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Gareth Steven Lord

Sequence stratigraphy and facies development of the Triassic succession of Svalbard and the northern Barents Sea

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Thesis for the degree of Philosophiae Doctor

Trondheim, June 2017

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Preface

This doctoral thesis was initiated by the Norwegian Petroleum Directorate (NPD) as part of their mandate to gain continual insight and understanding into the geological development of the Norwegian continental shelf. The proximity of Triassic exposures on Svalbard to the Barents Sea makes its stratigraphy suitable as an analogue to nearby offshore areas. The project has been supported by the NPD for a period of three and a half years. Supervision has been given by Professor Atle Mørk at the Norwegian University of Science and Technology (NTNU), and by Professor Snorre Olaussen from the University Centre in Svalbard (UNIS). Work conducted at NPD has been facilitated and supervised by Bjørn Anders Lundschien, Dag Bering and Espen Simonstad.

The project began as the continuation of a Master Thesis by the candidate, undertaken at NTNU, during which a sound understanding of the region's structural geology and an extensive sedimentological dataset was attained. This allowed for more detailed investigations into the sedimentological and sequence stratigraphic development of the Triassic succession in Svalbard. With the implementation of seismic and core data provided by the NPD, this understanding could subsequently be extended offshore.

Much of the sedimentological research on the Triassic succession in Svalbard was conducted by David Worsley, Atle Mørk and Ragnar Knarud starting in the 1970's, followed by the later studies of Rita S. Rød (NTNU and NPD), Ingrid B. Hynne (NTNU) and Tore Klausen (University of Bergen, UiB). These sedimentological studies have formed the framework for this thesis. Researchers at the NPD and the University of Oslo (UiO) (e.g. Fridtjof Riis, Tore Høy, Bjørn Anders Lundschien, Evy Glørstad-Clark and Ingrid Anell), have focussed on the seismic sequence stratigraphy of the northern Barents Sea and their understanding has formed the basis for seismic studies conducted in this thesis.

This thesis is part of a wide-ranging project, where work on the Triassic succession is being conducted by many workers at collaborating institutions. Geologists from Sintef Petroleum AS, NTNU, UNIS, UiO, UiB, the Norwegian Polar Institute and the oil industry, have all participated in expeditions, academic collaborations and research workshops. The aim of these projects being primarily to increase the understanding of the Triassic succession in Svalbard and document its nature in the Barents Sea.

Throughout this project, I have been fortunate to participate in some 16 field excursions to Svalbard. In addition, extensive periods of time have been spent at the NPD headquarters in Stavanger, interpreting seismic from the northern areas and stratigraphic cores drilled close to Svalbard. Several courses have been taken at UNIS, in order to attain the number of credits required for doctoral studies at NTNU.

A large portion of work has been conducted in collaboration with active researchers and master students at NTNU, UiB and UNIS. Most notably Rita S. Rød, Kristoffer Solvi, Turid Haugen, Sondre K. Johansen and Simen Støen, whom have all completed their master theses on parts of the study area, supervised by Atle Mørk. These persons were part of two main research groups, the SINTEF Petroleum Hopen Geology Project and the NTNU East Svalbard Triassic Research Group. Tore Klausen implemented field data from Svalbard and compared the Triassic succession to that in the Barents Sea, as part of his PhD thesis and later post-doctoral work.

The results of this collaboration has amounted to six articles, of which four have been published (Papers 1, 2, 3 and 4), one has been submitted (Paper 5) and one is a manuscript in preparation (Paper 6). A new geological map (Appendix 1) of Hopen has also been produced and published by the Norwegian Polar Institute. Work relating to this thesis has been presented at conferences, such as the NGF Winter Conference, AAPG 3P Arctic, Boreal Triassic II and Force Seminar Series (see conference contributions section). The final appendix (Appendix 2) is a magazine article produced by Halfdan Carstens at GEO 365, to create outreach about work by the Hopen Geology Project in Svalbard.

Acknowledgements

I would like to thank the NPD and its staff for funding and allowing me to pursue this fantastic project. Bjørn Anders Lundschien, Dag Bering, Espen Simonstad, Andreas Bjørnestad and Tore Høy are all greatly thanked for their assistance and support during periods spent at the NPD office in Stavanger and excellent cooperation in the field.

To my supervisors and friends Atle Mørk and Snorre Olaussen, thank you! Your guidance, teaching and support have been invaluable. Discussions in the office and field have led to a fantastic new understanding of the Triassic in Svalbard and of course more questions than we yet have answers. Atle, thanks for that meeting all those years ago that put me on this path to where I am now. I'm glad you weren't too reluctant to let another Englishman into your research team.

I must of course mention all of the excellent geologists I have had the opportunity to work with and share a camp with in the field, no matter how miserable the weather. Motivation was always high and their ability in the field is beyond question; Tore Klausen, Valentin Zuchuat, Turid Haugen, Sondre Krogh Johansen, Simen Støen, Cathinka Forsberg, Bård Heggem, Nina Bakke, Even Nikolaisen, Niall Paterson, Espen Simonstad, Alexey Deryabin, Katrine Karlsen, Terje Solbakk and Bo Haugen, you guys are all excellent geologists and great friends. Thanks for the good times, the hard times, the cold-wet-and-rainy times and for all the fantastic memories. I really appreciate it!

Thanks are also extended to the many companies, licence groups and institutions that have assisted with fieldwork, funding and logistical support. Namely: Det Norske Oljeselskap (now Aker BP), ENI, Total, Wintershall, Lundin, Capricorn, The Svalbard Science Forum Artic Field Grant and the UNIS logistics department.

Finally, I wish to thank my family, for all their love and support and of course understanding in my desire to disappear off the radar for prolonged periods of time without contact, only to surface when in desperate need.

Gareth S. Lord

Trondheim, 2017.

Abstract

The Triassic succession of Svalbard is regarded as an analogue to the subsurface in the Barents Sea. In this thesis the sedimentology, facies development and sequence stratigraphy of the succession in Svalbard is addressed. The project has resulted in 4 journal articles, a submitted manuscript and a manuscript in preparation. A geological map has also been produced.

The project has created a new stratigraphic unit the Hopen Member, which is the south-eastern equivalent to the Isfjorden Member of Spitsbergen. This is based on the properties of the unit, its biostratigraphic and magnetostratigraphic characteristics. The Hopen Member is a succession of marine shale and subordinate sandstone deposits, different to the paralic deposits of the underlying part of the De Geerdalen Formation.

A study of channel bodies on Hopen shows they are confined to discrete stratigraphical intervals in the De Geerdalen Formation, defined as channel zones. Three zones are described and categorised as; a lower fluvial, middle tidal zone and upper fluvial zones. A paralic depositional environment for the De Geerdalen Formation on Hopen is maintained, however the nature of channels shows a greater influence of fluvial deposition, for the formation in this part of Svalbard. A multidisciplinary study of the Kapp Toscana Group (De Geerdalen, Flatsalen and Svenskøya formations) on Hopen is also presented and this provides an enhanced palaeo-environmental interpretation for the Upper Triassic succession on the island.

Upper Triassic deltaic sediments are seen throughout north-eastern Svalbard and analysis shows the De Geerdalen Formation to consist of three discrete informal units, defined by the gross depositional environment. The lower interval is dominated by shallow marine and delta front / shoreface deposits, the middle interval is composed of delta front to delta top deposits, and the upper interval is primarily delta top, lagoonal and lacustrine deposits. The De Geerdalen Formation represents a distal depositional setting in this area, in comparison to the depositional environments reported on the islands of Edgeøya and Hopen.

A facies study, conducted on the Svenskøya Formation in Eastern Svalbard, interprets the formation to be composed of sandstones deposited in a mixed fluvial, shoreface and shallow marine setting. Petrographic analysis of sandstones shows the formation as being arkosic, on Hopen and in the Sentralbanken area. The sandstone reservoir quality at Hopen is reduced compared to Sentralbanken, due to more extensive diagenetic impacts by compaction, mineral dissolution and extensive precipitation of pore-filling clay minerals. Similar properties are observed on Wilhelmøya and Kong Karls Land.

A regional study into the sequence development of the Triassic succession in Svalbard is the final component to this project. Analysis shows an increase in the number of low rank sequences in the western area of Svalbard, compared with central and eastern areas, in the Lower and Middle Triassic succession. This is due to the style of facies development, close to the basin margin at that time. The Upper Triassic shows the opposite trend, with an increase in low ranking sequences towards the east of Svalbard. Offshore the entire succession thickens as a result of deltaic development in these areas.

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Author statement of contributions and list of publications

This thesis is presented as a collection of peer-reviewed articles and manuscripts either submitted or in preparation. As such, the following list states the candidate's contribution to each article and appendix that are presented herein. For papers where the candidate is first author, many of the interpretations, discussion and concluding remarks reflect the understanding and view of the candidate, thus any errors or misinterpretations remain with him. Scientific contributions to articles by other persons, that do not warrant co-authorship, are subsequently acknowledged in each paper respectively.

Paper 1: The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard.

Lord, G.S., Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W. & Paterson, N.W.

The candidate produced the main body of text in addition to most of the figures. Text and figures referring to palynology were provided by Marianne Ask (MSc.) and Dr. Niall Paterson, whilst magnetostratigraphic data and figures were provided by Dr. Mark Hounslow. Kristoffer Solvi (MSc.) provided the original observations of the member unit, thickness and extent from the geological model of the island. Discussion and conclusions are based on the candidate's own interpretations of the provided data, with additional support from Dr. Atle Mørk. All authors contributed to the production of the manuscript.

Paper 2: Triassic Channel Bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution.

Lord, G.S., Solvi, K.H., Klausen, T.G. & Mørk, A.

The candidate produced the main body of text, tables and all figures used in the article. The fundamental observations were conducted with the assistance of Kristoffer Solvi (MSc.) and Dr. Tore Klausen. Discussion and conclusions were based on the candidate's own interpretations with additional refinement by Dr. Atle Mørk and Dr. Tore Klausen. All authors participated in the production of the manuscript and subsequent revisions.

Paper 3: A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway.

Paterson, N.W., Mangerud, G., Cetean, C.G., Mørk, A., Lord, G.S., Klausen, T.G. & Mørkved, P.T.

The candidate provided a detailed sedimentological section, samples and the fundamental geological understanding of the Svenskøya Formation to the manuscript and also provided data and text regarding the

Hopen Member. The candidate also assisted in the revision process. Invitation to co-author this article was given by Dr. Niall W. Paterson.

Paper 4: Facies Development of the Upper Triassic Succession on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard.

Lord, G.S., Johansen, S.K., Støen, S.J. & Mørk. A.

The candidate initiated the study and produced the main body of text and figures used within the article. Sedimentological interpretation and discussion was to a large extent based on master thesis work by Sondre K. Johansen (MSc.) and Simen J. Støen (MSc.). Dr. Atle Mørk contributed with refinements, discussion and provided a detailed understanding of previous geological work in the study area. All authors contributed to the production of the manuscript and subsequent revisions.

Paper 5: Sedimentology and Petrography of the Svenskøya Formation on Hopen, Svalbard: An analogue to sandstone reservoirs in the Realgrunnen Subgroup.

Lord, G.S., Mørk, M.B.E., Mørk. A., & Olaussen, S.

The candidate initiated the project and collected the original data and samples used. Samples have been prepared as thin sections at NTNU and have been analysed by Dr. Mai Britt E. Mørk for their petrographic qualities. The candidate produced the outline and sedimentological figures used in the article and provided the outline text, overview of sedimentology and comparisons to the Barents Sea. Dr. Mai Britt E. Mørk provided data, text and figures regarding the petrographic component. Dr. Atle Mørk provided text based on the Sentralbanken wells and review of the manuscript. Dr. Snorre Olaussen provided insight on the stratigraphy from Kong Karls Land and reviewed the sedimentological and regional implications components. All authors contributed to the discussion chapter in addition to their own contributions associated to their fields of specialty.

Paper 6: Sequence Patterns in the Triassic Succession of Svalbard and the Northern Barents Sea.

Lord, G.S., Mørk. A., & Høy, T.

The manuscript was initiated following discussion between the candidate and Dr. Atle Mørk. The candidate produced the main body of text and a number of figures. Dr. Atle Mørk provided detailed interpretations for the Lower and Middle Triassic component of the paper as well as producing key figures and parasequence data. Senior Geologist Tore Høy (NPD), provided text and figures regarding the seismic component to the paper. All authors participated in discussions and proof reading of the manuscript.

Appendix 1: Geological Map of Svalbard 1:100 000, Sheet G14G Hopen.

Mørk, A., Lord, G.S., Solvi, K.H. & Dallmann, W.K.

The candidate provided the main body of text for the map description, in addition to the cross-section and facies correlation panel. The candidate provided structural data from the field to the geological map, as well as formation thickness values. The geological map was then produced by Winfried K. Dallmann at the Norwegian Polar Institute. Kristoffer Solvi provided information regarding the extent of the Hopen Member, confirmed structural data and formation thicknesses based on data from the 3D Geological Model of Hopen. Atle Mørk initiated the project, organised fieldwork to the island, provided log sections, stratigraphic table, dating of rock units, discussion and review.

Appendix 2: På jakt etter reservoaranalog (in Norwegian)

Halfdan Carstens (Editor)

Magazine article published in GEO, about Gareth Lord and Atle Mørk's research on Hopen. March 2014.

The candidate participated in interviews with the editor, Halfdan Carstens from GEO 365. In addition to giving comments about the geology of Hopen, the candidate provided the majority of photographs used in the article and produced the scientific figures that are also presented. The article text was written in Norwegian by the editor, Halfdan Carstens, and featured as a cover page and article in GEO Magazine, published in March 2014.

Language & Referencing Style

This thesis follows the referencing style of the Norwegian Journal of Geology (*Norsk Geologisk Tidsskrift*). References are given at the end of individual parts to the thesis. The reference style in the presented academic papers reflects that of the journal to which they have been submitted. Papers 1,2,4 and 6 follow the standard of the Norwegian Journal of Geology. Paper 3 follows that of Palaeo 3 and Paper 5 follows the style of Polar Research. The thesis uses British English throughout.

Part I

Introduction

Introduction

The archipelago of Svalbard covers the north western area of the Norwegian Arctic from 74° to 81° north and 10° to 35° east (Fig. 1A). It consists of several major islands: Spitsbergen, Nordaustlandet, Edgeøya, Barentsøya, Wilhelmøya, Hopen and Bjørnøya (Dallmann et al., 2015b). Much of Svalbard is categorised as nature reserves or national parks by the Norwegian Government, who have been awarded sovereignty over the islands as a result of the 1920 Svalbard Treaty, currently signed by 42 other nations (Dallmann et al., 2015c).

The presence of world-class outcrops, with little to no vegetation cover, enables geologists to explore 'textbook' exposure of strata. However, exposures are sometimes covered by glaciers, snow drifts or scree slopes and this can complicate outcrop observations. The extent of geological time, which is exposed in the stratigraphy of the archipelago, also adds to its endearing status with those interested in sedimentology and stratigraphy. This is especially the case for geoscientists tasked with conducting geological research and hydrocarbon exploration in the Barents Sea. In this regard, Svalbard acts as a suitable and accessible window to the subsurface.

The aim of this thesis is to increase the understanding of sedimentary facies and sequence stratigraphic development throughout the Triassic succession of Svalbard and give comparison to the succession seen in the northern part of the Barents Sea. Due to the nature of field data collection, specific objectives were not defined at the outset. However, objectives for each component paper are stated in the respective parts to those papers. In short, the main objective of this study is to implement outcrop data in order to increase the understanding of the Triassic succession in Svalbard, with a focus on eastern areas of the archipelago.

Facies studies have largely been confined to the Upper Triassic succession (Carnian and Norian) as older parts of the stratigraphy have been well documented by earlier studies and are relatively poorly exposed in eastern Svalbard, where much of the field work for this thesis has been conducted. Sequence stratigraphy has focussed on a large portion of the Triassic succession; however this has been constrained between the Induan to mid-Norian part of the stratigraphy (Sassendalen Group and Storfjorden Subgroup). This is due to the overlying succession (Wilhelmøya Subgroup) being studied in detail by other researchers (e.g. Rismyhr et al., in prep.)

The study area (Fig. 1B) includes the Svalbard archipelago and the immediate offshore area, north of the present licence block areas and up to the 2011 maritime border with Russia. Fieldwork has primarily focussed on data collection on the islands of Hopen, Edgeøya, Barentsøya, Wilhelmøya. Other areas of Svalbard were covered by Knarud (1980), Mørk et al. (1982, 1990), Mørk et al. (1999a, b), Rød et al. (2014) and Vigran et al. (2014). Geological ages applied to stratigraphic units throughout this study generally follow the recent macrofossil review and palynological works by Vigran et al. (2014), Paterson and Mangerud (2015) and Paterson et al. (2016, Paper 3). In Paper 1 magnetostratigrapy and ammonoid biostratigraphy has also been applied.

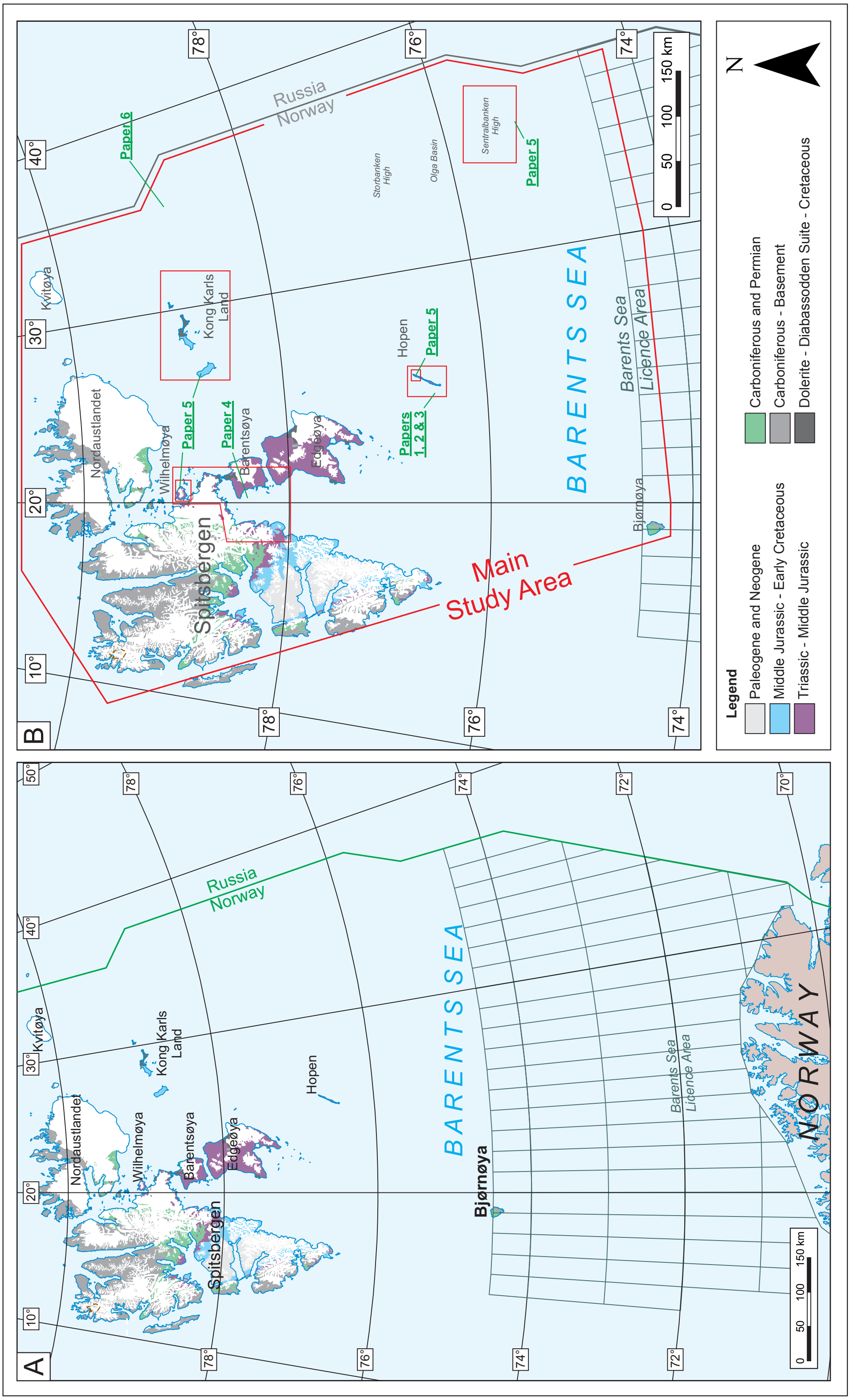


Figure 1: ***A****, Overview map of the Barents Sea and Svalbard showing the high Arctic position of the archipelago in relation to mainland Norway. The 2011 border with Russia is denoted along with the present hydrocarbon exploration licence block area.* ***B****, An*

overview map of the main study area, showing the basic Carboniferous to Early Cretaceous geology for the archipelago. The study areas for each individual paper are represented by red boxes. Papers 1, 2 and 3 focus on the facies and stratigraphic development of Hopen. Paper 4 extends the geological understanding from Hopen (Mørk et al., 2013; Klausen & Mørk, 2014; Lord et al., 2014a, b), Spitsbergen and Edgeøya (Mørk et al., 1982; Rød et al., 2014), to document facies and stratigraphical developments in the northern Storfjorden area. Paper 5 focusses on the facies development of the Svenskøya Formation on Hopen with comparisons to Wilhelmøya, Kong Karls Land and Sentralbanken. The study area for Paper 6 is constrained with the entire main study area.

As much of the data stems from the eastern islands, a large proportion of work has focussed on the Carnian, De Geerdalen Formation (Papers 1, 2, 3 and 4). The island of Hopen features heavily in this study and much of the fundamental understanding of the island's geology was initially presented in Mørk et al. (2013, Appendix 1), e.g. the Hopen Member and the distribution of sandstone channel bodies. These were then described in more detail in Lord et al. (2014a, b, Papers 1 and 2).

A facies study from Edgeøya and central Spitsbergen by Rød et al. (2014) provided the sedimentological framework for this part of the succession and has formed the basis for studies conducted in this project. The interpretations from central Spitsbergen and Edgeøya by Rød et al. (2014) covered the De Geerdalen Formation and Papers 2 and 4 have extended these facies studies to larger areas in Svalbard. The objective is to create a uniform understanding of facies types seen within the Carnian part of the Triassic succession, which can be used to define overall depositional environments throughout the study area.

The use of earlier facies frameworks has been especially evident in Paper 4, which builds directly upon the work of Rød et al. (2014) by extending their facies study northwards from Edgeøya to Barentsøya, Wilhelmøya and Triassic exposures along the coastline of eastern Spitsbergen. On Hopen (Papers 1 and 2), facies are not discussed explicitly, as this was covered by Klausen and Mørk (2014). However, the types of depositional environments defined by Rød et al. (2014) have been maintained and applied to the stratigraphy of the island. A multidisciplinary study of the Triassic succession on Hopen, conducted by Paterson et al. (2016, Paper 3), implements all of the recent understanding from the island (e.g. Mørk et al., 2013, Appendix 1; Klausen & Mørk, 2014; Lord et al., 2014a, b, Papers 1 and 2) to create biofacies subdivisions and discuss palaeo-climate.

Offshore studies have been made possible with the availability of confidential seismic data sets, owned by the NPD. This seismic data has been collected in the offshore areas to the east and southeast of Svalbard, north of the current (2016) petroleum licence block area (Fig. 1A, B). Implementation of this data by co-authors into Paper 6 has improved the understanding of the development of the Triassic succession offshore. Lord et al. (submitted, Paper 5), focusses on comparing facies and reservoir properties seen in the Svenskøya Formation, deposited in the latest part of the Triassic. The study extends data from Hopen to the island of Wilhelmøya and to wells in the Sentralbanken area of the Barents Sea (Fig. 1B). Lord et al. (in prep. Paper 6) attempt to quantify different order of sequences seen throughout the Triassic succession (Induan to Carnian) in Svalbard and relate this to the development of these units offshore.

Regional Structural Geology

The Svalbard archipelago has a long and complex history of geological development. To its north lies the Arctic Ocean and to its west lies the northernmost part of the Greenland Sea and the Fram Strait (Dallmann, 2015a). The uplifted corner of continental shelf (Worsley, 2008) that forms the archipelago is bound to the north and west by large-scale fault systems, along passive continental margins of Cenozoic age (Myhre & Eldholm, 1988; Leever et al., 2011; Dallmann et al., 2015a). Svalbard itself is dissected by a series of near N–S trending structures (see Fig. 2A, Dallmann et al., 2015a; Dallmann & Elvevold, 2015). From west to east these are the West Spitsbergen Fold and Thrust Belt, the Central Tertiary Basin (Dallmann et al., 2015a) with the Adventdalen Décollement Zone (Parker, 1966; Major & Nagy, 1972), the Billefjord Fault Zone (Harland et al., 1974; Bælum & Braathen, 2012) and the Lomfjord Fault Zone (Harland, 1979; Bergh et al., 1997). Further to the east lie the Storfjorden Fault Zone (Eiken, 1985; Dallmann et al., 2015a; Dallmann and Elvevold, 2015) and the enigmatic Rindedalen structure in Barentsøya (Lock et al., 1978).

The West Spitsbergen Fold and Thrust Belt (WSFTB, Figs. 2A, B) (Leever et al., 2011), is a NNW–SSE trending, 100–200 km wide complex of contractional fold and thrust structures, formed as a result of kinematic decoupling of contractional and transcurrent elements, close to an intracratonic palaeo-transform fault (Braathen et al., 1999). This tectonic system resulted from the northwards migration of the Atlantic rifting throughout the Cenozoic, as Greenland transpressed into the Barents shelf, then separated (Faleide et al., 2008). This contraction caused approximately 20–40 km of crustal shortening perpendicular to the margins (Bergh et al., 1997; Leever et al., 2011) and involved both basement rocks and cover strata. Folding and thrusted structures formed within this regime were emplaced above strata with a pre-existing south / south-east regional dip.

The Mesozoic succession in the Central Tertiary Basin (CTB, Figs. 2A, B) is partitioned by the Cenozoic aged Adventdalen Décollement Zone (Parker, 1966; Major and Nagy, 1972; Haremo et al., 1990; Haremo & Andresen, 1992; Andresen et al., 1994; Eiken, 1994). The floor thrust is situated in soft 'paper-shale' of the Botneheia Formation, with the roof thrust situated in the marine shales of the Agardhfjellet Formation (Haremo et al., 1990; Eiken, 1994; Braathen et al., 1999).

The Billefjord Fault Zone (BFZ, Figs. 2A, B) is the eastern boundary of the Central Tertiary Basin (Dallmann et al., 2015a; Dallmann & Elvevold, 2015), consisting of a complex array of structural elements, some 10 km (20–30 km at its widest) in width and 150 km in length. The BFZ has an extensive history of activity, dating back to Palaeozoic times (Harland et al., 1974; Harland, 1979; Manby et al., 1994; Dallmann et al., 2002; Bælum & Braathen, 2012; Dallmann & Elvevold, 2015). It was initiated during a transcurrent and contractional regime in the Caledonian – Devonian (Haremo & Andresen, 1992). Later, during the Carboniferous, its style changed to extensional, as evidenced by the formation of half-graben structures and monoclines (Haremo & Andresen, 1992; Bergh et al., 2011). Further activity occurred during the Cretaceous (Parker, 1966; Harland et al., 1974; Haremo et al., 1990) as the BFZ witnessed a brief period of extension, followed by minor contraction during the Cenozoic (Bælum & Braathen, 2012).

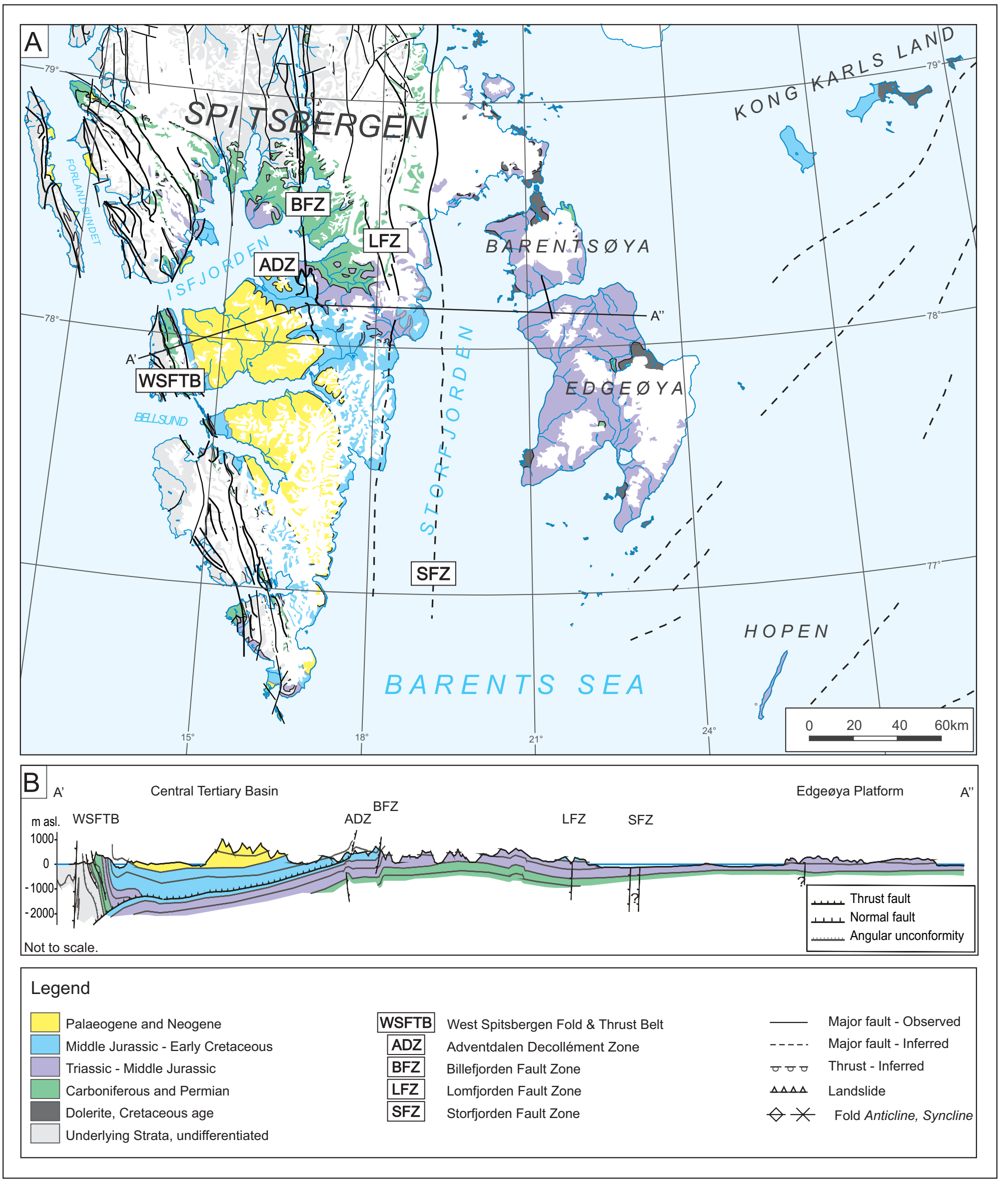


Figure 2: *A**, Geological map of the Svalbard archipelago with major structural lineaments denoted.* ***B**, Cross section along line A' – A'' showing the nature of Cenozoic deformation seen in the central part of Svalbard. Map and cross-section edited after Elvevold et al. (2007).*

The Lomfjord Fault Zone (LFZ, Figs. 2A, B) (Harland, 1979; Andresen et al., 1988; Maher & Craddock, 1988; Nøttvedt & Rasmussen, 1988) is an elongated, N–S trending structural complex (Dallmann et al., 2015a; Dallmann & Elvevold, 2015). The fault zone shows evidence of thin-skinned contractional tectonics in line with the Cenozoic west to east crustal shortening, evidenced throughout Spitsbergen (Maher & Craddock, 1988), but this is most probably the result of re-activation of an existing deep rooted lineament.

