The Triassic – Early Jurassic of the northern Barents Shelf: a regional understanding of the Longyearbyen CO_2 reservoir

Ingrid Anell, Alvar Braathen & Snorre Olaussen

Anell, I., Braathen, A. & Olaussen, S.: The Triassic – Early Jurassic of the northern Barents Shelf: a regional understanding of the Longyearbyen CO_2 reservoir. *Norwegian Journal of Geology,* Vol 94, pp. 83–98. Trondheim 2014, ISSN 029-196X.

We address the spatial and temporal development during the Triassic to Middle Jurassic of the NW Barents Shelf in order to provide a regional framework for the targeted reservoir of the Longyearbyen CO_2 Lab. The reservoir is Middle Triassic to Middle Jurassic stacked sandstones at a depth of 670–970 m in Adventdalen, Svalbard. The predominantly Carnian De Geerdalen Formation, the lower reservoir, is composed of immature shallow-marine, deltaic to paralic mudstones and sandstones of which over 250 m have been cored at the proposed CO_2 injection site. The overlying mid-Norian to Bathonian Knorringfjellet Formation is distinctly more mature and very condensed, with a thickness of just 25 m at the same site. While Early to Mid Triassic sediment influx in Western Svalbard appears dominated by a western source, the De Geerdalen Formation is regionally linked to advancing delta systems from the Uralide mountains and Fennoscandian Shield. The Gardarbanken high hindered Early Triassic progradation and Late Triassic sediment deposition was influenced by the Edgeøya platform. The platform was structurally higher than surrounding areas and limited accommodation space combined with high sediment influx probably caused a rapid advance of the platform edge. The Upper Triassic to Middle Jurassic deposits are condensed with several hiati onshore, and thin and in places eroded offshore. This indicates a strongly linked development across the whole northern Barents Shelf related to limited accommodation space, condensation and/or sediment starvation and erosion.

Ingrid Anell, Department of Geosciences, University of Oslo, Sem Sælands vei 1, 0371 Oslo Norway. Alvar Braathen, Department of Geosciences, University of Oslo, Sem Sælands vei 1, 0371 Oslo Norway. Snorre Olaussen, UNIS, The University Centre in Svalbard, Postboks 156, 9171 Longyearbyen, Norway.

E-mail corresponding author (Ingrid Anell): ingrid.anell@gmail.com

Published December 24. 2014.

Introduction

The Longyearbyen CO_2 Lab aims to store carbon dioxide from the local coal-combusting power plant in Upper Triassic to Lower Jurassic sandstones in Adventdalen, on Svalbard (Fig. 1). The uplifted unconventional reservoir is located at 670–970 m depth at the proposed injection site (Braathen et al., 2012; other articles in this volume). Water injectivity has been verified in the Carnian De Geerdalen Formation and the upper Norian to Bathonian Knorringfjellet Formation of the Wilhelmøya Subgroup (Fig. 2). The upper unit shows the best injection potential (Braathen et al., 2012).

The presently exposed Svalbard archipelago was a shelf area until the early Carnian (Riis et al., 2008), with sediment influx primarily from a western source and a potentially distal influence from deltas advancing northwestwards, sourced from the Uralide mountains and the Fennoscandian Shield. Towards the late Ladinian these large-scale prograding systems began to exert significant influence on sedimentation in present onshore areas (Høy & Lundschien, 2011) with deposition of the pro-deltaic Tschermakfjellet and deltaic De Geerdalen formations (Mørk et al., 1999a). There are questions regarding if and when a decline in western influence occurred, and uncertainty concerning the degree of influence from northern sources. Lateral variations within the onshore Triassic exposures suggest complex variations in sedimentation (Mørk et al., 1999a) and the links between depositional sources are unclear. Offshore seismic and well data are limited and of varying quality and the onshore-offshore correlation is particularly difficult to ascertain.

Using available well data, geological outcrops, palaeocurrent and provenance studies in conjunction with reflection seismic data, the purpose of this study is to explore the regional context of the proposed potential CO_2 storage unit. The aim is to provide a detailed understanding of the Triassic to Early Jurassic development and depositional environment on Svalbard and down across the northern Barents shelf. This may help to delineate the extent and structure of sandstone

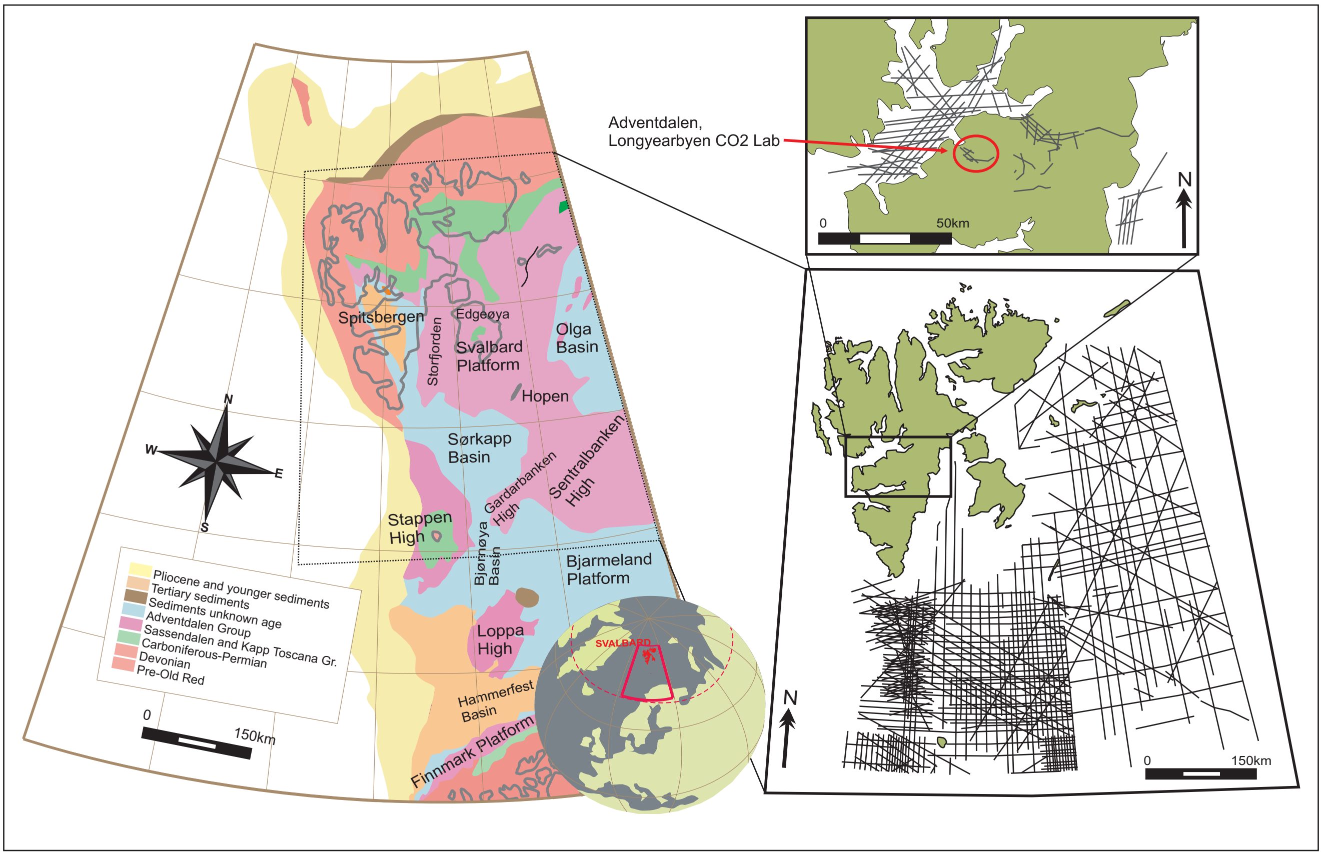


Figure 1. Geological map of the Barents Sea and outline of the geological sub-crop below a thin Quaternary cover. Adapted from Sigmond (1992). The study area is outlined and the seismic lines used in this study (courtesy of the NPD) are shown on the map in the lower right corner. The upper-right map shows an enlargement of the area in the map below, with the seismic lines in Isfjorden and onshore Svalbard, including those of the Longyearbyen CO_2 Lab (shown in a red circle).

bodies as well as depositional factors influencing the formation and quality of the reservoir units: provenance, rate of deposition, resedimentation and reworking, faulting and regional tectonics, and post-depositional development. It may also contribute to the overall understanding of regional stratigraphic correlations and the palaeogeography of the Barents Sea.

Geological background

Tectonic overview

The Barents Shelf consists of a complex series of basins, platforms and highs (Fig. 1) and the Svalbard archipelago is an uplifted region of the shelf (Elverhøi et al., 1988; Riis & Fjeldskaar, 1992; Faleide et al., 1993, 2008; Henriksen et al., 2011). The development of the area is dominated by two major continental collisions, the Silurian–Devonian Scandian phase of the Caledonian orogeny in the west (McKerrow et al., 2000 and references therein) and later the Carboniferous–Triassic Uralian orogeny in the east (Rickard & Belbin, 1980; Ziegler, 1988; Gee et al., 2006; Pease, 2011). Following the Caledonian orogeny, erosion of hinterland areas and deposition of Old Red Sandstone in supra-detachment basins characterised the Devonian to Early Carboniferous (Faleide et al., 1993). The Late Permian through Early Triassic saw the completion of the formation of the Uralides and the final assembly of Pangea. The Uralide orogeny provided a significant sediment source and large delta systems prograded from the southeast across the Barents Shelf from the Late Permian and onwards (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011). Ensuing periodic rifting during the lengthy onset of North Atlantic spreading and reactivation along old sutures and zones of weakness created rift-basins during the main phases of extension in the Early–Mid Devonian, Carboniferous to Early Permian, Triassic and Late Jurassic–Cretaceous (Eldholm & Thiede, 1980; Faleide et al., 1984; Doré, 1995; Gudlaugsson et al., 1998).

Palaeocontinental reconstructions suggest that Svalbard moved rapidly northward during the Triassic, from 45 to 60°N. The climate was temperate and relatively humid, in contrast to the Mid Permian arid environment (Mørk et al., 1982). Northwestern Eurasia hosted a large epicontinental sea during the Triassic, which included the Barents Sea region. The area was bounded by landmasses to the south, west and east (the Fennoscandian Shield, North America, present-day Novaya Zemlya) with an open seaway toward the northwest. The fundament for

