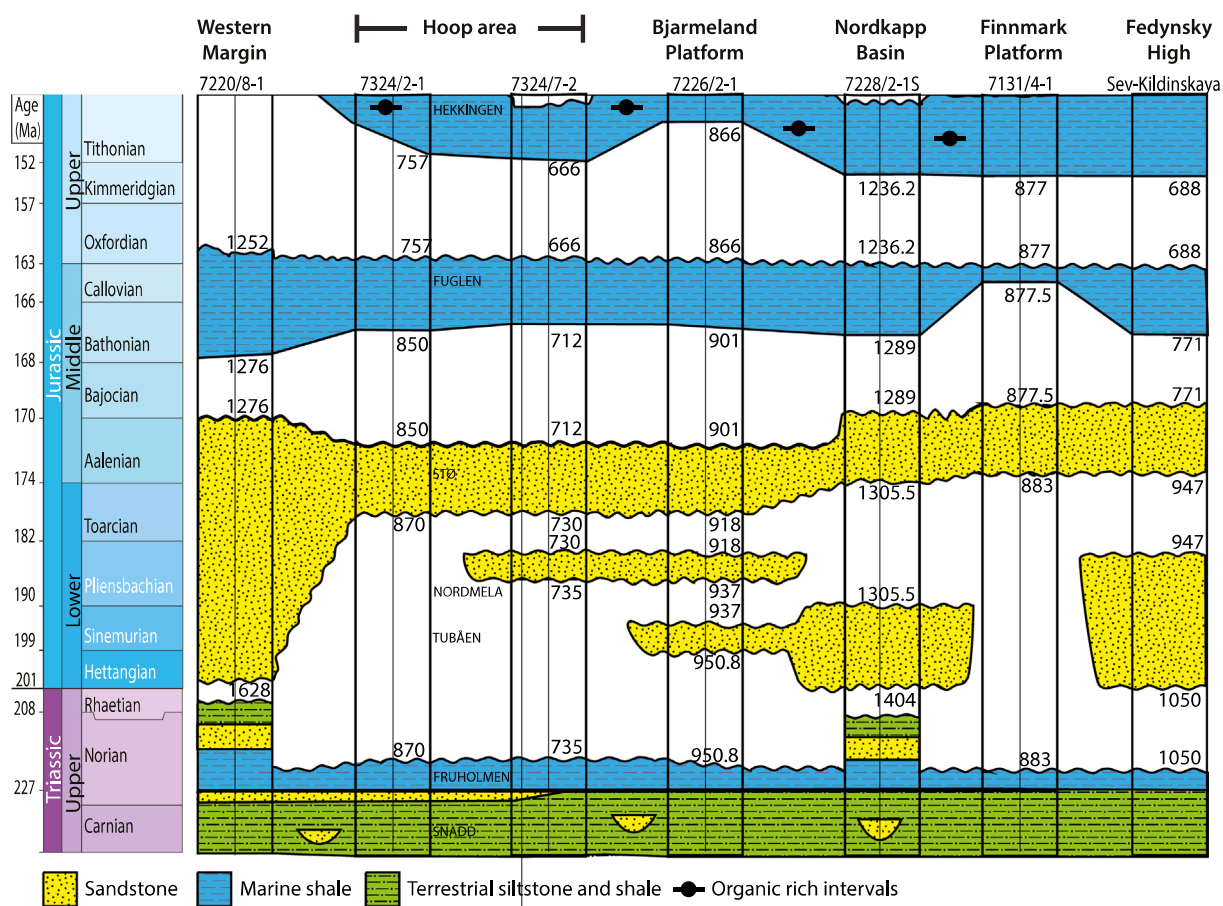
Fig. 2. Gaptogram illustrating the important hiatus at the Triassic-Jurassic transition in time and space, and how it is manifested in different parts of the NBSB and the eastern Barents Sea. The figure illustrates the presence of several unconformities at different time intervals within the Realrgunnen Subgroup, suggesting the uplift history was punctuated and long-lasting. Wells used in the gaptogram are shown in the following correlation panel (Fig. 3), and its location is shown in Fig. 1c.
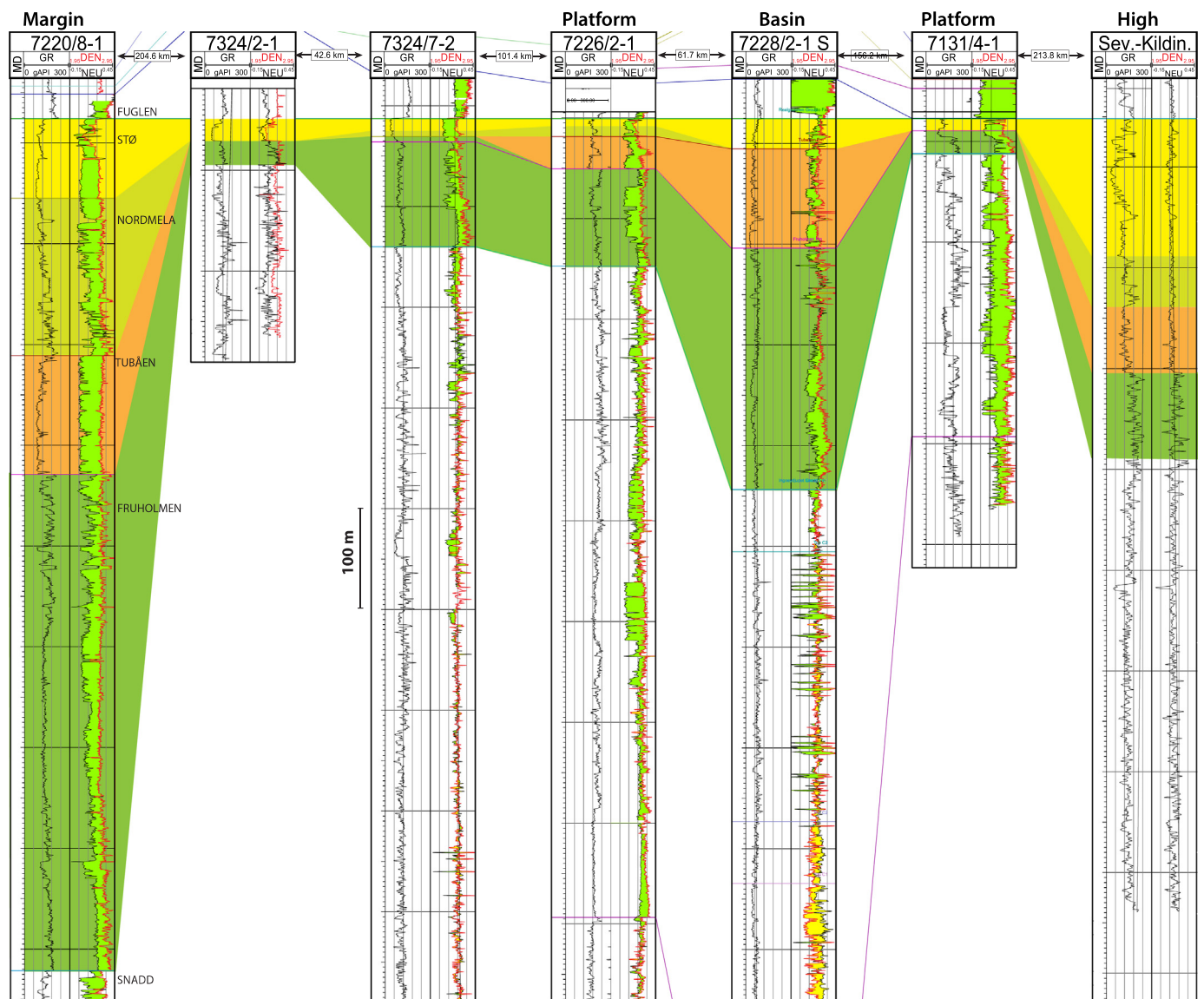
Fig. 3. Stratigraphic thickness variations from west to east in the NBSB and eastern parts of the Fedynsky High. The location of the correlation panel is shown in Fig. 1c and it corresponds to the Gaptogram in Fig. 2. The correlation shows differential preservation and non-preservation of the different stratigraphic intervals (the Fruholmen, Tubåen, Nordmela and Stø formations, as defined by the Norwegian Petroleum Directorate) in the Realgrunnen Subgroup. On the western margin of NBSB, the Realgrunnen Subgroup is very thick compared to the Bjarmeland Platform and Nordkapp Basin. In the Hoop area and on the Finnmark Platform, many of the formations are absent and the Realgrunnen Subgroup is condensed.

Stø formations (e.g. 7324/7-2 and 7324/8-1).

Towards the southeastern margin of the basin and on the *Fedynsky High*, for example in well 7131/4-1, the Norian is thin (c. 29 m) and is overlain by a thin Stø Formation of Aalenian age (Fig. 3). The same trend is observed along the southern part of the basin where Tubåen Formation (latest Rhaetian-Hettangian) is unconformably overlying a condensed early Norian package.

No wells are yet drilled on the Fedynsky High, but Norian deposits are overlain unconformably by condensed Lower to Middle Jurassic deposits in the adjacent Severo-Kildinskaya and Severo-Murmanskaya wells (Suslova, 2013a, 2013b; Norina et al., 2014). Although, the biostratigraphic analysis available for the Russian wells shows a considerable hiatus, it varies from study to study.

A more complete sedimentary package of the Realgrunnen Subgroup, compared to the platform areas, is present in the basins of the southern and central parts of NBSB (e.g. 7228/2-1 S; Fig. 3). The thickness of the Fruholmen Formation ranges from c. 50 m up to 220 m, while the Tubåen Formation varies in thickness from about 70 m to

150 m in the Hammerfest and Nordkapp basins (Fig. 3). In the Hammerfest Basin and parts of the Nordkapp Basin, there are seemingly no distinct biostratigraphic hiatus between the late Triassic and earliest Jurassic formations (e.g. 7228/2-1 S). However, the basal boundary of the Tubåen Formation is characterised by a general change from mudstone to sandstone – often with an erosive base.

Along the western margin of the Barents Sea, the Realgrunnen Subgroup reaches as much as c. 800 m (e.g. 7220/8-1) and is more complete with fewer and shorter hiatuses (Figs. 2 and 3). In these western wells, the formation includes thick successions of deltaic heterolithic deposits associated with the Krabbe Member of the Fruholmen Formation which is largely absent from wells on the Bjarmeland Platform.

The Tubåen Formation also reaches considerable thicknesses along the western margin. It is, however, absent in both the Hoop and Fingerdjupet areas (Fig. 3). A similar trend is mapped for the Nordmela Formation, for which the thickest intervals are observed within in the Bjørnøyrenna Fault Complex (e.g. 7220/8-1). The Stø Formation also

shows the same thickness trends as the underlying Nordmela Formation, reaching more than 140 m along the western margin of the southwestern Barents Sea. Unlike older Jurassic sequences, the Stø Formation is present as a relatively thin succession (10 to 30 m) across most of the eastern and northern parts of the Bjarmeland Platform (Fig. 3) (Klausen et al., 2017). Biostratigraphic data suggests that the Realgrunnen Subgroup is more complete in the western areas compared to for example the wells on the margin of the Finnmark Platform and the Bjarmeland Platform (Fig. 2).

In the Eastern Barents Sea, the thickness of Jurassic strata increases to more than 1000 m, and a maximum thickness of c. 1500 m thickness is penetrated in the Arcticheskaya well in the central parts of southeastern Barents Sea (Suslova, 2013a, 2013b). Stratigraphic unit subdivision is based primarily on biostratigraphy. However, since the paleontological data are quite scarce and fossils are poorly preserved, sequence stratigraphic principles and stratal relationships are emphasized when evaluating the Jurassic strata in seismic data from the Eastern Barents Sea. A total of nine cycles have been defined within the Jurassic strata based on logs (Suslova, 2013a, 2013b), of which the Top Realgrunnen Subgroup equivalent (Middle Jurassic) is used as a regional datum for correlation between the Russian and Norwegian sectors.