Within Storfjorden, east to west oriented seismic sections shot by the NPD in 1974 and 1980 exhibit a well expressed fault system, believed to be of regional importance (Eiken, 1985). This structure, termed the Storfjorden Fault Zone (SFZ, Figs. 2A, B), is comprised of numerous north to south oriented and westerly-dipping extensional normal faults with a fault throw over one kilometre (Eiken, 1985; Dallmann et al., 2015a). Fault blocks within the SFZ are considered to consist primarily of Permian strata, with the onset of faulting being linked to an episode of graben development, which occurred from the Late-Devonian to Late-Carboniferous (Steel & Worsley, 1984; Eiken, 1985). This fault zone is also considered to be the cause of recent seismic activity in the Storfjorden area (Nasuti et al., 2015).

The eastern region of Svalbard is characterised by near flat-lying strata of post-Caledonian age, superimposed on a basement complex (Lock et al., 1978). The Triassic of Edgeøya rests on a Permian carbonate platform (Worsley, 1986; Gabrielsen et al., 1990), often referred to as the Edgeøya Platform (Fig. 2B). Lock et al. (1978) mapped the topography of the boundary between the Botneheia and Tschermakfjellet Formations and identified a series of gentle antiformal and synformal domes. Other than one large fault, seen at Negerpynten on southern Edgeøya (Klubov, 1965; Lock et al., 1978) and a monocline in the north, no large-scale tectonic lineaments are formally reported or presented in geological maps of the island (Dallmann et al., 2002; Dallmann & Elvevold, 2015). Syn-sedimentary growth-faulting seen at various locations along the west coast of Edgeøya (Edwards, 1976; Rød, 2011; Anell et al., 2013; Rød et al., 2014; Osmundsen et al., 2014) is most obvious on the mountainsides of Klinkhamaren and Kvalpynten. Here shallow normal faults detaching at the contact with the Botneheia Formation are overlain by younger un-deformed strata (Rød, 2011; Osmundsen et al., 2014). Growth faulting at Kvalpynten is seen to strike to the WNW–ESE and dip to the south (Anell et al., 2013). The mechanism for the formation of these growth faults is argued to be related to deep-rooted faulting (e.g. Anell et al., 2013; Osmundsen et al., 2014), however the study by Rød (2011) shows that the underlying Botneheia Formation is not affected at Klinkhamaren and the mountains further south.

To the east of Svalbard, the southern margin of the Edgeøya Platform features a series of E–NE trending fault systems of Palaeozoic age (Doré, 1995; Grogan et al., 1999; Faleide et al., 2008; Glørstad-Clark et al., 2010) forming a series of terraces stepping down towards the Sørkapp Basin. This trend continues offshore from Kong Karls Land (Gabrielsen et al., 1990; Johansen et al., 1992; Grogan et al., 1999; Riis et al., 2008; Høy and Lundschien, 2011). Faulting and basin formation in these eastern areas also occurred during the Late-Palaeozoic, in relation to a period of failed rifting (Faleide et al., 2008).

Around Hopen a similar structural trend is also observed (Max & Ohta, 1988; Doré, 1995), where faulting has resulted in a horst, bound to the northwest and southeast by a series of delineated terraces consisting of ENE–WSW trending normal faults, dipping in opposite directions (Max & Ohta, 1988; Johansen et al., 1992; Doré, 1995; Grogan et al., 1999).

Hopen most likely represents a spur in the highest segment of this system, albeit significantly eroded or the tip of an anticline (Anell et al., 2016). These faults are of an unknown age; however, it is likely that their formation is controlled by deep seated faults, originating during a phase of rifting during the late-Palaeozoic. This suggests post-Triassic reactivation, possibly in the Jurassic and Cretaceous during a further period of failed rifting (Faleide et al., 2008).

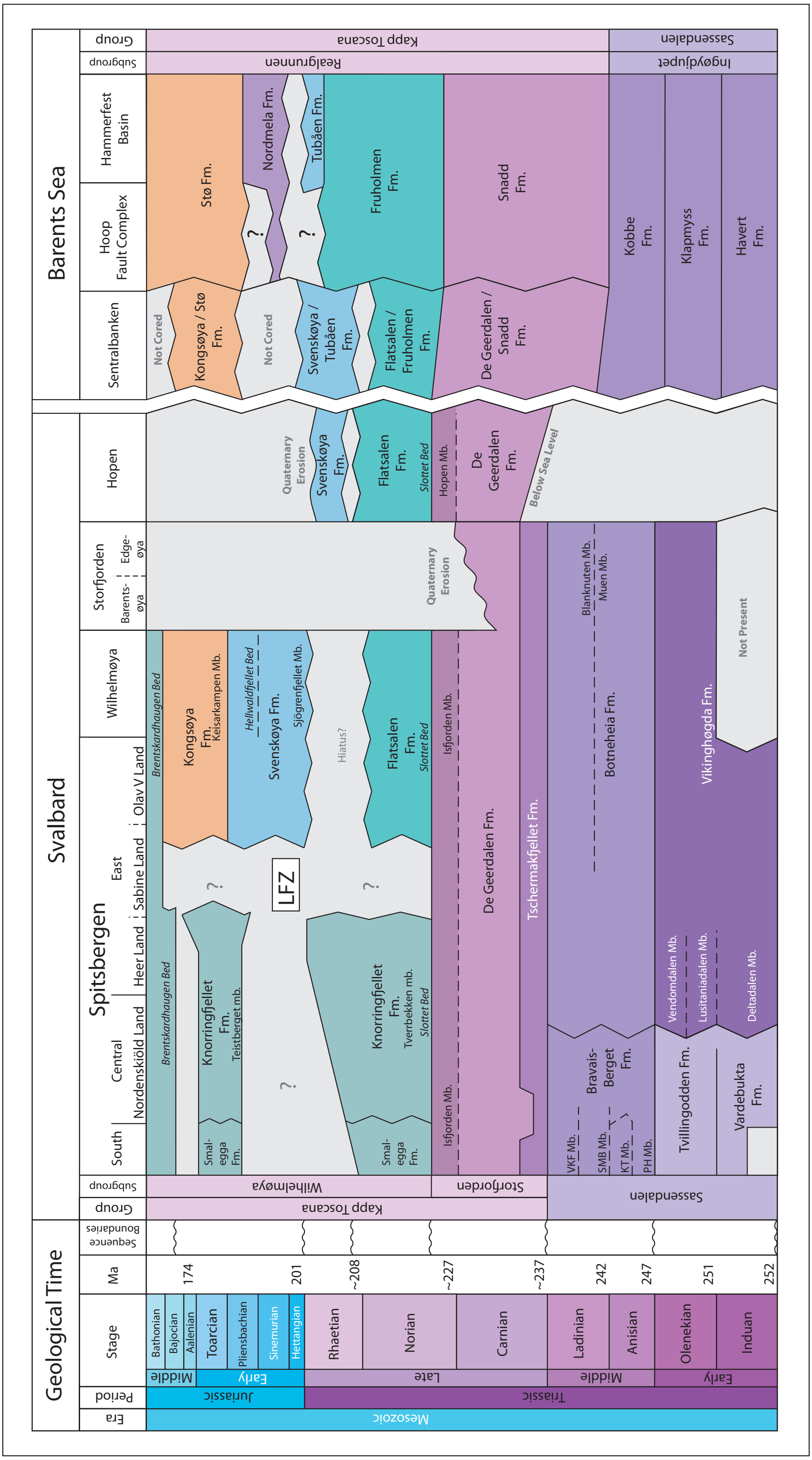
On a local scale, the island of Hopen is dissected by NW–SE trending normal faults, dipping to both to the SW and NE, in addition there are gentle synclines and monoclines (Smith et al., 1975; Lord, 2013; Mørk et al., 2013; Appendix 1). Some faults exhibit minor rotational components, due to the presence of contrasting fault throws being observed on opposite sides of the island. Instances of syn-depositional deformation have also been reported (Osmundsen et al., 2014).

Triassic – Mid Jurassic Stratigraphy in Svalbard

In the majority of the study area, the Triassic succession lies roughly horizontal and with the exception of local faulting, is somewhat un-deformed (Fig. 2). Localities in the west of Spitsbergen often feature near-vertically dipping strata, deformed during the Cenozoic (Dallmann et al., 2015a), allowing for easy access to sections along coastlines (e.g. Festningen) and mountain ridges (e.g. Bravaisberget). Throughout southern and central areas of Spitsbergen, much of the lower and middle Triassic succession is hidden in the subsurface. However, in northern and eastern areas of central Spitsbergen, this part of the succession outcrops. At some locations, low angle thrust faults and layer-parallel duplexes are present. These complicate the lower and middle parts of the Triassic stratigraphy, by shearing out or stacking strata, resulting in sections with reduced or exaggerated thickness (Haremo & Andresen, 1992). The fine-grained lithologies of these units mean that faults are discrete and often impossible to observe in the field.

In eastern areas, Triassic strata are well exposed, with the underlying Permian only being seen in very low lying areas or along the coastline. Large portions of the succession are also missing from Edgeøya and Barentsøya (Mørk et al., 1999a; Rød et al., 2014) and this raises the question of exactly how much has been removed by Cenozoic and Quaternary erosion. The island of Wilhelmøya features a near complete succession of the Carnian, some 250 m in thickness, in central Spitsbergen the Carnian reaches 240 m in thickness, whilst on Hopen data from the "Hopen-2" well (7625/5-1) shows a Carnian succession that is near 1200 m in thickness (Lord et al., 2014a, Paper 1; Anell et al., 2014a). On Edgeøya the exposed Carnian stratigraphy is approximately 200 m thick, which suggests not only a significant component of erosion occurred during the Cenozoic, but also the stratigraphy thins extensively towards the north and west.

The Triassic to Middle Jurassic succession is divided into two groups following the present lithostratigraphic subdivision by Mørk et al. (1999a). The Lower and Middle Triassic are defined as the Sassendalen Group and the Upper Triassic to Middle Jurassic being termed the Kapp Toscana Group. The Kapp Toscana Group is further subdivided into two Subgroups; the Carnian to early Norian Storfjorden Subgroup and the middle Norian to Bathonian Wilhelmøya Subgroup (see Fig. 3).



Geological Time
Svalbard
Barents Sea
Era
Period
Stage
Ma
Sequence Boundaries
Group
Subgroup
Mesozoic
Jurassic
Triassic
Middle
Early
Late
Middle
Early
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
174
201
~208
~227
~237
242
247
251
252
Kapp Toscana
Sassendalen
Wilhelmøya
Storfjorden
Realgrunnen
Ingøydjupet
Spitsbergen
South
Central
Nordenskiöld Land
Heer Land
East
Sabine Land
Olav V Land
Wilhelmøya
Storfjorden
Barents-øya
Edge-øya
Hopen
Sentralbanken
Hoop Fault Complex
Hammerfest Basin
Brentskardhaugen Bed
Knorringfjellet Fm.
Teistberget mb.
Smal-egga Fm.
Tverrbekken mb.
Slottet Bed
Kongsøya Fm.
Keisarkampen Mb.
Hellwaldfjellet Bed
Svenskøya Fm.
Sjögrenfjellet Mb.
Hiatus?
Flatsalen Fm.
LFZ
Isfjorden Mb.
De Geerdalen Fm.
Tschermakfjellet Fm.
Botneheia Fm.
Blanknuten Mb.
Muen Mb.
Bravais-Berget Fm.
VKF Mb.
SMB Mb.
KT Mb.
PH Mb.
Vikinghøgda Fm.
Vendomdalen Mb.
Lusitaniadalen Mb.
Deltadalen Mb.
Tvillingodden Fm.
Vardebukta Fm.
Not Present
Quaternary Erosion
Hopen Mb.
Below Sea Level
Not Cored
Kongsøya / Stø Fm.
Svenskøya / Tubåen Fm.
Flatsalen / Fruholmen Fm.
De Geerdalen / Snadd Fm.
Stø Fm.
Nordmela Fm.
Tubåen Fm.
Fruholmen Fm.
Snadd Fm.
Kobbe Fm.
Klapmyss Fm.
Havert Fm.

Figure 3: *Triassic to Middle Jurassic stratigraphic chart for Svalbard and the northern Barents Sea (after Lord et al. submitted, Paper 5). Stratigraphy for southern areas e.g. the Hoop fault area and the Hammerfest Basin is also included.*

The Sassendalen Group – Lower and Middle Triassic

The Sassendalen Group (Fig. 3) was defined by Buchan et al. (1965) and spans the lower and middle parts of the Triassic. The group's nomenclature is maintained throughout the Barents Sea, where it includes the Ingøydjupet Subgroup (Worsley et al., 1988), comprised of the Havert, Klappmyss and Kobbe formations. Throughout Svalbard the Sassendalen Group represents deposition of clastic sediment into a shallow basin. In southern and western parts of the present Barents Sea, small deltaic advances occurred along the basin margins close to significant landmasses (Riis et al., 2008; Høy & Lundschien Eide et al., in press). Proximal marine deposits are characteristic of the Lower Triassic in western and southern Svalbard. Prior to the opening of the North Atlantic, Svalbard was situated close to Laurentia (North America and Greenland), an extensive area of denudation which provided sediment to these marginal areas throughout the Early and Middle Triassic (Riis et al., 2008; Glørstad-Clark et al., 2010; Bue & Andresen, 2013).

Lower Triassic – The Induan and Olenekian

One of the most spectacular lithostratigraphic boundaries in Svalbard can be found in the strata marking the end of the Palaeozoic era, where the Upper Permian is overlain by Lower Triassic strata. The boundary is prominent and easily recognised. Dolomite and hard, siliceous shales of the Kapp Starostin Formation form a sharp boundary at their contact with soft laminated mudstones of the Induan Vardebukta and Vikinghøgda formations (Mørk et al., 1999a, b). Whilst the chronostratigraphic boundary between the Permian and Triassic epochs is technically some ca. 8–10 m above this contact (Zuchuat, 2014), the lithostratigraphic boundary is excellent for mapping and stratigraphic purposes.

The Permian – Triassic boundary throughout Svalbard and the Barents Sea represents a hiatus. With the exception of deltaic sequences close to the basin margin, many areas were sub-aerially exposed during the Olenekian. In the regions of Bjørnøya (Mørk et al., 1990; Vigran et al., 2014), Sørkapp Land (Worsley & Mørk, 1978) and Edgeøya in Svalbard, the lowermost Triassic beds are missing. The oldest Triassic rocks on Edgeøya are dated as Olenekian (Pčelina, 1977; Vigran et al., 2014).

The Vardebukta Formation represents the Induan in southern and western Spitsbergen, with the Deltadalen Member of the Vikinghøgda Formation being the equivalent for central Spitsbergen. The Olenekian is represented in western Svalbard by the Tvillingodden Formation and the Lusitaniadalen and Vendomdalen members of the Vikinghøgda Formation, in central Spitsbergen (Mørk et al., 1999a, b). The Induan and Olenekian in eastern Svalbard remains undifferentiated and is defined simply as the Vikinghøgda Formation without any member units (Mørk et al., 1999b). The formation in the west and southern areas of Spitsbergen lies atop the Permian Kapp Starostin Formation, at a sharp lithological boundary and forms multiple upwards coarsening units. These are interpreted as representing a shallow marine to deltaic environment (Mørk et al., 1999a). Ammonoid biostratigraphy provides evidence for the Induan age (Korčinskaja, 1980, 1982; Weitschat & Dagys, 1989). The equivalent Deltadalen Member in central Spitsbergen, of the Vikinghøgda

Formation (Mørk et al., 1982; Mørk et al., 1999b), is composed of fine-grained lithologies and represents a shallow shelf environment. The member is determined to be Induan in age based on the presence of ammonoids and by palynology (Korčinskaja, 1982; Mørk et al., 1982; Mørk et al., 1999a, b).

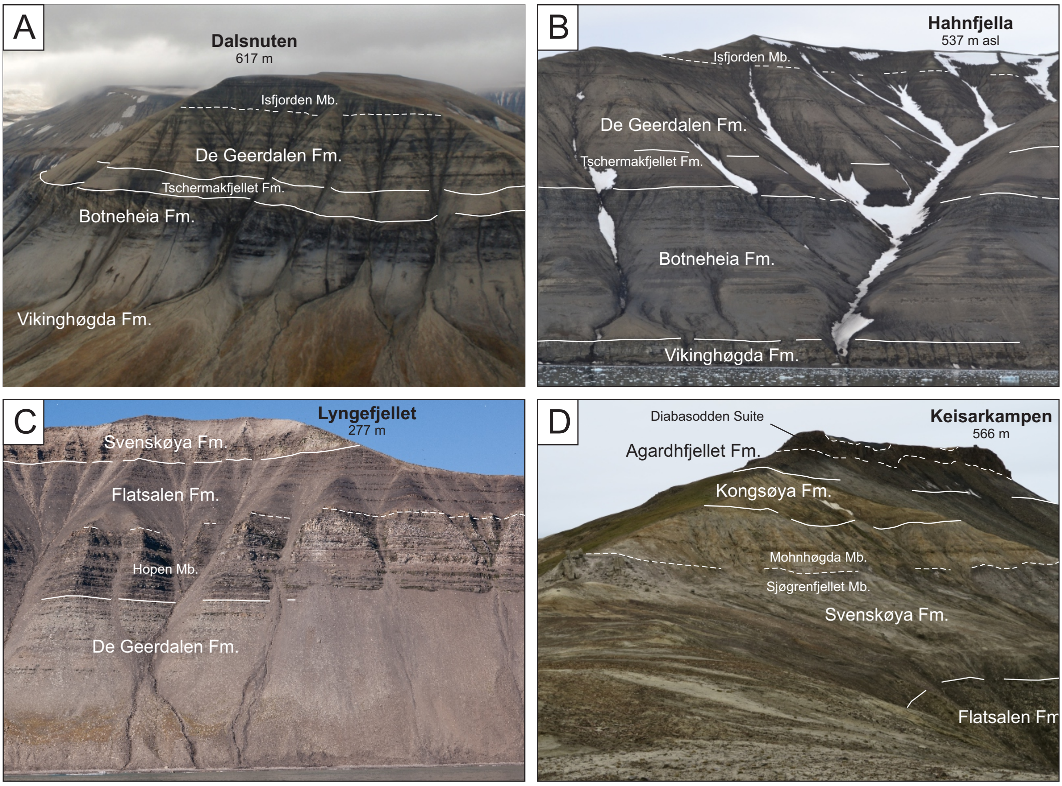


***Figure 4:** **A**, Photograph of the mountain of Dalsnuten in central Spitsbergen showing the well exposed Botneheia, Tschermakfjellet and De Geerdalen Formations. **B**, Photo of the mountain of Hahnfjella in eastern Spitsbergen showing well exposed Lower and Middle Triassic stratigraphy (Vikinghøgda and Botneheia formations). The overlying Upper Triassic succession features the Tschermakfjellet and De Geerdalen formations with good exposures of the Isfjorden Member. **C**, Photograph of the mountain of Lyngefjellet in northern Hopen. Here well-exposed channel bodies and well-developed delta plain deposits are seen in the De Geerdalen Formation. The Hopen Member, defined by Lord et al. (2014a, Paper 1) is composed of marine deposits. Excellent exposures of the Flatsalen Formation and its basal Slottet Bed are also present at this locality. The white cliff-forming sandstone at the top of the mountain is the Svenskøya Formation and is the key focus of Lord et al. (submitted, Paper 5). **D**, Exposures of the Wilhelmøya Subgroup at the type section on Keisarkampen, Wilhelmøya. The Flatsalen Formation is marine and poorly exposed. The overlying Svenskøya and Kongsøya formations are sandstone units. Here however, they are poorly exposed due to their unconsolidated nature. The uppermost exposures are of the Agardhfjellet Formation shales (Adventdalen Group), which are penetrated by a dolerite sill of Cretaceous age belonging to the Diabasodden Suite.*

In southern Spitsbergen, on the Sørkapp-Hornsund High, the Vardebukta Formation is represented by its Kistefjellet Member (Mørk et al., 1982; Pčelina, 1983; Mørk et al., 1999a), a local unit composed of a basal polymictic conglomerate and sandstones with bivalves. The member represents deposition in a shallow marine environment with a transgressive lag (Brevassfjellet Bed, Mørk et al., 1982; 1999a) at the base.

The Tvillingodden Formation forms the Olenekian strata in the westernmost parts of Spitsbergen. The formation is the equivalent to the Lusitaniadalen and Vendomdalen members of the Vikinghøgda Formation (Mørk et al., 1999a, b). Two member units are present in the Tvillingodden Formation, the Iskletten and Kaosfjellet members and these correspond to the Lusitaniadalen and Vendomdalen members of the Vikinghøgda Formation respectively (Mørk et al., 1999a). The Iskletten and Kaosfjellet members are well defined in the field however this terminology has been constrained to Oscar II land and the outer Isfjorden area of Spitsbergen. Elsewhere the Tvillingodden Formation consists of dark grey, shales and laminated siltstones. Several upwards coarsening units are observed and sandstone beds are present (Mørk et al., 1999a).

In central Spitsbergen the Lusitaniadalen and Vendomdalen members span the Olenekian. The Lusitaniadalen Member is interpreted to represent clastic deposition in a distal shelf environment and marks the onset of a transgression from the underlying, Induan Deltadalen Member. The Vendomdalen Member is interpreted by Mørk et al. (1999b) to represent clastic deposition below wave base, in a low oxic environment, in a regressive stage. For the eastern areas of Spitsbergen and eastern Svalbard, the Vikinghøgda Formation is undifferentiated into member units.

On Bjørnøya, part of the Induan is missing, which suggests a significant hiatus at the Permian – Triassic boundary. The Urd Formation on Bjørnøya spans the latest part of the Induan and the Olenekian, as a marine mudstone with intra-formational sandstones (Mørk et al., 1990; 1999a; Vigran et al., 2014).

Middle Triassic – The Anisian and Ladinian

The Middle Triassic rocks of Svalbard mark a prominent change from grey fissile shales and siltstones of the Tvillingodden and Vikinghøgda Formations, to the dark, bituminous and cliff-forming paper shales of the Botneheia and Bravaisberget formations (Mørk et al., 1982; Mørk et al., 1999a; Krajewski et al., 2007; Krajewski, 2008). The Bravaisberget Formation is defined throughout western Spitsbergen (Mørk et al., 1999a; Krajewski et al., 2007), whilst the Botneheia Formation (Figs. 4A, B) is defined for central Spitsbergen and eastern Svalbard (Mørk et al., 1999a; Krajewski, 2008).

The separation of these two units arises from the differing lithologies; the western areas feature more heterogeneous sandstones and shales whilst to the east the lithology is more uniform dark shales (Mørk et al., 1999a; Krajewski et al., 2007). The southern Barents Sea equivalent of the Botneheia Formation is defined as the Kobbe Formation (Fig. 3) close to the Norwegian mainland, with the Steinkobbe Formation being defined in the Hammerfest Basin and extended to the Svalis Dome and Loppa High areas of the Barents Sea. The Steinkobbe Formation was defined given its potential as the best source rock for this area (Leith et al., 1993; Mørk & Elvebakk, 1999; Riis et al., 2008; Lundschien et al., 2014).

Shales of the Bravaisberget and Botneheia formations are composed of clay, with significant organic material. They emit a strong hydrocarbon aroma from fresh surfaces and bituminous residue can be found in calcite veins. Phosphatic nodules, well-preserved marine vertebrate fossils, thin dolomitic beds and septarian nodules are common to formations in the Middle Triassic. The formations have a total organic carbon (TOC) values ranging between ca. 1–10 % (Mørk et al., 1982; Mørk & Bjorøy, 1984; Lock et al., 1978; Leith et al., 1993; Krajewski et al., 2007; Krajewski, 2008). The oil rich content of the Sassendalen Group in Svalbard led to one of the original stratigraphic names for the Middle Triassic being the 'Oil Shales Group' (Falcon, 1928).

The Bravaisberget Formation in the west has a more complex development than its eastern equivalent. The Bravaisberget Formation is composed of the Passhatten, Karentoppen, Somovbreen and Van Keulenfjorden members (Mørk et al., 1999a). The Passhatten Member forms the lower and middle parts of the Bravaisberget Formation (Krajewski et al., 2007); the remainder is defined as the Somovbreen Member with the Van Keulenfjorden Member at the top (Mørk et al., 1982, 1999a; Krajewski et al., 2007). While the Passhatten Member was deposited in deep shelf setting, deltaic sandstones form the Karentoppen Member. Coastal progradation is reflected in the coarsening upwards unit forming the Somovbreen Member, while the Van Keulenfjorden Member is deposited when the basin was filled up at several localities to lagoon conditions (Mørk et al., 1982, 1999a; Pčelina, 1983; Krajewski et al., 2007).

In Sørkapp Land, the Karentoppen Member is composed of deltaic channel sediments, conglomerates and bioturbated sandstones and regarded as mainly of Anisian age (Mørk et al., 1982; Mørk et al., 1999a; Krajewski & Weitschat, 2015; Krajewski et al., 2007). The member represents deltaic distributary sandstones that form a wedge between the Passhatten and Somovbreen members. The uppermost part of the Bravaisberget Formation is defined as the Van Keulenfjorden Member and is Ladinian in age. The member is interpreted as being deposited in a brackish environment in a prodelta setting (Mørk et al., 1999a; Krajewski et al., 2007).

The Botneheia Formation of central Spitsbergen and eastern Svalbard (Figs. 4A, B) is composed of two member units, the lower Muen (Krajewski, 2008) and upper Blanknuten (Mørk et al., 1982; 1999a; Krajewski, 2008). These members approximately span the Anisian and Ladinian stages respectively (Mørk et al., 1982, 1999a; Krajewski, 2008). The Muen Member was defined by Krajewski (2008) and represents deposition of shale and mudstone under oxic to dysoxic bottom water conditions. The Blanknuten Member is a prominent cliff-forming unit that is easily traced throughout large areas of the archipelago (Flood et al., 1971; Lock et al., 1978; Krajewski, 2008). The unit consists of mudstone and shale, with abundant phosphate nodules, forming nodule beds and phosphatic grainstones (Krajewski, 2008).

On Bjørnøya, the Verdande Bed at top of the Urd Formation is a remanié conglomerate of phosphate nodules, interpreted to be Anisian age (Mørk et al., 1990). Above this bed, shales and subordinate sandstone of the lower part of the Skuld Formation (Mørk et al., 1990) are dated as Ladinian age by palynology. The top of the Urd Formation is Carnian in age (Böhm, 1903, Pčelina, 1972; Mørk et al., 1990) with dating derived from ammonoid biostratigraphy and palynology.

The Kapp Toscana Group – Late Triassic to Middle Jurassic

The onset of the Late Triassic in Svalbard is marked by a clear change in lithology and depositional style (Figs. 4A, B). The deposits that make up the Late Triassic to Middle Jurassic succession show clear evidence of repeated episodes of transgression and regression (Mørk & Smelror, 2001). The group comprises of the Storfjorden and Wilhelmøya Subgroups, which are further subdivided into six formations. The Tschermakfjellet and De Geerdalen formations are assigned to the Storfjorden Subgroup, with the Knorringfjellet, Flatsalen, Svenskøya and Kongsøya and Skuld formations being assigned to the Wilhelmøya Subgroup (Mørk et al., 1999a).

Late Triassic – The Carnian to early Norian

The boundary between the Middle Triassic Botneheia Formation and the early Carnian Tschermakfjellet Formation is evident throughout much of central Spitsbergen and eastern Svalbard (Figs. 4A, B). Black organic rich shales, give way to light grey silty shales with subordinate shallow marine sandstones (Mørk et al., 1982, 1999a; Vigran et al., 2014). The Tschermakfjellet Formation is prevalent throughout Svalbard forming a prodeltaic shale and siltstone unit to the overlying De Geerdalen Formation of early Carnian age (Korčinskaja, 1982; Dagys & Weitschat, 1993). In western areas, the formation tends to thin to some metres or is absent; whilst in eastern parts of Svalbard, the thickness can be considerable and variable. Its lower boundary is diachronous, with the deposition of the lower Snadd Formation beginning in the Ladinian (Worsley, 2008; Riis et al., 2008; Glørstad-Clark et al., 2010; Lundschien et al., 2014).

The remainder of the Carnian and early part of the Norian is comprised of the De Geerdalen Formation (Buchan et al., 1965; Mørk et al., 1982; 1999a). The De Geerdalen Formation consists of numerous upwards coarsening units, where lithologies and sedimentary properties vary greatly (Figs. 4A–C). The unit represents the exposed part of a vast deltaic system that extended throughout the Barents Sea during the Carnian (Worsley, 2008; Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011; Anell et al., 2013; Klausen & Mørk, 2014; Lundschien et al., 2014). The lower and middle parts of the De Geerdalen Formation consist of silt and sandstones of varying thickness and extent. Minor marine incursions are evident and this gives rise to a number of prominent parasequences (Paper 6). The formation is composed of shallow marine and shoreface deposits with delta front and delta top and plain deposits being prominent throughout (Klausen & Mørk, 2014; Rød et al., 2014; Lord et al., 2017, Paper 4). The formation thins considerably from the northern Barents Sea through Hopen (Fig. 4C) and into Spitsbergen. This thinning is attributed to the Svalbard area becoming a platform area during the middle to late Triassic where deltaic advance becomes more rapid as accommodation space becomes limited (Anell et al., 2014a, b).

The upper part of the De Geerdalen Formation is defined as the Isfjorden Member in western and central Spitsbergen (Pčelina, 1983; Mørk et al., 1999a). This definition was extended to eastern Spitsbergen and Wilhelmøya by Haugen (2016) and Lord et al. (2017; Paper 4). Much of the upper De Geerdalen Formation is lacking from Edgeøya and Barentsøya due to Quaternary erosion. On Hopen, however, the

Hopen Member (Mørk et al., 2013; Lord et al., 2014a, b, Papers 1 and 2; Appendix 1) is the equivalent to the Isfjorden Member in this area (Fig. 4C).

The late Carnian to early Norian Isfjorden Member consists of thinly bedded sandstone and siltstone, bioclastic carbonate beds and weathered clays that give the member its distinctive colour. The unit is interpreted as representing a lagoon and delta top environment (Mørk et al., 1999a; Haugen, 2016; Lord et al., 2017, Paper 4). The correlative Hopen Member represents the same time period, but is, however, only present in the south-eastern area of Svalbard. The unit consists of silt and fine-grained sandstones deposited in a shallow marine environment. None of the defining characteristics of the Isfjorden Member are present on Hopen (Lord et al., 2017, Paper 4).

The Wilhelmøya Subgroup – Early Norian to Bathonian

The Wilhelmøya Subgroup is defined on Wilhelmøya (Mørk et al., 1999a), originally as a formation (Worsley, 1973). The Flatsalen Formation is the lowermost unit of the Wilhelmøya Subgroup (Figs. 3, 4C) and is composed of deep marine shales, with minor upwards coarsening packages and a prominent basal bed, the Slottet Bed (Mørk et al., 2013; Appendix 1; Lord et al., 2014a; Paper 1). The formation is present in its entirety on Hopen, with the type section being defined at the mountain of Flatsalen, in the northern part of the island. The Flatsalen Formation is seen to be slightly condensed on eastern Spitsbergen (Lord et al., 2017; Paper 4). Marine vertebrate fossils are also present in the middle of the formation on Wilhelmøya and Hopen. Dating by palynology, ammonoid biostratigraphy and magnetostratigraphy determine the unit to be Norian in age (Mørk et al., 1999a; Lord et al., 2014a; Paper 1).