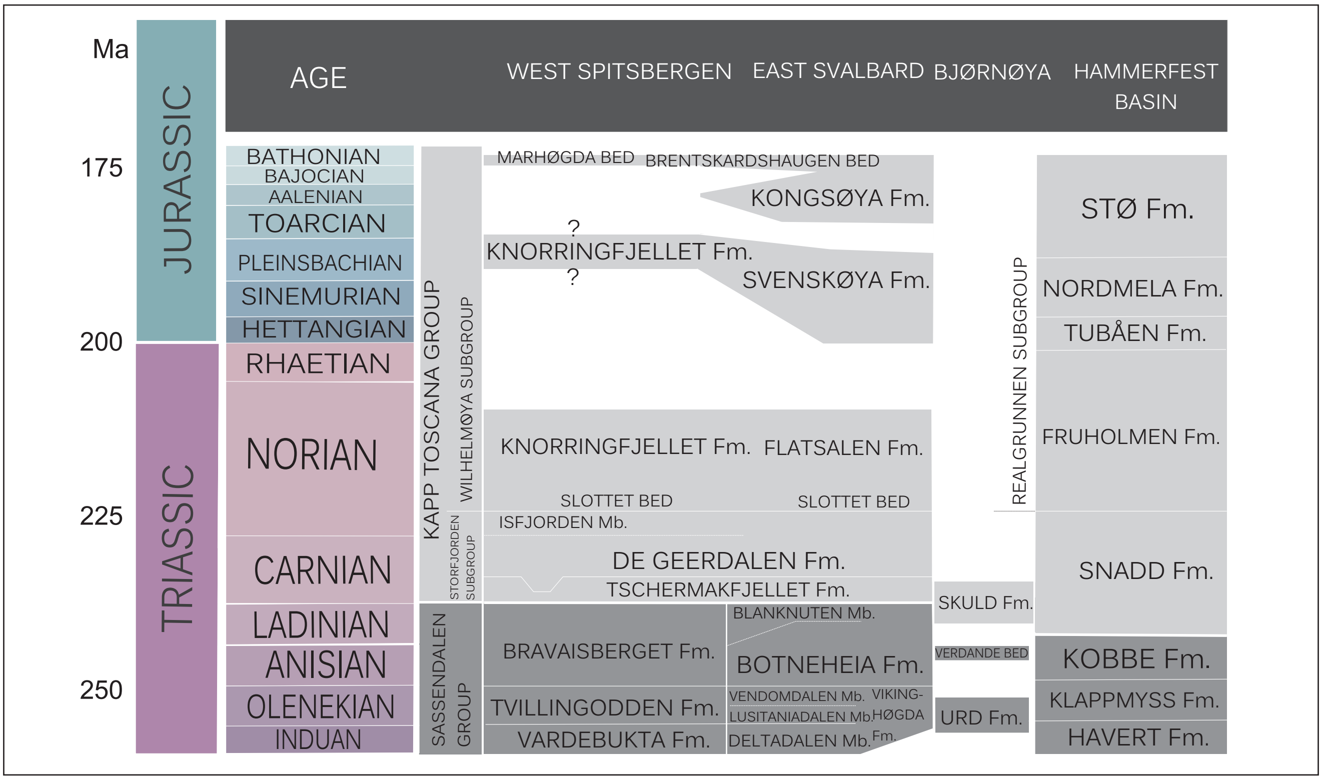


Figure 2. *Lithostratigraphy of the Sassendalen Group and Kapp Toscana Group from the Barents Sea and Svalbard, redrawn from Mørk et al. (1999a).*

Triassic sedimentation was a complex series of horst-and-grabens of Devonian to Carboniferous age, draped by Permian platform deposits. Tensional movements along lineaments slowed down in Late Carboniferous–Permian time (Høy & Lundschien, 2011). Basins that were initially fault-controlled experienced rapid infill and subsidence without much fault movement (Gudlaugsson et al., 1998). In the Late Permian–Early Triassic, an extensional event occurred in the southern Barents Sea which marked the onset of basin formation in the western Barents Sea and amplified the relief of the palaeo-Loppa High (Faleide et al., 1984; Ziegler, 1988; Gabrielsen et al., 1990). Farther east, at the same time, the northern and southern Barents Sea basins in the Uralian foreland were undergoing rapid subsidence (Johansen et al., 1992; Riis et al., 2008). The Triassic was generally tectonically quiescent in the northern Barents Sea. However, syn-sedimentary processes generated a series of growth faults (Edwards, 1976; Lock et al., 1978) and deep-rooted faults may have experienced small-scale movement (Anell et al., 2013).

Late Jurassic rifting extended into the southern Barents Sea through the Hammerfest and Bjørnøya basins. The rift was connected to an embryonic spreading in the Arctic Ocean via a transform fault between Svalbard and northern Greenland (Faleide et al., 1993). Many deep basins developed, subsided rapidly and segmented into sub-basins and highs. The Mid–Late Jurassic rifting thinned the crust significantly and contrary to previously largely continental rifting this phase submerged the rift below sea-level. Early evidence of the break-up of the North Atlantic is evident in the Cretaceous magmatic activity associated with the Arctic Large Igneous Province (*c.* 125 Ma) which caused regional uplift in the north and southward sediment propagation in the Barents Sea region (Grogan et al., 1998; Maher, 2001; Corfu et al., 2013). Early Cretaceous strata are progressively truncated northwestward by a low-angle regional unconformity reflecting this crustal tilting event (Braathen et al., 1999a). On the northern Barents Shelf, sea-floor spreading culminated in a partial collision with northern Greenland and development of the Palaeogene fold-and-thrust belt before separation was achieved and a passive margin developed (Bergh et al., 1997; Braathen et al., 1999b).

Mesozoic sedimentation

The Permian–Triassic transition is widely exposed onshore. Offshore, it is generally a prominent reflector marking a change from silicified cemented spiculitic shales and carbonates to non-siliceous shales and dolomites which occurred in the latest Permian (Stemmerik & Worsley, 2005; Worsley, 2008). The boundary is, in places, an erosive and/or unconformable surface (Worsley et al., 1986; Nøttvedt et al., 1992; Worsley, 2008) possibly reflecting updoming due to heat accumulation resulting from the continental assembly of Pangea (Nance et al., 1988; Doré, 1992).

Lower Triassic deposits on Svalbard, the Sassendalen Group, are dominated by non-siliceous fine clastics (marine shales) with subordinate siltstones and sandstones and minor carbonates (Steel & Worsley, 1984), representing a series of stacked transgressive-regressive sequences, each initiated by a significant transgression. On Western Spitsbergen the deposits comprise coastal, deltaic to shallow shelf deposits grading into shelf mudstones towards the east and south (Mørk et al., 1982). Large amounts of Caledonian zircons indicate a probable source to the west (Greenland; Bue et al., 2010). While markedly different in lithology and fauna from the underlying Tempelfjorden Group, the Lower–Middle Triassic Sassendalen Group is also locally rich in organic material (Worsley, 2008).

In the Barents Sea, the Sassendalen Group consists mainly of mudstones of varied thickness (Mørk et al., 1999a) although in places thicker sandy deposits occur. The Uralides, Timan–Pechora and Fennoscandian Shield supplied large amounts of S–SE-sourced sediments (Mørk et al., 1989) and generated an influx of three major Induan–Anisian progradational units (the Havert, Klappmyss and Kobbe formations). These can be fairly well correlated with three upward-coarsening sequences onshore Svalbard (the Vardebukta, Tvillingodden and lower Bravaisberget formations) (Fig. 2; Mørk et al., 1989).

Onshore Svalbard, the Middle Triassic to Middle Jurassic Kapp Toscana Group consists of grey shales progressively grading into immature sandstones with a sudden transition to mature sandstones in the latest Triassic (Mørk, 1999). The difference between the Kapp Toscana Group and the underlying Sassendalen Group is mainly the higher sandstone content in the former. The boundary between the groups may reflect a period of low sedimentation (Steel & Worsley, 1984) or, as recent data indicate, a significant hiatus (Hounslow et al., 2007; Hounslow & Nawrocki, 2008). The Kapp Toscana Group is characterised by shallow-marine and coastal reworked deltaic sediments, with increasing proportions of sandstone towards the southwest, northeast and east in large- and small-scale, upward-coarsening sequences (Mørk et al., 1999a). On most exposures wave and storm reworking is evident, suggesting deltaically introduced sediments in marine environments (Steel & Worsley, 1984). The Group is locally up to 400 m thick on Svalbard and up to 2 km thick in the Barents Sea. The two thickest depositional formations onshore, the Tschermakfjellet and De Geerdalen formations, form eastward- and northeastward-thickening wedges. The uppermost Triassic to Lower Jurassic formation on Svalbard, the Wilhelmøya Subgroup, is very condensed and thin, thickening eastward (Worsley et al., 1988). Offshore, the time-equivalent Realgrunnen Subgroup is comparatively thicker than its onshore counterpart, although thin compared to underlying units.

Studies suggest that widespread transgression occurred in the Late Triassic and Late–Early Jurassic with intervening periods of non-deposition (Steel & Worsley, 1984). Overlying the Kapp Toscana Group is a 1–2 m-thick phosphatic and quartzitic conglomerate representing a major Mid Jurassic (Bathonian) transgression that flooded many areas and cut off the supply of coarse clastics (Worsley, 2008). Middle Jurassic to Lower Cretaceous sediments are characterised by deeper shelf sedimentation with a periodically anoxic sea bottom, which again reversed to shallow shelf and delta deposits in the Hauterivian (Dallman, 1999). The ensuing deposits make up the Adventdalen Group which comprises four formations: the mainly Upper Jurassic, organic-rich Agardhfjellet Formation, the Lower Cretaceous dominantly shaly shelf deposits of the Rurikfjellet Formation, the Barrermian fluvio-deltaic Helvetiafjellet Formation and finally the shallow-marine to inner-shelf, heterolithic, Aptian to Albian Carolinefjellet Formation. The alluvial influx of the Helvetiafjellet Formation with subordinate volcaniclastics and time-equivalent lavas occurred in response to northerly uplift associated with the High Arctic Large Igneous Province.

Data

The results from this study are based on interpretation of 2D seismic data from the northern Barents Shelf (Fig. 1) and palaeocurrent data collected on Hopen, Edgeøya and Eastern and Central Svalbard. The 2D seismic lines are courtesy of the Norwegian Petroleum Directorate (NPD) and the grid is generally spaced between 5 and 10 km (Fig. 1). The quality of the data is adequate for regional mapping in the basin areas but generally poor near highs and platform areas where high-velocity rocks sub-crop near the sea floor and poor penetration of seismic energy occurs (Riis et al., 2008). The seismic data lose resolution near-shore making the onshore-offshore connection difficult. Compilations of previous data such as stratigraphic logs, additional palaeocurrent data, onshore sediment thickness and various sedimentary analyses have been compared with the results from this study in order to provide a comprehensive overview of the Triassic sedimentary development.

The seismic boundaries that have been traced and used to delineate the ages of the sedimentary successions are based mainly on the work of others (Rønnevik et al., 1982; Rønnevik & Jacobsen, 1984; Breivik et al., 2005; Riis et al., 2008; Glørstad-Clark et al., 2010, 2011; Høy & Lundschien, 2011), which includes ties to wells farther south and ties to recently drilled shallow cores on the Sentralbanken high and east of Kong Karls Land (Riis et al., 2008). The seismic boundaries have been correlated to the Hopen-2 well.

Triassic sedimentary development

Results

Isopachs of the two main Triassic lithostratgraphic groups (Sassendalen and Kapp Toscana) are created combining onshore measurements (Harland & Geddes, 1997; Mørk & Worsley, 2006) and offshore seismic interpretations (Fig. 3). The seismic TWT data are converted to metres using a simplified 4000 m s^{-1} velocity conversion based on general Triassic onshore and offshore velocities (Renard & Malod, 1974; Faleide et al., 1991; Czuba et al., 2008). Based on the isopach maps of Triassic sedimentation, seismic characteristics, mapping of the platform edge location, palaeocurrent data and a compilation of stratigraphic logs, we discuss the sedimentary development during the Triassic period.

Early Triassic sedimentary development – the Sassendalen Group

The isopach map of the Lower Triassic Sassendalen Group shows the advancing delta systems in the southeast, thickening towards the source area (Fig. 3). The earliest clinoforms terminate against the Gardarbanken high (Anell et al., 2014b) (Fig. 4), which generates the concave shape of the isopachs as the platform edge advanced more rapidly in the eastern part of the study area. The Gardarbanken high appears to have developed similarly to the Stappen and Loppa highs, which were uplifted during Permian tectonism and received little sedimentation until the Middle Triassic (Riis et al., 2008). In the Sørkapp basin, there is a second depocentre which is elongated NE–SW in line with the delta-front (Fig. 3). Indications from the seismic data (Fig. 4) suggest that these deposits were sourced mainly from the southeast; however, it is difficult to rule out input from other sources (Mørk et al., 1982, 1999b; Mørk, 1999). Palaeotopographic highs, such as the Stappen and Gardarbanken highs, could have been local sources of sediment for this depocentre. A third, Early Triassic depocentre is located onshore Svalbard, elongated NNW to SSE. It has been suggested that these deposits were sourced from close proximity in the west (Mørk et al., 1982, 1999b; Nøttvedt et al., 1992; Mørk, 1999; Bue et al., 2010; Bue, 2012). Towards the east, with increasing distance from this western source, deposition becomes increasingly shale-dominated (Mørk et al., 1982). The organic-rich shales of the Botneheia Formation, deposited in a shelf environment (Mørk et al., 1999a), may represent distal suspended sediment from several sources.