4.2. Stratigraphic development in regional 2D seismic data

Regional seismic lines, tied to well logs with stratigraphic information confirm that thickness variations and hiatuses observed in wells, correspond to truncation of underlying Triassic intervals. Coincident with this truncation are often distinct angular unconformities between Triassic and Lower Jurassic strata that become evident when flattening the top Realgrunnen or BCU seismic horizon (e.g. Fig. 4). This regional seismic cross section example shows some of the most important characteristics of the Triassic-Jurassic transition: i) Truncation of Lower to Upper Triassic strata, partially draped by Lower to Middle Jurassic deposits, along the southern margin of the basin. ii) Subtle angular unconformities between Upper Triassic strata and Jurassic strata above older basement rooted faults within the basin, exemplified by truncation of the Norian Fruholmen Formation on the southeastern margin of the Nordkapp Basin. iii) Differential preservation associated with reactivated salt structures. iv) General northwestward thinning of Upper Triassic strata caused by truncation below the Jurassic.

The full extent of the late Triassic to early Jurassic basin inversion is however partly masked by later erosion events, e.g. the URU, in certain areas within the basin and along the southern margin. Below we show these different erosion patterns in key parts of the NBSB. Since it is not possible to distinguish between the Lower Jurassic formations (Tubåen, Nordmela and Stø) in seismic, these are grouped together. In addition to the angular unconformity between the Upper Triassic and the Lower to Middle Jurassic, mapping also include erosion of both the Triassic and Jurassic strata below URU where this applies.

4.2.1. Northwest NBSB (Hoop area)

Data coverage and quality in the northwest part is exceptional and this offers crucial insights into the importance of the Triassic-Jurassic transition in the NBSB. This area surrounds the Svalis Dome (Fig. 1) where the Realgrunnen Subgroup varies considerable in thickness (Fig. 5). In particular, the thickness of the Norian-Rhaetian Fruholmen Formation varies significantly between the Hoop area and the adjacent Maud Basin (Fig. 5). Along the margins of the Svalis Dome, abrupt decrease in thicknesses are associated with distinct angular unconformities between the Upper Triassic (Fruholmen and Snadd formations) and the overlying Lower to Middle Jurassic intervals (Fig. 5). Away from the dome, thicknesses increase and no angular unconformities are identified. In this part of the basin, the Lower Jurassic Tubåen Formation is not present (Fig. 3), instead there is a long hiatus

between the Upper Triassic formations and the Nordmela and Stø formations (Fig. 2).

Regional seismic lines indicate that uplift of the Svalis Dome is coupled with diapirism of thick Permian salt (Fig. 5a). Because Lower Jurassic strata are unconformable overlying truncated Triassic successions (Fig. 5b), it is apparent that the Lower Permian salt below the Svalis Dome moved in the late Triassic to early Jurassic and came to a halt around the end of the deposition of the Realgrunnen Subgroup in the middle Jurassic.

High-resolution P-Cable seismic data provide unique insight into the truncation trends at the Triassic-Jurassic transition in the Hoop area as it provides an image of higher resolution that resolves details about the truncation pattern and internal thickness variations within the Realgrunnen Subgroup not clearly imaged in standard broadband seismic (e.g. Fig. 5b). P-Cable seismic data in Fig. 6 shows that the Lower Jurassic Stø and Nordmela formations are unconformably overlying the Fruholmen and Snadd formations with an angular unconformity, and there is pronounced incision at this boundary.

In other parts of the Hoop area and towards the northwest, there is a decrease in the overall thickness of the Snadd Formation. Regional 2D seismic lines tied to well logs (Fig. 5c) show that the Top Snadd seismic horizon converge on the base Realgrunnen Subgroup while also the stratigraphic thickness between the Top Kobbe and Top Snadd horizons decreases in a basinward direction.

### 4.2.2. West and south NBSB (Loppa High and Hammerfest Basin)

Due to Pleistocene glaciations, all evidence for potential uplift and erosion or deposition at the Triassic-Jurassic boundary has been removed. We can observe this in Fig. 7, where both the Upper Triassic and Jurassic strata are truncated below URU. This unconformity partly obscures the mapped truncation trends within the basin. The high has been argued to have been reactivated several times during the basin evolution (Gabrielsen et al., 1993) but be the site of sediment accumulation during the late Triassic to early Jurassic (Indrevær et al., 2017). Westward thickening of the Relagrunnen Subgroup in Fig. 7a suggest that this area could have been a site of deposition during this period.

South of the Loppa High, the thickness of the Realgrunnen Subgroup increases westward (Fig. 7b) in a similar manner as we see tendencies for east of Loppa High (Fig. 7a). This complicates our understanding of the nature of the stratigraphic boundary. North of the high, Triassic strata show angular unconformities to preserved Lower Jurassic strata, whereas the Realgrunnen Subgroup gradually thicken towards the west in the Hammerfest Basin.

4.2.3. Central NBSB (Bjarmeland Platform and Nordkapp Basin)

Truncation of Triassic strata is also evident in central parts of the NBSB, including the Bjarmeland Platform and Nordkapp Basin (Fig. 1). Truncation patterns are generally much subtler on the Bjarmeland Platform than elsewhere in the basin. Angular unconformities between Norian strata belonging to the Fruholmen Formation and the Lower to Middle Jurassic intervals unconformably above are, however, clearly seen in the central parts and towards the northwest (Fig. 4). Towards the Loppa High, an increase in thickness of Norian strata contrasts the general thinning trend (Fig. 7). Although an angular unconformity is identified towards this high as well. This truncation occurs below URU and affects both Triassic and Lower Jurassic strata, and post-dates the basin inversion at the Triassic-Jurassic transition. Elsewhere on the Bjarmeland Platform, especially in eastern parts, Lower Jurassic strata are oriented parallel to Triassic intervals and there are no distinct angular unconformities (Fig. 7b). Thickness maps however indicate that there might be erosion in this part of the basin as well due to the thinning of the Fruholmen and Tubåen formations in this area (Fig. 3).

The Nordkapp Basin is divided into a NE and SW segment (Fig. 1), and salt structures are present in both but angular unconformities between Triassic and Jurassic strata are concentrated along the margins of
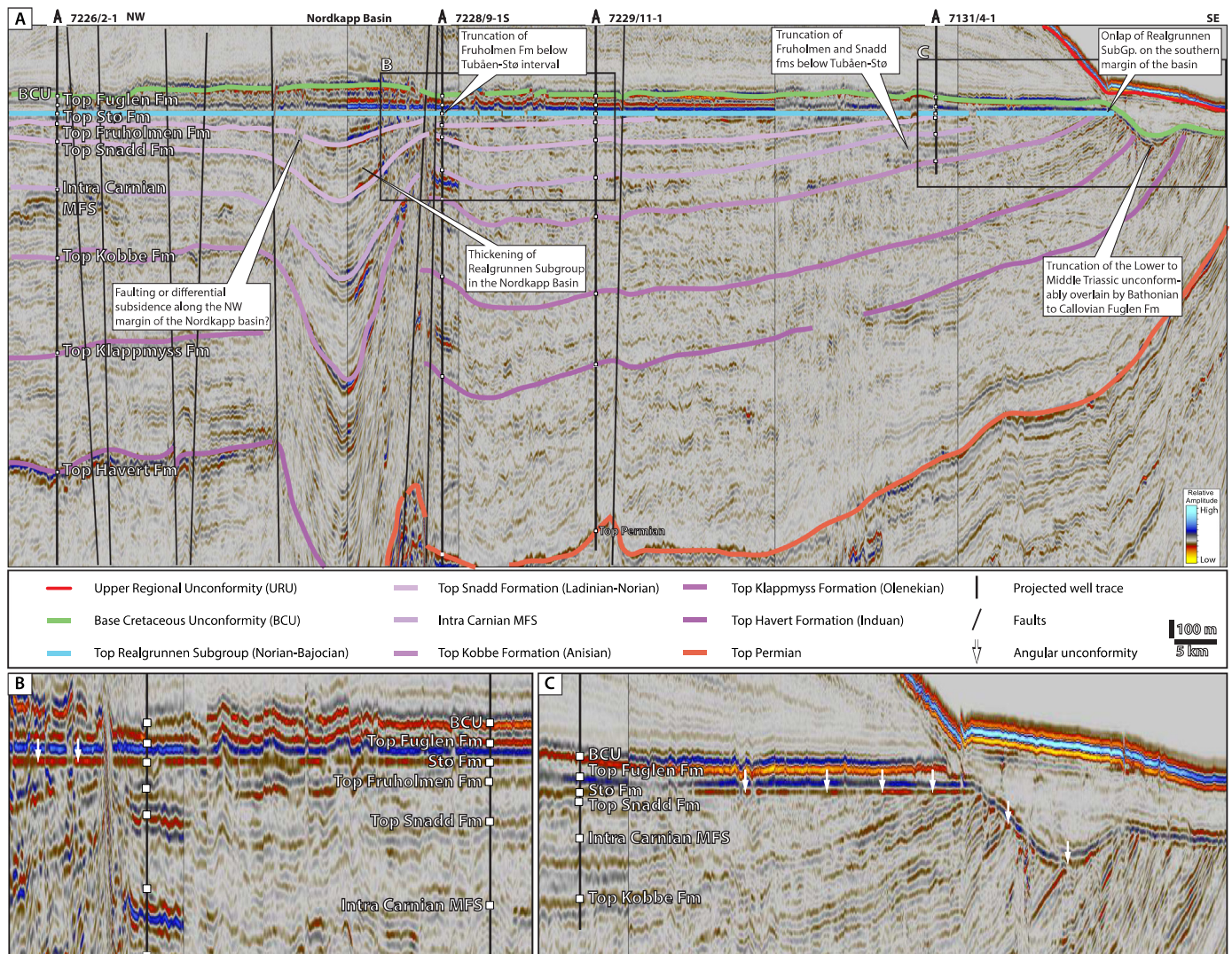
Fig. 4. Example of the different truncation patterns and differential preservation of Triassic strata from the SE Finnmark Platform to NW Bjarmeland Platform. Upper Triassic strata has an angular unconformity with overlying Jurassic strata, in addition to relatively large thickness variations. The seismic section is flattened on top Realgrunnen Subgroup. Note the truncation of Lower Triassic also in the unflattened part of the section to the left (SE) in the figure. In this part of the basin, it is difficult to trace top Realgrunnen Subgroup, but Upper Jurassic strata can be mapped above truncated Lower Triassic strata with an angular unconformity to these. The Realgrunnen Subgroup is better preserved in the Nordkapp Basin and shows greater thickness here, but there are subtle thickness variations on highs and platform areas as illustrated here by thinning towards NW and above the margins of the Nordkapp Basin. Location of profile shown in Fig. 1c. White arrows shows where the Triassic formations show angular unconformity to the overlying Jurassic strata.

the basin, not the salt structures. This is different from observations on the Svalis Dome (Fig. 5a). Interestingly, although the margins of the southern segment of the Nordkapp Basin is associated with thinning of Upper Triassic strata (Fig. 4), margins of the northern segment are not.

4.2.4. Eastern Barents Sea (Russian sector)

East of the NBSB, regional 2D seismic data show that the Triassic-Jurassic transition can be tied to the uplift of Novaya Zemlya in the Russian sector of the Barents Sea basin (Fig. 8a). In addition to the previously documented thickening of Norian and Lower Jurassic strata in the foreland basin of the Novaya Zemlya Fold and Thrust Belt (Scott et al., 2010; Suslova, 2013a, 2013b), seismic transects show the results of folding and truncation of the Triassic strata immediately west of and adjacent to the Novaya Zemlya uplift (Fig. 8c). This uplift is also associated with distinct onlap of Upper Jurassic strata (Fig. 8c), showing that the uplift had ended by the late Jurassic and thus that the compressional forces creating the fold and thrust event was time-equivalent with the uplift and erosion event in the NBSB.