The Slottet Bed is somewhat enigmatic throughout Svalbard. On Hopen, the Slottet Bed is a hard, carbonate cemented sandstone with phosphate nodules, which is ca. 2 m thick (Mørk et al., 1999a; Mørk et al., 2013; Appendix 1). On Wilhelmøya the Slottet bed is represented by a 3–5m thick limestone, overlying bioclastic sandstone that sits directly atop the red and green, nodular clays of the Isfjorden Member (Haugen, 2016; Lord et al., 2017; Paper 4).

The Late Triassic – Early Jurassic Svenskøya Formation (Figs. 4C, D) unconformably overlies the Flatsalen Formation, with an erosive base and may represent a major sequence boundary in this area (Mørk et al., 1999a; Lord et al., 2014a, Paper 1; Paterson et al., 2016, Paper 3; Paper 5). The thickest exposures of this unit are present at the type section on Svenskøya, Kong Karls Land (Mørk et al., 1999a). Exposures of the unit are also present on Hopen, Wilhelmøya and eastern Spitsbergen (Paterson et al., 2016, Paper 3; Paper 5).

The Svenskøya Formation is fluvial-deltaic in nature and consists of mature, well sorted and medium to coarse-grained sandstone deposited in fluvial channels, shoreface and tidal flat environments. Exposures show well developed large scale cross-stratification and plant fragments are abundant (Lord et al., submitted, Paper 5). On Kong Karls Land, the formation is devised into two member units, the Sjøgrenfjellet and Mohnhøgda members (Mørk et al., 1999a). The Kongsøya Formation (Fig. 4D) is defined at its stratotype on Kong Karls Land by Mørk et al. (1999a) and regarded as being Toarcian to Bathonian in age, consisting of heavily bioturbated fine-grained sandstones and mudstones containing siderite beds or concretions (Mørk et al., 1999a). On Wilhelmøya, the Keisarkampen Member is defined as representing the Kongsøya Formation and consists of an unconsolidated, orange-yellow coloured, medium-grained sandstone unit (Mørk et al., 1999a). Coal lenses and tree trunks are abundant, as are nodules of ferrous sandstone.

The De Geerdalen Formation in central and western Spitsbergen is overlain by the Knorringfjellet Formation of the Wilhelmøya Subgroup, which was deposited throughout the Norian to Bathonian (Pčelina, 1965; Bjærke & Dypvik, 1977; Korčinskaja, 1980; Bäckström & Nagy, 1985; Mørk et al., 1999a). The Knorringfjellet Formation is defined within the Wilhelmøya Subgroup, consisting of a succession of phosphate rich conglomerates, which represents a condensed section (Mørk et al., 1999a).

The Wilhelmøya Subgroup is an extensive unit extending discontinuously through time, to near the end of the Bathonian period (Pčelina, 1965; Bjærke & Dypvik, 1977; Korčinskaja, 1980; Bäckström & Nagy, 1985). The Wilhelmøya Subgroup terminates at the Brentskardhaugen Bed (Mørk et al., 1982; Bäckström & Nagy, 1985; Mørk et al., 1999a). The Brentskardhaugen Bed is overlain by a succession consisting mostly of fine-grained black shale with a silty-sandy base belonging to the Agardhfjellet Formation (Fig. 4D) of the Adventdalen Group and Janusfjellet Subgroup (Mørk et al., 1999a).

Triassic Palaeogeography

Continental plate reconstructions, by Cocks and Torsvik (2007), have led to the interpretation that the Barents Sea shelf and the Svalbard archipelago was situated in a shallow epicontinental sea in the northern part of Pangea, during the Triassic (Riis et al., 2008). The sea was bound to the west by Greenland (Laurentia), to the south by Fennoscandia and Baltica, and to the east by the Siberian terrane. The epicontinental seaway formed a suitable basin that allowed for the deposition of sediment throughout the Triassic.

The Uralian Mountains provided a significant sediment input into the Barents Sea basin from the east and southeast (Mørk, 1999; Riis et al., 2008; Glørstad-Clark et al., 2010; Miller et al., 2013). Mørk (1999), Harstad (2016) and Fleming et al. (2016) present arguments for sediment being derived from areas further to the east, likely the Taimyr region, especially for the latest part of the Carnian in the Svalbard and northern Barents Sea area; this is also suggested by provenance studies by Bue and Andresen (2013). Sediment yield was significant enough to infill large areas of the basin with siliciclastic material in deltaic deposits extending from the basin margins from the Permian (Eide et al., in press), eventually infilling the entire basin by the Late Triassic (Mørk et al., 1982; 1999a; Glørstad-Clark et al., 2010; Lord et al., 2014a; Paper 1; Lundschien et al., 2014; Rød et al., 2014; Enga, 2015).

During the Early Triassic, pelagic shales and siltstones were deposited in the central areas of the basin, with coarser clastic sediments being deposited at the basin margins (Mørk et al., 1982; Nystuen et al., 2008a, b; Riis et al., 2008). During the Middle Triassic, widespread subsidence and deepening of the basin occurred, which resulted in an overall deep shelf environment and highly organic-rich muds were deposited (Mørk et al., 1982; Mørk & Bjorøy, 1984; Krajewski, 2008, Mørk & Bromley, 2008).

The De Geerdalen Formation on Svalbard represents the north-western deposits of a large-scale regressive deltaic system, prograding into the shelf area during the late Triassic. In the southern and central parts of the Barents Sea it is defined as the Snadd Formation with a lower boundary beginning in the Ladinian (Mørk et al., 1982, 1989; Worsley et al., 1988; Riis et al., 2008; Glørstad-Clark et al., 2010; Lundschien et al., 2014; Klausen et al., 2015). Ladinian to Norian clinoforms can be viewed in seismic lines shot to the east and south-east of Svalbard (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011; Anell et al., 2013, 2014a, b; Lundschien et al., 2014; Paper 6).

Triassic Sequence Stratigraphy in Svalbard

The Triassic transgressive – regressive sequences are well documented in Svalbard (e.g. Mørk et al., 1989; Mørk, 1994; Egorov & Mørk, 2000; Mørk & Smelror, 2001). These sequences in Svalbard closely match lithostratigraphic subdivisions (Mørk, 1997) and can be seen to correlate well to stages in geological time. Mørk (1994, 1997) shows that transgressive and regressive events in Svalbard can be seen to be near contemporaneous with stage subdivisions, based on biostratigraphic dating for each major sequence. Four of these boundaries are interpreted as being synchronous throughout the Early and Middle Triassic in Arctic Basins. Eustasy is interpreted as the primary mechanism for transgressive – regressive cycles, whether controlled by tectonics or not (Mørk et al., 1989). Mørk (1994) also concludes that individual transgressions that are independent between each Arctic basin are likely controlled by tectonics.

Earlier works documenting the extent of circum-arctic sequences, such as Mørk et al. (1989), recognised the presence of at least nine transgressive – regressive sequences in the Mesozoic succession in the Arctic. Later studies by Riis et al. (2008) and Glørstad-Clark et al. (2010), presented a sequence stratigraphic framework for the northern Barents Sea area, based on seismic data collected by the NPD. The study documented a series of well-developed clinoforms prograding in a NW direction towards the Svalbard platform from the Ladinian to the Olenekian. Unlike Mørk et al. (1989), Mørk (1994), Mørk and Smelror (2001), Mørk and Worsley (2006) or Embry and Mørk (2006), the study concluded that five major seismic sequence boundaries are present in the northern areas of the Barents Sea for the Early and Middle Triassic, as opposed to the earlier recognised number of major sequences (3) by Mørk and Smelror (2001) for the same interval.

Høy and Lundschien (2011) furthered this study by including northern seismic datasets and interpreted a sequence of clinoforms from the Ladinian to Carnian. Sequences are seen to be in the order of 2–400 m in thickness which is inferred to represent water depths at the time of deposition, although it is not clear if compaction is taken into account. Four seismic sequences are recognised throughout the Carnian succession offshore, which are not immediately evident in Svalbard. Anell et al. (2014b) relates this lack of obvious clinoforms to the advance of deltaic sequences onto the Svalbard platform, where lack of accommodation space causes rapid advance and a shallower trajectory.

The indication of a fixed number of high order sequences throughout the Boreal Triassic, that can be further recognised worldwide, implies a common control on the formation of these sequences, a suggestion leading to the idea of global tectonics as the driving force (Embry, 2006; Embry & Mørk, 2006).

Work Synthesis

An expedition to the island of Hopen in 2011 focussed on collecting valuable sedimentological and map data. This work resulted in several publications, in addition to an updated geological map (Mørk et al., 2013, Appendix 1) and the definition of a new lithostratigraphic unit (Lord et al., 2014a, Paper 1). The map was a significant improvement over the unpublished version (Dallmann, 2009) and incorporated the description onto the map sheet. Mørk et al. (2013, Appendix 1) also introduced the Hopen Member, prior to the formal definition by Lord et al. (2014a, Paper 1). The addition of a new member unit was further strengthened by palynological studies by Paterson and Mangerud (2014) and Paterson et al, (2016, Paper 3). The correlation to the Isfjorden Member defined for Spitsbergen at the time (Pčelina, 1983; Mørk et al., 1999a) suggested a change in depositional styles from northwest to southeast.

The cause for the change in depositional style within the upper part of the De Geerdalen Formation in eastern Svalbard is unknown. A potential cause may have been due to increased accommodation space in the east of Svalbard, as a result of faulting along the Lomfjorden and Storfjorden fault zones (Dallmann et al., 2015a). However, studies in the Agardhbukta area (Haugen, 2016; Lord et al., 2017, Paper 4) discovered that this was not the case and the Isfjorden Member was present on both sides of the fault zone, with no change in depositional styles being observed. A shallow drilling program by the NPD in 2015 (Simonstad et al., 2017) collected core samples from much of the Late Triassic Succession offshore Kvitøya, in the north-eastern corner of Svalbard and this new data may shed further light on the extent of these two member units. However, this data is still confidential at present.

As the main interest in Hopen was driven by exploration interests in the Barents Sea, a major focus of the 2011 and subsequent 2012 and 2013 expeditions to the island was to document the occurrence of sandstone channel bodies. The fundamental data collection was a series of high resolution photographs to be used to construct a geological model of the island. This mammoth task was completed by Solvi (2013) and incorporated data provided from onshore field studies. Klausen and Mørk (2014) furthered this work by conducting a sedimentological study of the islands, documenting its palaeogeography and comparing the channel bodies to those observed in seismic lines from the Barents Sea.

Lord et al. (2014b, Paper 2) focussed on expanding the work of Solvi (2013), by classifying all of the identified sandstone body types into different channel types and positioning them in the stratigraphy, in order to ascertain their stratigraphic importance. The understanding gained from this study and Lord et al. (2014a, Paper 1) also had implications for the understanding of the De Geerdalen Formation north of Hopen. On Edgeøya, the formation is widely exposed and early geological maps (prior to those presented by Dallmann

& Elvevold, 2015) featured the Wilhelmøya Subgroup in the southern part of the island. An expedition to the Tjuvfjorden area of Edgeøya was conducted in 2014, with samples collected from the highest exposed point by the candidate being submitted for palynological dating to ascertain the age. The results indicated a distinctively Carnian age for the shale units seen on the summit of mountains in southern Edgeøya (Niall Paterson pers. comm. 2014). Thus, the geological map was amended following this new interpretation with the updated maps being published in Dallmann and Elvevold (2015). The exposed section from Hopen could then be inferred to represent the missing Upper Triassic succession from Edgeøya as suggested by Lundschien et al. (2014).

It is not known exactly what interval the lower part of the Upper Triassic succession on Edgeøya represents in relation to that from Hopen, but a number of observations regarding the Upper Triassic succession in south east Svalbard can be made:

1. There is significant thinning of the Triassic Succession from Hopen, as envisaged by the gamma log from well 7626/5-1 ("Hopen 2" see Mørk et al., 2013, Appendix1) in comparison to recorded sections in Spitsbergen (Mørk et al., 1999a; Vigran et al., 2014; Lord et al., 2017, Paper 4).
2. The exposed section of the Upper Triassic from Hopen can be somewhat 'superimposed' atop sections from Edgeøya, in order to gain insight into the nature of the succession (e.g. Lundschien et al., 2014). However, a considerable thinning of the Upper Triassic has either occurred between Edgeøya and Hopen, or a larger proportion of the section is still missing. Thus, thickness estimates for the missing Triassic succession from Edgeøya should still be regarded as tenuous.
3. The considerable thinning of the Upper Triassic succession, from the east and southeast, towards the west is likely due to the emergence of the Svalbard platform, probably during the Late Triassic. The emergence of this area may be argued to be a contributing factor to syn-depositional growth faulting, seen in the Tschermakfjellet and lower part of the De Geerdalen formations, throughout eastern Svalbard (Edwards, 1976; Rød, 2011; Anell et al., 2013; Osmundsen et al., 2014). A lack of accommodation space due to the emergence this platform area of eastern Svalbard (Fig. 2B, Dallmann et al., 2015a), may have resulted in an unstable delta front at the time, which rested on a hard shale unit (the Botneheia Formation) which had undergone early cementation. Growth faulting in the Upper Triassic succession is notably seen at Kvalpynten in southern Edgeøya. However, it is also evident elsewhere in Edgeøya and Barentsøya. Growth faults are seen to become listric at the boundary with the Botneheia Formation at many localities, with no evidence for underlying fault activity or offset in the Middle Triassic units (Rød, 2011). A tectonic mechanism, with deep-rooted faults driving growth faulting at Kvalpynten, is proposed by Anell et al. (2013) and Osmundsen et al. (2014). However, conclusive evidence from the field is still lacking and reasonable counter arguments have been made (e.g. Klausen, 2013). It is most likely the result of a combination of factors that have resulted in the destabilisation of the delta front and growth faulting in eastern Svalbard.

Following an extensive period of fieldwork in eastern Spitsbergen and northern Storfjorden, it was possible to begin extending the understanding of the Upper Triassic succession, that had been gained from Edgeøya and Hopen, to more northern localities. In Paper 4, the sedimentology of the Upper Triassic succession in eastern Spitsbergen, Barentsøya and Wilhelmøya is addressed.

The study found that the lower part of the Upper Triassic succession represents shallow marine deposits, with the remaining part of the succession being deltaic and composed largely of proximal facies. This included the northernmost exposures at Wilhelmøya. Prior to fieldwork it was expected, based on earlier works, that this area should be formed from the most distal facies. This trend in facies development bolsters the interpretations of a delta system prograding from a northern area, possibly sources from the Taimyr area of Siberia (Harstad, 2016; Fleming et al., 2016) as opposed to being purely derived from the Uralide Mountains. Recent data from wells drilled in the Kvitøya area also show a significant thickness increase (1500–1800 m) in the Upper Triassic succession in the northeast (Simonstad et al., 2017) which may further strengthen this hypothesis. However, significant evidence from seismic and outcrop studies still supports the presence of a north westwards prograding deltaic system at this time (e.g. Riis et al., 2008; Glørstad-Clark et al., 2010; Høy and Lundschien, 2011; Lundschien et al., 2014; Klausen & Mørk, 2014; Anell et al., 2014a) with counter arguments only being supported by limited provenance data.

Prior to the fieldwork campaign in 2015, the Isfjorden Member was not extended further than eastern Spitsbergen and it was hypothesised by Lord et al. (2014a, Paper 1) that the Hopen Member may extend to Wilhelmøya. However, this was proven to not be the case (Haugen, 2016; Lord et al., 2017, Paper 4), as alternating red and green palaeosol beds of the Isfjorden Member were observed at localities in north-eastern Spitsbergen and Wilhelmøya. The shallow marine deposits in the Hopen Member may thus reflect a lateral change in deposition as part of a deltaic system, e.g. an interdistributary bay (Olaussen et al., 2015), as opposed to being a direct result of eustatic changes in sea level.

A number of visits to Hopen in 2012 allowed for detailed studies to be conducted on one of the enigmatic lithostratigraphic units on the island, the Svenskøya Formation. The unit is included within the Wilhelmøya Subgroup, the onshore equivalent to the Realgrunnen Subgroup of the southern Barents Sea. Recent exploration interests in the Realgrunnen Subgroup have actualised the requirement for gaining an improved understanding of the unit's onshore equivalents.

Hopen does not feature a complete succession of the Svenskøya Formation, only the lower 35 m. However, this part is missing from the type section on Kong Karls Land (Smith et al., 1976; Larssen et al., in prep.; Smelror et al., in prep.). This means the base of the unit is exposed and can be discussed, as it is considered to be an important sequence stratigraphic boundary throughout eastern Svalbard. The same boundary can be seen in wells from the Sentralbanken area of the Barents Sea. The nature of the Svenskøya Formation on Hopen, Wilhelmøya, Kong Karls Land and Sentralbanken is addressed in Paper 5.

The unconformity at the base of the Svenskøya Formation can be traced from Hopen to Wilhelmøya, Kong Karls Land and Sentralbanken and is likely traceable to southern areas of the Barents Sea. The Svenskøya Formation corresponds to the upper part of the Fruholmen Formation and the Tubåen Formation (Mørk et al., 1999a; Klausen et al., 2016). Towards Wilhelmøya the base is somewhat covered and the earlier interpretations of an erosive base by Worsley (1973) and Smith (1975) have been maintained as it is likely the case.

The Svenskøya Formation on Hopen was interpreted to be composed of fluvial and deltaic sandstones, deposited as part of a destructive delta. Samples were recovered and these were submitted for thin sectioning at NTNU. Petrographic analysis determined the composition to be sub-arkosic on Hopen with the uppermost part of the formation being arkosic. This was then compared with petrographic data from the Sentralbanken area provided by the NPD to discuss the reservoir properties of the unit.

Understanding of the development of the Triassic succession in Svalbard, and to ascertain good links to the succession offshore in the northern Barents Sea, is most feasible using sequence stratigraphy. In Paper 6, the sequence stratigraphic development of the Triassic succession is addressed, building on numerous early studies (e.g. Mørk et al., 1989; Mørk, 1994; Egorov & Mørk, 2000; Mørk & Smelror, 2001; Riis et al., 2008; Glørstad-Clark et al., 2010; Anell et al., 2014a; Vigran et al., 2014). Here, the major transgressive – regressive sequences are broken down in to parasequences and sub-sequences using an extensive dataset collected throughout Svalbard. These sequences are then used to discuss the regional development of the Triassic succession throughout Svalbard and the northern Barents Sea.

Paper 6 is part of an ongoing project with the NPD and has the benefit of access to a continuous stream of new data, which has direct implications for the study. This, however, is of great benefit and allows for improved understanding in a number of areas:

1. The assignment of stratigraphic nomenclature has been avoided by many studies (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011), opting instead to use ages for sequences observed in seismic lines. With improved well control, from new data (e.g. Simonstad et al., 2017) integrated with the understanding from Svalbard, accurate use of stratigraphic terminology for the offshore area can potentially be achieved.
2. With the increased discussion of Triassic provenance areas, a concise understanding of the development of Triassic sequences in the north-easternmost part of the Barents Sea will aid the discussion regarding a system depositing sediment derived from Novaya Zemlya or the Taimyr area of Siberia as proposed by Mørk (1999), Harstad (2016) and Fleming et al. (2016). These studies at present are still tenuous, as they are based purely on provenance studies without supporting evidence from sedimentology or seismic. The latter two fields of study have shown largely contradictory evidence to this theory (e.g. Riis et al., 2008; Høy & Lundschien, 2011; Anell et al., 2014a, b).

Concluding Remarks

It is without doubt that there is still a significant amount of work that remains to be conducted on the Triassic succession in Svalbard. The enigmatic region of Oscar II Land in the northwest of Svalbard, for example, has eluded sedimentologists, due to the extreme levels of deformation that occurred during the Cenozoic. The thickness development in the Lower Triassic in this region is touched upon in Paper 6. However, detailed measurement of sections and a strong understanding of compressional tectonics in a foreland area are required to unravel the nature of Triassic rocks in this area.

Similarly, to the east and offshore into the Barents Sea, little understanding has been gained as to the development of the Svalbard platform, following the deposition of the Botneheia Formation during the Middle Triassic. Considerable thickness variations of the Upper Triassic succession are observed throughout the region. The Upper Triassic thins from some 1200 m to around 270 m, from the east (offshore) to west (central Spitsbergen) and little advances have been made in the understanding as to how the units thin so considerably from offshore areas onto the Svalbard platform. The presence of marine shales of the Botneheia Formation throughout the region suggests that the mechanism driving uplift of the platform did not occur until the Carnian and this is evidenced by the lack of observable clinoforms in the archipelago.

Advances in provenance studies and new data from confidential stratigraphic wells, suggest a new palaeogeographical model for the Late Triassic is also required and this will be aided by the understanding gained from Paper 6. A system building from the south east is logical for the Early and Middle Triassic, whilst for the study area, provenance studies suggest a varying sediment type originating from the Uralides and likely the Timanide areas of Siberia. Well defined clinoform sequences in the northern Barents Sea show a linear coastline prograding towards the northwest (Klausen et al., 2015). Thus, there is little evidence for a system prograding westwards from the east or northeast, that has yet been observed in seismic data. Thus, developing a model that can account for this sediment input should be of great importance, especially to those attempting to unravel the complex sediment dispersal patterns for the northern Barents Sea and Svalbard during the Triassic.

References

Andresen, A., Bergh, S., Hansen, H., Klovjan, O., Kristensen, S.E., Lifbjerg, F., Lund, T., Mair, B.F., Midboe, P. & Nøttvedt, A. 1988: Geometry and structural development of the Billefjorden and Lomfjorden fault zones in the Isfjorden - Sabine Land area, Spitsbergen. Abstract 18, *Nordiske Geologiske Vintermøde,* Copenhagen, January 1988, 33–34.

Andresen, A., Bergh, S.G., & Haremo, P. 1994: Basin inversion and thin-skinned deformation associated with the Tertiary transpressional West Spitsbergen orogeny. *Proceeding from International Conference on Arctic Margins,* Anchorage, Alaska, 6p.

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

Anell, I.M., Braathen, A. & Olaussen, S. 2014a: The Triassic – Early Jurassic of the northern Barents Shelf: a regional understanding of the Longyearbyen CO2 reservoir. *Norwegian Journal of Geology 94*, 83–98.

Anell, I.M., Faleide, J.I. & Braathen, A. 2016: Regional tectono-sedimentary development of the highs and basins of the northwestern Barents Shelf. *Norsk Geologisk Tidsskrift 96 (1)*, 27–41.

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*, 167–179.

Bäckström, S.A. & Nagy J., 1985: Depositional history and fauna of a Jurassic phosphorite conglomerate (the Brentskardhaugen Bed) in Spitsbergen. *Norsk Polarinstitutt 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 Geologist Bulletin 81*, 637–661.

Bjærke, T. & Dypvik, H. 1977: Sedimentological and palynological studies of Upper Triassic - Lower Jurassic sediments in Sassenfjorden, Spitsbergen. *Norsk Polarinstitutt Årbok 1976*, 131–150.

Böhm, J. 1903: Über die Obertriadische fauna der Bären-insel. *Kungliga Svenska Vetenskaps-akademiens Handlingar 37 (39)*, 76p.

Braathen, A., Bergh S.G., & Maher, H.D. 1999: Application of a critical wedge taper model to the Tertiary transpressional fold-thrust belt on Spitsbergen, Svalbard. *Geological Society of America Bulletin 111 (10)*, 1468–1485.

Buchan, S.H., Challinor, A., Harland, W.B., & Parker J.R., 1965: The Triassic Stratigraphy of Svalbard. *Norsk Polarinstitutt Skrifter*, 135.

Bue, E.P. & Andressen, A. 2013: Constraining depositional models in the Barents Sea region using detrital zircon U-Pb data from Mesozoic sediments in Svalbard. *Geological Society, London, Special Publication 386*. 261–279.

Bælum, K. & Braathen, A. 2012: Along-strike changes in fault array and rift basin geometry of the Carboniferous Billefjorden Trough, Svalbard, Norway. *Tectonophysics 456-457*, 38–55. doi:10.1016/j.tecto.2012.04.009

Cocks, L.R.M. & Torsvik, T.H. 2007: Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic. *Earth-Science Reviews 82,* 29–74.

Dagys, A.S. & Weitschat, W. 1993: Correlation of the Boreal Triassic. *Mitteilungen Geologisches-Paläontologisches Institut Universität Hamburg 75*, 249–256.

Dallmann, W.K. 2009: Hopen Geological Map 1:100,000. Norwegian Polar Institute, Tromsø.

Dallmann, W.K. & Elvevold, S. 2015: Chapter 7 – Bedrock Geology. In Dallmann, W.K. (ed.): Geoscience Atlas of Svalbard. Report Series 148, Norsk Polarinstitutt, Tromsø. 133–174.

Dallmann, W.K., Elvevold, S., Majka, J. & Piepjohn, K. 2015a: Chapter 8 – Tectonics and tectonothermal events. In Dallmann, W.K. (ed.): Geoscience Atlas of Svalbard. Report Series 148, Norsk Polarinstitutt, Tromsø. 175–224.

Dallmann, W.K., Forwick, M., laberg, J.S. & Vorren, T. 2015b: Chapter 2 – Physical Geography. In Dallmann, W.K. (ed.): Geoscience Atlas of Svalbard. Report Series 148, Norsk Polarinstitutt, Tromsø. 19–30.

Dallmann, W.K., Ohta, Y., Elvevold, S. & Blomeier, D. (eds.) 2002: Bedrock map of Svalbard and Jan Mayen. Norsk Polar Institutt Temakart No.33.

Dallmann, W.K., Reymert, P.K. & Sander, G. 2015c: Chapter 12 – Management and infrastructure. *In* Dallmann, W.K. (ed.): *Geoscience Atlas of Svalbard*. Report Series 148, Norsk Polarinstitutt, Tromsø. 259–266.

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

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

Eide, C.H., Klausen, T.G., Katkov, D., Suslova, A.A. & Helland-Hansen, W. in press: Linking an Early Triassic delta to antecedent topography: source-to-sink study of the southwestern Barents Sea margin. *GSA Bulletin*.

Eiken O. (ed.) 1994: Seismic atlas of western Svalbard. *Norsk Polarinstitutt Meddelelser 130*. Oslo: Norwegian Polar Institute.71p.

Eiken, O. 1985: Seismic mapping of the post-Caledonian strata in Svalbard. *Polar Research 3*, 167–176.

Elvevold, S., Dallman, W.K. & Bloomeier, D. 2007: *The Geology of Svalbard*. Norwegian Polar Institute, Tromsø, 38pp.

Embry, A.F. 1995: Sequence boundaries and sequence hierarchies: problems and proposals. *In* Steel, R.J., Felt, V.L., Johannessen E.P. & Mathieu, C. (eds.): *Sequence stratigraphy of the Northwest European Margin, NPF Special Publication 5*, Elsevier, Amsterdam, 1–11.

Embry, A.F. 2006: Episodic global tectonics: sequence stratigraphy meets plate tectonics. *GeoExpro 3*, 27–30.

Embry, A. & Mørk, A. 2006: Large magnitude, tectonically generated sequence boundaries near all Triassic stage boundaries- significance and implications. Boreal Triassic 2006. *NGF Abstracts and Proceedings of the Geological Society of Norway* Number 3, 2006, 47–52.

Enga, J. 2015: *Palaeosols in the Triassic De Geerdalen and Snadd formations*. Master Thesis, Norwegian University of Science and Technology, 127p.

Falcon, N.L. 1928: Geology. The Cambridge Expedition to Edge Island. *Geographical Journal 72*, 134–139.

Faleide, J.I., Tsikalas, F., Breivik, A.J., Mjelde, R., Trizmann, O., Engen, Ø., Wilson, J. & Eldholm, O. 2008: Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes 31*, 51–61.

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

Flood, B., Nagy, J. & Winsnes, T.S. 1971: The Triassic succession of Barentsøya, Edgeøya and Hopen (Svalbard). Norsk Polarinstitutt Meddeler Nr. 100.

Gabrielsen, R.H., Færseth, R.B., 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, 3–33.

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.

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 Fleet, A.J. & Boldy, S.A.R., (ed.): Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, 247–259.

Haremo. P., Andresen. A., Dypvik. H., Nagy. J., Elverhei. A., Eikeland, T. A. & Johansen. H. 1990: Structural development along the Billefjorden Fault Zone in the area between Kjelstrømdalen and Adventdalen/ Sassendalen, Central Spitshergen. *Polar Research 8,* 195–216.

Haremo P. & Andresen, A. 1992: Tertiary Décollement thrusting and inversion structures along Billefjord and Lomfjorden Fault Zones, East Central Spitsbergen. *Structural and Tectonic Modelling and Its Application to Petroleum Geology Special Publication 1*, 481–491.

Harland, W.B. 1979: A review of major faults in Svalbard. *Regional Tectonic Series (Cambridge Arctic Shelf Programme) 132*, 157–180.

Harland, W. B., Cutbill, J. I., Friend. P. F., Gobbett. D. S., Holliday. D. W., Maton, P. I., Parker, J.K. & Wallis. R.H. 1974: The Billefjorden Fault Zone, Spitsbergen*. Norsk Polar Institutt Skrifter 161*, 72p.

Harstad, T. 2016: *Sandstone Provenance of the De Geerdalen Formation on Svalbard – Emphasis on Petrography and Chromum Spinel Compostions*. Master Thesis, Norwegian University of Science and Technology, Trondheim, 98p.

Haugen, T. 2016: *A Sedimentological Study of the De Geerdalen Formation with Focus on the Isfjorden Member and Palaeosols*. Master Thesis, Norwegian University of Science and Technology, 155p.

Høy, T. & Lundschien B.A. 2011: Triassic deltaic sequences in the northern Barents Sea. *Geological Society, London, Memoirs 2011, 35*, 249–260.

Johansen, S.E., Ostisty, B.K., Birkeland, Ø., Fedorovsky, Y.F., Martirosjan, V.N., Brunn Christensen, O., Cheredeev, S.I., Ignatenko, E.A. & Margulis, L.S., 1992: Hydrocarbon potential in the Barents Sea region: Play distribution and potential. *Arctic Geology and Petroleum Potential, NPF Special Publication, No.2*, Elsevier, Amsterdam, 273–320.

Klausen, T.G. 2013: Does evidence of faulting contradict at quiescent northern Barents Shelf during the Triassic? Letters to the editor. *First Break 31* (9), 69–70.

Klausen, T.G. & Mørk, A. 2014: Upper Triassic paralic deposits of the De Geerdalen Formation on Hopen: Outcrop analogue to the subsurface Snadd Formation in the Barents Sea. *The American Association of Petroleum geologists Bulletin*, 98. 1911–1941.

Klausen, T.G., Müller, R., Slama, J. & Helland-Hansen, W. 2016: Evidence for Late Triassic tectonism in enigmatic provenance areas and Early Jurassic sediment supply turnover in northern Pangea. *Geological Society of America 8 (6)*. doi: 10.1130/L556.1

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

Klubov, B.A. 1965: Outline of the Geology of Edgeøya. In Sokolov, V.N. (ed.) Materialy po geologii Špicbergena. Leningrad, 71–82. (In Russian)

Knarud, R. 1980: En sedimentologisk og diagenetisk undersøkelse av Kapp Toscana Formasjonens sedimenter på Svalbard. Candidate Realfag Thesis, University of Oslo, 208p.