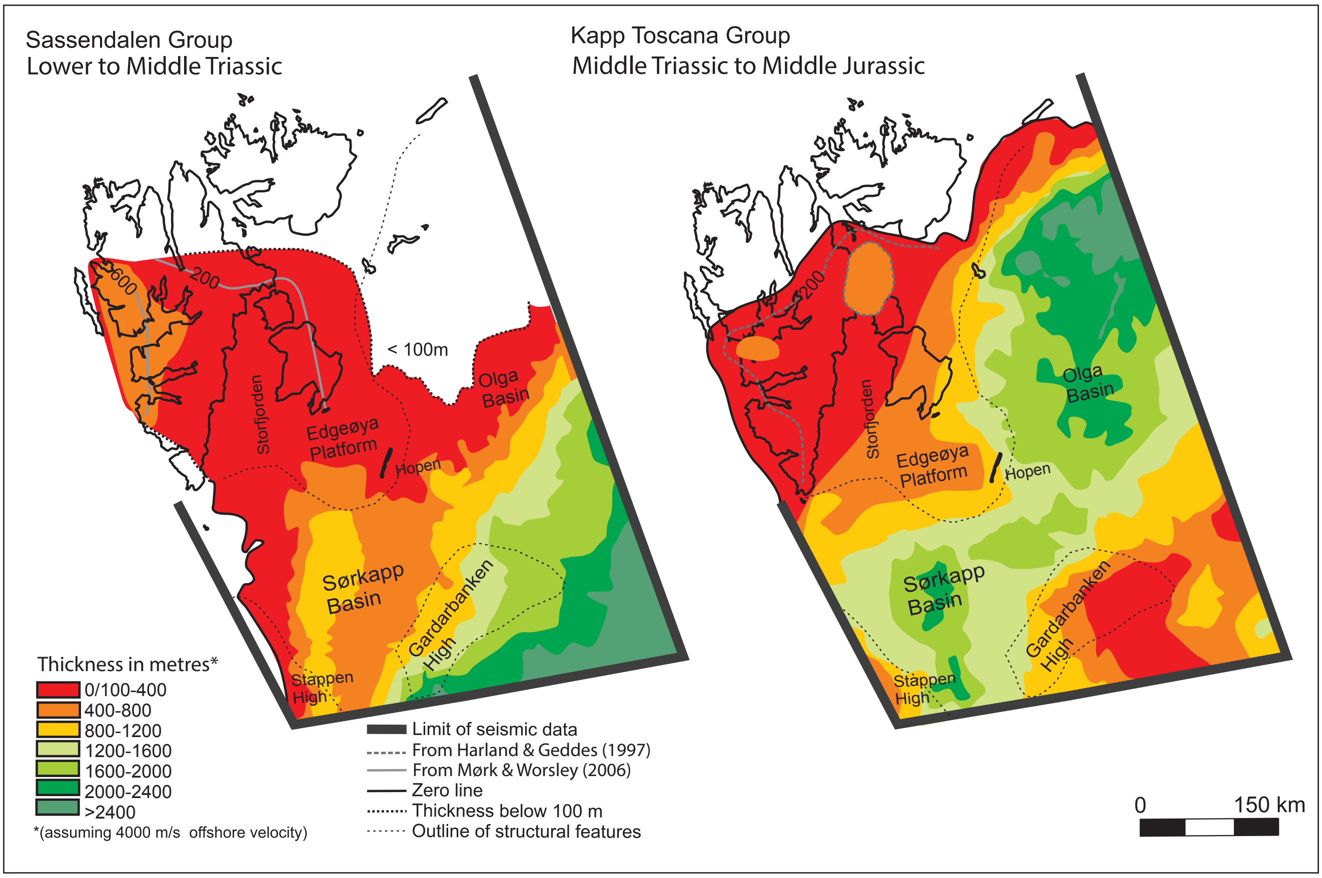


Figure 3. Isopachs of the Sassendalen and Kapp Toscana groups. Onshore measurements from Harland & Geddes (1997) and Mørk & Worsley (2006) are used and connected to the offshore interpretations. Of note is that the Kapp Toscana Group onshore-offshore connection is diachronous (see Fig. 2). Offshore thicknesses are based on two-way-time maps generated in petrel. An assumed velocity of 4000 m s^{-1} is applied to the offshore accumulations based on typical velocities of Triassic sediments.

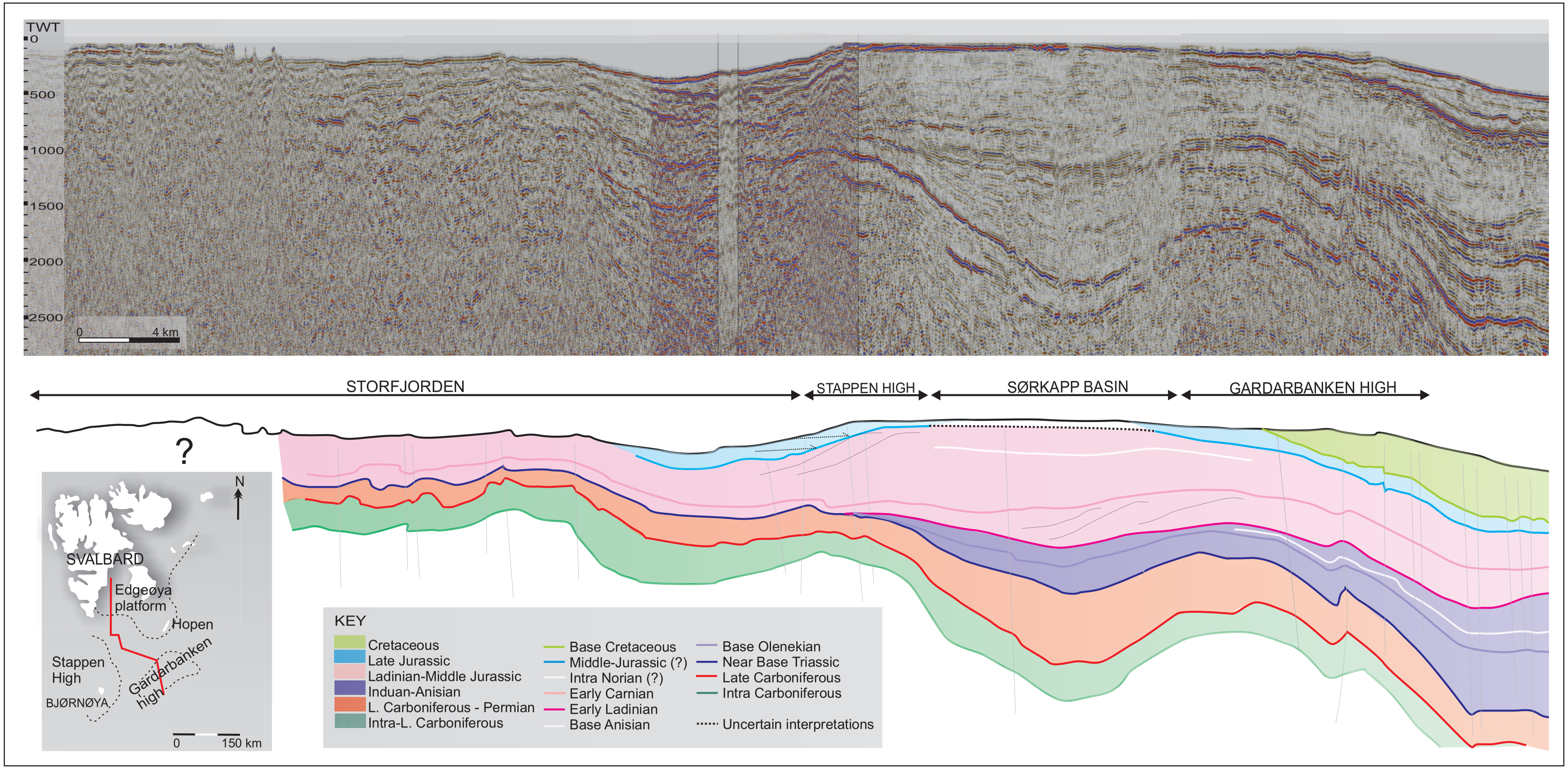
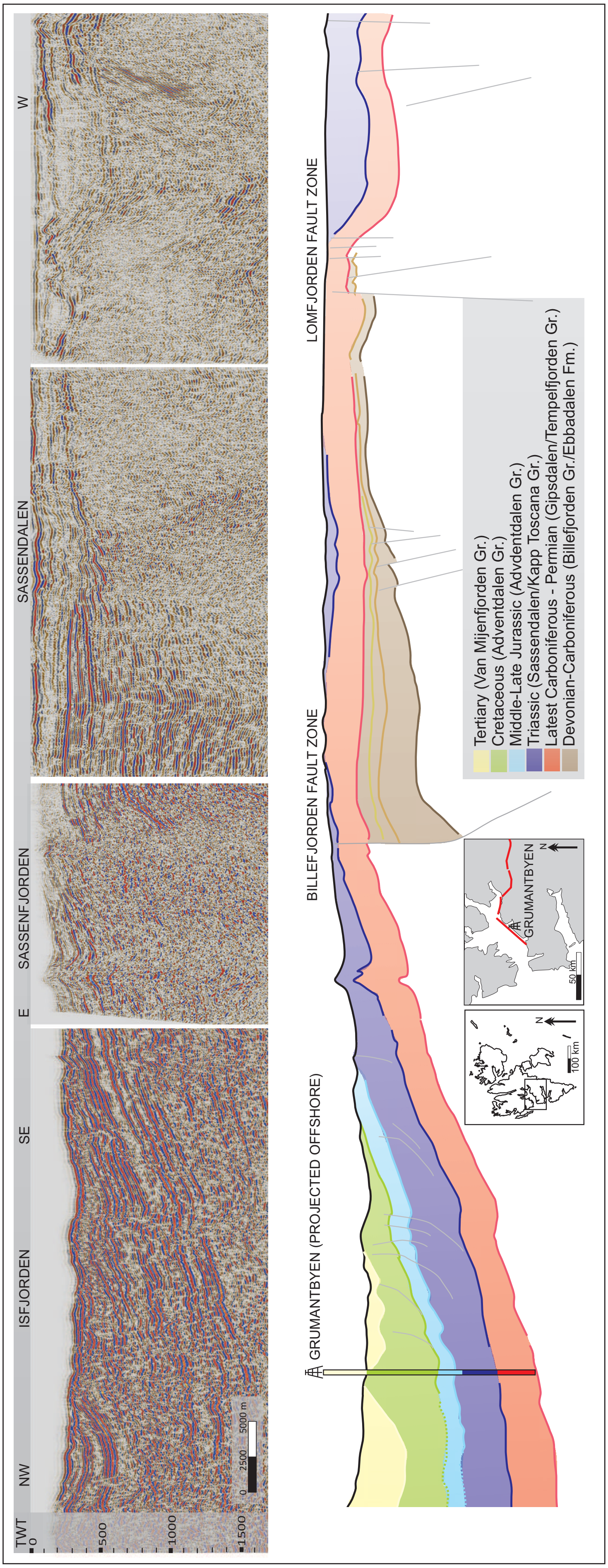


Figure 4. Seismic transect across the Sørkapp basin and into Storfjorden showing two of the main structural elements of the Northern Barents Shelf: the Gardarbanken and Stappen highs. Of note is the diminishing quality of the seismic data in Storfjorden, where it becomes increasingly difficult to resolve any seismic horizons and hence also to map the onshore-offshore connection. Seismic lines by courtesy of NPD.

Figure 5. A seismic transect starting offshore Svalbard in Isfjorden and then across Svalbard to the east coast using available seismic land data. The results of the Grumantbyen parametric drilling are projected offshore (Skola et al., 1980). Interpretations are guided by the work of Eiken (1994).