4.3. Regional mapping of truncation trends

When mapping the abovementioned truncation trends on a regional scale, we differentiate areas with angular unconformity between 1) Triassic and Lower Jurassic strata; and 2) URU and underlying strata, including both Jurassic and Triassic strata (e.g. Fig. 7a). There is considerable erosion even in areas without distinct angular unconformities since distinct thickness variations and hiatuses are observed in wells (Fig. 3).

The Snadd Formation is truncated below the Lower Jurassic succession on the Finnmark Platform and in the northwestern part of the basin (Fig. 9). The formation is also eroded in the area between the Hammerfest and Nordkapp basins (Fig. 7b) and juxtaposed salt domes (e.g. Figs. 4a and 5b). Truncation of the Fruholmen Formation below the Lower Jurassic is observed regionally, whereas truncation of the older Snadd Formation occurs farther to the northwest and towards the basin margins (Fig. 9). Unlike this formation, erosion of the Fruholmen Formation is also seen above older basement rooted faults such as the flanks of the Nordkapp Basin (e.g. Fig. 4). In addition, there is a distinct
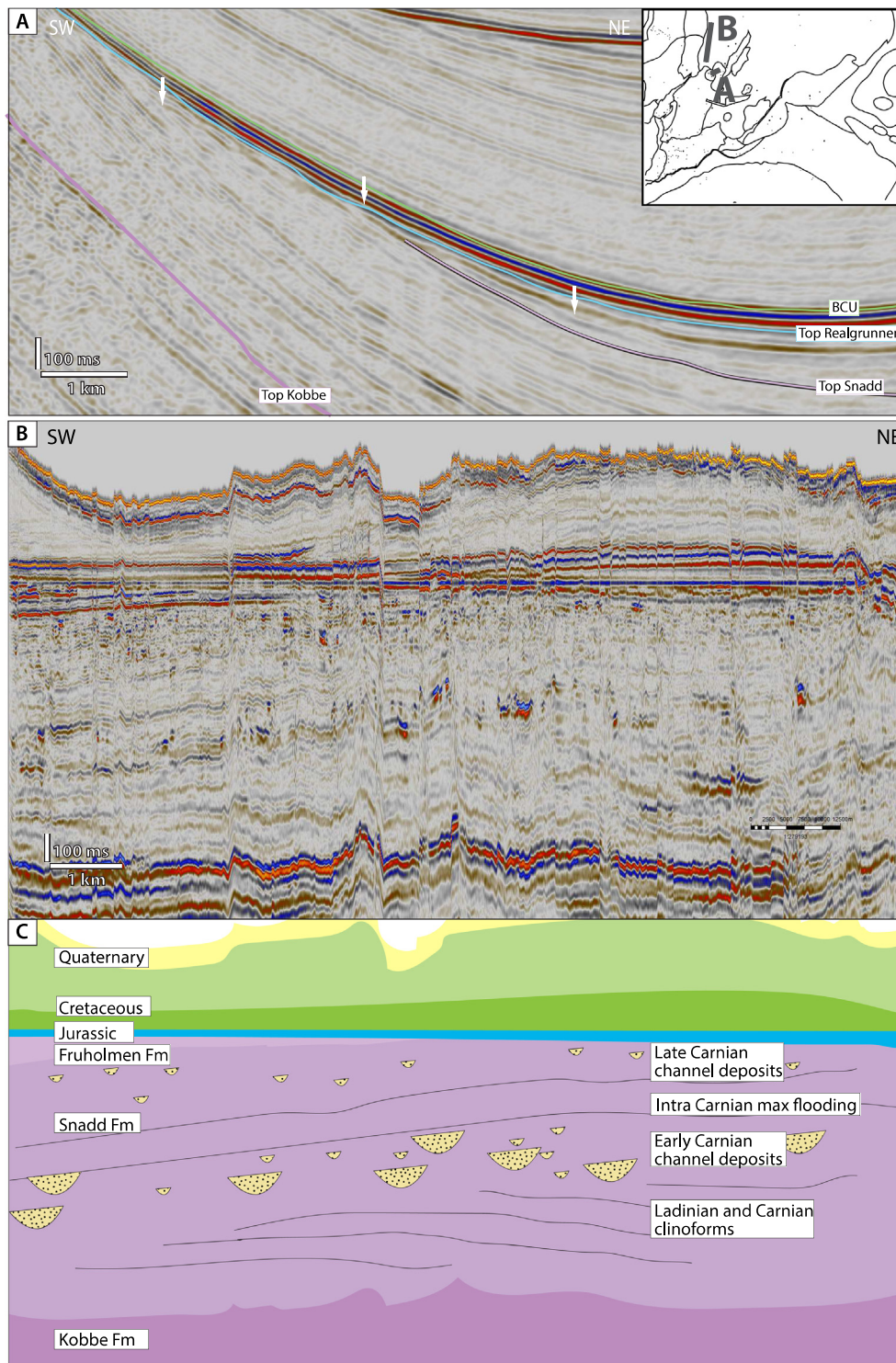
Fig. 5. A) Angular unconformity between Upper Triassic and Lower Jurassic strata on the eastern flank of the Svalis Dome. White arrows highlight reflectors that are truncated at different angles. B) Seismic section flattened on the Top Realgrunnen Subgroup reflector, without interpretation. C) Schematic representation of the uninterpreted seismic in B. Angular unconformity between the Upper Triassic and Lower Jurassic strata is clearly seen. Also evident is the pronounced truncation of the Snadd Formation northward, where intervals with channelized deposits (as interpreted in Klausen et al., 2015) converge towards the flattened datum set to Middle Jurassic.

belt of Fruholmen Formation truncation on the Bjarmeland Platform that is also evident in the Hammerfest Basin (Fig. 9; e.g. Fig. 7).

Our mapping reveals a pattern of intra-basinal erosion of Upper Triassic strata below the Jurassic that broadly follow N-S striking trends (Fig. 9). Except for discrete areas overlying older structural features, such as for example the Nordkapp Basin margin and areas close to the southern margin of the NBSB, angular unconformities between the Upper Triassic strata and Lower Jurassic are characterised by erosion of the Fruholmen Formation in the central part of the Bjarmeland Platform. This erosion gradually propagates lower into the older stratigraphy towards the west where the erosion penetrates down into the

Snadd Formation (Fig. 5c).

4.4. Outcrop analogues in Svalbard

Important evidence for the basin-wide distribution of an unconformity near the Triassic-Jurassic boundary is evident in the stratigraphic record on Svalbard (Johannessen and Embry, 1989; Mørk et al., 1999; Smelror et al., 2009). Most of these authors related the break to faulting or tectonic uplift of the archipelago. The Norian to late Pliensbachian succession of the Wilhelmøya Subgroup in Svalbard, i.e. the onshore equivalents to Fruholmen, Tubåen and Nordmela
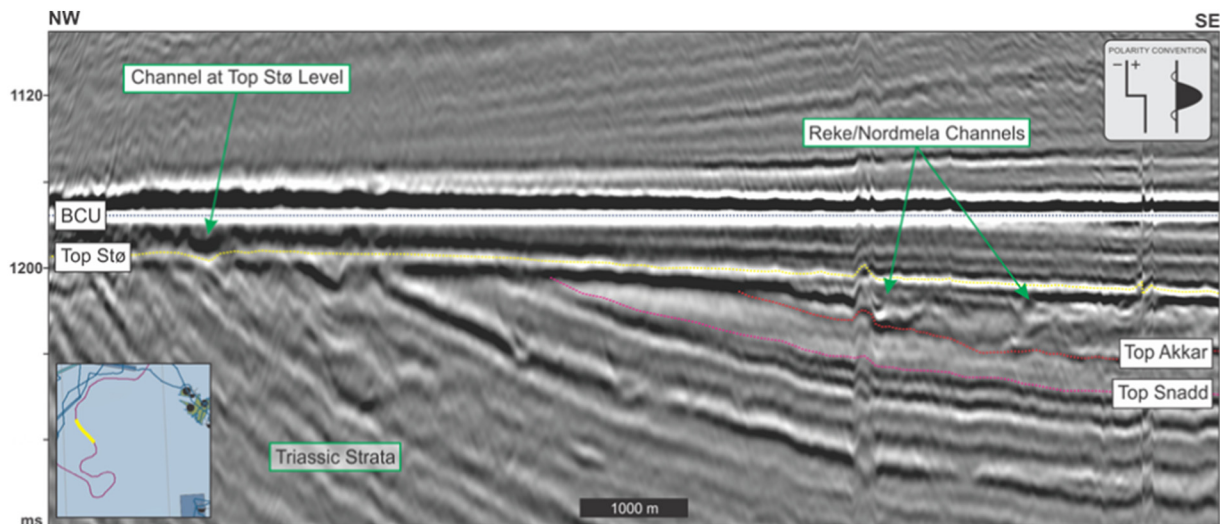
Fig. 6. Truncation pattern and internal depositional characteristics of the Realgrunnen Subgroup in high-resolution P-Cable seismic data, revealing distinct erosional relief interpreted as channels at the Triassic-Jurassic transition adjacent to the Svalis Dome. This suggests pronounced subaerial erosion of uplifted local highs during the period and corroborates the angular unconformity mapped on a regional scale.

formations, varies from c. 200 m thick successions in the east (Kong Karls Land) to less than 10 m condensed or eroded units with several hiatuses or lacunas in western Spitsbergen (Bäckstrøm and Nagy, 1985; Johannessen and Embry, 1989; Krajewski, 1990; Grogan et al., 1999; Nagy and Berge, 2008, Olaussen et al., In press; Rismyhr et al., In press).

The best exposure of the Triassic-Jurassic unconformity in Svalbard is found in northern Agardhbukta, East Spitsbergen (Fig. 1a). Here, condensed, shallow marine Lower Jurassic strata of Pliensbachian age rest unconformably on reworked Upper Triassic strata (Fig. 10). The Upper Triassic comprise a condensed and reworked meter-thick marine succession of the Norian Flatsalen Formation found unconformably above terrestrial deposits of the Carnian to Norian De Geerdalen Formation (Rismyhr et al., 2019). The upper part of this formation is regionally characterised by shallow marine, transgressive deposits overlain by offshore marine Flatsalen Formation (Klausen and Mørk, 2014; Paterson et al., 2016). The fact the Rhaetian to Early Toarcian are missing and that Norian Flatsalen is thin or preserved as remanie in most part of Spitsbergen, unlike the eastern islands Hopen and Kong Karls Land, Svalbard, suggests significant uplift and erosion near the Triassic-Jurassic boundary. The Svenskøya Formation above is Pliensbachian in age, and the hiatus separating it from the wave ravinement in the condensed Flatsalen Formation is substantial.

5. Discussion

Our novel observations from wells, seismic and outcrop document the presence of a regional unconformity on the Triassic-Jurassic transition in the Barents Sea, which is partly represented by a pronounced angular unconformity. This reveal that an important basin-wide tectonic regime was active in the Greater Barents Sea during the late Triassic and continued into the early Jurassic. The importance of this tectonism on the basin configuration in the western part of the Barents Sea has hitherto been overlooked by previous studies but is crucial in order to understand the overall structural and stratigraphic evolution of the basin. Although our present dataset is inadequate to constrain the full geodynamic evolution of the basin, the mapped angular unconformities and salt reactivations throughout the basin show that there was basinwide compression which are time equivalent to the protrusion of the Novaya Zemlya Fold and Thrust Belt. In the context of our findings, it is clear that the diametric shift in basin setting from high to low accommodation is best explained as a forebulge uplift, and

below, we discuss the cause for this uplift, its impact on older basin rooted faults and salt, and the implications of this important tectonic event.