Korčinskaja, M.V. 1980: Rannenorijskaja fauna arhipelaga Sval'bard (Early Norian fauna of the Archipelago of Svalbard). In Semevskij, D.V. (ed.) Geologija osadočnogo čehla arhipelaga Sval'bard (Geology of the sedimentary platform of the Archipelago of Svalbard), NIIGA, Leningrad, 30–43 (in Russian).

Korčinskaja, M.V. 1982: Ob'jasnitel'naja zapiska k stratigrafičeskoj scheme mezozoja (trias) Sval'barda (Explanatory note to the stratigraphic scheme of Mesozoic (Triassic) Svalbard). PGO "Sevmorgeologija", Leningrad, 40–99.

Krajewski, K.P. 2008: The Botneheia Formation (Middle Triassic) in Edgeøya and Barentsøya, Svalbard: lithostratigraphy, facies, phosphogenesis, palaeoenvironment, *Polish Polar Research 29*, 319–364.

Krajewski, K.P., Karcz, P., Wozny, E. & Mørk, A. 2007: Type section of the Bravaisberget Formation (Middle Triassic) at Bravaisberget, western Nathorst Land, Spitsbergen, Svalbard. *Polish Polar Research 28*, 79–122.

Krajewski, K. & Weitschat, W. 2015: Depositional history of the youngest strata of the Sassendalen Group (Bravaisberget Formation, Middle Triassic–Carnian) in southern Spitsbergen, Svalbard. *Annales Societatis Geologorum Poloniae 85*, 151–175.

Leever, K.A., Gabrielsen, R., Faleide, J.I. & Braathen, A. 2011: A transpressional origin for the West-Spitsbergen fold-and-thrust belt: Insight from analogue modelling. *Tectonics 30*, 1–24.

Leith, T., Weiss, H., Mørk, A., Århus, N., Elvebakk, G., Embry, A., Borisov, A.V. 1993: Mesozoic hydrocarbon source-rocks of the Arctic region. In: Vorren, T.O. (ed.): *Arctic Geology and Petroleum Potential. Norwegian Petroleum Society (NPF) Special Publication 2*, 1–25.

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 Polarinstitutt Skrifter 168*, 64p.

Lord. G.S. 2013: *Steep fracture patterns and their characteristics within the Triassic De Geerdalen Formation on Svalbard: An emphasis on regional trends, local variations and lithological controls.* Master Thesis, Norwegian University of Science and Technology, 200p.

Lord, G.S., Solvi, K.H., Klausen, T.G. & Mørk, A. 2014a: Triassic channel bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution. *Norwegian Petroleum Directorate Bulletin 11*, 41–49.

Lord, G.S., Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W. & Paterson, N.W. 2014b: The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 81–96.

Lord, G.S., Johansen, S.K., Støen, S.J. & Mørk, A. 2017: Facies Development of the Late Triassic De Geerdalen Formation on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard. *Norwegian Journal of Geology 97*, 33–62.

Lundschien, B.A., Høy, T. & Mørk, A. 2014: Triassic hydrocarbon potential in the Northern Barents Sea: Integrating Svalbard and stratigraphic core data. *Norwegian Petroleum Directorate Bulletin 11*, 3–20.

Maher, H. D. Jr. & Craddock, C. 1988: Decoupling as an alternate model for transpression during the initial opening of the Norwegian-Greenland Sea. Polar Research 6, 137–140.

Major, H. & Nagy, J. 1972: Geology of the Adventdalen map area with a geological map, Svalbard C9G 1:100 000. Norsk Polarinstitutt Skrifter 138, 59p.

Manby, G.M., Lyberis, N., Chorowicz, J. & Thiedig, F. 1994: Post-Caledonian tectonics along the Billefjorden fault zone, Svalbard and implications for the Arctic region. Geological Society of America Bulletin 106, 201–216.

Max, M.D. & Ohta, Y. 1988: Did major fractures in continental crust control orientation of the Knipovich Ridge – Lena Trough segment of the plate margin? *Polar Research 6*, 85–93.

Miller, E.L., Soloviev, A. V., Prokopiev, A. V., Toro, J., Harris, D., Kuzmichev, A.B., Gehrels, G.E. 2013: Triassic river systems and the palaeo-Pacific margin of northwestern Pangea. *Gondwana Research 23*, 1631–1645.

Myhre, A.M. & Eldholm, O. 1988: The western Svalbard Margin (74°-80°N). *Marine and Petroleum Geology 5*, 134–156.

Mørk, A. 1994: Triassic transgressive-regressive cycles of Svalbard and other Arctic areas: a mirror of stage subdivision. *In* Guex, G. & Baud, A. (eds.), Recent developments on Triassic Stratigraphy (Proceedings of the Triassic Symposium, Lausanne, 20-25 Oct. 1991). *Mémoires de Géologie* (Lausanne), No. 22, 69–82.

Mørk, A. 1997: Triassic sequences, stages and high order sequence boundaries. *Albertiana 19*, 9–11.

Mørk, A. & Bjorøy, M. 1984: Mesozoic source rocks on Svalbard. *In* Spencer, A.M. (ed.) *Petroleum Geology of the North European Margin*. Norwegian Petroleum Society (Graham & Trotman), 371–382.

Mørk, A., Embry, A.F. & Weitschat, W. 1989: Triassic transgressive-regressive cycles in the Sverdrup Basin, Svalbard and the Barents Sea. *In* Collinson, J.D. (ed.), *Correlation in Hydrocarbon Exploration*. Norwegian Petroleum Society, Graham & Trotman, London, 1989, 113–130.

Mørk, A., Dallmann, W.k., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pčelina, T.M. & Worsley, D. 1999a: Mesozoic Lithostratigraphy. *In* Dallmann, W.K., (ed.): *Lithostratigraphic Lexicon of Svalbard, Upper Palaeozoic to Quaternary Bedrock – Review and recommendations for nomenclature use*. Norwegian Polar Institute, Tromsø. 127–214.

Mørk, A. & Elvebakk, G. 1999: Lithological description of sub-cropping Lower and Middle Triassic rocks from the Svalis Dome, Barents Sea. *Polar Research 18*, 83–104.

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, 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. 371–398.

Mørk, A., Lord, G.S., Solvi, K.H. & Dallmann, W.K. 2013: Geological Map of Svalbard 1:100 000, Sheet G14G Hopen. Norsk Polarinstitutt Temakart No. 50.

Mørk, A. & Smelror, M. 2001: Correlation and Non-Correlation of High Order Circum-Arctic Mesozoic Sequences. *Polarforschung 69*, 65–72.

Mørk, A., Vigran, J.O. & Hochuli, P.A. 1990: Geology and palynology of the Triassic succession of Bjørnøya. *Polar Research* 8, 141–163.

Mørk, A. & Worsley, D. 2006: Triassic of Svalbard and the Barents Shelf. Boreal Triassic 2006. NGF Abstracts and Proceedings of the Geological Society of Norway, Number 3, 2006, 23–29.

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

Nasuti, A., Ottemöller, L., Dallmann, W.K., Storheim, B.M., Atakan, K. & Olesen, O. 2015: Chapter 9 – Geophysics. *In* Dallmann, W.K. (ed.): *Geoscience Atlas of Svalbard*. Report Series 148, Norsk Polarinstitutt, Tromsø, 225–240.

Nystuen, J.P., Andresen, A., Kumpulainen, R.A. & Siedlecka, A. 2008a: Neoproterozoic basin evolution in Fennoscandia, East Greenland and Svalbard. *Episodes 31*, 35–43.

Nystuen, J.P., Mørk, A., Müller, R. & Nøttvedt, A. 2008b: From desert to alluvial plain – from land to sea, Triassic; 251-200 million years ago. *In* Ramberg, I.B., Bryhni, I., Nøttvedt, A. & Rangnes, K. (eds.): *The making of a Land, Geology of Norway*. Norges Geologiske Forening, Trondheim, 330–355.

Nøttvedt, A., & Rasmussen, E. 1988: Tertiary deformation in central-west Spitsbergen, as interpreted from marine reflection seismic data. Abstract 18*, Nordiske Geologiske Vintermøde*, Copenhagen, January 1988, 320–321.

Olaussen, S., Husteli, B., Lord, G.S., Rismyhr, B., Johannessen, E.P. & Mørk, A. 2015: The Early Norian transition in Svalbard and the Barents Sea: A record of slowing down of basin subsidence, alteration of facies associations and shift of provenance and climate change. 2nd Boreal Triassic Conference 2015, Svalbard, *Abstract and proceedings Geol. Soc. Norw*. 39–42.

Osmundsen, P.T., Braathen, A., Sande, Rød, R. & Hynne, I. 2014: Styles of normal faulting and fault controlled deposition in the Triassic of Hopen and Edgeøya, Svalbard. *Norwegian Petroleum Directorate Bulletin 11,* 61–80.

Parker, J.R. 1966: Folding, faulting and dolerite intrusions in the Mesozoic rocks of the fault zone of Central Spitsbergen. *Norsk Polarinstitutt Årbok 1964*, 47–55.

Paterson, N.W. & Mangerud, G. 2015: Late Triassic (Carnian – Rhaetian) palynology of Hopen, Svalbard. *Review of Palaeobotany and Palynology 220*, 98–119.

Paterson, N.W., Mangerud, G., Cetean, C.G., Mørk, A., Lord, G.S., Klausen, T.G. & Mørkved, P.T. 2016: A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway. *Palaeogeography Palaeoclimatology Palaeoecology 464*, 16–42.

Pčelina, T.M. 1965: Mezozojskie otloženija rajona Van-Kjlenf'orda Zapadnyj Špicbergen (Mesozoic deposits around Van Keulenfjorden, Western Spitsbergen). *In* Materialy po geologii Špicbergena. Leningrad, 1965. (In Russian).

Pčelina, T.M. 1972: Triassovye otloženija ostrova Medvežij. (Triassic deposits of Bjørnøya). *In* Sokolov, V.N. and Vasilevskaja, N.D. (eds.), Mezozoiskie otloženija Sval'barda (Mesozoic deposits of Svalbard), NIIGA, Leningrad, 5–20. (in Russian).

Pčelina, T.M. 1977: Permskie i triasovye otloženia ostrova Ėdž (Sval'bard). (Permian and Triassic deposits of Edgeøya (Svalbard)). *In* Stratigrafija i palaeontologija dokembrija i palaeozoja severa Sibiri (Stratigraphy and palaentology of the Precamrian and Palaeozoic of northern Siberia). Collection of scientific Papers. NIIGA, 59–71. Leningrad. (In Russian).

Pčelina, T.M. 1983: Novye dannye po stratigrafii mezozoja arhipelaga Špicbergen (New data on the Mesozoic stratigraphy of the Spitsbergen Archipelago). *In* Krasil'ščikov, A.A. & Basov, V.A. (eds.): Geologija Špicbergena (The Geology of Spitsbergen). PGO Sevmorgeologija", Leningrad, 121–141. (In Russian).

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.

Rismyhr B., Bjærke T. & Olaussen S. in prep: Depositional environments, sequence variability and palynostratigraphy of the uppermost Triassic–Middle Jurassic succession in the northwestern Barents Shelf.

Rød, R.S. 2011: Spatial occurrences of selected sandstone bodies in the De Geerdalen Formation, Svalbard, and their relation to depositional facies. Master Thesis, Norwegian University of Science and Technology, 122p.

Rød, R.S., Hynne, I.B. & Mørk, A. 2014: Depositional environment of the Upper Triassic De Geerdalen Formation – An E-W transect from Edgeøya to Central Spitsbergen, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 21–40.

Simonstad, E., Karlsen, K.L., Pedersen, N., Bering, D., Høy, T., Bjørnestad, A., Sand, M., Sandstå, N.R. & Stenløkk, J. 2017: *Preliminary results of the NPD 2015 shallow drilling campaign, Kvitøya, northern Norwegian Barents Sea*. Abstract. *In* Abstracts and Proceedings of the Geological Society of Norway, 32nd Geological Winter Meeting; 2017, Oslo, Norway. p.76.

Smelror, M., Larssen, G.B., Olaussen, S., Rømuld, A. & Williams, R. in prep: Late Triassic to Early Cretaceous palynostratigraphy of Kong Karls Land, Svalbard, Arctic Norway. *Norwegian Journal of Geology Special Publications.*

Smith, D.G., Harland, W.B. & Hughes,N.F. 1975: Geology of Hopen, Svalbard. *Geological Magazine 112*, 1–23.

Smith, D.G., Harland, W.B., Hughes, N.F. & Pickton, C.A.G. 1976: The geology of Kong Karls Land, Svalbard. *Geological Magazine 113 (3),* 193–304.

Steel, R.J. & Worsley, D. 1984: Svalbard's post-Caledonian strata – an analysis of sedimentational patterns and palaeogeographic evolution. *In* Spencer, A.M. (ed.) *Petroleum Geology of the North European Margin*. Norwegian Petroleum Society (Graham & Trotman), 109–135.

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*. 269p.

Weitschat, W. & Dagys, A. 1989: Triassic biostratigraphy of Svalbard and a comparison with NE-Siberia. *Mitteilungen aus dem Geologisch-Paläontologisches Institut der Universität Hamburg 68*, 179–213.

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

Worsley, D. 1986: *The geological history of Svalbard. Evolution of an Arctic archipelago*. (ed.) Aga, O.J. Den norske stats oljeselskap A.S, Stavanger, 121p.

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

Worsley, D. & Mørk, A. 1978: The Triassic stratigraphy of southern Spitsbergen. *Norsk Polarinstitutt Årbok 1977*, 43–60.

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

Zuchuat, V. 2014: *A Sedimentary Investigation of the Lower Triassic Formations and their Underlying Permo-Carboniferous Units across Spitsbergen, Svalbard*. Master Thesis, Norwegian University of Science and Technology, 167p.

Part II

Summary of Papers & Appendices

Paper 1: The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard.

Gareth S. Lord, Kristoffer H. Solvi, Marianne Ask, Atle Mørk, Mark W. Hounslow & Niall W. Paterson

Published in *The Norwegian Petroleum Directorate Bulletin 11*, 2014.

Summary

This paper focuses on providing a formal description of the Hopen Member and was accepted by the Norwegian Committee on Stratigraphy in April, 2014. The base of the Hopen Member was initially recognised as a surface, that could be used for correlation of logs and deduce the offset of strata by faulting in the PhotoModeler™ model of the island created by Solvi (2013). Further investigations showed that the unit is extensive throughout the island and its thickness is relatively uniform. The article presents the findings of these investigations, which implemented photo modelling, sedimentology, palynology, ammonoid biostratigraphy and magnetostratigraphy, to ensure a strong case for the creation of a member unit.

The sedimentological characteristics of the Hopen Member are discussed in comparison to underlying facies. It has been determined that the facies show a change in depositional style during the latest Carnian to early Norian on Hopen. The member was interpreted as representing an overall marine environment, potentially an inter delta lobe bay. It is thought to have been formed as a result of delta switch following the avulsion of a primary sediment source. The areal extent of the unit is not fully known; however, the paper suggests the Hopen Member may extend to Wilhelmøya, although now subsequently disproven.

Ammonoid biostratigraphy deduced the member to be of earliest Norian age and likely older, based on the presence of *Neosirenites* (*Norosirenites*, Bragin et al., 2012) ammonoids in the overlying Flatsalen Formation. Palynology helped constrain the dating of the member unit with the recognition of the *Prorodiploxypinus* Acme Zone in the upper part of the member with a higher diversity of assemblages being seen in comparison to the underlying De Geerdalen Formation. The transition in the composition of palynomorph assemblages corresponds well to the onset of the Hopen Member. The abundance of marine palynomorphs supports the sedimentological interpretations as a marine unit. Dating from palynology suggests that the unit is late Carnian in age. Magnetostratigraphic dating suggests that the base of the Hopen Member corresponds to a well-defined magnetostratigraphic marker at the base of the Isfjorden Member in central Spitsbergen. Dating from magnetostratigraphy also places the Hopen Member as Carnian in age, with the Slottet Bed likely marking the Carnian – Norian boundary in the Hopen area.

A case was argued against using Spitsbergen stratigraphic nomenclature for the unit on Hopen. The distance from Hopen to Spitsbergen and the marine facies present in the unit resulted in the definition of a separate unit, as opposed to extending the Isfjorden Member to this area. The correlative Isfjorden Member is composed of continental and lagoon facies, especially in its upper part where red and green

weathered clays representing palaeosols are abundant alongside bioclastic carbonate beds (Haugen, 2016; Lord et al., 2017, Paper 4). These are the defining features for geologists attempting to recognise the Isfjorden Member in the field, which are not present on Hopen and thus defining the unit as the Hopen Member was preferred.

Paper 2: Triassic Channel Bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution.

Gareth S. Lord, Kristoffer H. Solvi, Tore G. Klausen & Atle Mørk

Published in *The Norwegian Petroleum Directorate Bulletin 11*, 2014.

Summary

This paper focusses on providing an overview of the fundamental characteristics of sandstone channel bodies observed in the steep cliffs of Hopen, with data being derived from the PhotoModeler™ 3D geological model of the island, constructed by Solvi (2013). In that respect, the article presents itself as a data source or a guide for geologists conducting reservoir analysis on channel bodies in the Late Triassic Snadd Formation in the Barents Sea. The application of the geological model and the interpretation of high resolution photographs were necessary in the case of Hopen, due to the remoteness of the island and the fact that many of the observed channels are inaccessible in the steep cliffs.

The PhotoModeler™ (EOS Systems) 3D geological model was produced by Solvi (2013) as part of a master thesis at the Norwegian University of Science and Technology. The use of photogrammetry was an entirely recent concept at the time and was the first study of its kind to be attempted in Svalbard, for geological modelling. The intention was to address whether this method could replace costly Lidar scans of outcrops (e.g. Rød, 2011; Rød et al., 2014), that typically require helicopter based apparatus. The method is relatively simple; a number high resolution images are interpreted with corresponding points in each image being entered into a point database and given a x, y, z, position format that can be constrained to UTM coordinates and altitude, based on known marker positions. This is then compared and adjusted to suit a digital elevation model. The same method was also conducted on aerial imagery provided by the Norwegian Polar Institute.

A comprehensive facies and palaeogeography discussion has been presented by Klausen and Mørk (2014). This article builds upon this study by documenting the width, thickness and type of channels observed, throughout the entire island. This data also compared the stratigraphic position of each channels in order to strengthen interpretation of the depositional environment, for the De Geerdalen Formation on the island.

As channels were observed to be constrained to particular levels in the islands stratigraphy, three 'channel zones' were constructed. 1) A lower channel zone containing fluvial trunk and distributary channels with paralic delta plain sediments. 2) A middle channel zone, dominated by shallow marine facies with estuarine and tidal channels. 3) An upper channel zone, which marks a return to fluvial trunk and distributary

channels. These are subsequently overlain by the Hopen Member (Mørk et al., 2013, Appendix 1; Lord et al., 2014a, Paper 1).

The most impressive sandstone channel bodies observed on the island are those representing trunk channel and estuary deposits. Many channel bodies were seen to be heterolithic in nature (based on observations from photo interpretation), with clear lateral accretion surfaces and many appear to feature mud plugs. The small distributary channels provide insight into the nature of fluvial processes occurring on the delta plain. The channels indicate an extensive delta plain environment, with bifurcation and anastomosing of channels that have subsequently been abandoned.

In total 25 channel bodies were observed and measured for their geometrical properties. All except two (which formed a stacked system) were determined to be isolated within the stratigraphy, with contemporary channel geometries. The overall depositional environment was interpreted to represent two stages of fluvial dominated sedimentation in a paralic delta plain setting split by a marked period of marine deposition.

Paper 3: A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway.

Niall. W. Paterson, Gunn Mangerud, Claudia G. Cetean, Atle Mørk, Gareth S. Lord, Tore G. Klausen & Pål T. Mørkved

Published in *Palaeo 3: Palaeogeography, Palaeoclimatology, Palaeoecology 464*, 2016.

Summary

The article entitled '*A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway*' was initiated by Niall W. Paterson and Gunn Mangerud at the University of Bergen. The aim was to provide a high resolution biofacies characterisation for the Late Triassic strata present on the island of Hopen. This was achieved by implementing new data and re-evaluating existing data presented by Ask (2013) and in Vigran et al. (2014).

Motivation for the paper was spurred by a number of reasons. Firstly, a great quantity of palynological studies have been conducted on the Late Triassic succession on Hopen (e.g. Smith, 1974: Smith et al., 1975; Bjærke, 1977; Bjærke and Dypvik, 1977; Bjærke & Manum, 1977; Hochuli et al., 1989; Ask, 2013; Vigran et al., 2014; Paterson & Mangerud, 2015). However, the exact dating of the succession was still contentious, most notably in the upper part (Flatsalen and Svenskøya formations), as many works considered the Rhaetian (latest part of the Triassic) to be missing (Mørk et al., 1982, 1989; Jacobsen & Van Veen, 1984; Steel & Worsley, 1984; Hochuli et al., 1989). Secondly, few of these previous studies had integrated palynology and micropalaeontology and almost all focused on biostratigraphic dating as opposed to attempting to understand the palaeo-environment of samples.

In this paper, an effort has been made to investigate the De Geerdalen, Flatsalen and Svenskøya formations on the island by integrating palynology, palynofacies analysis and micropalaeontology, with contemporary sedimentological and stratigraphical methods. The study builds on previous works conducted on Hopen (e.g. Mørk et al., 2013, Appendix 1; Klausen & Mørk, 2014; Lord et al., 2014a, Paper 1; Lord et al., 2014b, Paper 2) to provide a detailed insight into the depositional environments and the palaeogeography of the region, during the Late Triassic. As well as constraining the ages of stratigraphical units on Hopen, the study found that the Upper Triassic exposures on Hopen reflect deposition in a number of palaeo-environments. These include; (1) fluvio-deltaic, (2) paralic, (3) open marine environments.

The De Geerdalen Formation was interpreted to have been deposited in a fluvial-dominated coastal plain, to marginal marine setting during a stage of regressive sedimentation during the late Carnian and supports interpretations by Klausen and Mørk (2014) and Lord et al. (2014b, Paper 2). The lower part of the formation on Hopen has been interpreted as representing deposition close to extensive, fern-dominated coastal mire (fern fossils have also been documented by Launis et al., 2014). Prevailing humid conditions allowing for coals to form were present, influenced by episodes of marine processes. The Hopen Member is interpreted as representing a nearshore, brackish marginal marine setting in the latest stages of the Carnian.

The Slottet Bed is a transgressive lag deposit (Klausen & Mørk, 2014) representing a circum-Arctic transgressive surface (Embry, 1997) of early Norian age. The Flatsalen Formation is interpreted as a fully marine unit deposited in an extensive shallow sea, in response to a marine transgression. The Svenskøya Formation is interpreted as a fluvio-deltaic unit with an erosive base potentially representing a significant sequence boundary, likely formed in response to a drop in relative sea level during the Norian–Rhaetian.

Paper 4: Facies Development of the Late Triassic De Geerdalen Formation on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard.

Gareth S. Lord, Sondre K. Johansen, Simen J. Støen & Atle Mørk

Accepted to the *Norwegian Journal of Geology*. February, 2017.

Summary

This article is the result of fieldwork conducted by the author and students from the Norwegian University of Science and Technology and the University Centre in Svalbard in 2015. The study area covers the easternmost areas of Spitsbergen, Barentsøya and Wilhelmøya. The objective of fieldwork was to collect detailed sedimentological logs throughout the Upper Triassic strata in these areas. The paper is a compilation of a SINTEF Petroleum research report and chapters originally presented as master thesis work by the students (Johansen, 2016; Haugen, 2016; Støen, 2016). The paper was submitted to the Norwegian Journal of Geology in October 2016 and accepted following revisions in February 2017.

Throughout eastern Svalbard, Upper Triassic rocks dominate the stratigraphy and the area is a key location for understanding the development of the De Geerdalen Formation. The paper extends earlier facies studies (Klausen & Mørk, 2014; Rød et al., 2014) northwards in order to understand the development of deltaic deposits.

Throughout the field area, deltaic sediments are prevelant and our analysis shows that the Upper Triassic De Geerdalen Formation can be disseminated into three discrete intervals based on the overall depositional environment. The lower interval is of early Carnian age and includes the Tschermakfjellet Formation and lowermost part of the De Geerdalen Formation. This interval is dominated by shallow marine and delta front/ shoreface deposits. The middle interval of approximately mid-Carnian age is dominated by delta front to delta top deposits where fluvial channels, palaeosols and coal beds become common. The upper interval of approximately late Carnian to early Norian age is dominated by a delta plain environment which includes lagoon and lacustrine deposits, as well as palaeosols. This upper unit is constrained to the Isfjorden Member.

Observations show that the De Geerdalen Formation represents a thinner package of deltaic deposits in comparison to that observed on the islands of Edgeøya and Hopen. Although proximal deposits are prevalent in the upper part of the unit, distal deltaic deposits are found in the lower and middle parts of the stratigraphy. This helps confirm the regional depositional model with a deltaic system building from the SE to NW across the Barents Shelf where distal deposits should be expected in northern areas.

The Isfjorden Member was found at all localities visited during the field campaign for this study, with the exception of Barentsøya which has seen significant Quaternary erosion, thus the upper part of the succession is missing. It was originally hypothesised that the Hopen Member may be observed in this region, this was however proved to be wrong and instead the Isfjorden Member has been extended to the northeasternmost part of this study area and Wilhelmøya by the paper, a conclusion further demonstrated by Haugen (2016).

Paper 5: Sedimentology and Petrography of the Svenskøya Formation on Hopen: A potential analogue to sandstone reservoirs in the Realgrunnen Subgroup

Gareth S. Lord, Mai Britt E. Mørk, Atle Mørk & Snorre Olaussen

Article submitted to *Polar Research*. February, 2017.

Summary

Following recent hydrocarbon discoveries in the Realgrunnen Subgroup in the Hoop area of the Barents Sea, attention was focussed on equivalent rock units in Svalbard as potential for onshore analogues. The Svenskøya Formation on Hopen is the time equivalent unit to the upper part of the Fruholmen and Tubåen formations (following dating by Paterson et al., 2016, Paper 3) in the Realgrunnen Subgroup.

The unit could largely be considered 'forgotten' and limited interest was driven by the fact the Snadd Formation was considered a good potential hydrocarbon reservoir, with the De Geerdalen Formation being a suitable analogue (Klausen & Mørk, 2014) at the time fieldwork was being conducted.

Earlier works such as Flood et al. (1971) or Smith et al. (1975) also paid little detailed attention to the formation on the island, whilst significant work was conducted on the formation in Kong Karls Land (Smith et al., 1976). During fieldwork to Hopen in 2012, a detailed section of the formation measured and samples for palynology and petrography were recovered. This data was subsequently implemented into the map (Mørk et al., 2013, Appendix 1), as a contribution to Vigran et al. (2014) and formed part of the work by the candidate presented in Paterson et al. (2016, Paper 3).

A detailed facies study was yet to be conducted on the Svenskøya Formation and this subsequently formed the motivation for producing Paper 5. This study compares the Svenskøya Formation on Hopen to other areas in Svalbard and also included a small number of NPD wells, drilled in the Sentralbanken area of the Barents Sea. A number of samples were collected during fieldwork in 2012 and petrographic studies were conducted, to deduce the reservoir properties of the formation on Hopen. The findings were compared to samples from the Sentralbanken area and from data in reports by the Norwegian Petroleum Directorate.

The Svenskøya Formation was interpreted as a mixed, fluvial deltaic environment with a major sequence boundary at its base. The formation could be split into four informal units. A lower unit comprised entirely of channel fill facies and erosive scours with mud flake conglomerate. A lower-middle unit comprised of shoreface sandstones. This is overlain by an upper-middle unit, with fluvio-deltaic deposits with a scouring channel at its base overlain by thick large scale cross bedded shoreface sandstones. The uppermost unit observed in the succession is somewhat enigmatic and was interpreted as representing small channels flowing in an estuarine environment, overlain by marine mudstone. Correlation to Wilhelmøya and Kong Karls Land was conducted, with comparable facies and overall depositional environments being observed.

Petrography showed a comparable composition for sandstones in the Sentralbanken area with slightly higher porosity. Overall the unit is arkosic in composition. Secondary porosity from the dissolution of chert and feldspar grains is common and detrital grains are seen to consist of quartz, feldspar, mica, chert and lithic rock fragments. Cement was generally seen to be composed of kaolinite or quartz. These compositions were comparable to that seen in Sentralbanken; however, offshore porosity is seen to be slightly higher.

The study of the Svenskøya Formation filled a missing gap with regards to understanding the sedimentology and also petrography of the unit, having been largely disregarded with the exception of dating (Vigran et al., 2014; Paterson et al., 2016, Paper 3).

Paper 6: Sequence pattern in the Triassic Succession of Svalbard and the Northern Barents Sea.

Gareth S. Lord, Atle Mørk & Tore Høy

Manuscript in preparation.

Summary

The manuscript presented as Paper 6 focusses on sequence stratigraphic units of various rank seen in the Triassic succession in Svalbard. An attempt to quantify the number of transgressive – regressive sequences, parasequences and sub-sequences, which can be observed within the Triassic succession throughout Svalbard, is made and the paper is largely conceptual. However, the ability to quantify variations in sequences over such a wide area allows for a true discussion of basin infill patterns to be made and builds upon the understanding from many earlier works (e.g., Mørk et al., 1989; Embry, 1997; Mørk et al., 1999a, b; Egorov & Mørk, 2000; Mørk & Smelror, 2001; Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011; Anell et al., 2014a, 2014b; Lundschien et al., 2014; Klausen & Mørk 2014; Lord et al., 2014a, b, 2017, Papers 1, 2 and 4; Klausen et al., 2015).

The paper focusses on the Induan to mid-Norian succession on Svalbard and the northern Barents Sea and discusses the distribution of low rank sequences (parasequences) and sub-sequences (also known as intra-parasequence bed sets) which occur between major sequence boundaries. A number of high ranking sequence stratigraphic surfaces, representing major transgressive and regressive episodes, are present in the Triassic succession and are seen to closely follow formation and stage subdivisions (Mørk, 1997; Mørk & Smelror, 2001). The defined sequences have been constructed from minor sub-sequences (intra-parasequence bed sets) that are not regarded to have formed as a result of changes in sea level, but instead represent local facies variability and internal architecture of parasequences. True parasequences are defined between flooding surfaces, as these are easily observed in outcrop following the original definition by Van Wagoner et al. (1990).

The Early Triassic of Svalbard consists of four parasequences observed in western and central areas of Spitsbergen. For south and southeastern areas only one parasequence is recognised. The west coast features in the Vardebukta and Tvillingodden formations, whereas four are interpreted in the Vikinghøgda Formation in central Spitsbergen. One main parasequence that corresponds to a major transgressive sequence occurring in eastern areas of Svalbard is defined for the Middle Triassic Botneheia Formation. However, in western Svalbard along the palaeo-basin margin, two to three parasequences are identified in the equivalent Bravaisberget Formation.

The Upper Triassic succession is bound by major sequence boundaries and is a regressive deltaic system formed in a paralic setting. Low rank sequence development, within the De Geerdalen Formation, is notable and upwards coarsening units are seen representing repeated, regressive deltaic advances.

These sequences are bound by minor flooding surfaces that are interpreted to be related to local variations in the delta system e.g. formed in response to avulsion.

In addition, a correlation to the northern part of the Barents Sea has been conducted in order to show the nature of sequence development seen in seismic lines shot offshore from Svalbard. Whilst low rank sequences cannot be quantified in this area due to relatively poorly resolved seismic and lack of lithological data from cores, this correlation allows for the thickness developments of the Triassic succession to be observed.