Lower Triassic deposits offshore thin significantly toward the Edgeøya platform (Fig. 3). As the reflectors shallow the resolution decreases and, hence, determining thickness and continuity of sedimentary sequences is difficult. In Storfjorden, tracing any Triassic reflectors is difficult (Fig. 4). The northern ends of the three seismic lines in Storfjorden (Fig. 1) terminate near an onshore line, on which it is possible to resolve the Near Base Triassic reflector. The reflector outlines a relatively thick succession of subsurface Triassic deposits east of the Lomfjorden Fault zone (Fig. 5). A concurrence of the total thickness of Triassic deposits can be found between the onshore and offshore lines (Figs. 4, 5), however, the resolution of the data limits detailed observations of Triassic sedimentation. East of Svalbard, the Lower Triassic deposits thin to within seismic resolution as the clinoforms downlap onto the Near Base Triassic reflector. Meanwhile, dark shales of the Botneheia Formation have been cored east of Kong Karls Land indicating the presence of Lower Triassic deposits farther north (Riis et al., 2008), illustrating the limitations of seismic mapping of diachronous prograding systems.

The vertical stacking pattern of the Lower Triassic deposits in the southern Barents Sea indicates that creation of accommodation was similar to or outpaced sediment infill, causing shore-line transgression followed by prograding events (Høy & Lundschien, 2011). In the northern Barents Sea, the Early Triassic clinoforms generally display an ascending regressive trend (Helland-Hansen & Hampson, 2009) with clinoforms laterally stacked, each platform edge break slightly higher and further forward than the next (Figs. 3, 6). Relatively thick topsets are commonly preserved and the trajectory angle (the angle between successive platform-breaks/rollover points) is high compared to the Late Triassic. This suggests the availability of accommodation (Helland-Hansen & Hampson, 2009) and a comparatively slow advance of the platform edge (Fig. 7). The general eustatic sea-level trend in the Triassic was transgressive (Vail et al., 1977, Haq et al., 1987), which suggests that sediment supply in the overall regressive delta-system was often high enough to outpace the rising sea-level. Meanwhile, the advance of the platform edge was relatively slow as the rising sea-level continually generated more accommodation. Transgression led to onlap and submergence of positive features (Worsley, 2008). While the Lower Triassic deposits are thin or absent across the Gardarbanken high, the Ladinian deposits are uniformly thick. It is inferred that the high was completely transgressed at this time, coevally with the Loppa High (Worsley et al., 2001; Larssen et al., 2002; Riis et al., 2008; Worsley, 2008) and Stappen High.

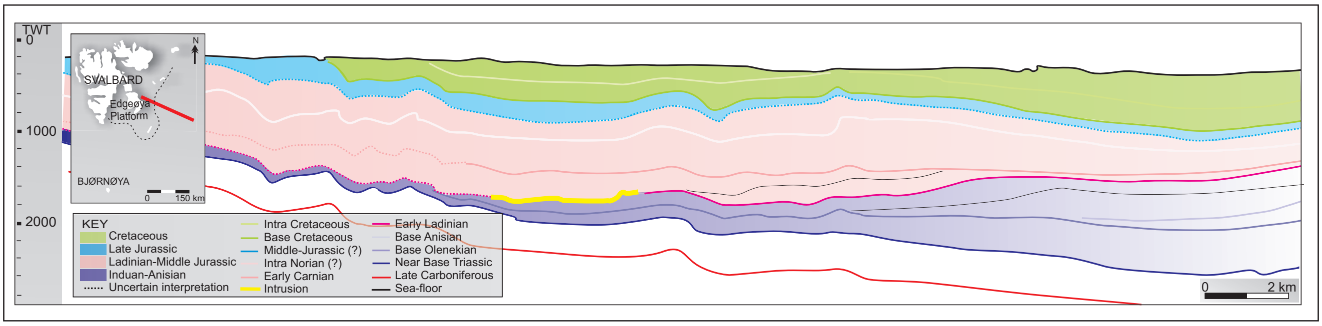


Figure 6. *A schematic profile showing sediment thicknesses in the southeastern part of the study area, drawn from interpretations of a composite seismic section of unreleased seismic data.*

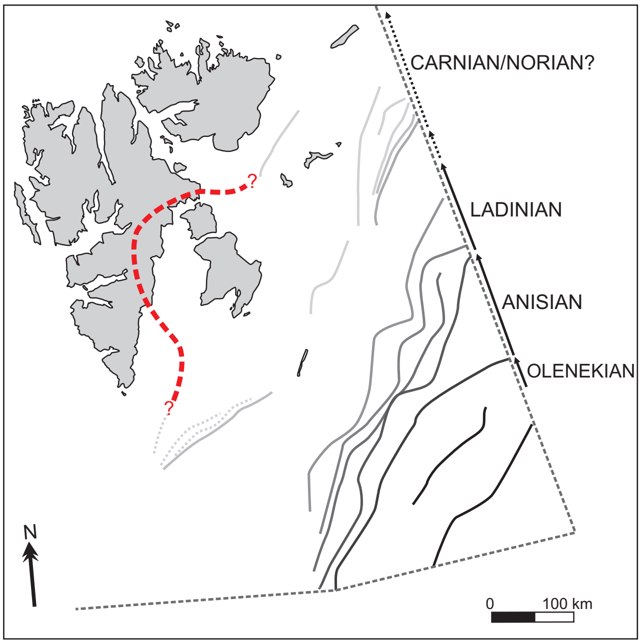


Figure 7. *The advance of the platform edge during the Triassic as interpreted from seismic data. Ages of the Early Triassic clinoforms are based on shallow well cores from the work of Riis et al. (2008). From the Ladinian onwards it is increasingly difficult to distinguish a clear platform edge and to ascribe an age to those clinoforms apparent in the seismic data. The thick, red dotted line across Svalbard shows an interpretation of how the rapid advance interacting with the Edgeøya platform may connect with the offshore platform edge breaks.*

Sedimentary development of the Kapp Toscana Group

Storfjorden Subgroup

The Early Triassic depocentre in Western Svalbard is no longer appreciable in the Late Triassic (Fig. 3). Instead, the sedimentary pattern is almost wholly governed by the advance of the platform edge from the southeast. The delta system, while still clearly advancing, shows a more complex pattern as compared to the Early Triassic. There are two separate depocentres, one in the Sørkapp basin and the other farther northeast, east of Edgeøya. While post-depositional erosion has influenced the present thickness of the Triassic to Middle Jurassic deposits, both onshore and offshore, inferences from the seismic data indicate that the main variations in thickness are probably due to depositional processes. The offshore Kapp Toscana Group accumulations of >2 km thin significantly on the Edgeøya platform, indicating that this structure exerted influence on accommodation (Fig. 3).

The platform edge becomes increasingly difficult to resolve around the early Ladinian and onwards (Fig. 7). While younger clinoforms can be mapped in both the Sørkapp basin and in the Olga basin and around the Kong Karls platform, it is complicated to connect isochronous platform edges across the whole area and ascribe a correct age. It is therefore hard to surmise what happened when the platform edge reached the Edgeøya platform. When accommodation space is limited a progradational system will advance more rapidly. As the Edgeøya platform was a structural high, advance would have been rapid with a lower and flatter trajectory, forming less distinct clinoforms. This might explain the lack of a clear platform edge and resolvable clinoforms in the seismic data near Edgeøya. Meanwhile, advance in the Sørkapp basin and in the eastern depocentre would have been comparatively slower. The resulting delta front would have formed a curved shape across the platform (Fig. 7). A rapid advance may have had significant effects on the depositional regime on the presently exposed onshore areas, such as the Longyearbyen CO_2 Lab reservoir, including effects on porosity and general sediment instability (Mills, 1983 and references therein; Riis et al., 2008). The Triassic clinoforms in the Sørkapp basin are poorly resolved. It appears, however, that the platform edge transitioned from a more northwesterly towards a more northerly advance around Ladinian time (Fig. 7).

The provenance areas for the prograding successions are likely Siberia, the Kola Peninsula and the Caledonides (Høy & Lundschien, 2011). The Uralide/Baltic source is visible in detrital zircon analysis, becoming the dominant provenance area in the Early Triassic on Bjørnøya and later onshore Svalbard and coevally on Franz Josef Land (Worsley et al., 1986; Bue et al., 2010; Bue, 2012). This is in accord with an advancing delta system, which is diachronous, with older deposits occurring toward the south and east. Provenance studies of Upper Triassic sandstones indicate a strong contribution from the Caledonides in the southern Barents Sea with a potentially greater influence from an eastern source farther north (Riis et al., 2008).

Palaeocurrent data in the De Geerdalen Formation are generally very complex, with multiple orientations measured (Fig. 8) (Knarud, 1980). While a clearer north-northwestern orientation is often apparent onshore Spitsbergen, the pattern becomes increasingly complex towards the east, on Edgeøya. Edgeøya reveals a large number of growth faults in the exposed De Geerdalen Formation (Edwards, 1976) and it is possible that faulting impacted on drainage patterns. The variability of drainage directions can also be explained if the delta front advanced rapidly across the Edgeøya platform and drainage was splayed (Fig. 8). It has also been suggested that uplift occurred in northern and eastern sources such as the Lomonosov Ridge, Franz Josef Land and Novaya Zemlya (Nøttvedt et al., 1992).

Offshore, the base of the Kapp Toscana Group is marked by the base of the Snadd Formation (early Ladinian). The base of the Snadd Formation is lithologically (and

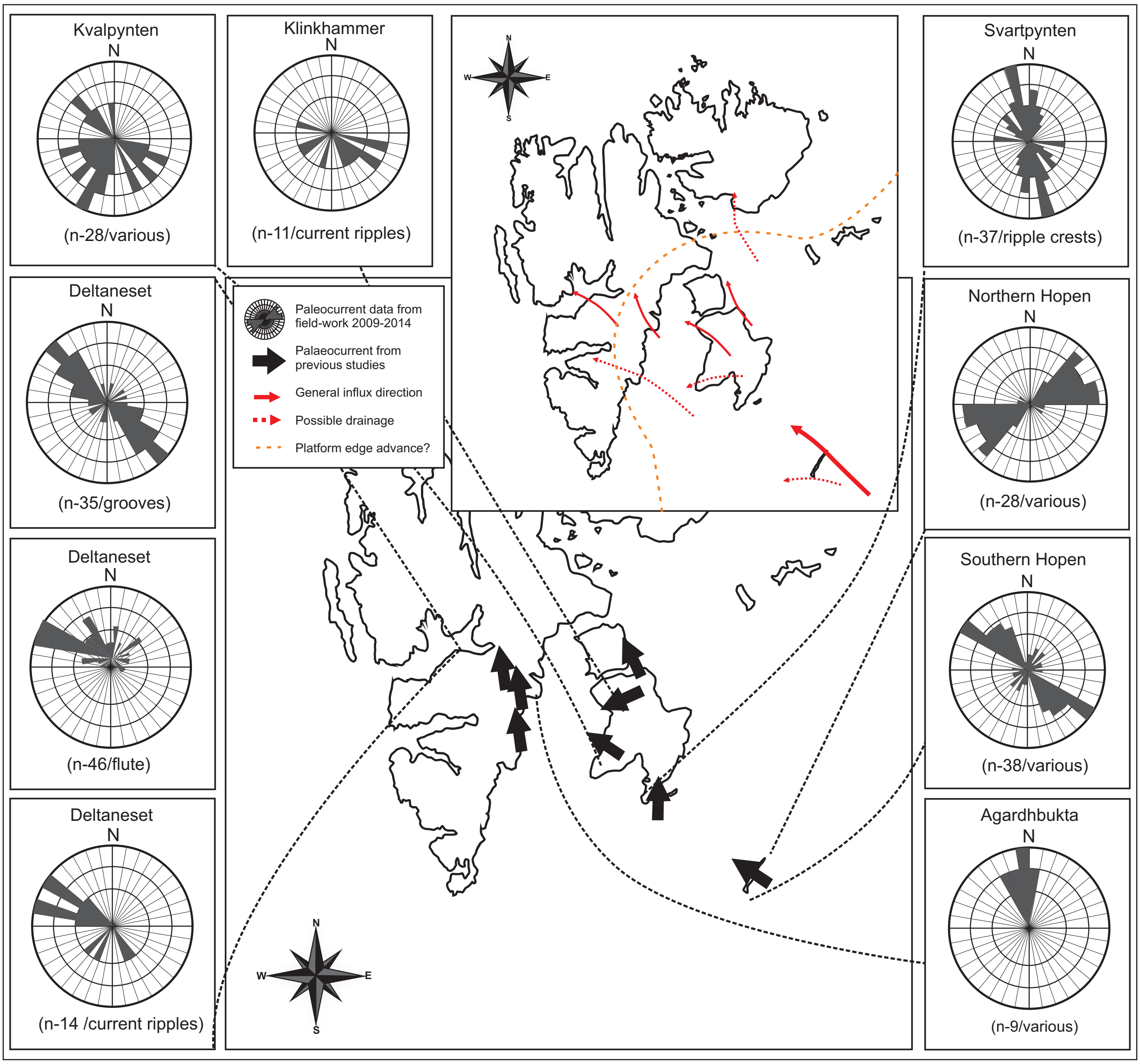


Figure 8. Palaeocurrent data measurements of the De Geerdalen Formation from various locations across Svalbard. Data from Deltaneset are based on the work of Ogata et al. (2014). The large map shows the locations of the palaeocurrent data collected from field-work (2011–2014) along with black arrows showing the results (current flow) from previous studies made by Knarud (1980) and Høy & Lundschien (2011). The smaller map shows the interpreted influx of the De Geerdalen Formation based on the palaeocurrent data and the seismic data and the advance of the platform edge. In rose diagrams indicated as 'various', the palaeocurrent measurements are based on multiple types of indicators including flutes, ripples, grooves and imbrications.