Although data coverage varies across the basin, we recognize that the two broad truncation trends mapped within the study area (Fig. 9) can be tentatively traced across the Greater Barents Sea: 1) a proximal uplift and erosion trend extends from northern parts of Norway, via the Fedynsky and Fersmanovskaya highs towards Kong Karls Land; and 2) a distal trend including the N-S striking truncation pattern of Fruholmen and Snadd formations with lower magnitude of uplift extending from the Hammerfest Basin towards Svalbard. These two distinct trends are located about 400 and 800 km away from the thrust front in Novaya Zemlya (Fig. 11).

5.1.1. Causes for regional uplift, truncation and reactivation

The mapped truncation trends in the NBSB, reactivation of older structures, and their regional extension based on outcrop data and previous studies align broadly parallel to the fold and thrust belt forming contemporaneously in the east. Correlation across the Barents Sea shows that in the east, Lower to Upper Triassic strata are folded and tilted and overlain unconformably by onlapping Lower to Middle Jurassic strata (Fig. 8c). Upper Triassic strata are less folded, but somewhat tilted relative to overlying Jurassic strata. This shows that compressional forces acted in the east, and that this folding and thrusting (Scott et al., 2010) was contemporaneous with tilting in NBSB – proving a direct link between the tectonism in eastern and western parts of the Barents Sea.

Proximal and distal truncation trends documented above (Fig. 9) suggest a forebulge-style uplift with diminishing magnitude away from the compression. Because of the basin configuration of the Barents Sea, this forebulge trend does not conform directly to standard models (e.g. Allen and Allen, 2005). Forebulge apices typically range in distance from their associated thrust front by about 200 to 600 km depending on the orogenic load and flexural strength of the lithosphere (Allen and Allen, 2005). This is exemplified by the approximately 200 to 400 km in the Western Interior Seaway (DeCelles and Giles, 1996; DeCelles, 2004); 500 to 600 km in the Amazonian Basin (Roddaz et al., 2005; Chase et al., 2009); c. 200 km in the Caucasus (Ershov et al., 1998); and c. 400 km in Himalaya (DeCelles, 2012). The distinct truncation trends in the Barents Sea are located about 400 and 800 km away from the
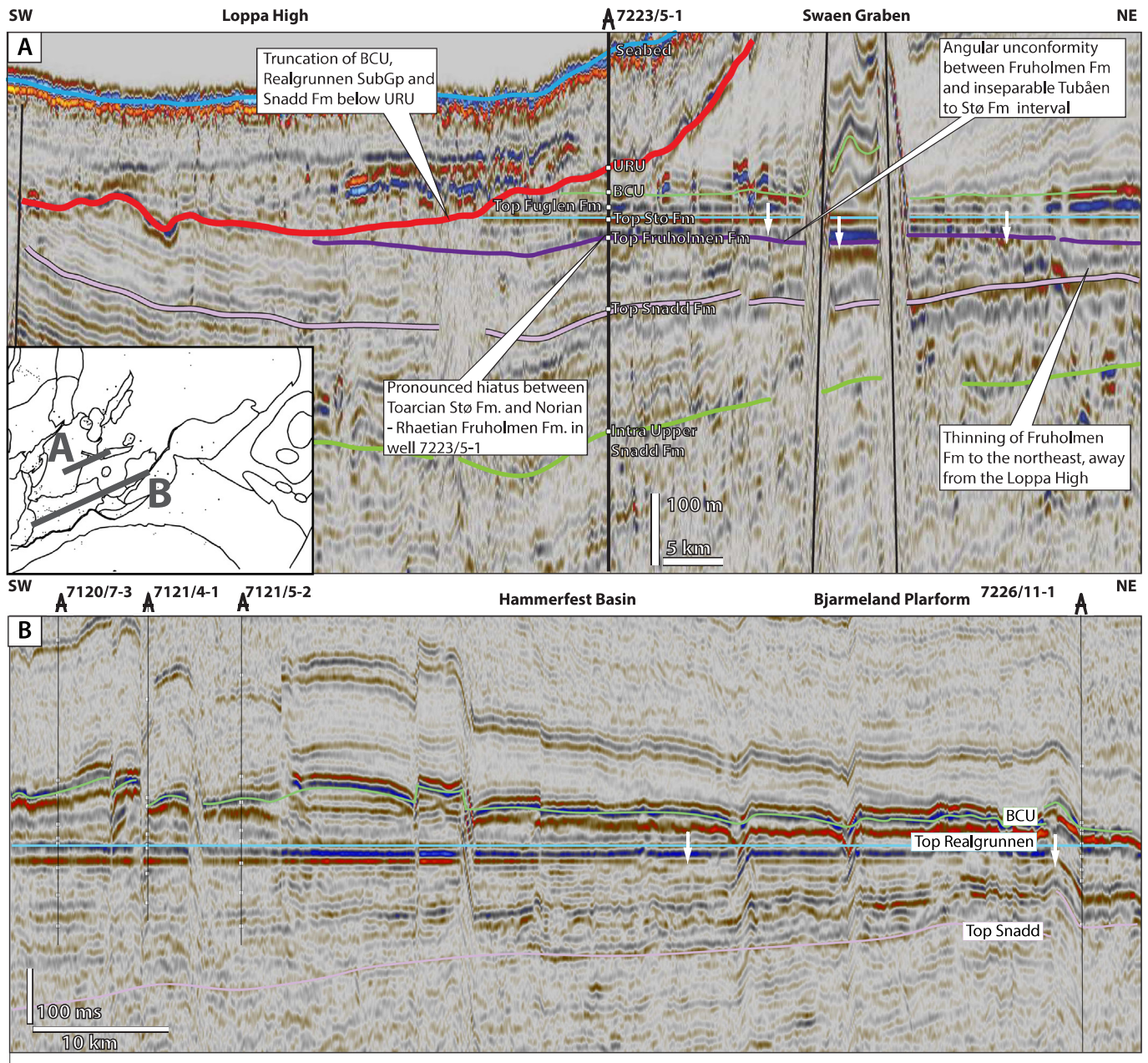
Fig. 7. A) Example of truncation pattern on the Loppa High with thinning of the Fruholmen Formation similar to other areas of the Bjarmeland Platform and Hammerfest Basin, but with an apparent thickening towards the Loppa High. It is not possible to determine how the trend continues westward since URU erodes both Jurassic and Triassic strata in this direction. B) Similar trends of westward thickening of Upper Triassic strata is observed in the Hammerfest Basin south of the Loppa High. Both seismic sections are flattened on the top Realgrunnen Subgroup reflector, but since this surface is eroded below URU in some places, discrete areas in A are not flattened. White arrows indicate truncation.

thrust front, suggesting that the proximal trend conforms to the relative position of typical forebulges. The forebulge apex at approximately 400 km distance from the Novaya Zemlya Fold and Thrust belt indicates the wavelength of the forebulge (Turcotte and Schubert, 2014). The amplitude of the uplift is more complicated since it evidently varies along strike and likely responded to dynamic topography (Burgess and Moresi, 1999), but erosion rates on the order of many hundreds of metres can be inferred based on the stratigraphic relationships and erosion observed on the Fedynsky High. The dome-shaped patterns of this forebulge uplift trend are however distinct from standard forebulge trends (e.g. Allen and Allen, 2005), but can be explained by the heterogeneous nature of the lithosphere below the Greater Barents Sea basin (Klitzke et al., 2015; Gac et al., 2016; Klitzke et al., 2019) that

complicate the forebulge uplift pattern (Fig. 11).

The uplifted part of the Barents Sea, including Svalbard, cover approximately 500,000 km² by conservative estimates based on shaded areas in Fig. 11. This is comparable in areal extent to other zones of uplift distal to the foreland basin, for example is the areal extent of uplifted zones in front of the Sevier forebulge in the Cretaceous Western Interior Seaway approximately 300,000 km² (based on outlines by White et al., 2002), whereas modern India has a forebulge area extent of about 450,000 km² (based on outlines by DeCelles, 2012, not including potentially uplifted back-bulge areas).

Three factors however distinguish the Barents Sea uplift from the classical setting for forebulge uplifts (e.g. Allen and Allen, 2005): 1) no pronounced underplating beneath the fold and thrust belt (Faleide
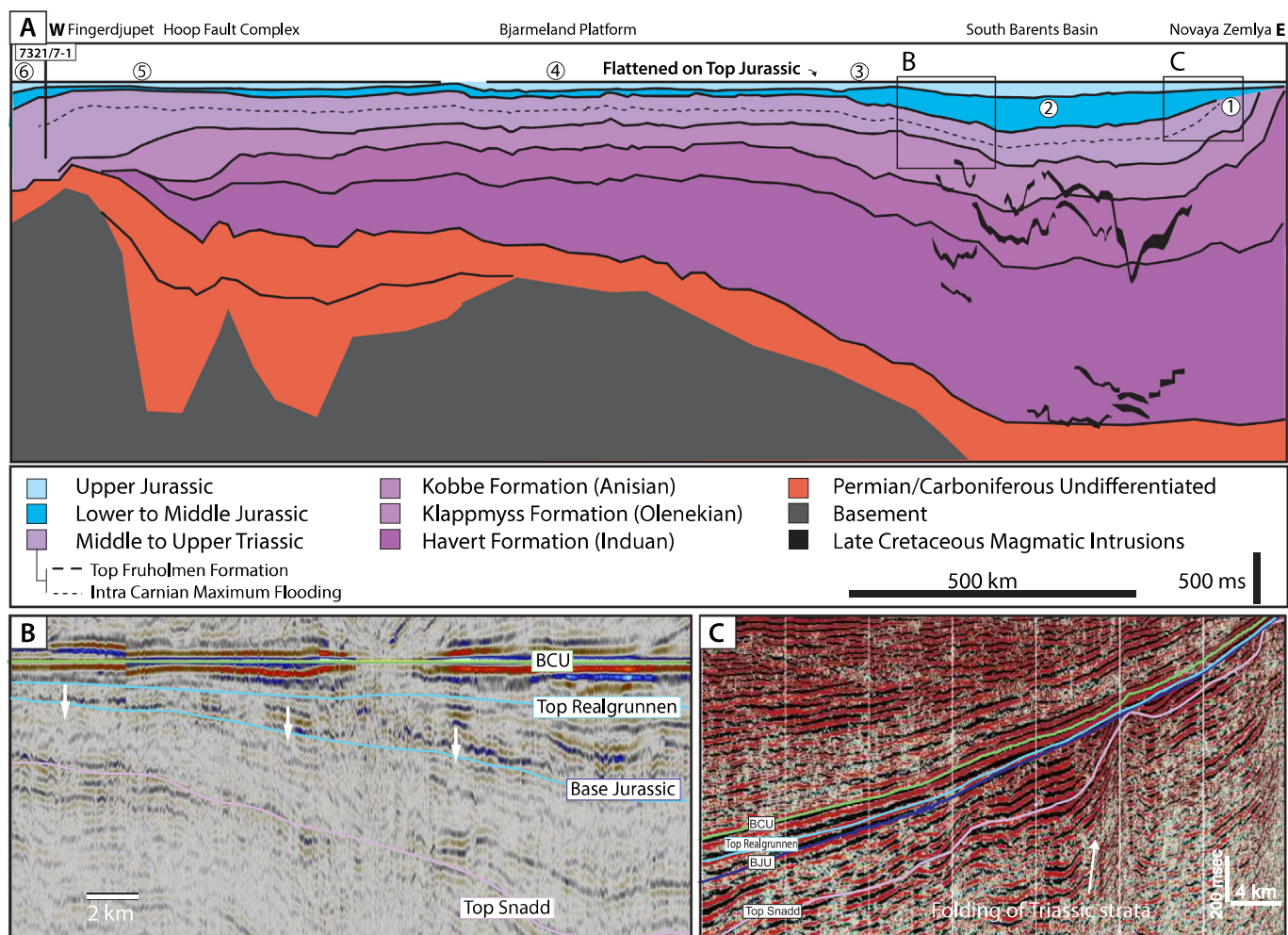
Fig. 8. A) Regional geoprofile from the Fingerdjupet Subbasin on the western margin of NBSB to Novaya Zemlya in the east. Numbers denote from east to west: (1) angular unconformities reflecting uplift of Triassic strata on the margin of Novaya Zemlya; (2) Jurassic foreland basin to the Novaya Zemlya fold and thrust belt; (3) truncation of Fruholmen Formation on the margin of the forebulge; (4) Truncation and differential preservation of Upper Triassic beneath Lower Jurassic deposits; (5) Truncation of the Snadd Formation in the Hoop Fault Complex Area; and (6) thickening of Upper Triassic and Lower Jurassic strata to the west. B) Close-up example of the truncation of Upper Triassic on the western, distal margin of the Jurassic foreland basin. White arrows highlight angular unconformity. C) Close-up of the eastern margin of the foreland basin, proximal to the fold and thrust belt. Note anticlinal compressional folding of Lower to Middle Triassic sedimentary strata, truncation of Upper Triassic strata and gradually more onlap towards the Jurassic (Top Realgrunnen Subgroup).