Paper 6 documents the nature of parasequence development throughout the entire Triassic succession and represents the culmination of work and the understanding of the Triassic succession for this thesis. The Paper implements the knowledge gained from Papers 1 to 4, in order to account for the development of low order sequences in the Late Triassic. The lower and middle parts of the Triassic succession are also well documented and interpretations are built on well-regarded earlier works.

Appendix 1: Geological Map of Svalbard 1:100 000, Sheet G14G Hopen

Mørk, A., Lord, G.S., Solvi, K.H. & Dallmann, W.K.

Thematic map published by the Norwegian Polar Institute.

Summary

The geological map of Hopen (Mørk et al., 2013, Appendix 1) was a caveat of the SINTEF Petroleum ‘Hopen Geology Project’ that ran from 2007 to 2014. The project ended with the publication of the geological map and the NPD Bulletin volume 11, in which a large number of papers covered the geology of the island.

Earlier maps from 2009 (Dallmann, 2009), produced by Winfried Dallmann at the Norwegian Polar Institute (NPI) covered the islands geology extensively; however, much of the information was based upon aerial photography and limited field data. The prolonged SINTEF – NPD Hopen expedition in the summer of 2011 and shorter expeditions to the island in 2012 and 2013 provided an opportunity to collect a comprehensive dataset of the island's stratigraphy, sedimentology and structural geology.

Data from the thesis of Solvi (2013), which created the initial geological model of the island, was fundamental in providing structural measurements and stratigraphical information on areas of the island deemed inaccessible. In addition, it was with this model that the Hopen Member was first identified as a useful marker horizon, as it was found on all mountain tops and could be used to measure fault offset. Unusual for the standard geological maps produced by NPI, the Hopen Member is included on the map itself and is differentiated from the remainder of the De Geerdalen Formation.

The map is presented as an excursion map in 1:100,000 scale, with an inset 1:50,000 map covering the northern end of the island. The traditional individual map sheet and outline booklet has been abandoned and all the information is presented in one large map sheet. This is due, primarily, to the size of the map itself being very small and the fact that larger informative figures can be included with accompanying text. Similar thematic map sheets of this type have been produced by NPI for the Billefjorden area of central Spitsbergen. The map contribution was also featured in Dallmann and Elvevold (2015) in the recent Geoscience Atlas of Svalbard (Dallmann, 2015)

Appendix 2: På jakt etter reservoaranalog (in Norwegian)

Halfdan Carstens (Editor)

Magazine article published in GEO, about Gareth S. Lord and Atle Mørk's research on Hopen. March 2014.

Summary

This article is included in the present thesis as an appendix to highlight scientific outreach by the candidate to advertise the findings of this and other projects since 2013. The article featured in the popular Norwegian geological magazine GEO, as a four page description of the project and an overview of the geology of Hopen.

The article covers the nature of fieldwork conducted on the island of Hopen by members of the Hopen Geology Project, during the 2011 and 2012 field seasons. In addition the article highlights the importance of the exposures on Hopen to the oil and gas industry as channel bodies described on the island (Klausen & Mørk, 2014; Lord et al., 2014b, Paper 2) are considered analogous to those seen in the Snadd Formation in the Barents Sea.

References

Anell, I.M., Braathen, A. & Olaussen, S. 2014a: The Triassic – Early Jurassic of the northern Barents Shelf: a regional understanding of the Longyearbyen CO2 reservoir. *Norwegian Journal of Geology 94*, 83–98.

Anell, I.M., 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*, 167–179.

Ask, M. 2013: *Palynological dating of the upper part of the De Geerdalen Formation on central parts of Spitsbergen and Hopen*. Master Thesis, University of Bergen, 79 pp.

Bjærke, T. 1977: Mesozoic palynology of Svalbard – II. Palynomorphs from the Mesozoic sequence of Kong Karls Land. *Norsk Polarinstitutt Årsbok 1976*, 83–120.

Bjærke, T. & Dypvik, H. 1977: Sedimentological and palynological studies of Upper Triassic–Lower Jurassic sediments in Sassenfjorden, Spitsbergen. *Norsk Polarinstitutt Årsbok 1976*, 131–150.

Bjærke, T. & Manum, S.B. 1977: Mesozoic palynology of Svalbard – I. The Rhaetian of Hopen, with a preliminary report on the Rhaetian and Jurassic of Kong Karls Land. *Norsk Polarinstitutt Skrifter 135*, 1–48.

Bragin, N.Y., Konstantinov, A.G. & Sobolev, E.S. 2012: Upper Triassic Stratigraphy and Palaeobiogeography of kotel'nyi Island (New Siberian Islands). *Stratigraphy and Geological Correlation 20 (6)*, 54–80.

Dallmann, W.K. 2009: Hopen Geological Map 1:100,000. Norwegian Polar Institute, Tromsø.

Dallmann, W.K. (ed.) 2015: *Geoscience Atlas of Svalbard*. Report Series 148, Norsk Polarinstitutt, Tromsø. 292p.

Dallmann, W.K. & Elvevold, S. 2015: Chapter 7 – Bedrock Geology. *In* Dallmann, W.K. (ed.): *Geoscience Atlas of Svalbard*. Report Series 148, Norsk Polarinstitutt, Tromsø. 133–174.

Egorov, A.Y. & Mørk, A. 2000: The East Siberian and Svalbard Triassic successions and their sequence stratigraphical relationships. *Zbl. Geol. Paläont. Teil 1*. 1377–1430.

Embry, A.F., 1997: Global sequence boundaries of the Triassic and their identification in the Western Canada sedimentary basins. *Can. Pet. Geol. Bull. 45*, 249–259.

Flood, B., Nagy, J. & Winsnes, T.S. 1971: The Triassic succession of Barentsøya, Edgeøya and Hopen (Svalbard). Norsk Polarinstitutt Meddeler Nr. 100.

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.

Haugen, T. 2016: *A Sedimentological Study of the De Geerdalen Formation with Focus on the Isfjorden Member and Palaeosols*. Master Thesis, Norwegian University of Science and Technology, 155p.

Hochuli, P.A., Colin, J.P. & Vigran J.O. 1989: Triassic biostratigraphy of the Barents Sea area. *In* Collinson, J. (ed.): *Correlation in Hydrocarbon Exploration.* Graham and Trotman, London (1989), 131–153.

Høy, T. & Lundschien B.A. 2011: Triassic deltaic sequences in the northern Barents Sea. Geological Society, London, Memoirs 2011, 35, 249–260.

Jacobsen, V. W. & van Veen, P. 1984: The Triassic offshore Norway north of 62°N. In Spencer, A. M. (ed.): *Petroleum Geology of the North European Margin, Norwegian Petroleum Society*, Graham & Trotman, London, 1984. 317–327.

Johansen, S.K. 2016: *Sedimentology and facies distribution of the Upper Triassic De Geerdalen Formation in the Storfjorden area and Wilhelmøya, eastern Svalbard*. Master Thesis, Norwegian University of Science and Technology, 193p.

Klausen, T.G. & Mørk, A. 2014: Upper Triassic paralic deposits of the De Geerdalen Formation on Hopen: Outcrop analog to the subsurface Snadd Formation in the Barents Sea. *The American Association of Petroleum geologists Bulletin 98*. 1911–1941.

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

Launis, A., Pott, C.P. & Mørk, A. 2014: A glimpse into the Carnian: Late Triassic plant fossils from Hopen, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 129–136.

Lord, G.S., Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W. & Paterson, N.W. 2014a: The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard. N*orwegian Petroleum Directorate Bulletin 11*, 81–96.

Lord, G.S., Solvi, K.H., Klausen, T.G. & Mørk, A. 2014b: Triassic channel bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution. *Norwegian Petroleum Directorate Bulletin 11*, 41–49.

Lord, G.S., Johansen, S.K., Støen, S.J. & Mørk, A. 2017: Facies Development of the Upper Triassic succession on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard. *Norwegian Journal of Geology 97*, 33–62.

Lundschien, B.A., Høy, T. & Mørk, A. 2014: Triassic hydrocarbon potential in the Northern Barents Sea: Integrating Svalbard and stratigraphic core data. *Norwegian Petroleum Directorate Bulletin 11*, 3–20.

Mørk, A. 1997: Triassic sequences, stages and high order sequence boundaries. *Albertiana 19*, 9–11

Mørk, A., Dallmann, W.k., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pčelina, T.M. & Worsley, D. 1999a: Mesozoic Lithostratigraphy. *In* Dallmann, W.K., (ed.): *Lithostratigraphic Lexicon of Svalbard, Upper Palaeozoic to Quaternary Bedrock – Review and recommendations for nomenclature use*. Norwegian Polar Institute, Tromsø. 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, A., Embry, A.F. & Weitschat, W. 1989: Triassic transgressive-regressive cycles in the Sverdrup Basin, Svalbard and the Barents Sea. *In* Collinson, J.D. (ed.): *Correlation in Hydrocarbon Exploration*. Norwegian Petroleum Society, Graham & Trotman, London, 1989, 113–130.

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, 371–398.

Mørk, A., Lord, G.S., Solvi, K.H. & Dallmann, W.K. 2013: Geological Map of Svalbard 1:100 000, Sheet G14G Hopen. *Norsk Polarinstitutt Temakart* No. 50.

Mørk, A. & Smelror, M. 2001: Correlation and Non-Correlation of High Order Circum-Arctic Mesozoic Sequences. *Polarforschung 69*, 65–72.

Paterson, N.W. & Mangerud, G. 2015: Late Triassic (Carnian–Rhaetian) palynology of Hopen, Svalbard. *Review of Palaeobotany and Palynology 220*, 98–119.

Paterson, N.W., Mangerud, G., Cetean, C.G., Mørk, A., Lord, G.S., Klausen, T.G. & Mørkved, P.T. 2016: A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway. *Palaeogeography Palaeoclimatology Palaeoecology 464*, 16–42.

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.

Rød, R.S. 2011: *Spatial occurrences of selected sandstone bodies in the De Geerdalen Formation, Svalbard, and their relation to depositional facies*. Master Thesis, Norwegian University of Science and Technology, 122 pp.

Rød, R.S., Hynne, I.B. & Mørk, A. 2014: Depositional environment of the Upper Triassic De Geerdalen Formation – An E-W transect from Edgeøya to Central Spitsbergen, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 21–40.

Smith, D.G. 1974: Late Triassic pollen and spores from the Kapp Toscana Formation, Hopen, Svalbard – a preliminary account. Review of Palaeobotany & Palynology 17, 175–178.

Smith, D.G., Harland, W.B. & Hughes, N.F. 1975: The Geology of Hopen, Svalbard. Geological Magazine 112, 1–23.

Smith, D.G., Harland, W.B., Hughes, N.F. & Pickton, C.A.G. 1976: The geology of Kong Karls Land, Svalbard. *Geological Magazine 113 (3),* 193–304.

Solvi, K.H., 2013: *Visualize and interpret the geometry, heterogeneity and lateral continuation of channel bodies in the De Geerdalen Formation at Hopen*. Master Thesis, Norwegian University of Science and Technology, 122p.

Steel, R.J. & Worsley, D. 1984: Svalbard's post-Caledonian strata - an atlas of sedimentational patterns and palaeographic evolution. In: Spencer, A.M. (Ed.) *Petroleum Geology of the North European Margin. Norwegian Petroleum Society*, Graham & Trotman, 1984. 109–135.

Støen, S.J. 2016: *Late Triassic sedimentology and diagenesis of Barentsøya, Wilhelmøya and eastern Spitsbergen*. Master Thesis, Norwegian University of Science and Technology, 165p.

Van Wagoner, J.C., Mitchum, R., Campion, K. & Rahmanian, V. 1990: Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. *AAPG Methods in Exploration Series 7*, 1–55.

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*. 269p.

Part III

Papers

Paper 1

The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard.

Gareth S. Lord, Kristoffer H. Solvi, Marianne Ask, Atle Mørk, Mark W Hounslow & Niall W. Paterson

Article published in the Norwegian Petroleum Directorate Bulletin 11, 2014.

The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard

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Hopen is a solitary island of Upper Triassic strata in the south-eastern most corner of the Svalbard archipelago. Outcrop studies throughout the island, supported by palynology, magnetostratigraphy and geological modelling have led to the identification of a new member unit within the upper part of the De Geerdalen Formation, the Hopen Member. Based on the distinctive visual properties of the strata observed in the mountain sides of Hopen, a recorded change in sediment style and an increase in the concentration of marine palynomorphs, the unit is well expressed. The Hopen Member represents an extensive, ~70 m thick succession of marine influenced shale and subordinate sandstones, distinguishing itself from the paralic and non-marine clastic sediment packages of the remaining part of the De Geerdalen Formation. The Hopen Member is traceable throughout the entire island, given its prominent darker colouration due to the lateral extent of its marine mudstones, unlike the bed packages below, which are laterally inextensive and more sandstone rich. Palynological and magnetostratigraphic studies have indicated an age of latest Carnian to earliest Norian for the member. With the age and stratigraphical position of the member being taken into account, it is possible to define this unit as a time equivalent to that of the Isfjorden Member of central Spitsbergen. However, its distinctively different lithological properties call for the creation of a new lithostratigraphic unit as opposed to simple correlation.

Key words: Hopen Member, Stratigraphy, Triassic, Svalbard.

Introduction

Expeditions organised by SINTEF Petroleum Research and the Norwegian Petroleum Directorate, have visited the island of Hopen in southeastern Svalbard regularly for the last six summers. Detailed lithological sections throughout the island have been measured (Klausen and Mørk, 2014; Mørk et al., 2013; Lord et al., 2014), in addition to biostratigraphic, palynological and magnetostratigraphic sampling. This has provided the basis for a considerable daraset, from which it has been possible to identify a new meber unit within the De Geerdalen Formation, the Hopen Member. In the construction of this member an interdisciplinary approach has been applied within its definition and this comprises primarily of; outcrop observation, sedimentology, magnetostratigraphy, palynology and photomosaic modelling.

Hopen is a narrow and elongate island consisting entirely of Late Triassic aged strata, which protrudes from the northern Barents Sea in the southeastern most corner of the Svalbard Archipelago (Fig. 1) (Mørk et al., 2013). At 32 km long and no wider than 2.5 km, Hopen features as somewhat of an oddity for the region, moreso given its relativley detatched position from the archipelago. The islands topographical expression is a result of the regional tectonic style, present in the eastern and southeastern areas of Svalbard, where the island represents the exposed tip of a tectonic high, within a fault system (Doré, 1995; Grogan et al., 1999). These faults trend northeast – southwest and extend throughout the offshore areas of south-eastern Svalbard and Kong Karls Land (Doré, 1995; Grogan et al., 1999), thus providing the basis for the islands axial orientation, with fault blocks down stepping to the southeast towards the Olga Basin.

Lord, G.S., Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W. & Paterson, N.W.: The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard. *Norwegian Petroleum Directorate Bulletin,* No. 11, pp. 81–96. Stavanger 2014, ISSN Online 1894-7670, ISBN 978-82-7257-117-6.

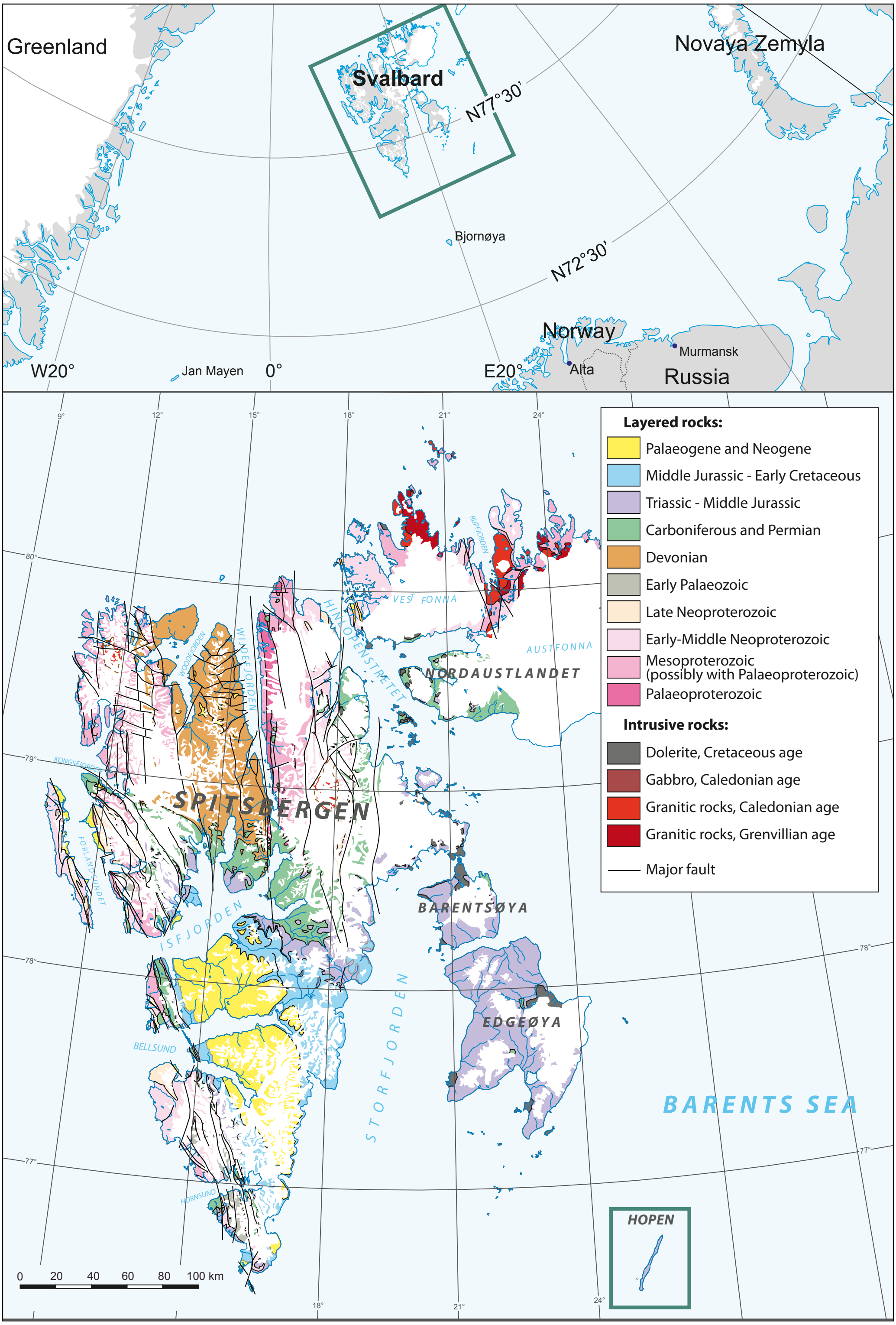

Figure 1. Overview areal map showing the position of Svalbard and basic bedrock geological map displaying the outcropping Mesozoic strata in purple with the position of Hopen denoted in the southeast. Map modified after Dallmann (in press).

The island is dissected by a series of NW-SE trending normal faults, which cut through the island at various intervals along its axis. Beds however are relatively horizontal with dips being in an order of no more than 1-2°, mainly to the NNE. The thickest exposures of the De Geerdalen Formation can be found at the southernmost mountain, Iversenfjellet, whilst in the north, the overlying Flatsalen and Svenskøya Formations are present (Mørk et al., 2013).

Pčelina (1972, 1983) noted the presence of her then defined Isfjorden 'Formation', from Central Spitsbergen, to represent the entirety of the De Geerdalen Formation on Hopen. She stated that the unit can be seen to extend over the entire archipelago, with the exception of Southern Spitsbergen. Her terminology included a much greater part of the succession within her Isfjorden 'suita' than in present nomenclature. Pčelina's Isfjorden 'Formation' and her Hahnfjella 'Formation' represented the Upper Triassic stratigraphic interval, which today is subdivided into the Tschermakfjellet and overlying De Geerdalen Formations. The revised lithostratigraphy of Mørk et al. (1999), have resulted in Pčelina's Isfjorden 'Formation' being downgraded to member status, within the De Geerdalen Formation, with its stratotype defined at Storfjellet in Sabine Land according to the section logged by Knarud (1980).

Mørk et al. (1999) (Fig. 2) did not recognise the Isfjorden Member outside of Spitsbergen, primarily due to poor constraints on stratigraphical thickness of the De Geerdalen Formation, its internal facies distributions and lithological variations in the eastern areas of Svalbard. Following a series of field studies and the creation of a computer based 3D geological model of Hopen, using photomosaics by Solvi (2013), the abrupt change in depositional style seen in the uppermost part of the De Geerdalen Formation became apparent. The 3D geological model of Hopen implemented a large photo dataset of the entire island (Solvi, 2013) and was made using Photomodeler™ software.

Mapping the lateral distribution of the base of the member, characterised by a notable colour change from light coloured yellow and grey, sands and shale to dark grey shale, was conducted using the 3D model, and this base could be followed all around the island. The surface was shown to be a more regional event unlike those more local facies variations of the stacked minor parasequences seen within the rest of the De Geerdalen Formation at Hopen (Klausen and Mørk, 2014; Lord et al., 2014). This also implies that the base of the Hopen Member may represent a major sequence stratigraphic boundary, expressing the onset of a marine transgression where the paralic deposits of the De Geerdalen Formation give way to more marine influenced deposition as a result of base level rise.

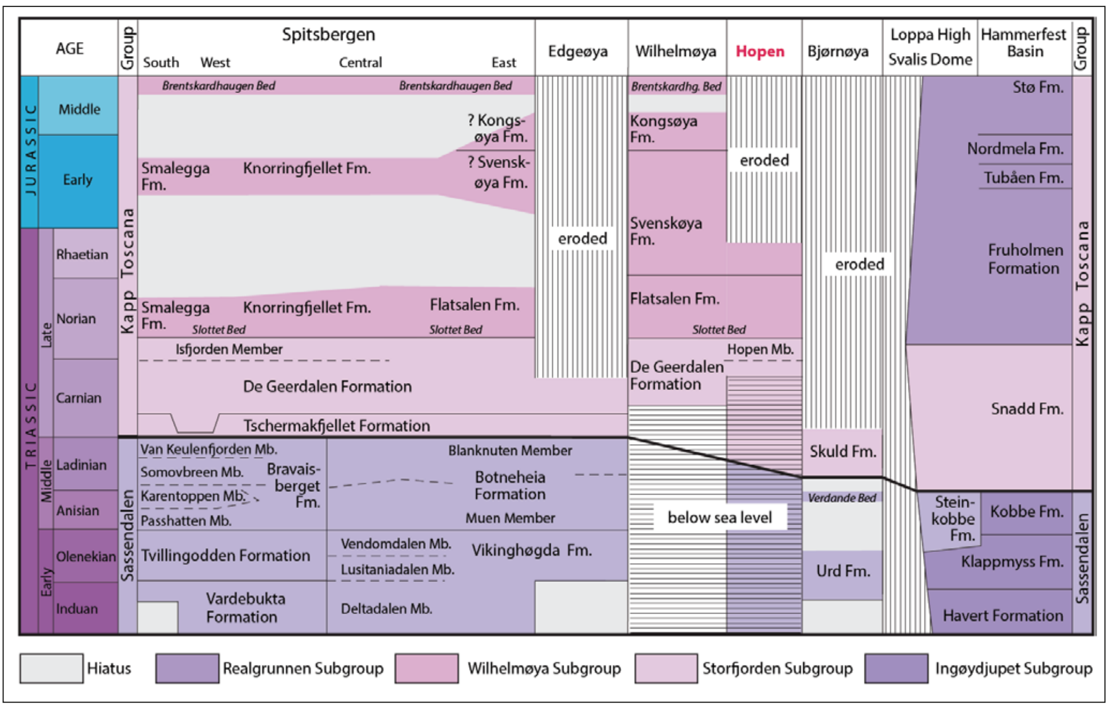

Figure 2. Stratigraphic subdivisions for the Triassic to mid-Jurassic succession of Svalbard and Barents Sea, with the Hopen Member included. Figure from Mørk et al. (2013).

Stratigraphy

Three formations are present on the island (Fig. 2) (Mørk et al., 2013). The thickest succession being the Carnian aged De Geerdalen Formation, deposited in a fluctuating deltaic environment close to an ancient shoreline (Klausen and Mørk, 2014). Overlying this is the Norian aged Flatsalen Formation, with the pronounced carbonate Slottet Bed at its base. Overlying this is the Svenskøya Formation of Norian to possibly Rhaetian age, a prominent, white and grey, cliff-forming succession of deltaic sandstones.

The De Geerdalen Formation in the region of Hopen is interpreted to be approximately 650 m thick based on data from the Hopen 2 well, an onshore well drilled by the Norsk Fina Group in 1973. A total of 165 m is exposed above sea level in the north of the island, while some 325 m (Smith et al., 1975) is exposed in the southern part of Hopen. This is in relatively strong contrast to the 200-300 m thickness of the entire formation seen in areas of central Spitsbergen; however, this is more akin to the development of the correlative Snadd Formation seen in the Barents Sea, which is considerably thicker (Worsley et al., 1988, Riis et al., 2008). The thickness of the De Geerdalen Formation on Edgeøya and Barentsøya is presently undefined, as the uppermost part of the formation is considered to have been significantly eroded during the Cenozoic.

Minor NW-SE trending normal faults on the island and the general dip of strata to the NNE have resulted in overlying units to the De Geerdalen Formation being exposed in some locations, most predominantly in the north of the island. The De Geerdalen Formation is overlain on Hopen, by the Norian aged marine mudstones of the Flatsalen Formation (Fig. 3). This formation consists entirely of dark marine shales, with a prominent hard carbonate bed at its base, the Slottet Bed (Mørk et al., 1999). The Flatsalen Formation represents a series of discrete, upwards-coarsening packages forming a 62 m thick, dark-shale dominated succession. The Flatsalen Formation's stratotype is also defined by Mørk et al. (1999) on the mountain of Flatsalen, in the northeast of Hopen.

The Flatsalen Formation is overlain with a low angle unconformity, by a thin ca. 45 m thick package of highly cross-stratified sandstones, featuring a coarse-grained erosive base. Interpreted as having been deposited in a fluvial to deltaic depositional environment; these prominent, cliff-forming, white and grey beds represent the Svenskøya Formation, as defined on Kong Karls Land (Smith et al., 1976; Mørk et al., 1999).

The island's underlying stratigraphic units at depth have been interpreted from information provided by the Hopen 2 well log. The base of the Kapp Toscana Group is at present suggested to be approximately 685 m below sea level. The deeper underlying units are un-interpreted, but are suggested to represent the Sassendalen Group. The base Triassic is interpreted in the well log to be at a depth of 1050 m below sea level (-1325 m on well log), where marine shales abruptly change to hard, silicified shale and sandstone of the Permian Kapp Starostin Formation. The proposed Hopen Member represents the upper ~70 m of the De Geerdalen Formation (Fig. 3) where it's notable, dark, cliff forming succession can be seen at numerous locations throughout the entire island. The thickness of the member is also seen to be relatively uniform, as measured in both in field sections and the Photomodeler™ 3D geological model.

Sedimentology

The base of the Hopen Member is marked by clear indication of marine facies being dominant in this interval, at all locations in northern Hopen where sedimentological logs (Figs. 3 and 4) have recorded the Hopen Member. Several logs document the nature of sediments and although facies types are seen to vary, they are all associated with marine deposition. There is seen to be a notable change in lithological type where stacked heterolithic packages are observed to become more mud rich, with a loss of any plant fragments, fossil leaves, root beds, palaeosols and minor coal beds, as seen in the underlying strata. A greater increases in the presence and intensity of bioturbation is observed in the basal beds of the Hopen Member.

The sedimentological logs have been acquired by various geologists, throughout successive visits to the island since 1995 and include sections at Blåfjellet, Lyngefjellet, Binnedalen and Nørdstefjellet (Fig. 4). Additional logs of the southern part of the island are presented by Mørk et al. (2013) and Lord et al. (2014). Alike the rest of the De Geerdalen Formation, the Hopen Member is composed of layered, heterolithic clastic rocks, in beds of varying lateral continuity and facies (Fig. 5). However, unlike the underlying strata, the facies are genetically related over the entirety of the island; whereas those lower in the succession are laterally discontinuous and facies types vary considerably over relatively short distances, at the same stratigraphic level. The member consists predominantly of minor upwards coarsening packages dominated by dark mudstones that are interspersed with thin sandstone beds.