lithostratigraphically) connected to the base of the Tschermakfjellet Formation (early Carnian) onshore (Mørk et al., 1999a), and isochronously connected to an early Ladinian horizon associated with a major transgressive pulse. This transgression submerged many of the highs, which is apparent in deposition across the Gardarbanken and Stappen highs (Fig. 4). The Snadd Formation consists of grey shales coarsening upward into siltstones and sandstones with thin coaly lenses in the upper parts (Dalland et al., 1988). The lower Snadd Formation consists of prograding clinoforms which form a tapering wedge thinning toward Edgeøya. The distal, fine-grained, suspended sediments associated with this delta-system may form part of the Botneheia Formation (of the upper Sassendalen Group) exposed on Edgeøya. The early Carnian reflector within the Snadd Formation correlates time-wise with the Sassendalen–Kapp Toscana Group transition onshore. Offshore, the reflector correlates with the base of the first massive sandstone in the Hopen-2 well (Anell et al., 2014a). Onshore, the Sassedalen–Kapp Toscana Group transition is probably marked by a regional hiatus broadening towards the southwest, indicating a period of erosion and/or non-deposition (Hounslow et al., 2007; Hounslow & Nawrocki, 2008). As the early Carnian reflector offshore is traceable regionally it is likely to be linked

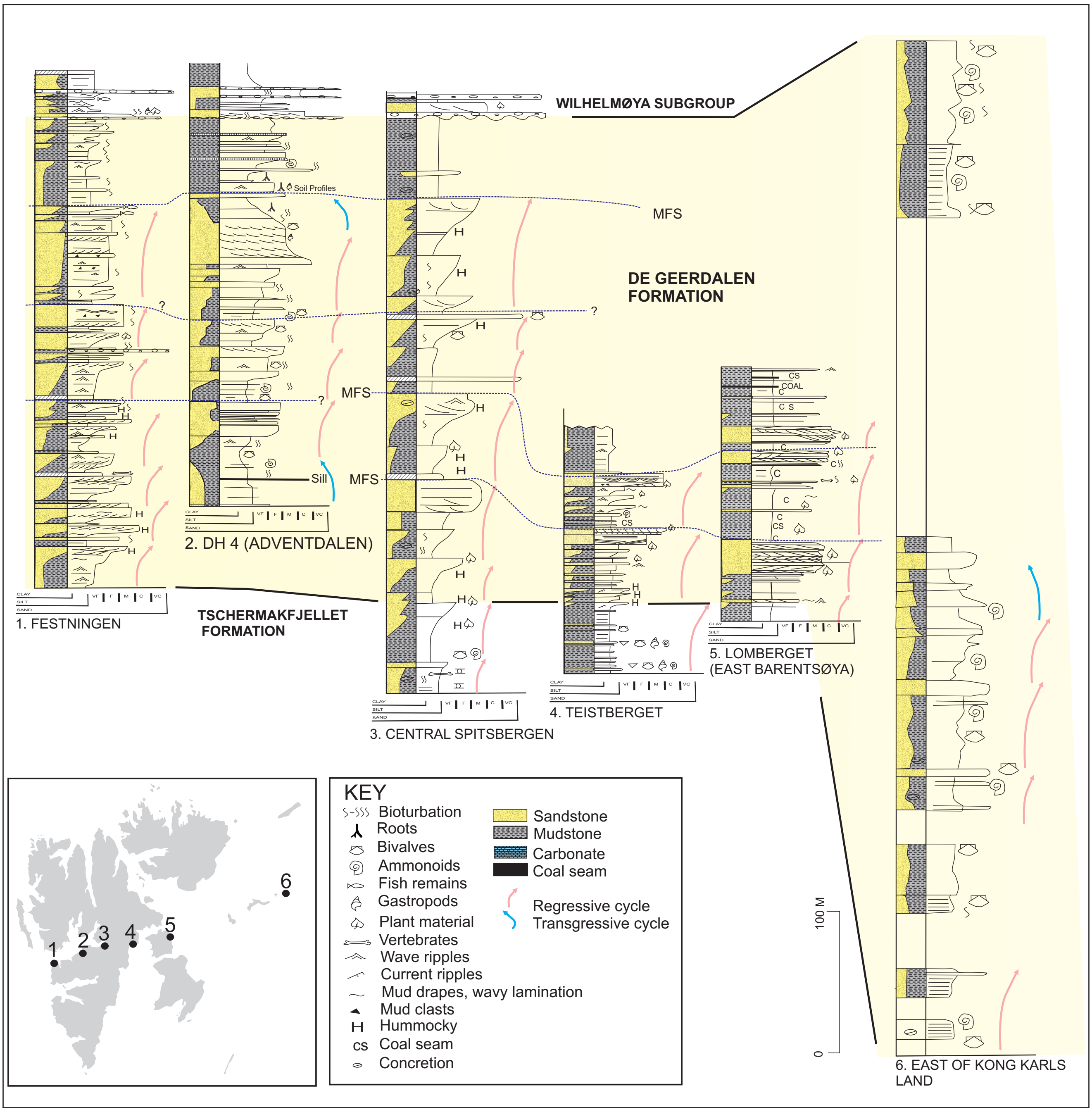


Figure 9. An E–W transect of sedimentary logs across Svalbard and offshore Kong Karls Land. The logs are re-drawn from Knarud (1980), Egorov & Mørk (2000) and Riis et al. (2008). The figure also shows tentative correlative surfaces.

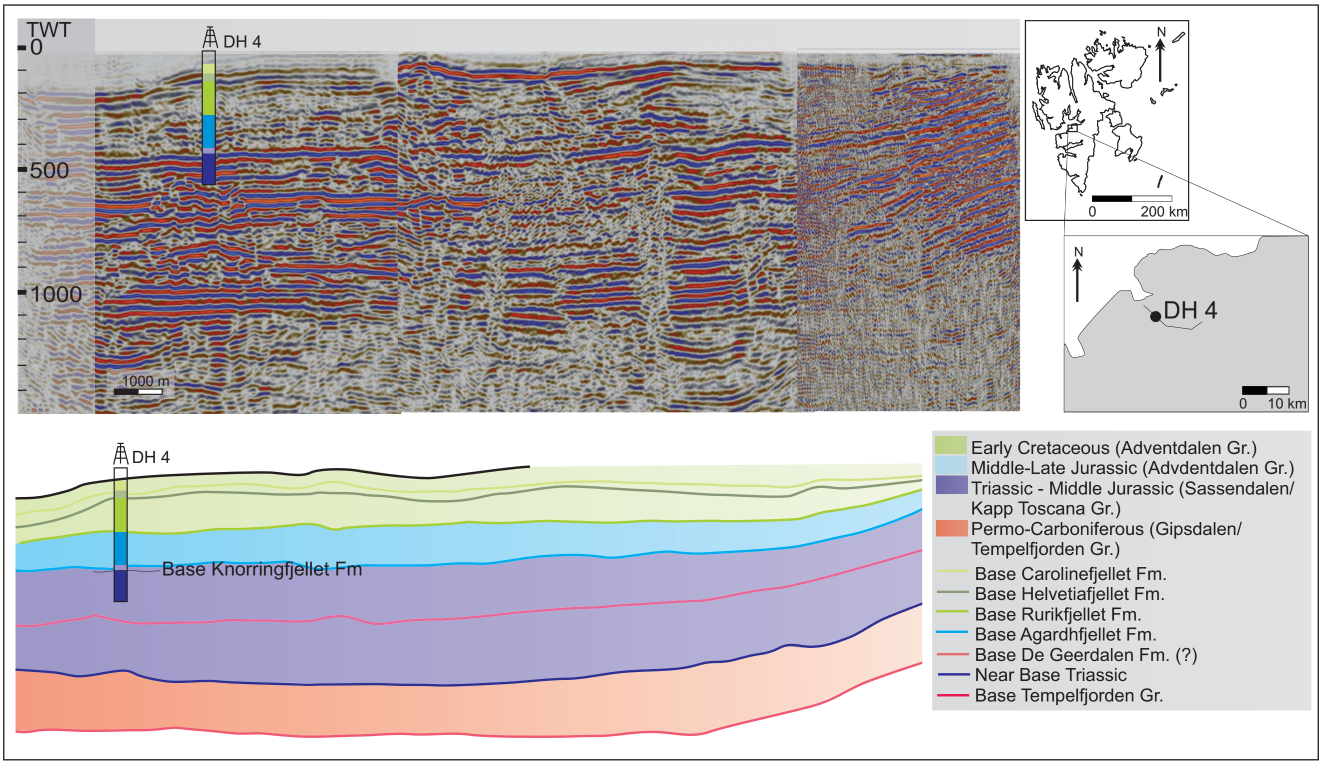


Figure 10. *Seismic transect across the proposed CO_2 storage site, seismic lines collected by the Longyearbyen CO_2 Lab. The transect also shows the DH 4 well which penetrates the two proposed reservoir units, the De Geerdalen and Knorringfjellet formations.*

to a significant event. The deposits above this reflector mark the progressive advance of the platform edge and a paralic influence on sedimentation.

The Tschermakfjellet Formation is a pro-delta succession consisting of dark shales with increasing intercalations of siltstone laminae and abundant siderite-rich beds (Mørk et al., 1999a) deposited during continuous and high rates of sedimentation (Hounslow et al., 2007). Generally, this formation grades into the overlying upward-coarsening successions of immature sandstones and shales of the De Geerdalen Formation, although in places it is missing, or very thin (Vigran et al., 2014). Shallow-marine sandstones characterise the De Geerdalen Formation deposits on Spitsbergen while eastern exposures on Edgeøya, Barentsøya and Hopen comprise deltaic channels and stacked sandstone bodies with minor coal (Edwards, 1976; Knarud, 1980; Mørk et al., 1982, 1999a; Dypvik et al., 2004; Høy & Lundschien, 2011). On Bjørnøya, the unconformably bounded Skuld Formation (Ladinian–early Carnian) forms an upward-coarsening unit (Mørk et al., 1982, 1989). The unit shows a similar development to equivalent sequences on Svalbard with basal beds consisting of prodeltaic facies grading upward into sandstone (Worsley et al., 2001). This suggests that the curve of the isopachs (Fig. 3) can be readily linked to the advancing delta front, giving rise to penecontemporaneous development on the Stappen High and the Edgeøya platform.