et al., 2018); 2) a limited orogenic wedge (Stoupakova et al., 2011); and 3) a deep sedimentary basin with heterogonous basement instead of continent-continent collision, which is the basis for many conceptual models. This heterogeneity is manifested by the differential uplift and erosion along the western margin of the Eastern Barents Sea basins where highs such as Fedynsky and Fersmanovskaya, underlain by old crustal blocks (Gac et al., 2016), show signs of erosion while juxtaposed areas such as the eastern Bjarmeland and Finnmark platforms show less erosion. Nevertheless, because of the many similarities between classical foreland basins and their forebulge areas and what we observe in the Greater Barents Sea, including proximal foreland basins (Scott et al., 2010; Suslova, 2013a, 2013b) and highs bordering a broad zone of uplift (Fig. 11), we interpret forebulge uplift to be the cause of the regional uplift in the Barents Sea. Importantly, there are also no other documented compressional tectonic regime at play in the basin during this period.

Across the basin, compression is distributed along a heterogeneous basement and lithosphere by thick-skinned compression and manifested in different degrees of deformation summarized in Fig. 12. First-order deformation can be linked to large-scale variability in the lithosphere (Gac et al., 2016), whereas second-order deformation corresponds to Paleozoic graben systems. In the immediate front of the Novaya Zemlya

Fold and Thrust Belt, a foreland basin accommodates several hundreds of meters of Jurassic sediments (Suslova, 2013a, 2013b). Proximal parts of the forebulge west of the foreland basin show relative large rates of uplift and erosion relative to the rest of the forebulge. Differential uplift and erosion within the forebulge seems to be controlled by faults linked to the basement. Reactivation of older basement rooted faults and a heterogeneous pattern of tectonism and relatively low rates of uplift and erosion compared to proximal parts of the compressional stress regime are classical traits of forebulge terranes (e.g. DeCelles, 2012). Truncation trends correspond to the orientation of older basement rooted normal faults that define Paleozoic rift basins (Fig. 12, Faleide et al., 2010), suggesting a link between these truncation trends and older faults - supporting thick-skinned compression. We regard it as likely that older basement rooted faults also control zones of differential uplift and erosion in other parts of the basin experiencing forebulge uplift (i.e. frontier areas around Svalbard and Franz Josef Land).

Areas overlying salt structures are differentially uplifted above local domes created either by mobilization or remobilization of underlying salt, and although no studies have evaluated salt movement at the Triassic-Jurassic transition, later salt movement has been attributed to basin shortening (Nilsen et al., 1995). The basin shortening previously assumed to post-date the Middle Mesozoic is more easily explained by
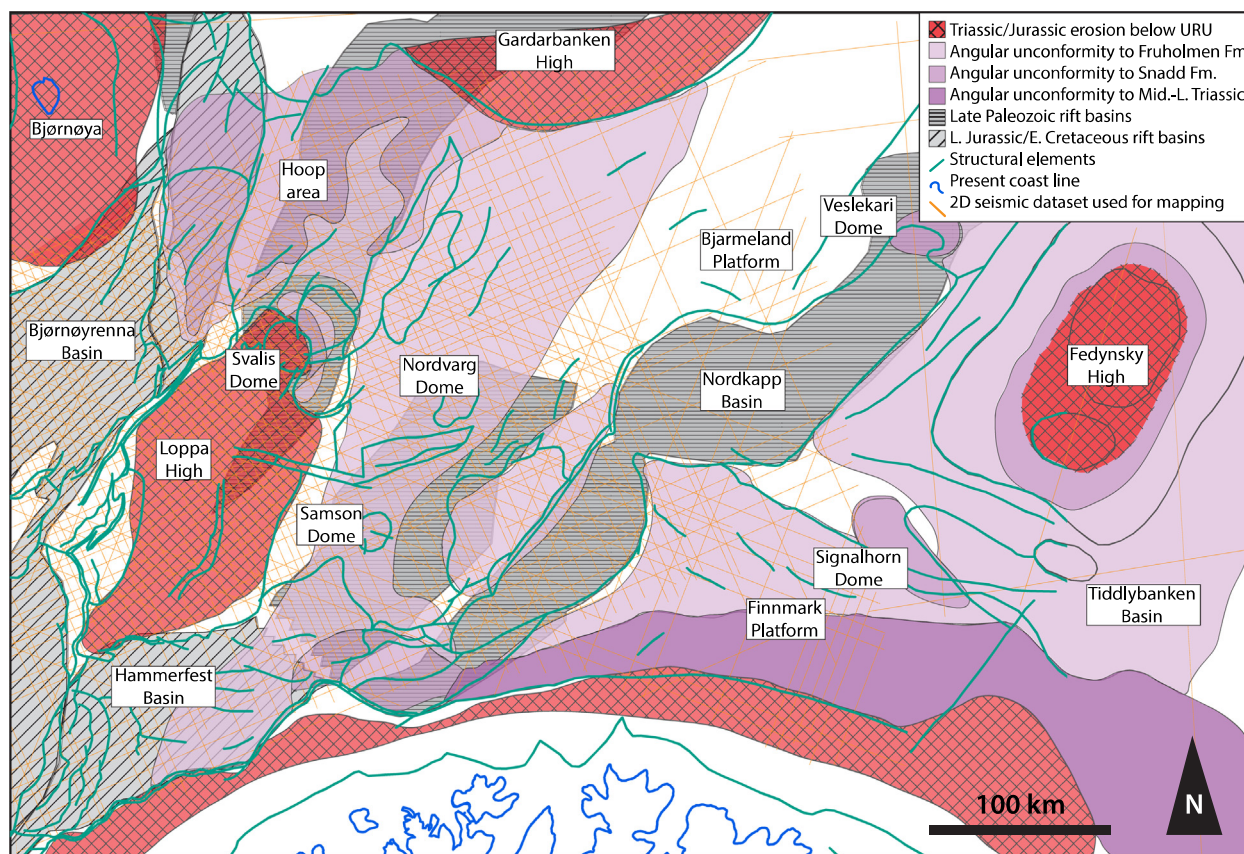
Fig. 9. Mapping of erosion and truncation patterns seen in regional 2D seismic and in well logs reveal two distinct broad north-south trends: one in the east including the Fedynsky High and the Finnmark Platform and one in the central NBSB running from the Hammerfest Basin to the Bjarmeland Platform. This trend is partly obscured by subsequent uplift and erosion below URU as highlighted in red colour. Areas with no specific colour code, and those marked as older rift basins, also experienced truncation of Triassic strata to different degrees, as evident by distinct thickness differences (e.g. Fig. 3). The areas highlighted in this figure are characterised by clear angular unconformity and likely represented elevated topography during periods of the early Jurassic. Structural elements are from Faleide et al. (2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compressional forces documented in our study than basin shortening by normal fault gliding in Nordkapp Basin (Nilsen et al., 1995) or late Cretaceous compression of the Svalis Dome (Kristoffersen and Elverhøi, 1978).

5.1.2. Inversion of basin rooted faults

On the Fedynsky High, uplift and erosion exposed Middle to Upper Triassic strata during the late Triassic to early Jurassic (Figs. 11 and 12). The deep erosion is interpreted to reflect that this area was located on the forebulge of the Novaya Zemlya Fold and Thrust Belt. Crustal heterogeneities (Klitzke et al., 2015; Gac et al., 2016) and Carboniferous structural trends favoured that this area was uplifted and contributed to its distinct dome-like shape. It is also reasonable that these heterogeneities gave rise to the differential uplift rates along the distal margin of the Eastern Barents Sea foreland basin. Areas immediately south and north of the Fedynsky High are characterised by lower rates of erosion and some sediment accumulation during this period, for example the Tiddlybanken Basin (Fig. 1c). South of the Tiddlybanken Basin, the basin margin again shows similar rates of erosion deep into Triassic strata (Fig. 9). These areas of pronounced uplift and erosion of Triassic strata roughly align along the same N-S trend that more or less correspond to the distal, western boundary of the eastern Barents Sea foreland basins (Fig. 11).

Basement rooted faults that lie west of this proximal uplift trend, and distal to the thrust front, are differentially inverted but all areas show less erosion compared to the Fedynsky High. Erosion rates are difficult to quantify since the transition from the Fruholmen Formation to the Tubåen Formation is ubiquitously erosive but based on the

thickness of the Fruholmen Formation along the western margin (Fig. 3), we regard it as likely that erosion was on the order of up to hundreds of meters throughout most of the basin. We also note anomalous thickness trends of Upper Triassic strata across the Asterias Fault Complex, which could be explained by reactivation and inversion of the margin of the Hammerfest Basin. Worth noting is the lack of truncation of Triassic strata along both margins of the northern segment of the Nordkapp Basins (Fig. 9), perhaps reflecting its position relative to the Fedynsky High.