The base of the member is most prominently seen from a distance (Fig. 5) due to the overall, highly heterolithic nature of the De Geerdalen Formation. Its base is defined where the presence of root structures and subordinate coal beds with associated palaeosols become absent, approximately 70 m below the Slottet Bed. A notable change in the colour of strata is observed at this level where the underlying heterolithic packages of light coloured sand and shale give way to a much darker,

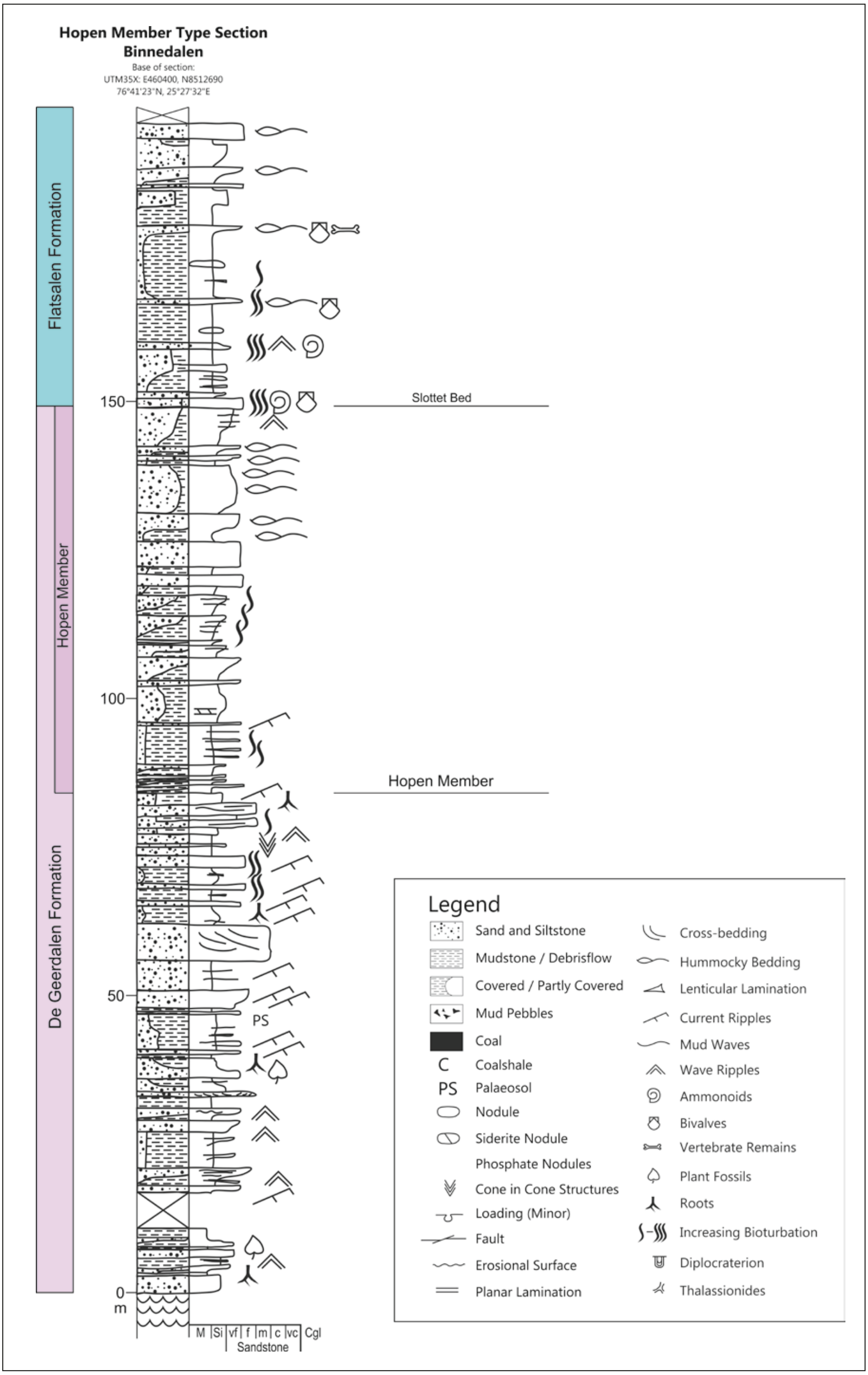

Figure 3. *Stratigraphic and sedimentological log of the Hopen Member type section, Binnedalen, eastern face of Lyngefjellet, northern Hopen.*

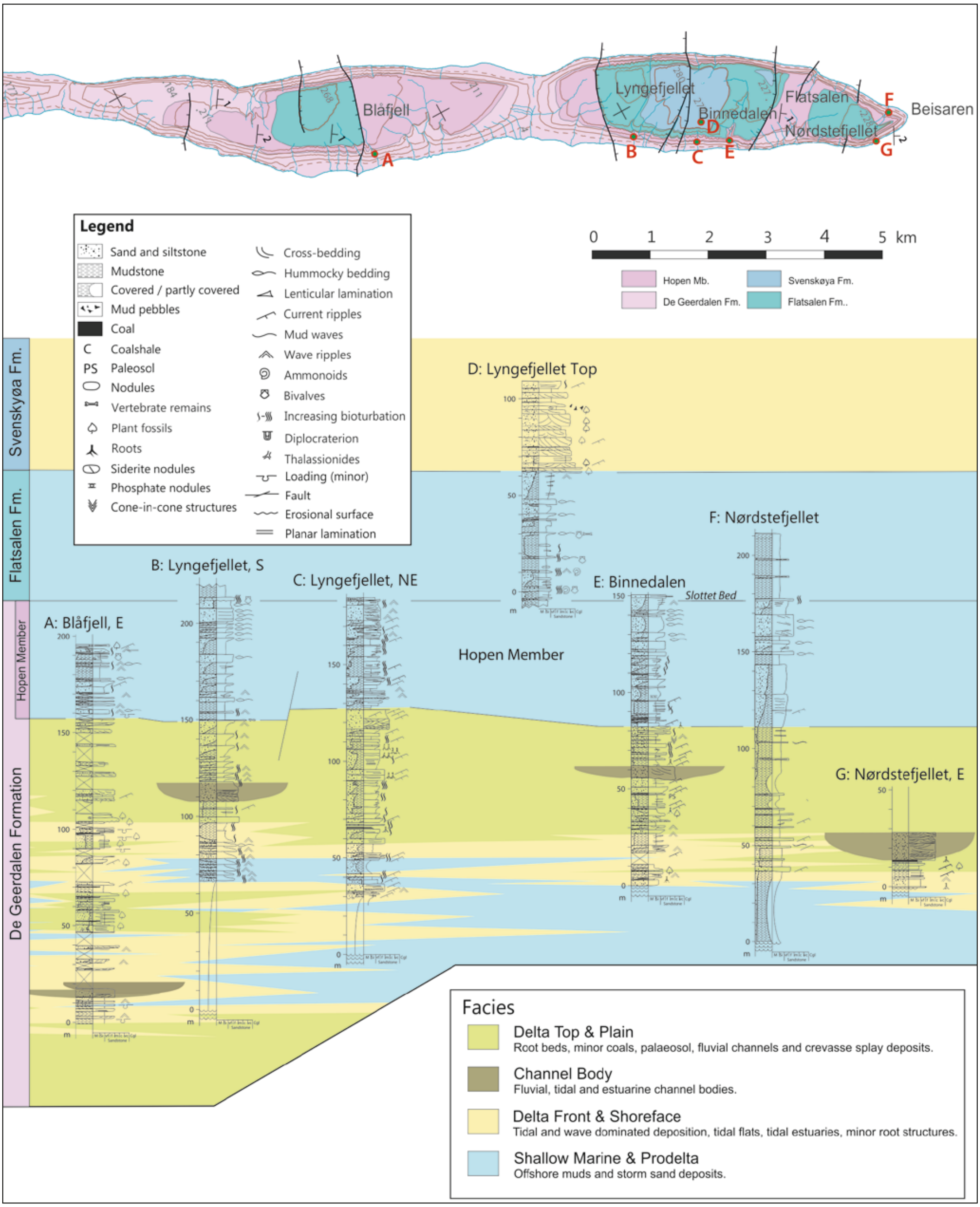

Figure 4. Facies association diagram throughout sections seen at Lyngefjellet in northern Hopen. Note the highly variable facies distribution in the De Geerdalen Formation below the base of the Hopen Member. A minor amendment has been made following the inclusion of palynological data, where the base of the Hopen Member has been set slightly lower in the Lyngefjellet NE log than previously shown in Mørk et al. (2013).

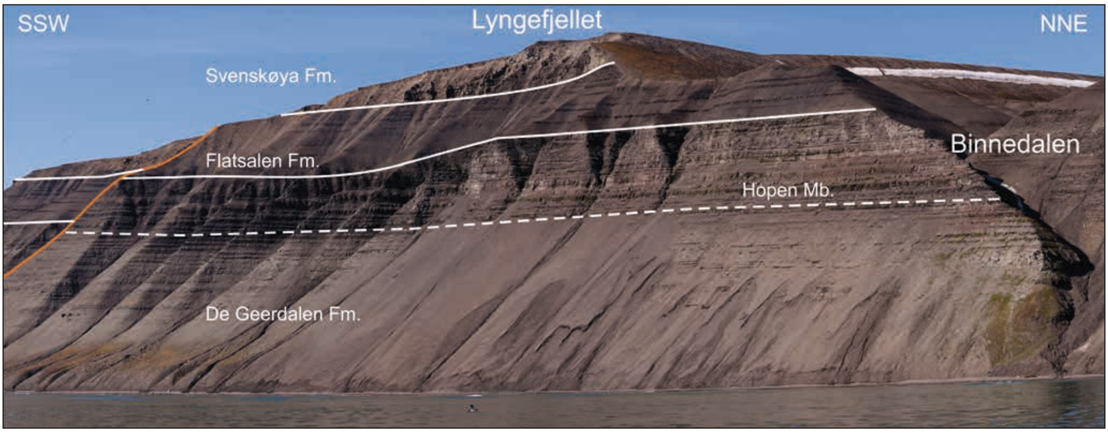

Figure 5. A panoramic view of Lyngefjellet displaying the stratigraphic subdivision of the Mesozoic strata on Hopen. The base of the Hopen Member is defined where the De Geerdalen Formation becomes notably darker in colour, in the upper cliffs of the formation. The type section is measured within the valley of Binnedalen in the right half of the picture. Photo: Terje Hellem.

laterally extensive succession (Figs. 5, 6, 7) that is visible in the Photomodeler™ 3D geological model. These lower beds, rich in mud and bioturbation, feature thin sandstones with both current and wave ripple structures, suggesting a relatively low energy environment of deposition. They most probably represent an inter delta lobe bay with fine grained sediments being deposited within the sub-tidal zone, with lamina and thin beds of sand representing reworked storm disrupted deposits.

Hummocky cross stratification is prolific throughout the sandstones within this interval, often being confined to more heterolithic sediment packages or thin sand beds in the uppermost part of the member. Wave and current ripples are also in abundance both in monolithic and heterolithic beds. In the case of Nørdstefjellet, a minor component of hummocky bedding is observed, in a more sandstone dominated package. Bioturbation is common and minor occurrences of bivalves are present. This suggests a slightly nearshore depositonal environment

Figure 6. Photograph showing the nature of the Hopen Member at the type section within Binnedalen, Lyngefjellet. Note the darker colouration of this interval, with bioturbated shales hosting subordinate, rippled, sandstone laminae.

Figure 7. Photograph depicting the nature of the shale within the Hopen Member. This is the dominant lithology throughout the unit and is seen to be highly bioturbated with the presence of minor sandstone laminations featuring wave and current ripples. Larger sandstone beds are also apparent and feature hummocky cross stratification.

for the upper part of the member, below or just within the range of normal wave base, but still within the depth for storm wave energy to both re-work and introduce sediments into the environment.

The northern most exposures of the Hopen Member at Binnedalen and Nørdstefjellet (Figs. 3, 4) are seen to feature larger proportions of sandstone in comparison to the sections logged in the southern part of the island at Russevika and Iversenfjellet (Mørk et al., 2013; Lord et al., 2014). This may suggest a very subtle, lateral facies change along the islands axis, where the Hopen Member represents more deeper facies in the southwest, gently shallowing to the northeast.

Based on the sedimentological logs (Figs. 3, 4), the facies within the Hopen Member are interpreted as being indicative of an extensive, yet fluctuating, storm influenced shallow marine environment. This is most probably an inter delta lobe bay or a very large scale inter distributary bay, formed as a result of delta lobe switch due to the avulsuion of primary channels on the delta flood plain. In this setting, calm periods have allowed for the deposition of dark marine mud and shales, below tidal range and normal wave base. The presence of disturbed sands, interspersed within the succession, suggests the influence of wave action below wave base, aggravating the sediments during storms or periods of higher energy. These become more abundant in the upper part of the member, suggesting a relative shallowing of the depositional environment, from deeper and calmer deposition offshore, to more wave and storm disturbed sedimentation in the upper part of the member.

Distribution and geometry

The clear, dark colouration of the Hopen Member allows for its visual profile to be traced throughout the entire island and by following the base of the boundary with the Photomodeler™ 3D geological model its distribution is seen to be widespread. The member also appears at a stratigraphically consistent level, with a similarly consistent thickness between 68-72 m. The basal surface is considered to be flat without evidence for underlying topography,

The member is present on nearly all of the major topographical highs of the island (Fig. 8). Due to the nature of faulting on the island the base of the Hopen Member has been used in order to reconstruct the islands stratigraphy, where erosion has removed significant proportions of the overlying formations, proving itself as a useable marker horizon. The most prominent locations for the change can be seen on the mountains of Iversenfjellet in the southwest and on the southern flank of Lyngefjellet in the northeast of Hopen.

The unit has been included in the Norwegian Polar Institute's geological map of Hopen (Mørk at al., 2013), due to its visual profile and pronounced continuous exposure on the island (Fig. 8).

Ammonoid biostratigraphy

Ammonoids from the Flatsalen Formation are determined to be sirenitid ammonoids, largely of the genus *Neosirenites* (now *Norosirenites*; Bragin et al., 2012), which were previously also named as *Argosirenites*).

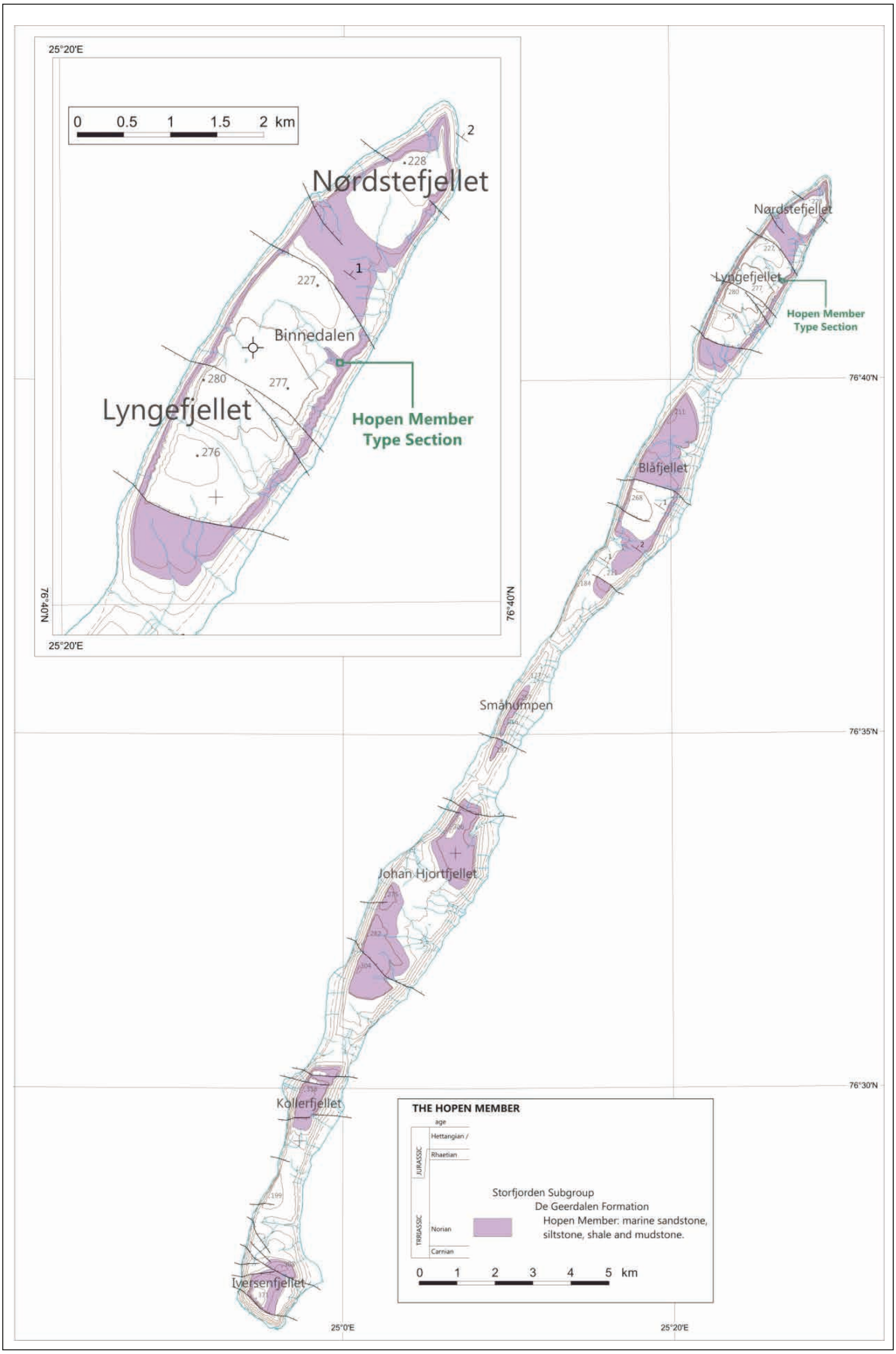

Figure 8. Geological map of Hopen displaying the overall distribution of the Hopen Member throughout the island. The type section location is marked in Binnedalen on eastern Lyngefjellet. Map modified after Mørk et al. (2013).

Sirenitid genera largely occur in Siberia and NE Asia, but do have representatives in Canada. They range in age, through the Boreal lower Norian with the last sirenitid ammonoids being either in the oldest parts of the NE Asian mid-Norian (within boreal ammonoid zone *Otapiria ussuriensis*; Zacharov 1997) or Siberian latest early-Norian (Konstantinov, 2008).

Korčinskaja (1980) describes *N. nelgehensis*, *N. obruchevi* and "Sirenites" *nabeshi* from the Flatsalen Formation on Hopen, which in NE Asia occurs in the *Pinacoceras verchojanicum* Zone. Bragin et al. (2012) and Konstantinov and Klets (2009) correlate this zone with the mid parts of the early Norian. The occurrence of the conodont *Norigondolella navicula* in the same beds bearing the *P. verchojanicum* Zone ammonoid fauna in NE Asia (Bragin et al., 2012), suggests much the same correlation, with *N. navicula* corresponding to the interval approximately from near the base of Lacian-I (Tethyan Jandianus Zone), to mid parts of Lacian-2 (Tethyan *Paulckei* Zone), of Krystyn et al. (2009) Norian sub-stage divisions (Orshard, 2010). This suggests the Hopen Member is at the very least, earliest Norian or older.

Palynological Age and Characteristics

Palynological investigation of the sedimentary succession on Hopen was initiated in the early 1970s. The first study was conducted by Smith (1974) who proposed that Rhaetian and possibly Norian to Hettangian aged strata are represented on Hopen, an age which was maintained by Smith et al. (1975). However based upon further palynological investigation, Bjærke and Manum (1977) supported the Rhaetian age assignment proposed by Smith et al. (1975); however, no palynological evidence supporting either a Norian or Hettangian age was found during their study. Recently, Hopen has been the subject of renewed palynological studies (Ask, 2013; Vigran et al., 2014), and below we present preliminary data from these ongoing studies.

In general, assemblages recovered from the lower part of the De Geerdalen Formation are dominated by spore taxa, while those from the Hopen Member are more pollen-rich. Marine palynomorphs are consistently present but become more abundant in samples from the Hopen Member. Many samples contain acritarchs assigned to *Michrystridium* and *Veryhachium* spp. Dinoflagellate cysts belonging to *Rhaetogonyaulax arctica* and *R. rhaetica* are also present in samples from the De Geerdalen Formation, but are exceptionally rare. Freshwater algae *Botryococcus* spp. and *Plaesiodictyon moesellaneum* are also present, with the latter becoming particularly abundant in samples from the Hopen Member.

Based upon semi-quantitative palynology, two distinct palynological zones are recognised in samples from the De Geerdalen Formation on Hopen (Fig. 9); these are the lower *Leschikisporis aduncus* Acme Zone and the upper *Protodiploxypinus* spp. Acme Zone. The transition between the two zones closely approximates the base of the Hopen Member.

Assemblages of the *Leschikisporis aduncus* Acme Zone have been recovered in samples from the lower portion of the De Geerdalen Formation on Hopen from the three sections investigated. The assemblages from this zone are characterised by the dominance *L. aduncus*. Other spore taxa present in this interval include: *Aratrisporites* spp., *Aulisporites astigmosus*, *Calamospora tener*, *Camerozonosporites rudis*, *Conbaculatisporites* spp., *Deltoidospora* spp., *Dictyophyllidites mortonii*, *Duplexisporites problematicus*, *Porcellispora longdonensis* and *Zebrasporites interscriptus*. Pollen comprises a relatively minor component of assemblages in this zone. Species recorded include: *Araucariacites australis*, *Chasmatosporites* spp., *Cycadopites* spp., *Eucommiidites* spp., *Illinites chitinoides*, *Ovalipollis ovalis*, *Triadispora verrucata* and *Vesicaspora fuscus*.

The *Protodiploxypinus* spp. Acme Zone is recognised in samples from the Hopen Member from Binnedalen, Blåfjell and Lyngefjellet. The diversity of assemblages from this zone is markedly higher than from those below. Assemblages from this zone are characterised by the dominance of pollen, particularly of *Protodiploxypinus* spp. Other pollen taxa present include: *Araucariacites australis*, *Chasmatosporites* spp., *Cycadopites* spp., *Eucommiidites* spp., *Illinites chitinoides*, *Ovalipollis ovalis*, *Triadispora verrucata* and *Vesicaspora fuscus*. *Leschikisporis aduncus* still occurs in assemblages from this zone but in significantly reduced numbers. The spore assemblage includes: *Annulispora folliculosa*, *Aratrisporites* spp., *Cingulizonates rhaeticus*, *Deltoidospora* spp., *Kyrtomisporis gracilis*, *K. laevigatus*, *K. speciosus*, *Ricciisporites tuberculatus*, *R. umbonatus*, *Rogalskaisporites cicatricosus*, *Semiretisporis gothae*, *Striatella seebergensis*, *Uvaesporites* spp., *Velosporites cavatus* and *Zebrasporites interscriptus*. Assemblages from the *Protodiploxypinus* spp. Acme Zone are also rich in freshwater algae, particularly *Plaesiodictyon moesellaneum*. Marine palynomorphs including the acritarchs *Michrystridium* and *Veryhachium* spp. and foraminifera test-linings are a consistent feature of this zone.

Bjærke and Manum (1977) reported the dominance of *Leschikisporis aduncus* in a coal sample from the lower De Geerdalen Formation near Iversenfjellet on the south of Hopen. Common to abundant *L. aduncus* is also a characteristic feature of the early to mid Carnian *Aulisporites astigmosus* Composite Assemblage Zone of Vigran et al. (2014). Those authors also report common bisaccate pollen with an abundance peak of *Protodiploxypinus* spp. in the upper part of the zone. These observations are consistent with the *Leschikisporis aduncus* Acme Zone and the *Protodiploxypinus* spp. Acme Zone as recognised here.

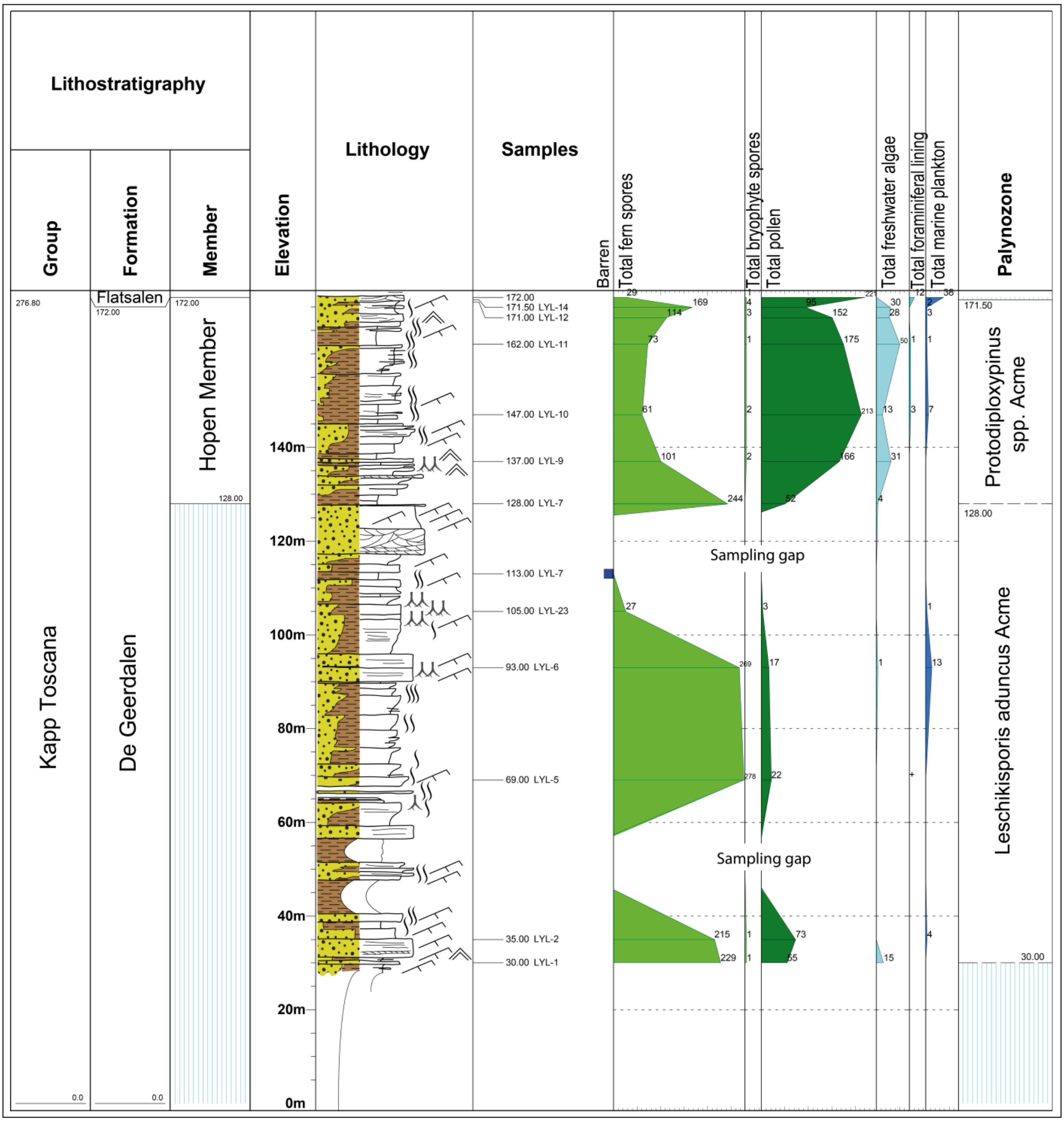

Figure 9. Relative abundances of main palynomorph groups from the De Geerdalen Formation, Lyngefjellet, Hopen. Samples and log from "Letesamarbeidet 1995".

The occurrence of *Triadispora verrucata* in assemblages assigned to the *Protodiploxypinus* spp. Acme Zone in the current study is indicative of a late Carnian age for the assemblage (Hochuli et al., 1989). Additionally, the common occurrence of the freshwater alga *Plaesiodictyon moesellaneum* within this zone is indicative of an age no younger than Norian (Hochuli et al., 1989). Combining ammonoid and palynology data we suggest that the Hopen Member is of late Carnian age, possibly continuing into the earliest Norian.

The Hopen Member coincides with a major transition in the composition of palynomorph assemblages on Hopen. Assemblages from lower De Geerdalen Formation are dominated fern spore taxa such as *Leschikisporis aduncus*. However, assemblages from the Hopen Member are dominated by conifer pollen (Fig. 9). This trend has been noted elsewhere in the region (Hochuli and Vigran, 2010; Hochuli et al., 1989). *L. aduncus* was produced by plants growing under humid conditions (Hochuli and Vigran, 2010) in a near-shore, deltaic environment (Pott, 2014; Launis et al., 2014). In general, high abundances of fern spores in palynomorph assemblages signify a close proximity to the fluvio-deltaic source, rapid deposition close to their provenance and humid climatic conditions to allow significant pteridophyte growth (Tyson, 1995).

The transition to the conifer pollen dominated assemblages of the Hopen Member may reflect a change to coastal vegetation dominated by conifers, possibly due to cooler or more arid conditions in the region during the latest Carnian. Alternatively, the increased relatively abundance of gymnosperm pollen in palynomorph assemblages may also signify more distal deposition from the fluvio-deltaic source (Tyson, 1995), the so-called "Neves effect "of Chaloner and Muir (1968). The latter interpretation would be consistent with deposition of the Hopen Member in a more distal marine environment.

Coinciding with the increased abundance of conifer pollen, the alga *Plaesiodictyon moesellaneum* also increases in relative abundance in the Hopen Member. Modern coenobial algae are common constituents in freshwater environments but are typically transported by rivers into marine settings (Brenner and Foster, 1994). *P. mosellanum* has been reported fluvial-lacustrine, marginal marine and offshore marine facies from ?Anisian-Norian-?Rhaetian age strata (Wood and Benson, 2000). The increased abundance of *P. mosellanum* in the Hopen Member probably indicates redeposition from areas of freshwater input (Tyson, 1995). Marine palynomorphs such as acritarchs are slightly more common in the Hopen Member but are still relatively rare due to the dominance of terrestrial organic matter in the assemblages. The low abundance and diversity of acritarchs in the Hopen Member is consistent with reduced salinities and freshwater input from a fluvio-deltaic source.

Magnetostratigraphy

The magnetostratigraphy on Hopen was constructed by sampling from the Binnedalen and Nørdstefjellet sections in northern Hopen. The sample-level data from these two sections were merged using a photo and log-based intersection correlation of the cliff sections. Data from the Nørdstefjellet section extends to slightly older intervals than that in the Binnedalen section. These data define parts of 8 major R-N magnetozone couplets, with 22 separate R plus N magnetozones plus sub-magnetozones (Fig. 10).

The reverse-polarity dominated interval HO3r to HO5r (Fig. 10) is one of the keys to understanding how the polarity may match the geomagnetic polarity timescale (GPTS). There are two intervals in the Late Triassic which have a reverse-dominated polarity pattern with three briefer normal polarity magnetozones within it. These are within the early Norian and across the Norian-Rhaetian boundary (Hounslow and Muttoni, 2010). This later possibility is implausible, since it would push the Flatsalen Formation *Norosirenites* fauna into the late Rhaetian. A third possibility using the ammonoid-age of the Flatsalen Formation in the middle parts of the early Norian pushes all of the De Geerdalen Formation on Hopen into the Carnian. This option, preferred here, fully satisfies the age constraints from the *Norosirenites* fauna in the Flatsalen Formation as well as the palynology, which should correspond to the upper part of Lacian-1 and lower part of the Lacian-2 sub-stage divisions (Fig. 10). The magnetostratigraphic match to the GPTS is broadly satisfactory for the interval HO3n to HO8n, but less so below HO3n- some sub-magnetozones have a match in the GPTS and some not. The GPTS of Hounslow and Muttoni (2010) through the mid Carnian is derived only from the non-marine Stockton Formation of the Newark Super-group, so the validity of the GPTS remains uncertain in this interval. We have chosen to remove the Stockton Formation data from our GPTS composite. Our preferred age option places the De Geerdalen Formation all within the Carnian, and the Slottet Bed on Hopen corresponds closely to the Carnian-Norian boundary.

The magnetostratigraphic data from the Isfjorden Member in central Spitsbergen (Hounslow et al., 2007) can now be considered in the light of this new data, since this unit is widely thought to correlate to the units on Hopen. The best magnetostratigraphic match is with the interval over the base of the Hopen Member and into its lower parts (Fig. 10). The relative stratigraphic thicknesses in metres of these two intervals are also quite similar.

Relationship to Isfjorden Member

The Hopen Member is prevalent on the island at which it is defined, Hopen in the southeast of the Svalbard archipelago. However, its notable similarity in stratigraphical position and thickness lends itself well to correlation with Triassic units elsewhere in the archipelago, most notably central and eastern Spitsbergen. In these regions the uppermost part of the De Geerdalen Formation is dominated by sediments of a marginal marine to lagoonal nature defined as the Isfjorden Member. These feature stacked heterolithic deposits of sandstone and shale as well as subordinate thin carbonates, nodular beds of siderite and phosphatic nodules (Mørk et al., 1999, Vigran et al., 2014). The most prominent features within the Isfjorden Member relate to its coloured, green and red beds, which are frequent in the upper strata of the member, below the Slottet Bed.

The Slottet Bed represents either a metre-scale hard carbonate bed in eastern Spitsbergen or a decimetre-scale bed of nodular phosphatic pebbles in central and western Spitsbergen (see logs in Vigran et al., 2014).