The WSW–ENE cross-section of stratigraphic logs reveals a relatively uniform thickness of the De Geerdalen Formation across Svalbard and an increase offshore towards Kong Karls Land (Fig. 9). A generally uniform thickness of Triassic sediments is also apparent in seismic data available on a local scale across the injection site (Fig. 10) corroborated by the uniform thickness of the Triassic sediments regionally across Svalbard (Fig. 5). On the NW–SE cross-section (Fig. 11), the De Geerdalen Formation appears to increase in thickness markedly towards the southeast (Fig. 11). However, the top deposits on Edgeøya have been eroded and therefore this trend is based largely on the increase towards the Hopen-2 well. The Hopen-2 well does not provide much information on sedimentary structures (Fig. 8). What is apparent is the transition from shales with interbedded sandstones towards sandstones with interbedded shales and abundant coal seams. This represents the progressive shallowing and transition towards alluvial deposition as the platform edge advanced. Farther northwest, in line with the advancing delta front, the sedimentary logs of the De Geerdalen Formation are characterised by a decreasing sand content and plant material, and increasing storm-influenced sedimentation with abundant hummocky cross-stratification and shell-beds consistent with a deeper to moderately deep shelf environment. Towards the upper beds, an increasing amount of fluvial, wave and tidal influence is apparent, including soil horizons in the DH4 well at the proposed injection site (Fig. 9). The trend is similar on the WSW–ENE cross-section with more cross-bedded sandstones, coal seams and abundant plant material on East Barentsøya and increasing hummocky cross-stratification, shells, fish remains and bioturbation towards the west (Fig. 9). It is possible to connect upward-coarsening units bounded by large flooding surfaces between logs (Figs. 9, 11). While the onshore clinoform geometries have not been established it should eventually be possible to map complete clinoforms between logs. On Edgeøya and Barentsøya, typical topset features grading upward from delta-front/shoreface to delta plain are evident, while farther west within the same succession more typical pro-deltaic strata associated with foresets and bottomsets are present (Figs. 9, 11).

The logs, palaeocurrent and seismic data suggest that the dominant influx for the Storfjorden Subgroup was from a delta-system advancing towards the northwest. This is further corroborated from analysis of the cores of the De Geerdalen Formation in Adventdalen, where high amounts of plagioclase and lithic grains of similar composition to the Snadd Formation are present (Mørk,

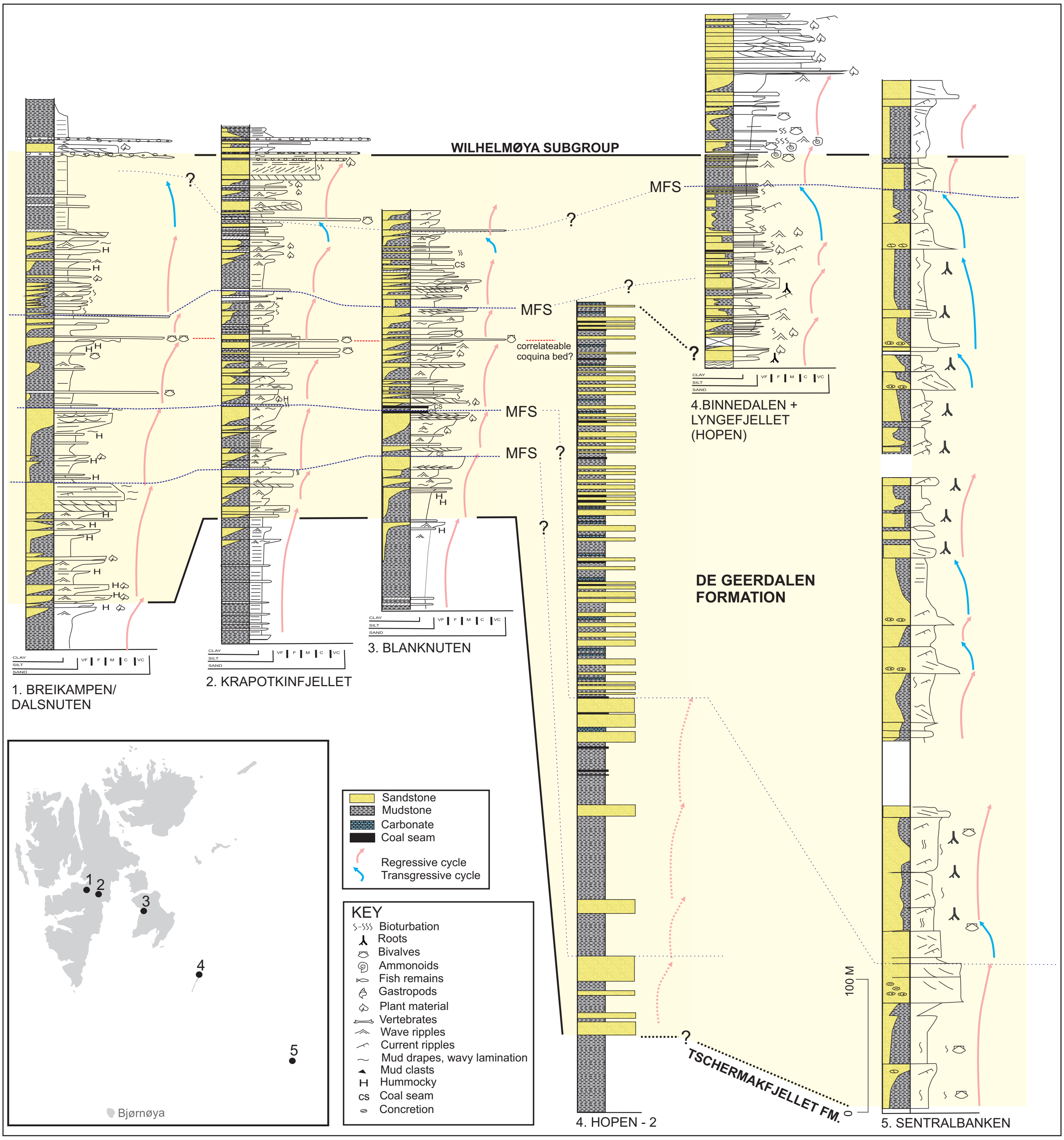


Figure 11. A NW–SE transect of sedimentary logs across Svalbard and the northern Barents Shelf. The logs are redrawn from Knarud (1980), Mørk et al. (1982) and Riis et al. (2008). The Hopen-2 log is compiled based on the original well data provided by the Norwegian Petroleum Directorate.

2013). It is inferred that the Upper Triassic deposits are characterised by generally progressively shallower environments both upwards in the stratigraphy and southeastward. Therefore, the sand content, coarseness of sand and larger channellised sandstone bodies will also be more prolific upwards in the stratigraphy and to the east and southeast.

Wilhelmøya Subgroup – Realgrunnen Subgroup

The Wilhelmøya Subgroup is contained between polymict (phosphatic) conglomerate beds. The basal formation is the Norian Slottet Bed, and the upper layer consists of the Bathonian Brendkardshaugen and Marhøgda beds (Fig. 2). The condensed calcareous, phosphate-rich, shallow-marine sandstone Slottet Bed is overlain by mudstones marking a widespread Early to Mid Norian transgression that can be recognised all over Svalbard, the Barents Sea and the Sverdrup Basin in Canada (Mørk et al., 1989). Offshore, this transgression marks the base of the Fruholmen Formation of the Realgrunnen Subgroup, which is the offshore counterpart of the Wilhelmøya Subgroup. Flooding was followed by regression and northwestward progradation, and establishment of coastal, deltaic and alluvial systems (Mørk et al., 1999a). Maximum regression was probably reached in the Early Toarcian followed by a period of condensation, non-deposition and erosion across the east and north Barents Shelf including Svalbard, which lasted until the Late Bathonian (Nøttvedt et al., 1992; Nagy & Berge, 2008; Henriksen et al., 2011). Large parts of Western and Central Spitsbergen were probably emergent during deposition of the Wilhelmøya Subgroup, and only transgressed at maximum highstand (Vigran et al., 2014).

The potential uppermost CO_2 storage reservoir in Adventdalen belongs to the Knorringfjellet Formation of the Wilhelmøya Subgroup. The drilled and cored 25 m-thick Norian to Bathonian unit is laterally condensed with several regional hiatuses consistent with intermittent deposition in Spitsbergen, as described by Bäckström & Nagy (1985), Dypvik et al. (2004) and Nagy & Berge (2008). The increased maturity likely reflects extensive reworking of the deposits (Mørk, 1999). In the eastern parts of the Svalbard archipelago, around Hopen, Wilhelmøya and Kong Karls Land, the Norian deposits are represented by the Flatsalen Formation. It forms a coarsening-upward unit representing a transition from offshore/pro-delta to lower shore-face/distal delta-front deposits. Westward on Spitsbergen, the time-equivalent deposits are represented by a condensed, only 12 m-thick, succession of inner-shelf and shallow-marine deposits, with several stratigraphic breaks. On Kong Karls Land, the Upper Triassic to Middle Jurassic deposits are represented by the 225 m-thick Svenskøya and Kongsøya formations (Larssen et al., 1993). The lower 200 m of the Svenskøya Formation show evidence of strong tidal influence in a coastal-plain shoreline environment. Overlying these deposits the Mohnhøgda Member reveals facies associated with an offshore to lower shore-face location. The up to 40 m-thick Kongsøya Formation is a condensed unit with several hiatuses thought to represent shallow-marine, inner-shelf deposits (Larssen et al., 1993). On Wilhelmøya and Hopen the Svenskøya Formation is thinner, *c.* 45 m, but with similar characteristics to those on Kong Karls Land. The time-equivalent, 13 m-thick deposits in Western Svalbard are severely condensed with several hiatuses.

A similar development is seen offshore in the Realgrunnen Subgroup in the southwestern Barents Sea where condensed units with several hiatuses occur on rift shoulders, structural highs and platforms, which thicken toward basins (Henriksen et al., 2011) and may reach up to 900 m on some terraces (well 7219/9–1, NPD fact pages). The sandstone-prone Realgrunnen Subgroup, which was deposited in a variety of inner-shelf, near-shore to alluvial environments, is the main reservoir unit in the southwestern Barents Sea (Olaussen et al., 1984; Berglund et al., 1986; Henriksen et al., 2011).

The Upper Triassic to Middle Jurassic deposits offshore are particularly difficult to trace in the seismic data. The characteristics of the upper 500 ms are generally masked by multiples together with very poorly defined reflectors (Fig. 5), and in the eastern Barents Sea a series of anticlines distort internal characteristics and confident tracing. On the Barents Shelf the Realgrunnen Subgroup is commonly relatively uniformly thick; however, it appears to have been deeply eroded and in places completely removed, notably on the Gardarbanken and Stappen highs (Anell et al., 2014a). It is a relatively thin unit compared to the underlying Snadd Formation (Fig. 6) particularly given the long time period of deposition spanning the Late Triassic to Middle Jurassic. In Storfjorden, where seismic lines tying to the onshore data are available, the intra-Norian reflector (the base of the Realgrunnen Subgroup) is truncated. Near Edgeøya, the deposits are more continuous, although a more detailed analysis of onshore dip is required to extrapolate between the offshore and onshore. Near Hopen, the projection of the mid-Norian reflector intersects at the base of the exposed Flatsalen Formation (Anell et al., 2014a). It is generally difficult to resolve clinoforms in the Realgrunnen Subgroup given the poor resolution mentioned before. It is, however, possible to resolve a succession of clinoforms near the southern tip of Spitsbergen which are possibly Norian in age. These appear to prograde in a more northerly direction in the Sørkapp basin, possibly changing gradually towards more northwesterly in the north (Fig. 7), where the structures of the Palaeogene fold-and-thrust belt have, however, overprinted the seismic signal. The limited accumulation and in places truncation and absence of the Realgrunnen Subgroup offshore suggests that limited accommodation and erosion played an important part in the development offshore.