In northwestern parts of the Barents Sea, the present model explains hitherto enigmatic sequence boundaries with the onset of compression from the east. The unconformable relation between sandstone-dominated Lower Jurassic intervals and the thin Norian Flatsalen Formation and deltaic De Geerdalen Formation in outcrops on eastern Spitsbergen has earlier been interpreted to be caused by multiple uplift and erosion events (Rismyhr et al., In press). Our model offers an alternative explanation to the complex stratigraphic relationship implicit in these data: Instead of multiple uplift events at different times in the same locality, a single significant uplift event caused erosion down into the Carnian/Norian strata of the De Geerdalen Formation during the Triassic-Jurassic transition (Fig. 10). This pronounced erosion reworked Norian strata and was followed by a long hiatus before strata of Pliensbachian age was deposited above. This development is similar to what is observed in the subsurface Barents Sea in the Hoop area (Fig. 5b and c). Further indications about the important tectonic event occurring at the Triassic-Jurassic transition in northwestern parts of the Barents Sea is offered by previous studies. However, the important change in sedimentation occurring at this boundary has generally been attributed
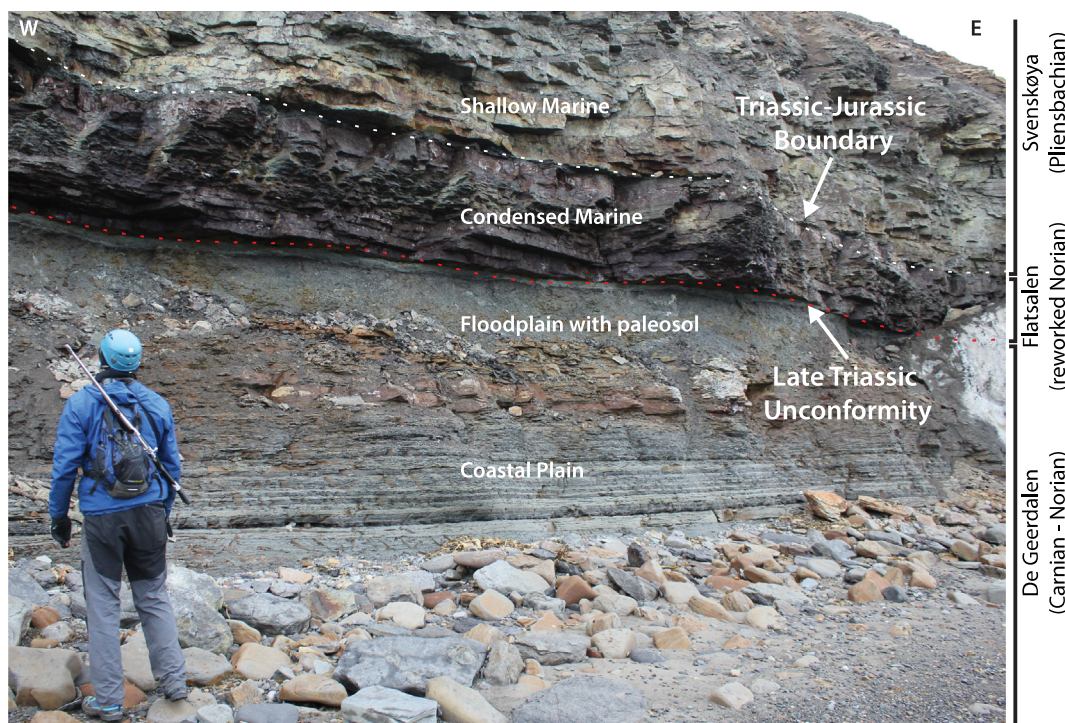
Fig. 10. The Triassic-Jurassic transition in Agardhbukta, eastern Spitsbergen, is characterised by thin, reworked, Flatsalen Formation unconformably overlying Upper Triassic De Geerdalen Formation with sandstone dominated Lower Jurassic Svenskøya Formation above the Flatsalen Formation. Location of outcrop is shown in Fig. 1a. The outcrop weathers back and the upper part of the Realgrunnen Subgroup is not exposed at this locality.

to changes in climate or sediment supply patterns instead of large-scale tectonism. Lord et al. (2017) record multiple sites where coarse-grained deposits of the Svenskøya Formation of early Jurassic age rest unconformably on offshore marine Flatsalen Formation of Norian age, e.g. on Hopen, Wilhelmøya, Kong Karls Land and Barentsøya. Olaussen et al. (2019) suggest a link between unconformities near the Triassic-Jurassic transition in Svalbard and the formation of the Novaya Zemlya foreland basin in the Early Jurassic. The increased thickness and the more completely preserved Lower Jurassic strata of the Wilhelmøya Subgroup on Kong Karls Land is also explained in the context of a foreland to Novaya Zemlya. This hypothesis fits well with what we have documented from the NBSB in the present study and can be used to tentatively extrapolate the observed truncation trend to the north (Fig. 11). Rhaetian ages in the Svenskøya Formation on Hopen (Paterson et al., 2016) has been recorded, but attributed relative sea-level changes as opposed to tectonism. Unconformable stratigraphic relationships in other parts of the basin can also be explained by the present model: Outcrops in Franz Josef Land show an erosional relationship between Triassic and Lower Jurassic strata (Krymholts, 1972) that correlates broadly with our extrapolated trend for the truncation of the Fruholmen Formation (Fig. 11). Additionally, in the subsurface of northwestern Barents Sea, shallow stratigraphic drillings reveal a similar unconformable relationship between the Svenskøya and the Flatsalen formations (Riis et al., 2008) along this trend.

5.1.3. Salt tectonics

Salt tectonics could be triggered by contraction, extension and differential loading (Peel, 2014), and the timing of the salt evacuation and formation of the domes are reportedly highly complex in the Barents Sea (Nilsen et al., 1995; Rowan, 2014; Rowan and Lindsø, 2017). The main salt movement in the Nordkapp Basin occurred in the early to middle Triassic, ending when Permian salt layers were depleted in the Middle Triassic and are believed to have remained inactive until Paleogene (Nilsen et al., 1995). The Svalis Dome (Kristoffersen and Elverhøi, 1978) was less affected by loading of Lower to Middle Triassic

sediment than the Nordkapp Basin, and the main salt reactivation phase here is believed to be of late Mesozoic age (Mørk and Elvebakk, 1999).

The differential thicknesses in the Nordkapp Basin and the angular unconformity above the Svalis Dome at the Triassic-Jurassic boundary presented above (Figs. 4 and 5) reveals prominent remobilization of salt structures in the NBSB which contrasts previous assumptions about the salt being inactive during the late Triassic to Cretaceous (Nilsen et al., 1995; Rojo and Escalona, 2018; Rojo et al., 2019).

Low sedimentation rates during salt remobilization in the late Triassic to early Jurassic implies relatively small buoyancy effect compared to the activation mechanism in the main phase of salt withdrawal during the early-middle Triassic when the salt responded to rapid differential loading (Bergendahl, 1989). Instead, at the Triassic-Jurassic basin shortening is the most likely driver for salt remobilization. Similar explanations are proposed for the Paleogene reactivation (Nilsen et al., 1995), where normal fault gliding is proposed to have shortened the Nordkapp Basin.

Subtle doming above other salt structures likely also affected the overall thickness of the Realgrunnen Subgroup (Fig. 4), and we furthermore note a similar tectono-stratigraphic relationship above the newly defined Veslekari and Signalhorn domes (Fig. 11).

5.2. Implications for basin infill dynamics

Regional uplift created a low accommodation setting in the Jurassic, which we have linked to a forebulge development in response to the Novaya Zemlya Fold and Thrust Belt. As emphasized by Ryseth (2014) and Klausen et al. (2017), the accumulation rate of the Jurassic succession was considerable lower than for the Triassic succession. This is a natural consequence of the large-scale uplift of the western Barents Sea and Svalbard. The subtle variations in accommodation arising from the differential uplift within the forebulge terrane documented herein have important implications for how we understand the sediment supply patterns to the basin. The present study shows that local highs, earlier hypothesised to have been possibly uplifted during this period (Faleide
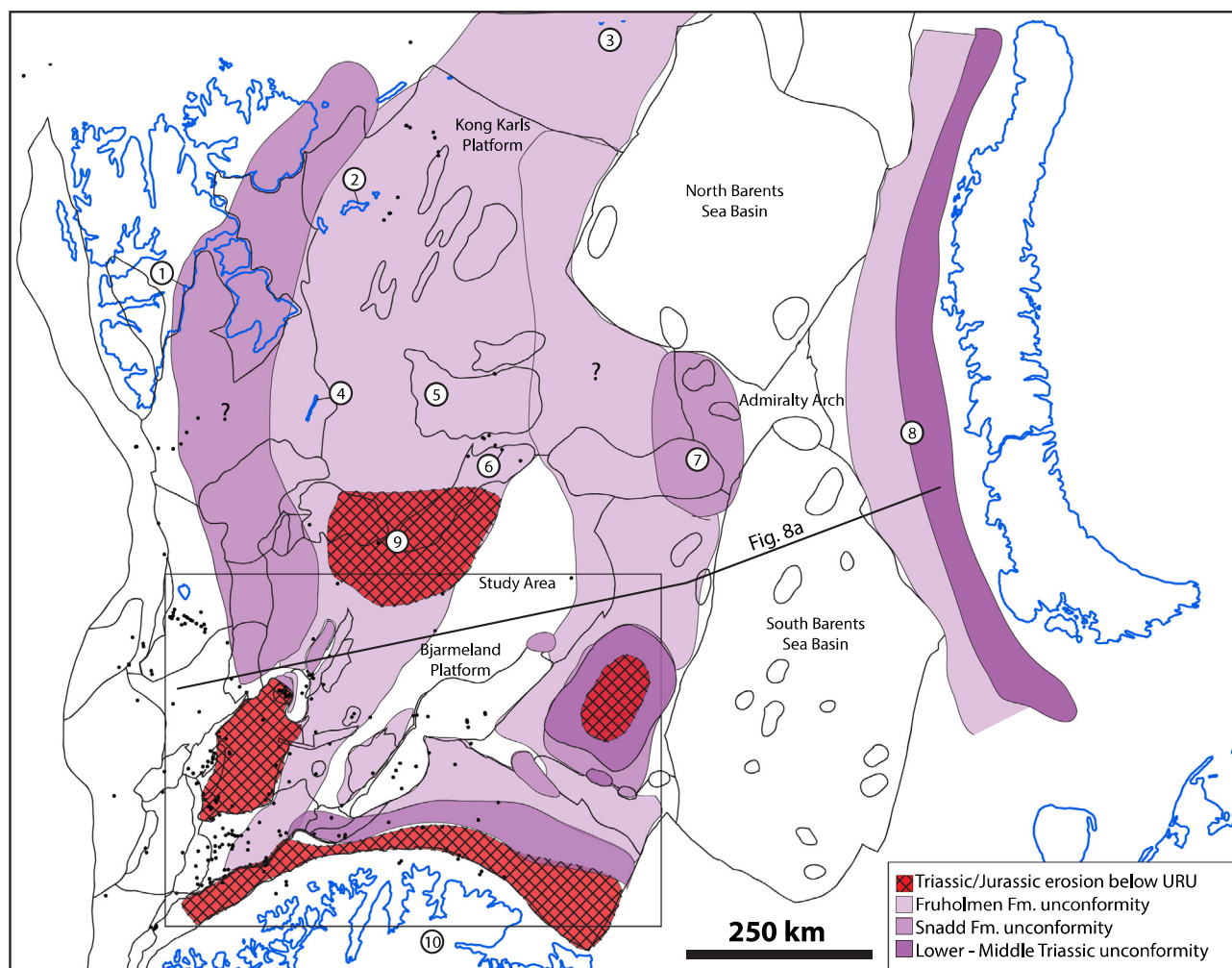
Fig. 11. Extrapolation of truncation trends observed in NBSB across the Greater Barents Sea basin. Numbers indicate observations outside the present study area, restricted to NBSB where data coverage is most dense. These observations have been used together with the structure maps to infer the regional distribution of uplift trends, and are numbered as follows: (1) outcrop observations from eastern Spitsbergen indicate erosion into Upper Triassic, and most likely also Snadd Formation equivalents at the Triassic-Jurassic transition (e.g. Fig. 10; (2) outcrop data from Kong Karls Land (Olaussen et al., 2019) indicate erosion into Fruholmen Formation equivalents; (3) similar unconformities between Upper Triassic and Lower Jurassic (Pliensbachian) strata are observed on Franz Josef Land (Krymholts, 1972); (4) on Hopen Island, the Fruholmen Formation equivalent (Flatsalen Formation) is unconformably overlain by Rhaetian (to possibly early Jurassic) deposits (Lord et al., 2014); (5) unknown magnitude of erosion of the Fruholmen Formation between points 4 and 6, Upper Triassic strata perhaps differentially preserved in the Ottar Basin as also seen in basins to the south; (6) erosion between Fruholmen Formation equivalents and Lower Jurassic strata in shallow stratigraphic cores (Riis et al., 2008); regional seismic lines indicate erosion of Triassic intervals at locations highlighted by numbers 7 and 8; (9) URU obscures the Triassic-Jurassic transition on the Gardarbanken High; (10) studies of denudation rates in northern Norway indicate significant erosion of Triassic sediments during the Jurassic (Hendriks and Andriessen, 2002). Pronounced angular and stratigraphic unconformity at the Triassic/Jurassic boundary are seen in every seismic profile close to Novaya Zemlya (Suslova, 2013a, 2013b), and the overall orientation of truncation trends in NBSB further substantiate the relationship between tectonic forcing from the Novaya Zemlya Fold and Thrust Belt in the east and compression, uplift and erosional trends in the west.

et al., 2018) were indeed prominent topographic features with erosion deep into the Triassic, and likely responsible for routing sedimentation in the early to middle Jurassic. Accurate knowledge about the sediment supply fairways is important because this interval contains prolific reservoir rocks.