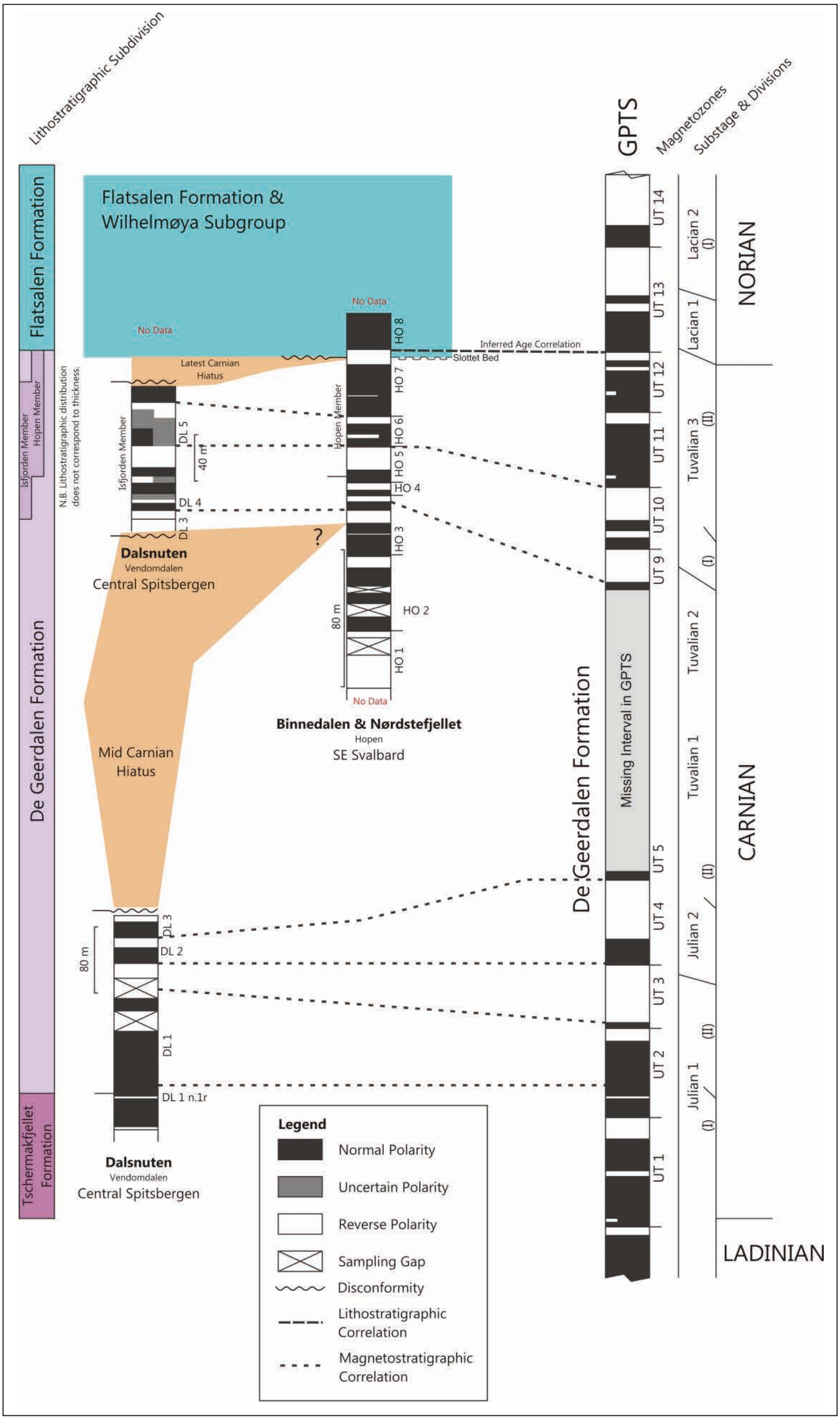

Figure 10. Summary of lithostratigraphy, age and magnetostratigraphy of the late Triassic of Svalbard based on data from Nørdstefjellet at Hopen (HO) and Dalsnuten (DL) in central Spitsbergen.

Palynology and magnetostratigraphy indicate that both member units represents the same period in time however it is unclear if the base of Isfjorden Member is synchronous to that of the Hopen Member as it is not directly observed or defined. The Isfjorden Member represents the onset of a lagoonal environment overlying a distal deltaic setting. The Hopen Member represents a dominantly shallow marine setting with inherently different lithological properties and facies, overlying a more proximal and paralic deltaic setting. This abrupt alteration seen in the De Geerdalen Formation shows a clear break and change in sediment style to marine facies, prior to the onset of a marine transgression, displayed by the Flatsalen Formation at Hopen and the Knorringfjellet Formation, in Spitsbergen.

Neither of these member units are reported to be present in the eastern areas of Svalbard, on either Barentsøya or Edgeøya, primarily due to the fact that considerable erosion has occurred into the De Geerdalen and the overall stratigraphic thickness is unascertained. On the island of Wilhelmøya, the upper part of the De Geerdalen Formation features bivalve coquina beds and consists of dark shale, resembling the Hopen Member.

The Hopen Member may be equivalent to the upper "Carnian clinoform unit" reported from seismic studies by Riis et al. (2008), Glørstad-Clark (2010, 2011), Høy and Lundschien (2011) and Lundschien et al. (2014).

Norian in age and magnetostratigraphic correlation with sections in central Spitsbergen, show that the base of the member correlates well to an interval of reverse polarity at the same period in time. Palynological studies show a clear increase in the presence of marine palynomorphs within the Hopen Member. This also co-incides with an increase in the abundance of terrestrial palynomorphs and algaes, interpreted as being flushed into the marine environment, palynological dating also defines the Hopen Member as being Carnian in age and possibly earliest Norian but no younger.

The Hopen Member has not been extended to eastern islands of the archipelago, e.g. Edgeøya and Barentsøya, but may occur on the island of Wilhelmøya, indicating that the member is an extensive marine equivalent to the more lagoonal sediments of the Isfjorden Member defined on Spitsbergen. The marine transgression resulting in the Hopen and Isfjorden members may be equivalent to the uppermost transgression of the Snadd Formation, that initiate the uppermost clinoform unit seen within Snadd Formation on the Barents Shelf. We further argue for a separate definition of this unit, aside from the Isfjorden Member (instead of simple stratigraphic correlation), as the presence of green and red beds, nodular sideritic beds and carbonate beds used in the definition of the Isfjorden Member in central Spitsbergen are not observed on Hopen, where the lithologies are predominantly dark grey clastic shales.

Conclusions

The Hopen Member represents a widespread and abrupt variation in the depositional environment of the upper part of the De Geerdalen Formation on Hopen. Lithological changes and sedimentary structures suggest that the member has been deposited in a marine environment of variable energy and biota. Slow and relatively low energy depositional processes define the lowermost of the member, whilst offshore muds and storm deposits dominate the uppermost bed packages. The stratigraphical thickness of the member is relatively uniform throughout the entire island, at approximately 68-72 m.

The prominent change from the lower, paralic facies of the De Geerdalen Formation to those deposited in a more extensive marine and lagoonal setting (as shown by the occurrences of the Hopen and Isfjorden Members), suggests that both of these member units represent a response to a regime change at their time of deposition. This can arguably represent a surface that may be traceable into the Barents Sea. This is also reflected in the nature of palynomorphs seen at the onset of this interval, where the presence of marine algae becomes apparent.

Ammonoid stratigraphy shows that the overlying Flatsalen Formation of the Hopen Member is at its earliest

Acknowledgements.
We thank all participants on the various Hopen expeditions. Part of the palynological data and several measured sections are from *"Letesamarbeidet 1995"*, a joint project, undertaken in association with; The Norwegian Petroleum Directorate (NPD), Statoil, Norsk Hydro and Saga Petroleum, who carried out fieldwork in 1995.

References

Ask, M. 2013: *Palynological dating of the upper part of the De Geerdalen Formation on central parts of Spitsbergen and Hopen*. Master Thesis, University of Bergen, 78 pp.

Bjærke, T. & Manum, S.B. 1977: Mesozoic palynology of Svalbard - I. The Rhaetian of Hopen, with a preliminary report on the Rhaetian and Jurassic of Kong Karls Land. *Norsk Polarinstitutt Skrifter, 165*, 1-48.

Bragin, N.Y., Konstantinov, A.G., & Sobolev E.S. 2012: Upper Triassic Stratigraphy and Paleobiogeography of Kotel'nyi Island (New Siberian Islands). *Stratigraphy and Geological Correlation, 20*, 6, 54-80.

Brenner, W. & Foster, C.B. 1994: Chlorophycean algae from the Triassic of Australia. *Review of Palaeobotany and Palynology, 80*, 209-234.

Chaloner, W.G. & Muir, M. 1968: Spores and floras. *In* Murchison, D.G. & Westoll, T.S. (eds.): *Coal and coal-bearing strata*. Edinburgh, Oliver and Boyd, 127-146.

Dallmann, W.K. (ed.) in press: *Geoscience atlas of Svalbard*. Norsk Polarinstitutt, Tromsø.

Doré, A.G. 1995: Barents Sea Geology, Petroleum Resources and Economic Potential. *Arctic, 48*, 3, 207-221.

Formal Definition Hopen Member	
STATUS OF UNIT:	Formal
FIRST USE OF NAME:	Geological map of Hopen, Mørk et al., 2013.
CURRENT DEFINITION:	Here
SYNONYM:	None
ORIGIN OF NAME:	The island Hopen where the member is defined.
TYPE SECTION:	Stratotype Binnedalen – UTM 35X E460400, N8512690 – 76° 41′ 23″N, 25° 27′ 32″E.
DEPOSITIONAL AGE:	latest Carnian possibly lowermost Norian.
REFERENCES FOR AGE:	Here; Vigran et al., 2014, overlying and underlying beds dated by Korčinskaja, 1980.
OVERLYING UNIT:	Flatsalen Formation
UNDERLYING UNIT:	Un-named; remainder part of De Geerdalen Formation
SUPERIOR UNIT:	De Geerdalen Formation
OTHER USE OF NAME:	None
THICKNESS:	68-72 m, Type section is 68 m
MAIN LITHOLOGIES:	Dark shale and fine-grained sandstones
LOWER BOUNDARY DEFINITION:	Where grey shale and fine-grained sandstones are overlain by dark grey shales with fine-grained sandstones
DESCRIPTION:	Dark grey shale with subordinate fine grained sandstones. The unit represent marine sediments deposited in a fluctuating energy environment.
The Hopen Member has been approved by the Norwegian Committee on Stratigraphy, April 2014.	

Glørstad-Clark, E., Faleide J.I., Lundschien, B.A. & Nystuen, J.P. 2010: Triassic sequence stratigraphy and paleogeography 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 area. *Marine and Petroleum Geology, 28*, 1294-1314.

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* Fleet, A.J. & Boldy, S.A.R. (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*, 247-259.

Hochuli, P.A. & Vigran, J.O. 2010: Climate variations in the Boreal Triassic – Inferred from palynological records from the Barents Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology, 290*, 20-42.

Hochuli, P.A., Colin, J.P. & Vigran, J.O. 1989: Triassic biostratigraphy of the Barents Sea area. *In* Collinson, J.D. (ed.): *Correlation in Hydrocarbon Exploration*. Norwegian Petroleum Society (Graham & Trotman, 1989), 131-153.

Hounslow, M.W., Hu, M., Mørk, A., Vigran, J.O., Weitschat, W. & Orchard, M.J. 2007: Magneto-biostratigraphy of the lower part of the Kapp Toscana Group (Carnian), Vendomdalen, central Spitsbergen, arctic Norway. *Journal of the Geological Society, London, 164*, 581-597.

Hounslow, M.W. & Muttoni, G. 2010: The Geomagnetic Polarity Timescale for the Triassic: linkage to stage boundary definitions. *In* Lucas, S. (ed.): *The Triassic Time scale. Geological Society, London, Special Publications, 334*, 61-102.

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

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

Knarud, R. 1980: *En sedimentologisk og diagenetisk undersøkelse av Kapp Toscana Formasjonens sedimenter på Svalbard.* Cand. Real. Thesis, University of Oslo, 208 pp.

Konstantinov, A.G. 2008: Triassic Ammonoids of Northeast Asia: Diversity and evolutionary stages. *Stratigraphy and Geological Correlation, 16*, 490-502.

Konstantinov A.G. & Klets T.V. 2009: Stage Boundaries of the Triassic in Northeast Asia. *Stratigraphy and Geological Correlation, 17*, 173–191.

Korčinskaja, M.V. 1980: Rannenorijskaja fauna arhipelaga Sval'bard (Early Norian fauna of the Archipelago of Svalbard). *In* D.V. Semevskij (ed.): *Geologija osadočnogo čehla arhipelaga Sval'bard (Geology of the sedimentary platform of the Archipelago of Svalbard)*, NIIGA, Leningrad, 30-43. (In Russian).

Krystyn, L., Mandl, G.L. & Schauer, M. 2009: Growth and termination of the Upper Triassic platform margin of the Dachstein area (Northern Calcareous Alps, Austria). *Austrian Journal of Earth Sciences, 102*, 23-33.

Launis, A., Pott, C. & Mørk, A. 2014: A glimse into the Carnian: Late Triassic plant fossils from Hopen, Svalbard. *Norwegian Petroleum Directorate Bulletin, 11,* 81-96.

Lord, G.S., Solvi, K.H., Klausen, T.G. & Mørk, A. 2014: Channels on Hopen, Svalbard: Their spatial distribution and paralic setting within the Triassic De Geerdalen Formation. *Norwegian Petroleum Directorate Bulletin, 11,* 41-59.

Mørk, A., Dallmann, W.K., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pčelina, T.M. & Worsley, D. 1999: Mesozoic Lithostratigraphy. *In* Dallmann, W.K., (ed.): *Lithostratigraphic Lexicon of Svalbard, Upper Palaeozoic to Quaternary Bedrock – Review and recommendations for nomenclature use.* Norwegian Polar Institute, Tromsø, 127-214.

Mørk, A., Lord, G.S., Solvi, K.H. & Dallmann, W.K. 2013: Geological Map of Svalbard 1:100 000, sheet G14G Hopen. *Norsk Polarinstitutt Temakart No. 50*.

Orchard, M.J. 2010: Triassic conodonts and their role in stage boundary definition. *In* Lucas, S.G. (ed.): *The Triassic timescale. Geological Society, London, Special Publications, 334*, 139-162.

Pčelina, T.M. 1972: K voprosu o vozraste osadočnoj tolšči ostrova Nadeždy (Sval'bard). (On the age of the sedimentary succession of the island of Hopen (Svalbard)). *In* V.N. Sokolov & N.D. Vasilevskaja (eds.): *Mezozoiskie otloženija Sval'barda (Mesozoic deposits of Svalbard)*, NIIGA, Leningrad, 75-81. (In Russian).

Pčelina, T.M. 1983: Novye dannye po stratigrafii mezozoja arhipelaga Špicbergen (New data on the Mesozoic stratigraphy of the Spitsbergen Archipelago). *In* Krasil'ščikov, A.A. & Basov, V.A. (eds.): *Geologija Špicbergena (The Geology of Spitsbergen). PGO Sevmorgeologija"*, Leningrad, 121-141. (In Russian).
Pott, C. 2014: The Upper Triassic flora of Svalbard. *Acta Palaeontologica Polonica, 59*, 709-740. doi: 10.4202/app.2012.0090.
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.
Smith, D.G. 1974: Late Triassic pollen and spores from the Kapp Toscana Formation, Hopen, Svalbard - A preliminary account. *Review of Palaeobotany and Palynology, 17*, 175-178.
Smith, D.G., Harland, W.B. & Hughes, N.F., 1975: Geology of Hopen, Svalbard. *Geological Magazine, 112*, 1-23.
Smith, D.G., Harland, W.B. & Hughes, N.F. & Pickton, C.A.G. 1976: The Geology of Kong Karls Land, Svalbard. *Geological Magazine, 113*, 193-304.
Solvi, K.H. 2013: *Visualize and interpret the geometry, heterogeneity and lateral continuation of channel bodies in the De Geerdalen Formation at Hopen*. Master Thesis, Norwegian University of Science and Technology, 122 pp.
Tyson, R.V. 1995: *Sedimentary organic matter: Organic facies and palynofacies*. Chapman and Hall, London, 615 pp.
Vigran, J.O., Mangerud, G., Mørk, A., Worsley, D. & Hochuli, P.A. 2014: Palynology and geology of the Triassic succession of Svalbard and the Barents Sea. *Geological Survey of Norway Special Publication, 14*, 270 pp.
Wood, G.D. & Benson, D.G. Jr. 2000: The North American occurrence of the algal coenobium Plaesiodictyon: Paleogeographic, paleoecologic, and biostratigraphic importance in the Triassic. *Palynology, 24*, 9-20.
Worsley D. Johansen, R. & Kristensen, S.E. 1988: The Mesozoic and Cenozoic succession of Tromsøflaket. *In* Dalland et al. (eds.): *A lithostratigraphy scheme for the Mesozoic and Cenozoic succession offshore mid and northern Norway. Norwegian Petroleum Directorate Bulletin, 4*, 42-65.
Zakharov, Y.D. 1997: Carnian and Norian sirenitid ammonoids of the NW circum-pacific and their role in the late Triassic faunal successions. *Memoires de Geologie (Lausanne), 30*, 137-144.

Paper 2

Triassic Channel Bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution.

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Triassic channel bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution

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Channelized deposits are observed in the steep cliff sections on the island of Hopen in SE Svalbard. This presents a unique opportunity to study the geometry and spatial distribution of these channel bodies within the paralic depositional environment of the Carnian aged De Geerdalen Formation.

In this study we have combined field observations with a 3D geological model of the island. Utilising PhotoModeler™ software, with an extensive photo database of the study area, it has been possible to identify the presence of 25 channel bodies on the island. 12 have been observed directly in the field, with the remainder being identified with photo mosaics and by implementing the 3D geological model. Analysis has shown that the channels were deposited in three different depositional environments; fluvial, tidal and estuarine. Channel deposits that have not been observed in the field are interpreted based on their geometries and visible internal architectures seen within high resolution outcrop photographs.

Channel bodies are seen to be confined to discrete stratigraphical intervals within the De Geerdalen Formation, defined as channel zones. Three zones are described, based upon the concentration of channels within each interval. These intervals are categorised as a lower fluvial zone, a middle tidal zone and an upper fluvial zone.

These zones are subsequently overlain by a marine flooding event represented by the Hopen Member. An overall paralic depositional environment for the De Geerdalen Formation on Hopen is maintained, however the nature of channels clearly shows a greater influence of fluvial deposition for the formation in this region of Svalbard. This indicates deposition in a more proximal position relative to the source area, than elsewhere on Svalbard.

Key words: Channels, Stratigraphy, Hopen, Svalbard, Triassic.

Introduction

The presence of cliff forming sandstone bodies, initially deposited in a continental fluvial environment, have long been known to form the island of Hopen, in the SE part of the Svalbard archipelago (Flood et al., 1971; Smith et al., 1975; Mørk et al., 2013). Economic interests in the northern Barents Sea have also increased scientific activity in the Upper-Triassic succession of Svalbard. Recent expeditions to Hopen have thus placed a greater interest in the understanding of these sandstone bodies, due to their potential as hydrocarbon reservoirs (Johansen et al., 1993; Riis et al., 2008; Lundschien et al., 2014). The sandstone bodies are laterally extensive, often seen in cross section and in some instances can be observed on both sides of the island. These represent ancient fluvial and estuarine channel systems which can be considered analogous to the upper part of the Snadd Formation in the Barents Sea (Klausen and Mørk, 2014).

Multiple short geological expeditions to Hopen have been conducted by SINTEF Petroleum Research, NPD and participant companies of production licences in the Barents Sea (PL438, PL533, PL609 and PL611),

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herein referred to as the *Hopen Geology Project*. These expeditions have visited the island annually since 2007 and this timespan has allowed for the acquisition of new geological data from the island, albeit by numerous workers. This includes an improvement on sedimentological knowledge from extensive logging, photographic modelling of the island, the creation of a new stratigraphical interval and an updated geological map (Mørk et al., 2013; Lord et al., 2014).

The objective of this paper is to add further documentation of these channel features seen on the island of Hopen. By positioning them accurately within the stratigraphy of the De Geerdalen Formation, it is possible to understand their spatial distribution in relation to the paralic environment which characterises the De Geerdalen Formation on Hopen. This is achieved through the combination of geological modelling and outcrop studies. This is intended to provide a firm basis of geological understanding and support future studies with onshore-offshore correlation of the Late-Triassic sediments, into the northern Barents Sea.

Geological Setting and Stratigraphy of Hopen

The island of Hopen lies in the SE corner of the Svalbard archipelago (Fig. 1) at approximately N76°35’ E25°20’ in the Norwegian high arctic. It is a small island of only 34 km in length and 0.5-2.5 km in width consisting entirely of Triassic aged strata, which protrude to a maximum height of 371 m above sea level. Its origin probably relates to the nature of deep rooted faulting in NE region of the Barents Sea (Doré, 1995; Grogan et al., 1999). The crustal structure around Hopen is dominated by a series of NE-SW trending lineaments, oblique to the regional N-S trend of structures in Spitsbergen (Doré, 1995; Grogan et al., 1999).

The island features regionally and gently northwards dipping strata, dissected by a series of NW-SE trending normal faults dipping to both the SW and NE. The stratum of the island also display gentle synclinal and monoclinal structures, with limbs dipping to both the NE and SW (Smith et al., 1975; Mørk et al., 2013; Klausen and Mørk, 2014).

Exposures of the island represent three formations (Fig. 2) of the Late-Triassic in Svalbard (Mørk et al., 1999). These include; the uppermost of the De Geerdalen Formation, with its heterolithic nature of alternating sandstone and siltstone deposited in a paralic deltaic setting (Klausen and Mørk, 2014). The entirety of the overlying Flatsalen Formation, with the Slottet Bed at its base can be observed at Lyngefjellet in the NE of the island. Lyngefjellet is capped by a c. 35 m thick cliff forming succession of the Svenskøya Formation of Norian and possibly Rhaetian age (Mørk et al., 2013; Vigran et al., 2014) and is the only locality at Hopen where this formation is present (Mørk et al., 1999; 2013).

The De Geerdalen Formation on Hopen is dated as Late-Triassic, Carnian to Norian in age, based on the presence of ammonites, palynology and magneto-stratigraphy (Pčelina, 1972; Korčinskaja, 1980; Tozer and Parker, 1968; Launis et al., 2014; Lord et al., 2014; Vigran et al., 2014). The uppermost part of the De Geerdalen Formation on Hopen is interpreted as showing an increasing marine influence, exhibiting lower net-to-gross succession, dominated by hummocky cross-stratification. This upper part of the De Geerdalen Formation has been defined as the Hopen Member (Mørk et al., 2013; Lord et al., 2014), a time equivalent unit to the Isfjorden Member of central Spitsbergen.

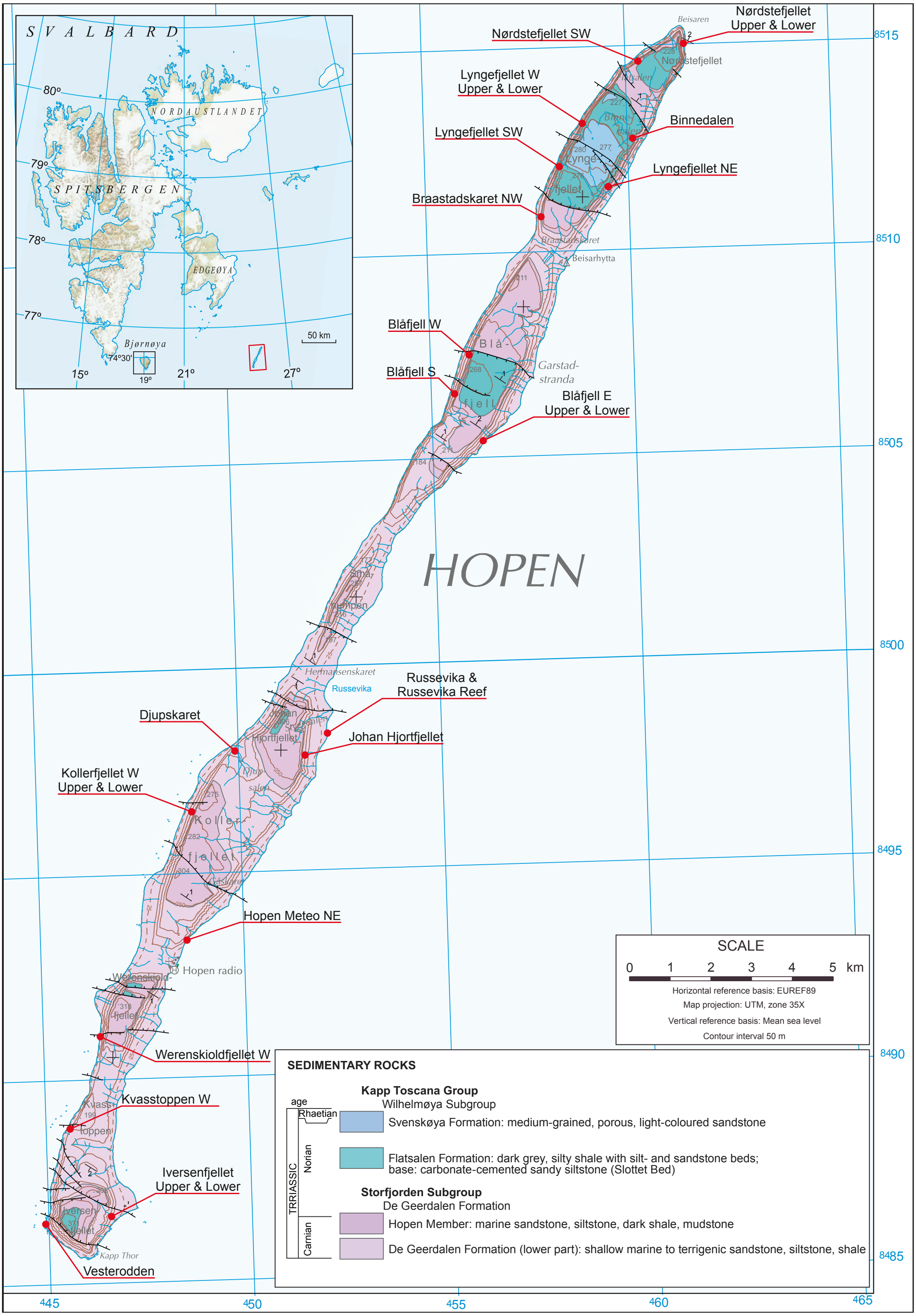
Recent advances in the understanding of the development of the De Geerdalen Formation throughout the Triassic (see Worsley, 2008; Klausen and Mørk, 2014; Glørstad-Clark et al., 2010; Lundschien et al., 2014, Lord et al., 2014; Rød et al., 2014) show that the Triassic strata of Hopen represent some of the youngest and most regressive onshore exposures, of a large-scale deltaic system, that gradually filled the Barents shelf during the Triassic (Worsley, 2008; Glørstad-Clark et al., 2010; Lundschien et al., 2014). The palaeogeographic map in Figure 2 illustrates a reconstruction of this deltaic environment during the Late-Triassic.

This enclosed shelf, in the northern coastline of the Pangean supercontinent stretched out to the boreal Panthalassa Sea and was gradually filled with sediments, derived from the Uralian mountain chain (Puchkov, 2009; Pózer Bue and Andresen, 2013; Lundschien et al., 2014). The Ural Mountains were uplifted as a series of tectonic and orogenic events throughout the Late Devonian, Late Carboniferous and Permian (Puchkov, 2009), as the Siberian Plate collided with the smaller landmasses of Kazakhstania and Pangea itself.

The outcrops that represent the most distal parts of this deltaic system are observed on central Spitsbergen within the De Geerdalen Formation, whereas the corresponding paralic and proximal part of this delta within the Triassic succession can be found on the islands of Barentsøya, Edgeøya and Hopen. The axis of Hopen lies relatively perpendicular to the interpreted NW direction of deltaic progradation (Klausen and Mørk, 2014; Lundschien et al., 2014).

The youngest Triassic exposures found in Svalbard are present on Spitsbergen and Hopen and are not exposed on

***Figure 1**. Location map and geological map of Hopen after Mørk et al. (2013). Channel locations are denoted.*



SVALBARD
NORDAUSTLANDET
SPITSBERGEN
EDGEØYA
Bjørnøya
80°
79°
78°
77°
74°30'
15°
19°
21°
27°
50 km
HOPEN
Nørdstefjellet SW
Nørdstefjellet Upper & Lower
Lyngefjellet W Upper & Lower
Binnedalen
Lyngefjellet SW
Lyngefjellet NE
Braastadskaret NW
Beisarhytta
Blåfjell W
Blåfjell S
Garstad-stranda
Blåfjell E Upper & Lower
Russevika & Russevika Reef
Djupskaret
Johan Hjortfjellet
Kollerfjellet W Upper & Lower
Hopen Meteo NE
Hopen radio
Werenskioldfjellet W
Kvasstoppen W
Iversenfjellet Upper & Lower
Vesterodden
Kapp Thor
Hermansenskaret
Russevika
8515
8510
8505
8500
8495
8490
8485
445
450
455
460
465
SCALE
0 1 2 3 4 5 km
Horizontal reference basis: EUREF89
Map projection: UTM, zone 35X
Vertical reference basis: Mean sea level
Contour interval 50 m
SEDIMENTARY ROCKS
age
TRRIASSIC
Rhaetian
Norian
Carnian
Kapp Toscana Group
Wilhelmøya Subgroup
Svenskøya Formation: medium-grained, porous, light-coloured sandstone
Flatsalen Formation: dark grey, silty shale with silt- and sandstone beds; base: carbonate-cemented sandy siltstone (Slottet Bed)
Storfjorden Subgroup
De Geerdalen Formation
Hopen Member: marine sandstone, siltstone, dark shale, mudstone
De Geerdalen Formation (lower part): shallow marine to terrigenic sandstone, siltstone, shale

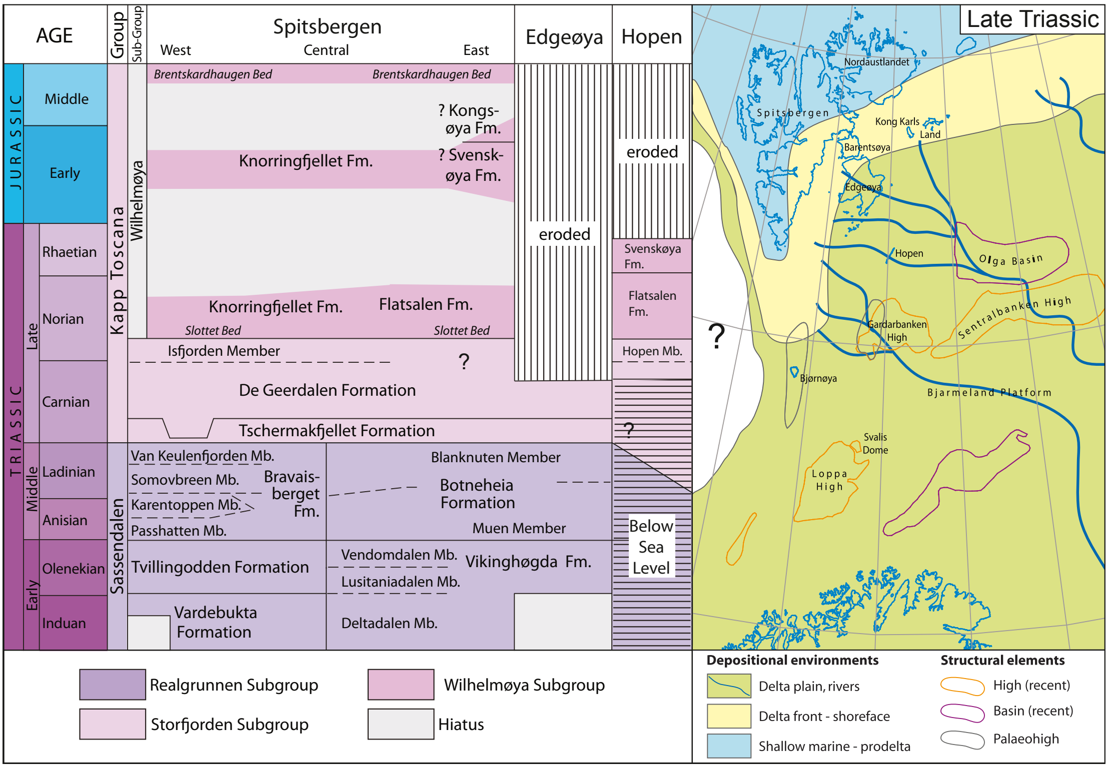


Figure 2. Stratigraphic chart over Svalbard after Mørk et al. (2013) and palaeogeographic map of the Late Triassic after Lundschien et al. (2014).

Edgeøya or Barentsøya. The Triassic strata of the eastern islands represent a proximal position within this delta system, relative to central Spitsbergen. The observation of extensive channel bodies within the strata of Hopen fits well with the regional Triassic development (Klausen and Mørk, 2014; Riis et al., 2008; Rød et al., 2014).