The Early to Middle Jurassic is characterised by transgression and landward displacement of shorelines (Doré, 1992; Henriksen et al., 2011). The top of the Kapp Toscana Group is marked by a 1–2 m-thick phosphatic and quartzitic conglomerate, the Brentskardhaugen Bed and additionally in places also the Marhøgda Bed (Mørk et al., 1999a). The Brentskardhaugen Bed has an erosive base representing a hiatus and is generally thought to represent a trangressive lag deposit due to a major Mid Jurassic transgression that flooded many areas and cut off the supply of coarse clastics (Dypvik, 1985; Worsley, 2008). The Brentskardhaugen Bed can be traced regionally via wells to structural highs in the Barents Sea, where a conglomerate marks the top of the Stø Formation. There is a marked change in sedimentary regime around the Middle Jurassic as sandstones grade into dark shales (Dypvik et al., 1991). The transgression is appreciable in onlapping the infill of the Upper Jurassic deposits (Fig. 4).

Conclusions

The targeted CO_2 storage reservoir in Adventdalen on Svalbard comprises two different sandstone units, the immature sandstones of the Carnian De Geerdalen Formation and the overlying, thin, Norian–Bathonian mature sandstones of the Knorringfjellet Formation. The main findings of this study, based on collation of previous studies and new data, are summarised below.

- The De Geerdalen Formation is composed dominantly of immature sandstones deposited from rapidly advancing delta systems sourced mainly from the Urals and Fennoscandian Shield. Influence on deposition from the previously dominant western, and/or local sources is difficult to surmise.
- The De Geerdalen Formation shows increasing thickness towards the east and southeast along with a higher degree of alluvial influence.
- The Early Triassic clinoforms in the southeastern part of the study area are well developed and reveal a comparatively slowly advancing platform edge. Rapid advance due to limited accommodation is inferred across the structurally higher area of the Edgeøya platform which influenced drainage patterns. Rapid deposition across Svalbard probably resulted in flatter trajectories, potentially poorer sorting and more structurally unstable deposits.
- Inferences from this study suggest that regionally limited accommodation controlled the development of the Wilhelmøya/Realgrunnen Subgroup (to which the Knorringfjellet Formation belongs). Although comparatively thicker deposits developed offshore, both onshore and offshore deposits on the northern Barents shelf experienced periods of condensation, sediment starvation, erosion and reworking. While ultimately the provenance of the Knorringfjellet Formation is probably the same as for the De Geerdalen Formation, the reservoir is likely to be the result of extensive reworking and redeposition.

Acknowledgements. We are grateful for the helpful input provided by Bjørn Anders Lundschien and an anonymous reviewer. Thanks go to the Norwegian Petroleum Directorate for data on the Hopen-2 well and for providing the reflection seismic data used in this study. Thanks to FME SUCCESS, UNIS and the Longyearbyen CO_2 Lab for financing this project. We are grateful to Atle Mørk for input and comments on the manuscript, and Aleksandra Smyrak Sikora, Berit Husteli, Harmon Maher, Kei Ogata, Oliver Hinchey and Per Terje Osmundsen for discussions in the field. Kei Ogata kindly shared palaeocurrent measurements from Deltaneset.

References

Anell, I., Braathen, A., Olaussen, S. & Osmundsen, P.T. 2013: Evidence of faulting contradicts a quiescent northern Barents Shelf during the Triassic. *First Break 31*, 67–76.

Anell, I., Braathen, A. & Olaussen, S. 2014a: Regional constraints of the Sørkapp Basin: A Carboniferous relic or a Cretaceous depression? *Marine and Petroleum Geology 53*, 124–138.

Anell, I., Midtkandal, I. & Braathen, A. 2014b: Trajectory analysis and inferences on geometric relationships of an Early Triassic prograding clinoform succession on the northern Barents Shelf. *Marine and Petroleum Geology 54*, 67–179.

Bäckström, S.A. & Nagy, J. 1985: Depositional history and fauna of a Jurassic Phosphorite conglomerate (the Brentskardhaugen Bed) in Spitsbergen. *Norsk Polarinstitutts Skrifter 183*, 1–61.

Bergh, S.G., Braathen, A. & Andresen, A. 1997: Interaction of basement-involved and thin-skinned tectonism in the Tertiary fold-and-thrust belt, central Spitsbergen, Svalbard. *American Association of Petroleum Geologists Bulletin 81*, 637–661.

Berglund, L.T., Augustson, J., Færseth, R., Gjelberg, J. & Ramberg-Moe, H. 1986: The evolution of the Hammerfest Basin. *In* Spencer, A.M. (ed.): *Habitat of Hydrocarbons on the Norwegian Continental Shelf*. Graham and Trotman, London, pp. 319–338.

Braathen, A., Bergh, S.G. & Maher Jr., H.D. 1999a: Application of a critical wedge taper model to the Tertiary transpressional fold-thrust belt on Spitsbergen. *Geological Society of America Bulletin 111*, 1468–1485.

Braathen, A., Maher, H.J., Haabet, T.E., Kristensen, S.E., Tørudbakken, B.O. & Worsley, D. 1999b: Caledonian thrusting on Bjørnøya: implications for Palaeozoic and Mesozoic tectonism of the western Barents Shelf. *Norsk Geologisk Tidskrift 79*, 57–68.

Braathen, A., Bælum, K., Christensen, H.H., Dahl, T., Eiken, O., Elvebakk, H., Hansen, F., Hanssen, T.H., Jochmann, M., Lie, T., Johansen, T.A., Johnsen, H., Larsen, L., Mertes, J., Mørk, A., Mørk, M.B., Nemec, W., Olaussen, S., Oye, V., Røed, K., Titlestad, O., Tveranger, J. & Vagle, K. 2012: Longyearbyen CO_2 Lab of Svalbard, Norway - first assessment of the sedimentary succession for CO_2 storage. *Norwegian Journal of Geology 92*, 353–376.

Breivik, A.J., Mjelde, R., Grogan, P., Shimamura, H., Murai, Y. & Nishimura, Y. 2005: Caledonide development offshore-onshore Svalbard base on ocean bottom seismometer, conventional seismic and potential field data. *Tectonophysics 401*, 79–117.

Bue, E.P. 2012: New U-Pb LA-ICPMS zircon provenance age data on Triassic sandstones (Vichekov, Vasilyev and Thegetthoff formations) from Franz Josef Land: preliminary results. *In* Nakrem, H.A. & Haukdal, G.K. (eds.): *Nordic Geological Winter Meeting 2013*. Norsk Geologisk Forening, Oslo, p. 140.

Bue, E.P., Andresen, A., Andersen, T. & Solbakken, R.T. 2010: Provenance of Mesozoic sediments from Spitsbergen, Wilhelmøya, Edgeøya and Hopen based on LA-MC-ICPMS U-Pb analyses of clastic zircons. *In* Brekke, H., Haukdal, G.K., Olesen, O. & Thorsnes, T. (eds.): *Tromsø Arctic Days: Abstracts and Proceedings of the Geological Society of Norway*. Geological Society of Norway 2, p. 9.

Corfu, F., Polteau, S., Planke, S., Faleide, J.I., Svensen, H., Zayoncheck, A. & Stolbov, N. 2013: U–Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province. *Geological Magazine 150*, 1127–1135.

Czuba, W., Grad, M., Guterech, A., Majdanski, M., Malinowski, M., Mjelde, R., Moskalik, M., Sroda, P. & Wilde-Piorko, M. & Nishimura, Y. 2008: Seismic crustal structure along the deep transect Horsted'05 Svalbard. *Polish Polar Research 29*, 279–290.

Dalland, A., Worsley, D. & Ofstad, K.E. (eds): 1988: A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *Norwegian Petroleum Directorate Bulletin Bulletin 4*, 87 pp.

Dallman, W.K. 1999: Introduction. *In* Dallman, W.K. (ed.): *Lithostratigraphic lexicon of Svalvard. Upper Palaeozoic to Quaternary bedrock*. Review and recommendations for nomenclature use. Norsk Polarinstitutt, Tromsø, 320 pp.

Doré, A.G. 1992: Synoptic palaeogeography of the Northeast Atlantic Seaway: late Permian to Triassic. *In* Parnell, J. (ed.): *Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution*. Geological Society of London Special Publications 62, 421–446.

Doré, A.G. 1995: Barents Sea Geology, Petroleum Resources and Commerical Potential. *Arctic 48*, 207–221.

Dypvik, H. 1985: Jurassic and Cretaceous black shales of the Janusfjellet Formation, Svalbard, Norway. *Geology 41*, 235–248.

Dypvik, H., Nagy, J., Eikeland, T.A., Backer-Owe, K. & Johansen, H. 1991: Depositional conditions of the Bathonian to Hauterivian Janusfjellet Subgroup, Spitsbergen. *Sedimentary Geology 72*, 55–78.

Dypvik, H., Mørk, A., Smelror, M., Sandbakken, P.T., Tsikalas, F., Vigran, J.O., Bremer, G.M.A., Nagy, J., Gabrielsen, R., Faleide, J.I., Bahiru, G.M. & Weiss, H.M. 2004: Impact breccia and ejecta from the Mjølnir impact crater in the Barents Sea - The Ragnarok Formation and Sindre Bed. *Norwegian Journal of Geology 84*, 143–167.

Edwards, M.B. 1976: Growth faults in upper Triassic deltaic sediments, Svalbard. *American Association of Petroleum Geologists Bulletin 60*, 341–355.

Egorov, A.Y. & Mørk, A. 2000: The East Siberian and Svalbard Triassic successions and their sequence stratigraphical relationships. *Zentralblatt für Geologie und Paläontologie 1*, 1377–1430.

Eiken, O.E. 1994: Seismic Atlas of western Svalbard: a selection of regional seismic transects. *Norsk Polarinstitutt Meddelelser 130*, 73 pp.

Eldholm, O. & Thiede, J. 1980: Cenozoic continental separation between Europe and Greenland. *Palaeogeography Palaeoclimatology Palaeoecology 30*, 243–259.

Elverhøi, A., Antonsen, P., Flood, S.B., Solheim, A. & Vullstad, A.A. 1988: Western Barents Sea - Shallow bedrock geology. *Norsk Polarinstitutts Skrifter 179*, 1–32.

Faleide, J.I., Gudlaugsson, S.T. & Jacquart, G. 1984: Evolution of the western Barents Sea. *Marine and Petroleum Geology 1*, 123–128.

Faleide, J.I., Gudlaugsson, S.T., Eldholm, O., Myhre, A.M. & Jackson, H.R. 1991: Deep seismic transects across the sheared western Barents Sea-Svalbard continental margin. *Tectonophysics 189*, 73–89.

Faleide, J.I., Vågnes, E. & Gudlaugsson, S.T. 1993: Late Mesozoic-Cenozoic evolution of the southwestern Barents Sea in a regional rift-shear tectonic setting. *Marine and Petroleum Geology 10*, 186–214.

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.

Gabrielsen, R., Færseth, R., Jensen, L.N., Kalheim, J.E. & Riis, F. 1990: Structural elements of the Norwegian Continental Shelf, Part 1: The Barents Sea Region. *Norwegian Petroleum Directorate Bulletin 6*, 1–47.

Gee, D.G., Bogolepova, O.K. & Lorenz, H. 2006: The Timanide, Caledonide and Uralide orogens in the Eurasian high arctic, and relationships to the Palaeo-contienents Laurentia, Baltica and Sibera. *In* Gee, D.G. & Stephernson, R.A. (eds.): *European Lithosphere Dynamics*. The Geological Society of London Memoirs 32, pp. 507–520

Glørstad-Clark, E., Faleide, J.I., Lundschien, B.A. & Nystuen, J.P. 2010: Triassic seismic sequence stratigraphy and palaeogeography of the western Barents Sea area. *Marine and Petroleum Geology 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. *Marine and Petroleum Geology 28*, 1294–1314.

Grogan, P., Nyberg, K., Fotland, B., Myklebust, R., Dahlgren, S. & Riis, F. 1998: Cretaceous magmatism south and east of Svalbard: evidence from seismic reflection and magnetic data. *Polarforschung 6*8, 25-34.