Pronounced truncation of Middle to Upper Triassic deposits on the southern Finnmark Platform suggest that the Norwegian mainland also experienced uplift and erosion in the latest Triassic. This supports previous analyses of uplift and denudation rates from apatite fission tracks in onshore areas to the south of the Barents Shelf (Eastern Finnmark and the Kola Peninsula) which indicate significant and rapid late Triassic to early Jurassic uplift and denudation estimated to be between 2.5 and 3 km (Hendriks and Andriessen, 2002; Hendriks, 2003). The possibility for such an uplift event is also considered as an explanation for changes in sediment supply to the NBSB in Ryseth (2014) but is complicated by a similar uplift episode probably occurring

further to the south (Goldsmith et al., 2003) showing that other regional tectonic regimes were active during this time interval. Areas with contemporaneous uplift in the Norwegian Mainland are located along the same trend SW-NE trend as the forebulge bordering the Eastern Barents Sea basins – suggesting a possible link in stress-regime. However, horizontal stress from fold and thrust belt induced compression is insufficient to exhume the Baltic Craton. Without more in-depth data on exhumation rates, it is difficult to know how far south this uplift and erosion effect extended, and its magnitude.

6. Conclusion

This study shows for the first time the extent, magnitude and causal mechanism of a major late Triassic to early Jurassic compressional tectonic regime that affected the Norwegian Barents Sea. We have mapped distinct truncation patterns and unconformities which formed
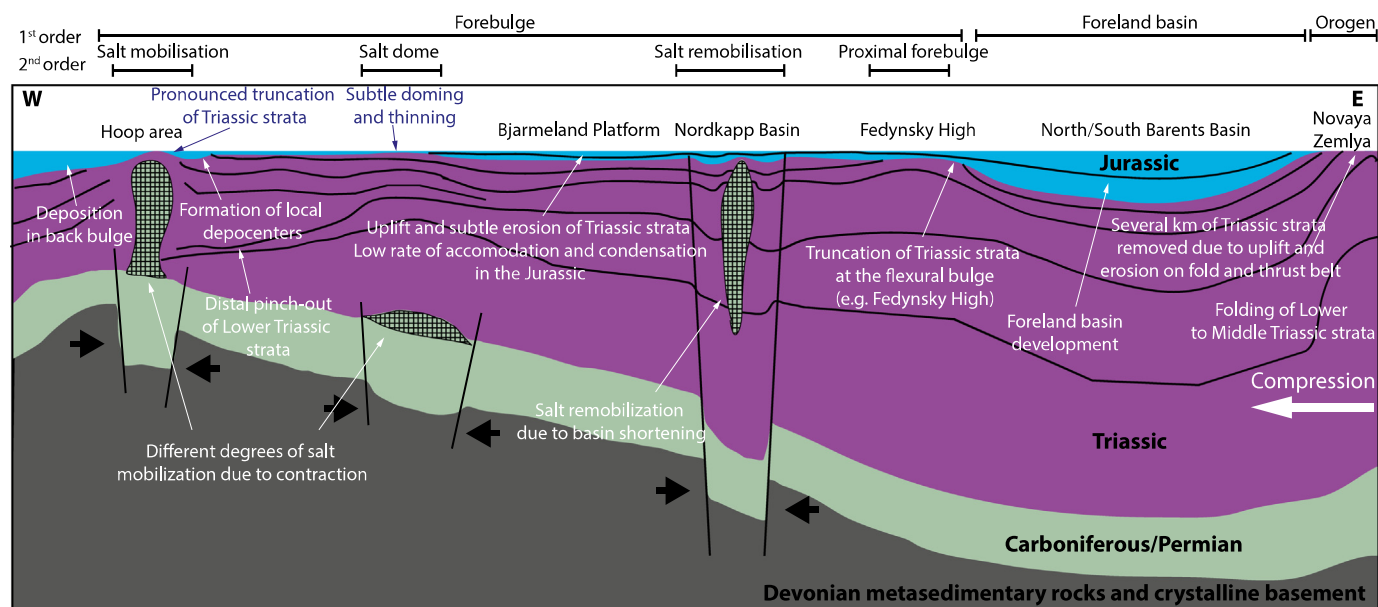
Fig. 12. Schematic regional profile showing the conceptual understanding of the different styles, and order, of deformation in relation to the compressional stress regime set up by the Novaya Zemlya Fold and Thrust Belt. Salt movement in the Hoop area is more pronounced than underneath for example the Nordvarg Dome on the Bjarmeland Platform, perhaps reflecting larger salt-volumes. Salt movement in the Nordkapp Basin is however only associated with remobilization since Permian salt layers were depleted after differential loading in the early to middle Triassic. Proximal parts of the forebulge, e.g. the Fedynsky High, show relatively higher rates of uplift and erosion than the rest of the NBSB, and to the west there is created accommodation for early Jurassic sediments.

over a considerable time span and explain these by compressional stress regimes in the forebulge uplift distal to the Novaya Zemlya Fold and Thrust Belt east of the basin. The impact of this major compressional tectonic regime has hitherto been largely overlooked despite its importance for understanding the tectonic setting and its implications for the basin evolution and infill pattern.

Since the basement of the Barents Sea basin represents a melange of different crustal blocks and rift basins overlain by thick sedimentary successions, the forebulge uplift pattern is more complex in the Barents Sea than compressional regimes involving large and relatively homogenous cratons. The Novaya Zemlya Fold and Thrust Belt reactivated salt and older basement rooted faults inherited from the Paleozoic and caused several widespread, but discrete, zones of truncation – propagating as far down as the Middle Triassic.

This new understanding can be used to explain several previously enigmatic issues related to the basin evolution: the evolution of the Loppa and Fedynsky highs; sediment supply patterns and reworking; thickness variability within the Upper Triassic formations as a function of differential preservation rather than deposition; and denudation rates in northern Norway. In sum, this attest to a period which is much more affected by tectonic forces than previously assumed and this has important implications for the basin infill history of the entire Greater Barents Sea basin and future research in the area.

Acknowledgements

References

Allen, P.A., Allen, J.R., 2005. Basin Analysis: Principles and Application to Petroleum Play Assessment. John Wiley & Sons.

Bäckstrøm, S.A., Nagy, J., 1985. Depositional history and fauna of a Jurassic phosphorite conglomerate (the Brentskardhaugen Bed) in Spitsbergen. Norwegian Polar Inst. Trans. 183, 1–61.

Bergendahl, E., 1989. Halokinetisk utvikling av Nordkappbassengets sørvestre segment. Master of Science thesis. University of Oslo, Norway (120 p. (In Norwegian)).

Brown, A.R., 2011. Interpretation of Three-Dimensional Seismic Data, Seventh edition. AAPG Memoir 42, SEG Investigations in Geophysics, No. 9 (Tulsa, Oklahoma, U.S.A. ISBN13: 978-0-89181-374-3).

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. Geol. Soc. Lond., Spec. Publ. 386, 261–279.

Buiter, S.J., Torsvik, T.H., 2007. Horizontal movements in the eastern Barents Sea constrained by numerical models and plate reconstructions. Geophys. J. Int. 171 (3), 1376–1389.

Burgess, P.M., Moresi, L.N., 1999. Modelling rates and distribution of subsidence due to dynamic topography over subducting slabs: is it possible to identify dynamic topography from ancient strata? Basin Res. 11, 305–314.

Chase, C.G., Sussman, A.J., Coblentz, D.D., 2009. Curved Andes: Geoid, forebulge, and flexure. Lithosphere 1, 358–363. https://doi.org/10.1130/L67.1.

Clark, S.A., Glørstad-Clark, E., Faleide, J.I., Schmid, D., Hartz, E.H., Fjeldskaar, W., 2014. Southwest Barents Sea rift basin evolution: comparing results from backstripping and time-forward modelling. Basin Res. 26, 550–566.

Dalland, A., Worsley, D., Ofstad, K., 1988. A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. Norw. Petrol. Direct. Bull. 4, 65.

DeCelles, P.G., 2004. Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA. Am. J. Sci. 304, 105–168.

DeCelles, P.G., 2012. Foreland basin systems revisited: variations in response to tectonic settings. In: Tectonics of Sedimentary Basins: Recent Advances, pp. 405–426.

DeCelles, P.G., Giles, K.A., 1996. Foreland basin systems. Basin Res. 8, 105–123.

Ershov, A.V., Brunet, M.F., Nikishin, A.M., Bolotov, S.N., 1998. Evolution of the eastern Fore-Caucasus basin during the Cenozoic collision: burial history and flexural modelling. In: Epicratonic Basins of Peri-Tethyan Platforms. vol. 179. pp. 111.

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. Mar. Pet. Geol. 10, 186–214.

Faleide, J.I., Solheim, A., Fiedler, A., Hjelstuen, B.O., Andersen, E.S., Vanneste, K., 1996. Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin. Glob. Planet. Chang. 12, 53–74.

Faleide, J.I., Tsikalas, F., Breivik, A.J., Mjelde, R., Ritzmann, O., Engen, Ø., Wilson, J., Eldholm, O., 2008. Structure and evolution of the continental margin off Norway and the Barents Sea. Episodes 31, 82–91.

Faleide, J.I., Bjørlykke, K., Gabrielsen, R.H., 2010. Geology of the Norwegian continental shelf. In: Bjørlykke, K. (Ed.), Petroleum Geoscience. Springer, Berlin, pp. 467–499.

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. Geol. Soc. Lond., Spec. Publ. 460, 285–314.

Gabrielsen, R.H., Grunnaleite, I., Ottesen, S., 1993. Reactivation of fault complexes in the Loppa High area, southwestern Barents Sea. In: Norwegian Petroleum Society Special Publications, vol. 2. Elsevier, pp. 631–641.

Gac, S., Klitzke, P., Minakov, A., Faleide, J.I., Scheck-Wenderoth, M., 2016. Lithospheric strength and elastic thickness of the Barents Sea and Kara Sea region. Tectonophysics 691, 120–132.

Gernigon, L., Brönner, M., Roberts, D., Olesen, O., Nasuti, A., Yamasaki, T., 2014. Crustal and basin evolution of the southwestern Barents Sea: from Caledonian orogeny to continental breakup. Tectonics 33, 347–373.

Gjelberg, J., Dreyer, T., Høie, A., Tjelland, T., Lilleng, T., 1987. Late Triassic to Mid-Jurassic sandbody development on the Barents and Mid-Norwegian shelf. In: Brooks, J., Glennie, K.W. (Eds.), Petroleum Geology of North West Europe. Geological Society, London, pp. 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. Mar. Pet. Geol. 27, 1448–1475.

Glørstad-Clark, E., Birkeland, E.P., Nystuen, J.P., Faleide, J.I., Midtkandal, I., 2011. Triassic platform-margin deltas in the western Barents Sea. Mar. Pet. Geol. 28, 1294–1314.

Goldsmith, P.J., Hudson, G., Van Veen, P., 2003. Triassic. In: Evans, D., Graham, C., Armour, A., Bathurst, P. (Eds.), The Millenium Atlas: Petroleum Geology of the Central and Northern North Sea. Geol. Soc. London, pp. 105–127.

Gramberg, I.S., 1997. Permian-Triassic paleorift of the Barents Sea and it's influence on the oil gas potential on the Barents-Kara shelf. In: DAN, Volume 352, Bulletin 6, (789-791 pp.).

Grogan, P., Østvedt-Ghazi, A.M., Larssen, G.B., Fotland, B., Nyberg, K., Dahlgren, S., Eidvin, T., 1999. Structural elements and petroleum geology of the Norwegian sector of the northern Barents Sea. In: Geological Society, London, Petroleum Geology Conference Series, vol. 5, 1. Geological Society of London, pp. 247–259.

Hendriks, B.W.H., 2003. Cooling and Denudation of the Norwegian and Barents Sea Margins, Northern Scandinavia: Constrained by Apatite Fission Track and (U-Th) he Thermochronology. Doctoral dissertation. Vrije universiteit.

Hendriks, B.W., Andriessen, P.A., 2002. Pattern and timing of the post-Caledonian denudation of northern Scandinavia constrained by apatite fission track thermochronology. In: Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P., White, N. (Eds.), Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration. Geological Society, London, Special Publications, vol. 196. pp. 117–137. https://doi.org/10.1144/GSL.SP.2002.196. 01.08.

Henriksen, E., Ryseth, A.E., Larssen, G.B., Heide, T., Rønning, K., Sollid, K., Stoupakova, A.V., 2011. Chapter 10 tectonostratigraphy of the greater Barents Sea: implications for petroleum systems. Geol. Soc. Lond. Mem. 35, 163–195.

Indrevær, K., Gabrielsen, R.H., Faleide, J.I., 2017. Early Cretaceous synrift uplift and tectonic inversion in the Loppa High area, southwestern Barents Sea, Norwegian shelf. J. Geol. Soc. 174, 242–254.

Johannessen, E.P., Embry, A.F., 1989. Sequence correlation: upper Triassic to lower Jurassic succession, Canadian and Norwegian Arctic. In: Correlation in Hydrocarbon Exploration. Springer, Dordrecht, pp. 155–170.

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: the De Geerdalen Formation on Hopen. AAPG Bull. 98, 1911–1941.

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. J. Sediment. Res. 84, 567–585.

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. Mar. Pet. Geol. 62, 102–122.

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.

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. J. Geol. Soc. 175, 130–145.

Klitzke, P., Faleide, J.I., Scheck-Wenderoth, M., Sippel, J., 2015. A lithosphere-scale structural model of the Barents Sea and Kara Sea region. Solid Earth 6, 153.

Klitzke, P., Franke, D., Ehrhardt, A., Lutz, R., Reinhardt, L., Heyde, I., Faleide, J.I., 2019. The Paleozoic evolution of the Olga Basin region, northern Barents Sea: A link to the Timanian orogeny. Geochem. Geophys. Geosyst. 20, 614–629. https://doi.org/10. 1029/2018GC007814.

Koevoets, M.J., Hammer, Ø., Olaussen, S., Senger, K., Smelror, M., 2018. Integrating subsurface and outcrop data of the Middle Jurassic to Lower Cretaceous Agardhfjellet Formation in central Spitsbergen. Nor. J. Geol. 98.

Krajewski, K.P., 1990. Phosphoritization in a starved shallow shelf environment: the Brentskardhaugen Bed (Toarcian-Bajocian) in Spitsbergen. Pol. Polar Res. 11, 331–344.

Kristoffersen, Y., Elverhøi, A., 1978. A diapir structure in Bjørnøyrenna. Nor. Polarinst. Aarb. 1977, 189–198.

Krymholts, G.Y. (Ed.), 1972. Stratigraphy of the USSR. Jurassic System. Nedra, Moscow (524 p. (In Russian).

Lord, G.S., Solvi, K.H., Klausen, T.G., Mørk, A., 2014. Triassic channel bodies on Hopen, Svalbard: their facies, stratigraphical significance and spatial distribution. Norw.

Petrol. Direct. Bull. 11, 41–59.

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. Nor. J. Geol. 97.

Mørk, M.B.E., 1999. Compositional variations and provenance of Triassic sandstones from the Barents Shelf. J. Sediment. Res. 69, 690–710.

Mørk, A., Elvebakk, G., 1999. Lithological description of subcropping Lower and Middle Triasic rocks from the Svalis Dome, Barents Sea. Polar Res. 18, 83–104.

Mørk, A., Dallmann, W.K., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pchelina, T.M., Worsley, D., 1999. Mesozoic lithostratigraphy. Lithostratigraphic lexicon of Svalbard. In: Upper Palaeozoic to Quaternary Bedrock. Review and Recommendations for Nomenclature Use, pp. 127–214.

Mulrooney, M.J., Rismyhr, B., Yenwongfai, H.D., Leutscher, J., Olaussen, S., Braathen, A., 2018. Impacts of small-scale faults on continental to coastal plain deposition: evidence from the Realgrunnen Subgroup in the Goliat field, southwest Barents Sea, Norway. Mar. Pet. Geol. 95, 276–302.

Nagy, J., Berge, S.H., 2008. Micropalaeontological evidence of brackish water conditions during deposition of the Knorringfjellet Formation, Late Triassic–Early Jurassic, Spitsbergen. Polar Res. 27, 413–427.

Nilsen, K.T., Vendeville, B.C., Johansen, J.T., 1995. Influence of Regional Tectonics on Halokinesis in the Nordkapp Basin, Barents Sea.

Norina, D.A., Stupakova, A.V., Kiryukhina, T.A., 2014. Depositional environments and the hydrocarbon generative potential of Triassic rocks of the Barents Sea Basin. Mosc. Univ. Geol. Bull. 69, 1–10.

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, London, pp. 61–79.

Olaussen, S., Larssen, G.B., Helland-Hansen, W., Johannessen, E.P., Nøttvedt, A., Riis, F., Rismyhr, B., Smelror, M., Worsley, D., 2019. Mesozoic strata of the Kong Karls Land, Svalbard, Norway; a link to the northern Barents Sea basins and platforms. Nor. J. Geol. https://doi.org/10.17850/njg98-4-06. (In press).

Paterson, N.W., Mangerud, G., Cetean, C.G., Mørk, A., Lord, G.S., Klausen, T.G., Mørkved, P.T., 2016. A multidisciplinary biofacies characterisation of the Late Triassic (Late Carnian–Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway. Palaeogeogr. Palaeoclimatol. Palaeoecol. 464, 16–42.

Peel, F.J., 2014. How do salt withdrawal minibasins form? Insights from forward modelling, and implications for hydrocarbon migration. Tectonophysics 630, 222–235.

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 Res. 27, 318–338.

Rismyhr, B., Bjærke, T., Olaussen, S., Mulrooney, M., Senger, K., 2019. Facies, palynostratigraphy and sequence stratigraphy of the Wilhelmøya Subgroup (Upper Triassic–Middle Jurassic) in western central Spitsbergen, Svalbard. Nor. J. Geol. https://doi.org/10.17850/njg98-4-06.

Ritzmann, O., Faleide, J.I., 2009. The crust and mantle lithosphere in the Barents Sea/ Kara Sea region. Tectonophysics 470, 89–104.

Roddaz, M., Baby, P., Brusset, S., Hermoza, W., Darrozes, J.M., 2005. Forebulge dynamics and environmental control in Western Amazonia: the case study of the Arch of Iquitos (Peru). Tectonophysics 399, 87–108.

Rojo, L.A., Escalona, A., 2018. Controls on minibasin infill in the Nordkapp Basin: evidence of complex Triassic synsedimentary deposition influenced by salt tectonics. AAPG Bull. 102, 1239–1272.

Rojo, L.A., Cardozo, N., Escalona, A., Koyi, H., 2019. Structural style and evolution of the Nordkapp Basin, Norwegian Barents Sea. AAPG Bull. https://doi.org/10.1306/01301918028. (20,190,301).

Rowan, M.G., 2014. Passive-margin salt basins: hyperextension, evaporite deposition, and salt tectonics. Basin Res. 26, 154–182.

Rowan, M.G., Lindsø, S., 2017. Salt tectonics of the Norwegian Barents Sea and Northeast Greenland Shelf. In: Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 265–286.

Ryseth, A., 2014. Sedimentation at the Jurassic-Triassic boundary, south-West Barents Sea. In: Martinius, A.W., Ravnås, R., Howell, J.A., Steel, R.J., Wonham, J.P. (Eds.), From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin. International Association of Sedimentologists Special Publication, vol. 46. pp. 187–214.

Scott, R.A., Howard, J.P., Guo, L., Schekoldin, R., Pease, V., 2010. Offset and curvature of the Novaya Zemlya fold-and-thrust belt, Arctic Russia. In: Geological Society, London, Petroleum Geology Conference series. 7. pp. 645–657.

Serck, C.S., Faleide, J.I., Braathen, A., Kjølhamar, B., Escalona, A., 2017. Jurassic to Early Cretaceous basin configuration (s) in the Fingerdjupet Subbasin, SW Barents Sea. Mar. Pet. Geol. 86, 874–891.

Smelror, M., Petrov, O.V., Larssen, G.B., Werner, S.C., 2009. Geological History of the Barents Sea. Geological Survey of Norway, Trondheim.

Smelror, M., Larssen, G.B., Olaussen, S., Rømuld, A., Williams, R., 2019. Late Triassic to Early Cretaceous palynostratigraphy of Kong Karls Land, Svalbard, Arctic Norway, with correlations to Franz Josef Land, Arctic Russia. Nor. J. Geol. 98 (04), 1–31. https://doi.org/10.17850/njg98-4-04.

Stoupakova, A.V., 2001. Evaluation of the sedimentary basins and its hydrocarbon potential (on the example of the Braents Sea basin). In: Oil and Gas Geology, Bulletin 4, 2000, (51-57 pp. (In Russian).

Stoupakova, A.V., Henriksen, E., et al., 2011. The geological evolution and hydrocarbon potential of the Barents and Kara shelves (Chapter 21). In: Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V., Sørensen, K. (Eds.), Arctic Petroleum Geology. Geological Society, London, Memoirs, vol. 35. pp. 325–344. https://doi.org/10. 1144/M35.21.

Suslova, A.A., 2013a. Seismostratigraphic complex of Jurassic deposits, Barents Sea shelf.

Mosc. Univ. Geol. Bull. 68 (3), 68–70. https://doi.org/10.3103/
    S0145875213030071.

Suslova, A.A., 2013b. УСЛОВИЯ ФОРМИРОВАНИЯ ПРИРОДНЫХ РЕЗЕРВУАРОВ
    ЮРСКОГО НЕФТЕГАЗОНОСНОГО КОМПЛЕКСА БАРЕНЦЕВОМОРСКОГО
    ШЕЛЬФА (Conditions for forming Jurassic reservoirs for oil and gas on the Barents
    Sea shelf).   [Ph.D. thesis]. Moscow University, Moscow (183 p.).

Turcotte, D., Schubert, G., 2014. Geodynamics. Cambridge university press (636 p).

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, pp. 269.

Vorren, T.O., Lebesbye, E., Andreassen, K., Larsen, K.B., 1989. Glacigenic sediments on a
    passive continental margin as exemplified by the Barents Sea. Mar. Geol. 85,
    251–272.

White, T., Furlong, K., Arthur, M., 2002. Forebulge migration in the Cretaceous Western
    Interior basin of the central United States. Basin Res. 14, 43–54.

Worsley, D., 2008. The post-Caledonian development of Svalbard and the western Barents
    Sea. Polar Res. 27, 298–317.