Gudlaugsson, S.T., Faleide, J.I., Johansen, S.E. & Breivik, A.J. 1998: Late Palaeozoic structural development of the south-western Barents Sea. *Marine and Petroleum Geology 15*, 73–102.

Harland, W.B. & Geddes, I. 1997: Triassic history. In Harland, W.B. (ed.): The geology of Svalbard. *Geological Society of London Memoirs 17*, pp. 340–362.

Helland-Hansen, W. & Hampson, G.J. 2009: Trajectory analysis: concepts and applications. *Basin Research 21*, 454–483.

Haq, B. U., Hardenbol, J. & Vail, R. 1987: Chronology of fluctuating Sea levels since the Triassic. *Science 23*, 1156–1167.

Henriksen, E., Ryseth, A.E., Larssen, G.B., Heide, T., Rønning, K., Sollid, K. & Stoupakova, A.V. 2011: Tectonostratigraphy of the greater Barents Sea: implications for petroleum systems. *In* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sørensen, K. (eds.): *Arctic Petroleum Geology*. Geological Society London Memoirs 35, 163–195.

Hounslow, M.W. & Nawrocki, J. 2008: Palaeomagnetism and magnetostratigraphy of the Permian and Triassic of Spitsbergen: a review of progress and challenges. *Polar Research 27*, 502–522.

Hounslow, M.W., Mengyu, H., Mørk, A., Vigran, J.O., Weitschat, W. & Orchard, M.J. 2007: Magneto-biostratigraphy of the Middle to Upper Triassic transition, central Spitsbergen, arctic Norway. *Journal of the Geological Society London 164*, 581–597.

Høy, T. & Lundschien, B.A. 2011: Triassic deltaic sequences in the northern Barents Sea. *In* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sørensen, K. (eds.): *Arctic Petroleum Geology.* Geological Society London Memoirs 35, 249–260.

Johansen, S.E., Ostisty, B.K., Birkeland, Ø., Fedorovsky, Y.F., Martirosjan, V.N., Bruun Christensen, O., Cheredeev, S.I., Ignatenko, E.A. & Mragulis, L.S. 1992: Hydrocarbon potential in the Barents Sea region: play distribution and potential. *In* Vorren, T.O., Bergsager, E., Dahl-Stamnes, Ø.A., Holter, E., Johansen, B., Lie, B. & Lund, T.B. (eds.): *Arctic geology and petroleum potential 2*, pp. 273–320.

Knarud, R. 1980: *En sedimentologisk undersøkelse av Kapp Toscana formasjonens sedimenter på Svalbard*. Cand. Scient. thesis, University of Oslo, Oslo.

Larssen, G.B., Johannessen, E.P., Nøttvedt, A., Olaussen, S. & Riis, F. 1993: Late Triassic to Early Cretaceous Geological Development of Kong Karls Land, *55th Meeting of EAEG/EAPG, DATE, Stavanger, Norway, 7–11th June 1993*.

Larssen, G.B., Elvebakk, G., Henriksen, L.B., Kristensen, S.E., Nilsson, I., Samuelsberg, T.J., Svånå, T.A., Stemmerik, L. & Worsley, D. 2002: Upper Palaeozoic lithostratigraphy of the southern Norwegian Barents Sea. *Norwegian Petroleum Directoriate Bulletin 9*, 76 pp.

Lock, B.E., Pickton, C.A.G., Smith, D.G., Batten, D.J. & Harland, W.B. 1978: The geology of Edgeøya and Barentsøya, Svalbard. *Norsk Polarinstitutts Skrifter 168*, 1–64.

Maher, H.D.J. 2001: Manifestations of Cretaceous High Arctic large igneous province in Svalbard. *Journal of Geology 109*, 91–104.

McKerrow, W.S., Mac Niocaill, C. & Dewey, J.F. 2000: The Caledonian Orogeny redefined. *Journal of the Geological Society London 157*, 1149–1154.

Mills, P.C. 1983: Genesis and diagnostic value of soft-sediment deformation structures – A review. *Sedimentary Geology 35*, 83–104.

Mørk, A. & Worsley, D. 2006: Triassic of Svalbard and the Barents Shelf. *NGF Abstracts and proceedings 3*, 23–35.

Mørk, A., Knarud, R. & Worsley, D. 1982: Depositional and diagenetic environments of the Triassic and lower Jurassic succession of Svalbard. *In* Embry, A.F. & Balkwill, H.R. (eds.): *Arctic geology and geophysics*. Canadian Society of Petroleum Geologists Memoir 8, pp. 371–398.

Mørk, A., Embry, A.F. & Weitschat, W. 1989: Triassic transgressive-regressive cycles in the Sverdrup Basin, Svalbard and Barents shelf. *In* Collinson, J.D. (ed.): *Correlation in Hydrocarbon Exploration,* Springer, Netherlands, pp. 113–130

Mørk, A., Dallman, W.K., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pchelna, T.M. & Worsley, D. 1999a: Mesozoic lithostratigraphy. *In* Dallman, W.K. (ed.): *Lithostratigraphic lexicon of Svalbard. Upper Palaeozoic to Quaternary bedrock. Review and recommendations for nomenclature use*, Norsk Polarinstitutt, Tromsø, pp. 127–214.

Mørk, A., Elvebakk, G., Forsberg, A.W., Hounslow, M.W., Nakrem, H.A., Vigran, J.O. & Weitschat, W. 1999b: The type section of the Vikinghøgda Formation: a new Lower Triassic unit in central and eastern Svalbard. *Polar Research 18*, 51–82.

Mørk, M.B.E. 1999: Compositional variations and provenance of Triassic sandstones from the Barents Shelf. *Journal of Sedimentary Research 69*, 690–710.

Mørk, M.B.E. 2013: Diagenesis and quartz cement distribution of low-permeabilty Upper Triassic-Middle Jurassic reservoir sandstones, Longyearbyen CO2 Lab well site in Svalbard, Norway. *American Association of Petroleum Geologists Bulletin 97*, 577–596.

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

Nance, R.D., Worsley, D. & Moody, J.B. 1988: The Supercontinent Cycle. *Scientific American July Issue*, 44–51.

Nøttvedt, A., Cecchi, M., Gjelberg, J.C., Kristensen, S.E., Lønøy, A., Rasmussen, A., Rasmussen, E., Skott, P.H. & van Veen, P.M. 1992: Svalbard-Barents Sea correlation: a short review. *In* Vorren, T., Bergsager, E., Dahl-Stamnes, Ø.A., Holter, E., Johansen, E., Lie, B. & Lund, T.B. (eds.): *Arctic Geology and Petroleum Potential.* Norwegian Petroleum Society, Special Publication 2, Elsevier, Amsterdam, pp. 15–17.

Ogata, K., Senger, K., Braathen, A., Tveranger, J. & Olaussen, S. (2014): Fracture systems and meso-scale structural patterns in the siliciclastic Mesozoic reservoir-caprock succession of the Longyearbyen CO$_2$ Lab project: implications for geologic CO$_2$ sequestration on Central Spitsbergen, Svalbard. *Norwegian Journal of Geology 94*, 121–154.

Olaussen, S., Dalland, A., Gloppen, T.G. & Johannessen, E. 1984: Depositional environments 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*. Graham and Trotman for the Norwegian Petroleum Directorate, London, pp. 61–79.

Pease, V. 2011: Eurasian orogens and Arctic tectonics; an overview. *In* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sorensen, K. (eds.): *Arctic Petroleum Geology.* Memoirs of the Geological Society of London 34, pp. 311–324.

Renard, V. & Malod, J. 1974: Structure of the Barents sea from seismic refraction. *Earth and Planetary Science Letters 24*, 33–47.

Rickard, M.J. & Belbin, L. 1980: A new continental assembly for Pangaea. *Tectonophysics 63*, 1–12.

Riis, F. & Fjeldskaar, W. 1992: On the magnitude of the late Tertiary and Quaternary erosion and tis significance for the uplift of Scandinvia and the Barents Sea. *In* Larsen, R.M., Brekke, H., Larsen, B.T. & Talleraas, E. (eds.): *Structural and tectonic modelling and its application to petroleum geology*. Norwegian Petroleum Society Special Publications 1, pp. 163–185.

Riis, F., Lundschien, B.A., Høy, T., Mørk, A. & Mørk, M.B.E. 2008: Evolution of the Triassic shelf in the northern Barents Sea region. *Polar Research 27*, 318–338.

Rønnevik, H. & Jacobsen, H.P. 1984: Structural highs and basins in the western Barents Sea. *In* Spencer, A.M. (ed.): *Petroleum Geology of the North European Margin: proceedings of the North European Margin Symposium (NEMS 83')*. Graham and Trotman for the Norwegian Petroleum Directorate, London, pp. 436.

Rønnevik, H., Beskow, B. & Jacobsen, H.P. 1982: Structural and stratigraphic evolution of the Barents Sea. *In* Embry, A.F. & Balkwill, H.R. (eds.): *Arctic geology and geophysics: proceedings of the third international symposium on Arctic Geology.* Canadian Society of Petroleum Geologists Memoir 8, pp. 431–440.

Sigmond, E.M.O. 1992: Bedrock map. Norway and adjacent ocean areas, *Norges geologiske undersøkelse, Trondheim*.

Škola, I.V., Pčelina, T.M., Mazur, V.B. & Alter, S.M. 1980: Novye dannye o sostave i stroenil osadočnogo čechla po materialam burenija grumantskoj parametričeskoj skvaziny (New data on the composition and structure of the sedimentary platform cover on the basis of materials from the drilling of a parametric hole at Grumantbyen). *In* Semevskij, D.V.(Ed): *Geologija osadocnogo cehla archipelaga Svalbard. Sbornik naucnyc trudo (Geology of the sedimentary platform cover of the archipelago of Svalbard),* Collection of Scientific Papers, NIIGA, Leningrad, pp. 13–24.

Steel, R.J. & Worsley, D. 1984: Svalbard's post-Caledonian strata - an atlas of sedimentational patterns and palaeogeographic evolution. *In* Spencer, A.M. (ed.): *Petroleum Geology of the North European Margin: Proceedings of the North European Margin Symposium*, Springer, Netherlands, pp. 109–134.

Stemmerik, L. & Worsley, D. 2005: 30 years on - Arctic Upper Palaeozoic stratigraphy, depositional evolution and hydrocarbon prospectivity. *Norwegian Journal of Geology 85*, 151–168.

Vail, P. R., Mitchum, R. M. J., Todd, R. G., Widmier, J. M., Thomson, S. I., Sangree, J. B., Bubb, J. N. & Hatelid, W. G. 1977: Seismic stratigraphy and global changes in sea-level. *In*: Payton, C.E. (ed.) *Seismic stratigraphy - Applications to Hydrocarbon exploration*. American Association of Petroleum Geologists Memoir 26, pp. 49–212.

Vigran, O.S., 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 Publications 14*, 270 pp.

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

Worsley, D., Aga, O.J., Dalland, A., Elverhøi, A. & Thon, A. 1986: *The geological History of Svalbard, evolution of the Arctic archipelago*. Den norske stats oljeselskap as, Aske Trykkeri, Stavanger, 120 pp.

Worsley, D., Johansen, R. & Kristensen, S.E. 1988: The Mesozoic and Cenozoic successions of Tromsøflaket. *In* Dalland, A., Worsley, D. & Ofstad, K.E. (eds): *A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway.* Norwegian Petroleum Directorate Bulletin 4, pp. 42–65.

Worsley, D., Agdestein, T., Gjelberg, J.G., Kirkemo, K., Mørk, A., Nilsson, I., Olaussen, S., Steel, R.J. & Stemmerik, L. 2001: The geological evolution of Bjørnøya Arctic Norway: implications for the Barents Shelf. *Norwegian Journal of Geology 81*, 195–234.

Ziegler, P.A. 1988: *Evolution of the Arctic-North Atlantic and the Western Tethys, American Association of Petroleum Geologists Memoir 43.* The American Association of Petroleum Geologists, Tulsa, OK, USA, pp. 164–196.