Channel Types and Architecture

Rivers and channels are a major pathways of sediment routing through a terrestrial environment and their nature can be considered complex (Collinson, 1996). Here we provide a simple overview of channel types seen in the rock record and the ways in which they can be interpreted in outcrop.

Ancient channels are generally classified with regards to their internal architectures (Collinson, 1996; Gibling, 2006; Miall, 1988, 1996, 2013). As no vertical sequence is diagnostic of any specific channel type, their architecture and geometry become major facets in determining the channel facies (Miall, 1985).

The description of channel sand body geometries is based primarily on the visual characteristics observed from photo mosaics and measured in the 3D model. Channel sand bodies can be seen to range in size and shape considerably and thus an overview of the terminology used for describing both sandstone channel bodies is presented in Figure 3. Individual sandstone channel bodies can be described as forming several distinctive geometrical shapes, being symmetrical, asymmetrical and lenticular. These become complex within channel systems involving multiple channels, where they can become multilateral, stacked or are seen to form laterally extensive sheets.

Channel forms and architecture can range from simple individual sandstone channels to multilateral channels or stacked channel systems. Individual channels can represent small systems with little or no avulsion. Multilateral / laterally accreting channels generally represent the lateral migration of a channel due to erosion on the outside of a bend and deposition on the inside. This often results in the presence of heterolithic channel bodies with notable accretion surfaces (Collinson, 1996). Stacked channel systems represent the repeated activation of a watercourse over time showing evidence of a primary sediment pathway where numerous rivers repeatedly erode into earlier underlying channels.

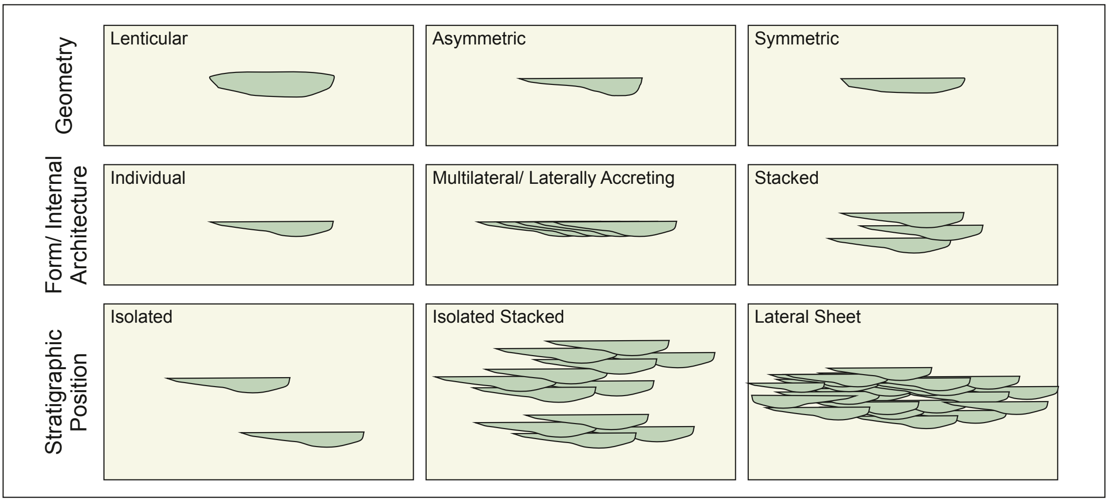


***Figure 3**. Simple overview figure showing channel geometry and forms for ancient channel nomenclature after Collinson (1996).*

Channels can be isolated within the stratigraphy or be amalgamated into systems representing a major watercourse, sediment routing pathway. These amalgamated systems can themselves be isolated within floodplain deposits or form widespread lateral sheet sands composed of multiple channel systems that spread over a wide area.

Methodology

PhotoModeler™ 3D Geological Model

A 3D geological model of the island has been produced utilising PhotoModeler™ software from EOS Systems (Solvi, 2013). The model applies a large database of high resolution digital photographs to make a 3D visualisation of the island, overlying a digital elevation model (provided by the Norwegian Polar Institute). This model can be manipulated and used to interpret the islands geological characteristics.

The method of constructing the model uses a series of photographs taken with a high resolution camera, using 85 mm or 300 mm lenses. In total 4900 photographs of the island have been used. Visual interpretation of these images was used to document the occurrence and distribution of channel bodies throughout the De Geerdalen Formation.

These photographs are then used in panoramic combinations within the PhotoModeler™ program, where known points are selected to reference their locations to a digital elevation model. The addition of aerial photographs of the island, provided by the Norwegian Polar Institute, allowed for a greater level of detail and accurate geometrical measurements of the geology to be made. Formation thicknesses have been calibrated based on stratigraphical log data recorded in the field and height reference points measured by GPS, to ensure feature are accurately represented in the model.

The criteria for the identification of channel bodies, observed within the geological model, rely on the identification of features evidently formed by an erosive process. Vertically incising and laterally constrained features that are seen within the model are interpreted as channel bodies, with the addition of evidence from their internal architectures.

Field Studies

Conventional field studies form the bulk of the geological understanding of Hopen. Sections are provided by the *Hopen Geology Project* and have been drawn by small team operating throughout the island over relatively short periods of time; herein we integrate these sections.

Those channels that have been logged and their sedimentary structures analysed to determine their facies association are displayed in Figure 4. Field studies are used to assist the interpretation of channels that have not been directly observed in the field. Understanding of channels seen within the geological model is based on observed channel architecture and geometry, whilst the nature of the depositional environment is inferred by extrapolating the stratigraphical level of the channel laterally towards logged sections.

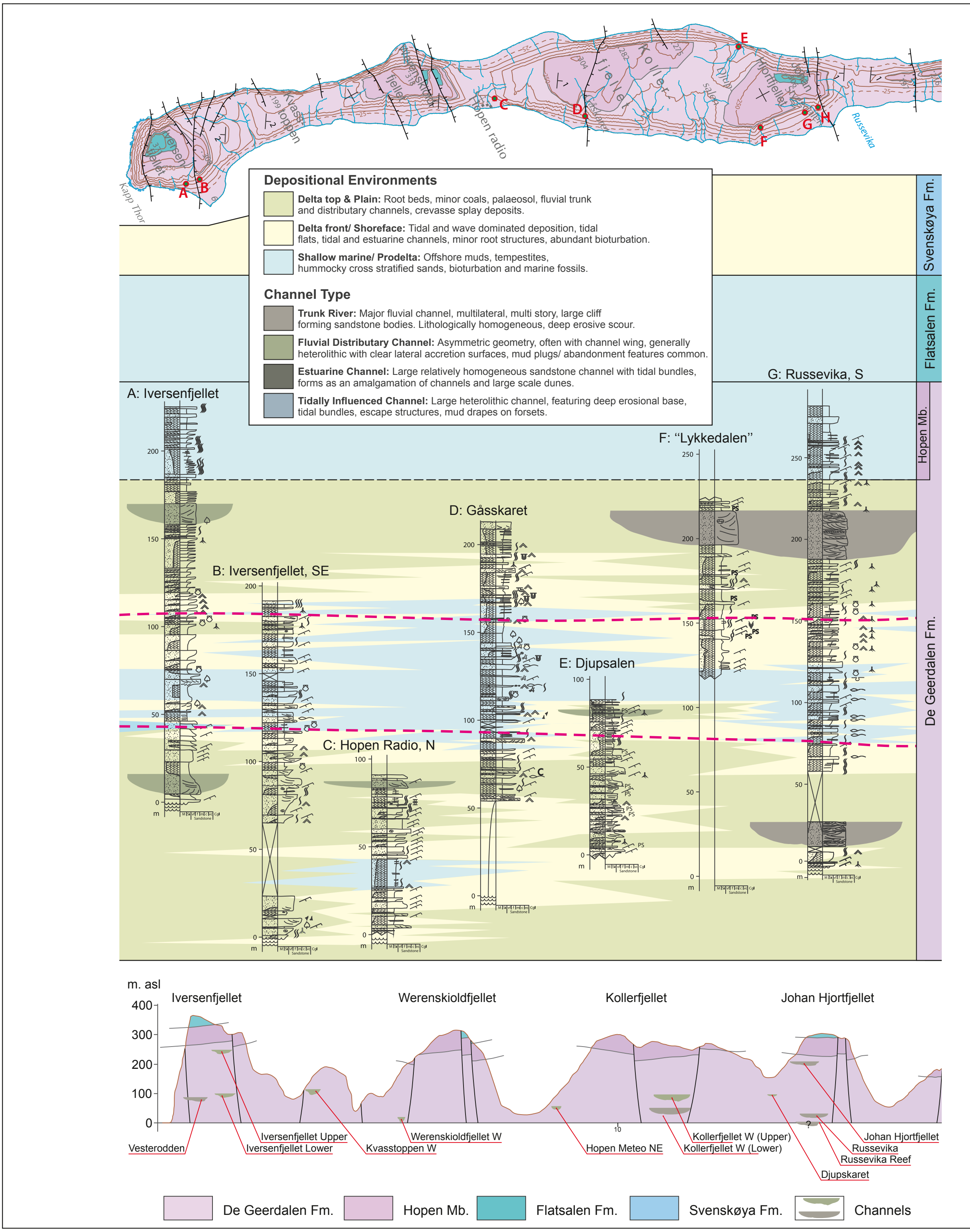
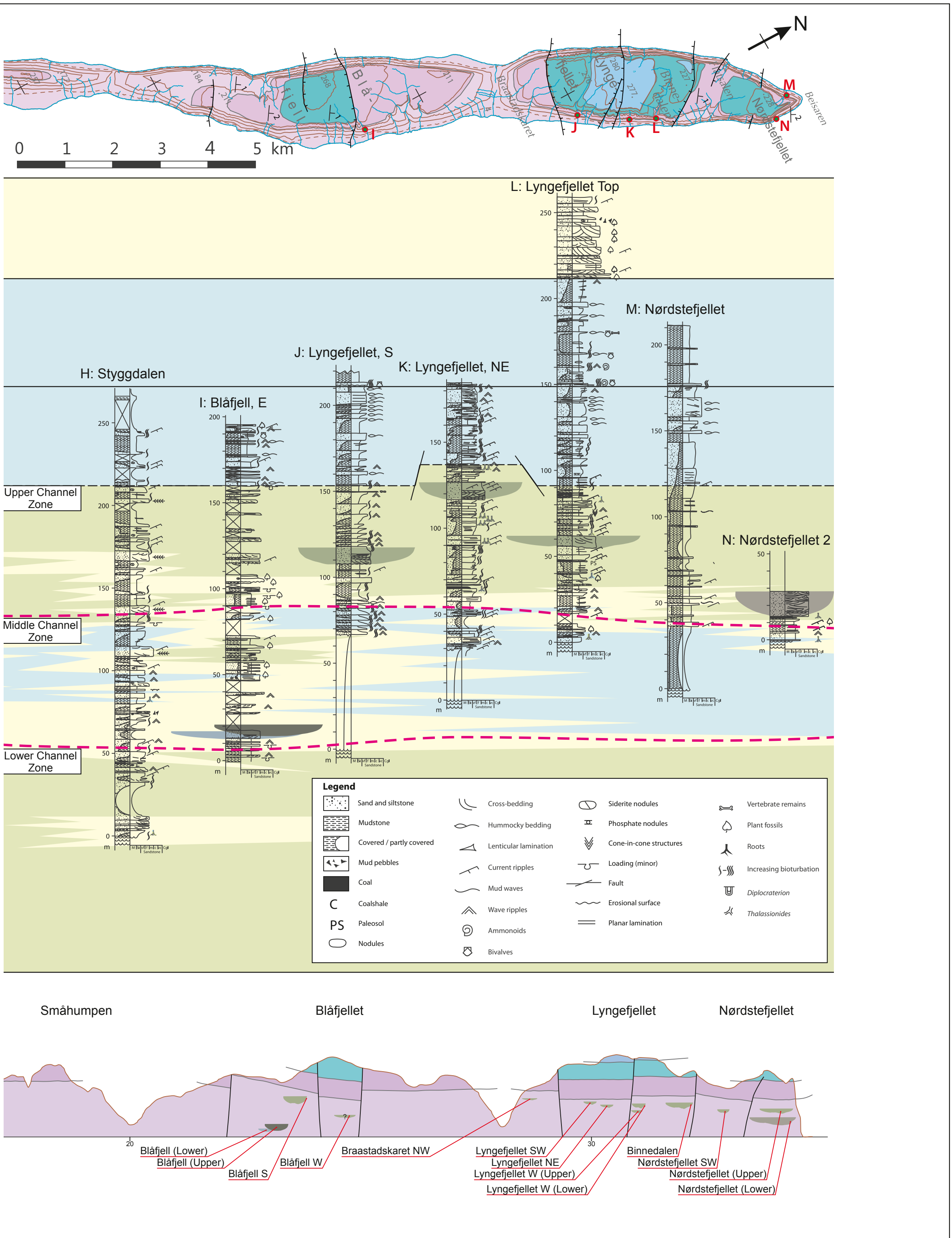


Figure 4. Overview of stratigraphical logs from Hopen, locations are marked on the map and stratigraphy is flattened at the base of the Hopen Member. Logged channels are highlighted and a simplified interpretation of depositional environment is given. Each channel zone is denoted



based on the depositional environments and the position of all channels identified is shown in the cross section. Logs are provided by the Hopen Geology Project with map, cross section and facies after Mørk et al. (2013).

Channels and the Stratigraphy

Throughout the stratigraphy channel sandstone bodies can be arranged into a relatively discrete stratigraphy (Solvi, 2013; Klausen and Mørk, 2014), herein we provide greater evidence for this trend and discuss the type of channels found at the varying stratigraphical intervals. When flattening the stratigraphy of the island in relation to the Slottet Bed and also the recently defined Hopen Member, to avoid disruption by faulting (Mørk et al., 2013; Lord et al., 2014); the stratigraphical relationships and the lateral extent of depositional environments can be seen (Fig. 4).

25 channel bodies have been identified on the island of which 12 have also been directly observed in the field. Those that have not been directly observed in the field have been identified within the 3D model and their nature is determined based on their visual characteristics. Here, we explain the basis for classifying the different channels and where they are located in the stratigraphy. Table 1 presents a complete overview of channel characteristics, geometries and architectures. These are ordered into three defined stratigraphical intervals and channels are ordered in relation to their stratigraphic position below the Hopen Member. These stratigraphic intervals are defined as the lower, middle and upper channel zones as shown in the correlation on Figure 4.

In most instances channel features are seen to scour into underlying, soft, highly heterolithic sediments and feature a lateral pinch out. Based on the observations presented in Table 1, three primary channel types are interpreted. Fluvial channels are observed and assist the definition of overall depositional environments for various stratigraphic intervals. Fluvial, tidally influenced fluvial and estuarine channels are also observed and defined based upon their internal channel heterogeneity and sedimentological characteristics. Fluvial channels are the most abundant and are seen to vary in facies type, with trunk rivers, distributary channels and individual channels often displaying abandonment features.

Strata of the De Geerdalen Formation, initially deposited within a shallow marine environment or prodelta environment (See legend in Fig. 4), are comprised of highly heterolithic beds formed in several marine facies types. These include: Sediments deposited in a low energy environment, consisting of fine grained mud and silt, with fine laminae containing distal storm beds host to minor hummocky cross-stratification. In addition bioturbated thin sandstones and shales often seen in conjunction with abundant wave ripple structures are common within this facies. This depositional environment also incorporates the uppermost unit of the De Geerdalen Formation, the Hopen Member, which represents a widespread flooding surface visible throughout the island (Mørk et al., 2013; Lord et al., 2014).

Some sections of Hopen's stratigraphy is interpreted to represent tidally dominated sedimentation within a delta front environment and here sediments are seen to be richer in sand, featuring abundances of bioturbation and hummocky cross-stratified sands (Fig. 4). Heterolithic packages of shale interspersed with minor cross stratified sand beds are present suggesting a greater influence of wave and tidal re-working of sediments. Minor root structures are present within this facies association and are interpreted as a tidal marsh environment.

The delta top setting present within the De Geerdalen Formation is evident based on the presence of notable root beds, minor coal beds and an abundance of plant fragments (Launis et al., 2014). Dominant facies within this environment are crevasse splay deposits, floodplain deposits of non-marine mud and shale, and minor root beds alongside palaeosol horizons.

The Upper Channel Zone

Fluvial Channels in the Upper Zone

At the SW cliff section of Lyngefjellet (Fig. 5A) some 4 m from the base of the Hopen Member a channel body with a thickness of 8 m and a lateral extent of 240 m is observed in the 3D geological model. The sandstone comprising this feature is laterally extensive for 90 m, whilst the pinch outs appear to consist of finer grained sediments. This channels architecture reveals that the NE pinch out is represented by a channel wing, whilst lateral accretion surfaces are present. This channel is interpreted as being a fluvial distributary channel.

On NE Lyngefjellet a channel body has been observed in the field and is shown in log K: Lyngefjellet NE (Fig. 4) and Figure 5B. This laterally extensive channel sandstone is 11 m in thickness and of unknown width, featuring trough cross stratified medium to coarse grained sand, upwards fining to current rippled fine sand. The log does not suggest any evidence for a stacked channel complex or, this having a multilateral architecture. However, the sandstone is capped by a succession of fines that coarsen upwards and include root horizons, probably representing abandonment features. This channel is interpreted as being a major fluvial channel, most probably a distributary although a trunk channel cannot be ruled out.

18 m below the base of the Hopen Member, on the mountain of Johan Hjortfjellet lays a 28-32 m thick sandstone body, measuring approximately 950 m in width (Fig. 5C). Its exact lateral extent is undetermined due to its northern pinch out (when observed from the eastern side of the island) being very discrete. This channel has been logged in its entirety, log G: Russevika, S which shows the fine to medium grained sandstone channel eroding into soft underlying shales. Its internal architecture is dominated by large scale trough-cross

***Table 1.** An overview of the individual channels observed on Hopen including geometries, characteristics and interpretation. Channels are ordered by their stratigraphical position in relation to the base of the Hopen Member. Three zones are evident.*

Channel Location	Fig.	Position below Hopen Member	Width / Thickness	Notes	Channel Type
Upper Channel Zone					
Lyngefjellet SW	5A	4 m	240 m / 8 m	Asymmetrical channel scour with channel wing, features lateral accretion surfaces terminating at the base of the channel. Visual characteristics suggest relatively homogeneous composition.	Fluvial Distributary Channel
Lyngefjellet NE	5B	10 m	Undetermined / 11 m	Trough cross-stratified medium/ coarse grained sandstone fining up wards to medium grained current rippled sandstone.	Fluvial Distributary Channel of potential Trunk River
Johan Hjortfjellet	5C	18 m	c. 600 m / 32 m	Single storey channel, with an erosive base and lithological homogeneity, featuring large scale trough cross stratification.	Trunk River (after Klausen & Mørk 2014)
Binnedalen	5D	24 m	Undetermined / 7-15 m	Prominent trough and cross trough bedding, mud clasts line the base of troughs. Gentle upwards fining observed into current rippled sandstone with rootlets.	Fluvial Distributary Channel
Braastadskaret NW	5E	25 m	100 m / 7 m	Amalgamated, multi lateral channel body with laterally accreting beds, channel wing and potential mud plug.	Fluvial Distributary Channel
Blåfjell	5F	c. 28 m	325-475 m / 13-19 m	Heterolithic composition with near symmetrical geometry. Laterally accreting beds present. No channel wing or evidence for mud plug. Features sand lenses.	Fluvial Distributary Channel
Lyngefjellet W (Upper)	5G	29 m	210 m / 11 m	Single storey, medium grained channel sandstone. Featuring an erosive base, extensive cross stratification with the uppermost fining to massive fine sand. Notable lateral accretion surfaces present with potential mud plug.	Fluvial Distributary Channel
Iversenfjellet (Upper)	-	29 m	Undetermined / 12 m	Trough and planar cross stratified sandstone with plant fragments. Fining upwards to small upwards coarsening deposits, representing lateral accretion beds.	Fluvial Distributary Channel
Nørdstefjellet (Upper)	5H	30 m	Undetermined / 10-15 m	Appears at similar stratigraphical level to the channel body in Binnedalen.	Fluvial Distributary Channel
Nørdstefjellet SW	-	42 m	200 m / 15 m	Symmetrical body. No notable internal structures, geometry is highly lenticular with a concave base and top. Bending of overlying beds suggests a component of differential compaction.	Major Fluvial Channel (Possible Trunk River)
Lyngefjellet W (Lower)	5I	50 m	145 m / 6 m	Heterolithic composition with accretion surfaces and mud plug, asymmetric geometry and isolated in the stratigraphy.	Fluvial Distributary Channel
Kvasstoppen W	5J	50 m	Undetermined / 30 m	Scouring sandstone body, truncated by fault however shows evidence for feint lateral accretion surfaces suggesting multilateral channel architecture with relative lithological homogeneity.	Fluvial Distributary Channel
Nørdstefjellet (Lower)	5K	60 m	1000 m / 36 m	Multilateral channel sandstone, laterally accreting surfaces, with an erosive base and lithological homogeneity. Minor trough cross stratification is observed, but is not prominent.	Trunk River (after Klausen & Mørk 2014)
Blåfjell W	5L	Undetermined	Undetermined	Asymmetrical geometry with notable channel wing. Laterally accreting beds terminating at the base of channel scour, heterolithic composition with a mud plug.	Fluvial Distributary Channel
Middle Channel Zone					
Kollerfjellet W (Upper)	5M	130 m	815 m / 25 m	Prominent cliff forming sandstone, deep scour and lenticular geometry, possible upwards fining trend with lateral accretion surfaces evident.	Fluvial Channel (with potential marine influence)
Djupskaret	-	135 m	150 m / 5 m	Lateral accretion surfaces are prevalent consisting clearly of lighter coloured sediments within finer grained (darker) material. Indication for possible mud plug.	Fluvial Distributary Channel
Blåfjell E (Upper)	5N	c. 140 m	415 m / 30 m	Amalgamated channel bodies, tidal bundles.	Estuarine Channel
Blåfjell E (Lower)	5N	145 m	100 m / 7 m	Erosional base, mud drapes, wave ripples and large scale trough-cross stratification.	Tidally Influenced Fluvial channel
Lower Channel Zone					
Iversenfjellet (Lower)	-	178 m	Undetermined / 15 m	Thick trough and planar cross bedded medium grained sandstone, fining upwards.	Fluvial Distributary Channel
Kollerfjellet W (Lower)	5O	179 m	915 m / 20 m	Highly vegetated, fractured and weathered exposure. Potential multilateral channel system with lateral accretion surfaces evident.	Trunk River
Vesterodden	5P	183 m	Undetermined / 15 m	Notable cliff forming sandstone, no apparent internal architecture, however a potential mud-plug is observed.	Trunk River
Werenskioldfjellet W	5Q	190 m	210 m / 22 m	Erosional scour, no obvious internal structures due to extensive fracturing and weathering of this exposure.	Fluvial Distributary Channel
Hopen Meteo NE	5R	200 m	232 m / 15 m	Asymmetrical geometry. Deep scour and mud plug, potentially stacked channel with some minor lateral accretion surfaces present.	Fluvial Distributary Channel
Russevika	5S	200 m	Undetermined / 13 m	Symmetrical channel geometry. Trough and cross stratified bedding within channel sandstone suggesting multilateral architecture. Deposited atop terrestrial sediments with coal and root beds.	Potential Trunk River Channel
Russevika Reef	5T	230 m	c. 150 m / unknown	Cross stratified medium grained sandstone with large tree fossils. Cutting into heterolithic sediments.	Potential Trunk River Channel

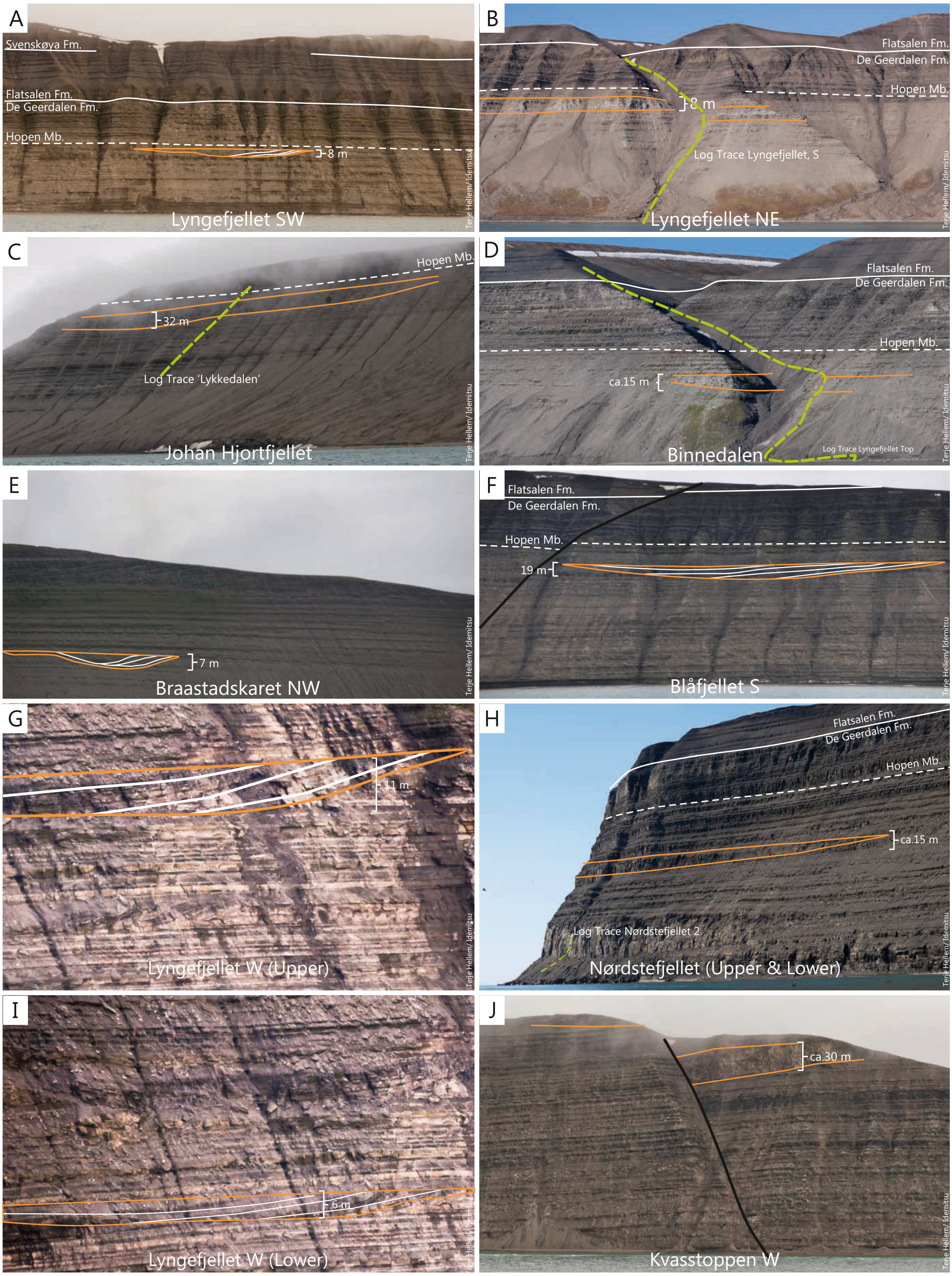
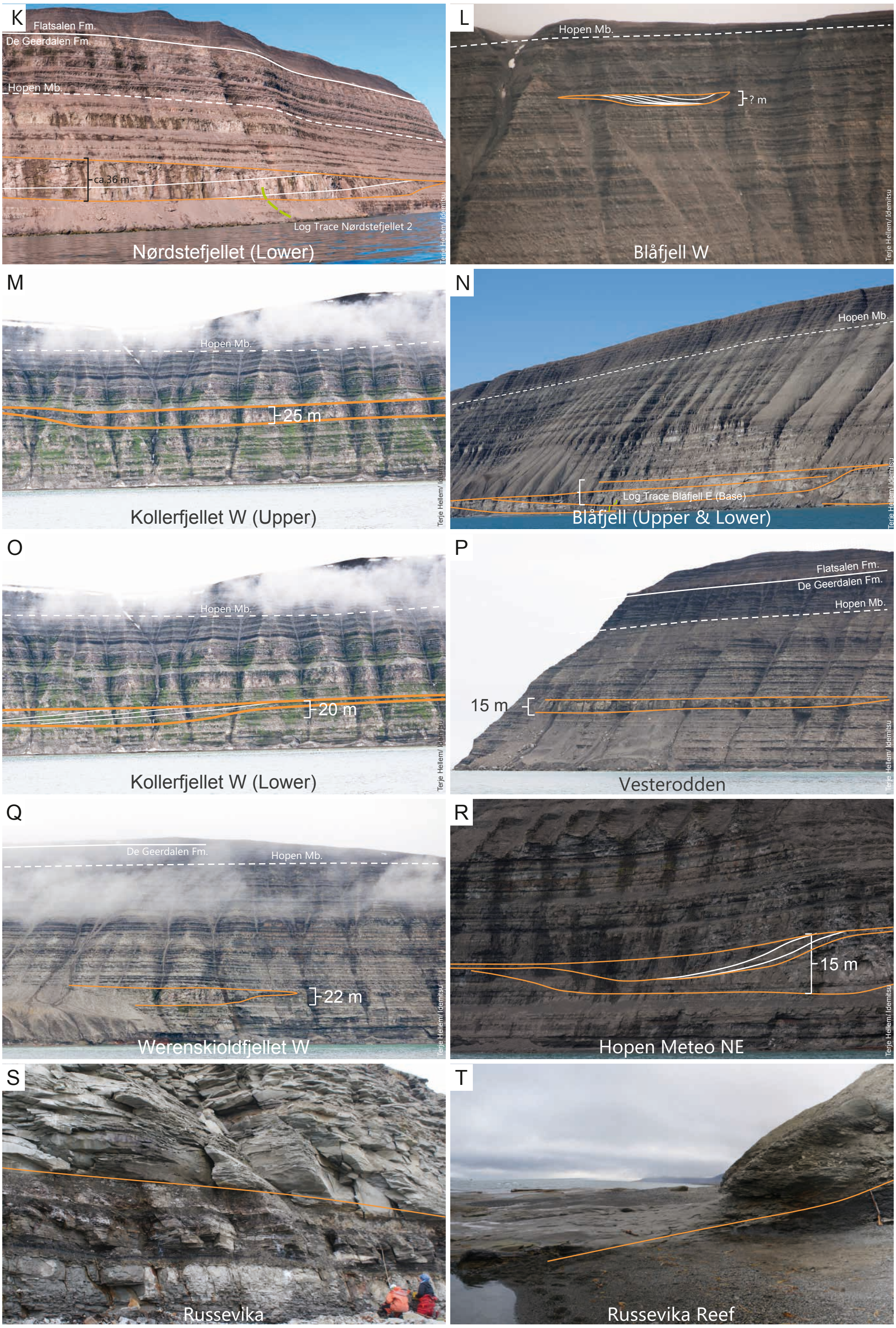


Figure 5 A-T. Images of channel bodies observed on Hopen. Photos relate to those indicated in Table 1 and channel positions are marked on the map in Figure 1. See text for detailed explanation of channels.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N
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O
Hopen Mb.
20 m
Kollerfjellet W (Lower)
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De Geerdalen Fm.
Hopen Mb.
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Vesterodden
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Hopen Mb.
22 m
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15 m
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S
Russevika
T
Russevika Reef
Terje Hellem/ Idemitsu

stratification. Due to this channels exposure being at a higher position in the stratigraphy, foresets of these troughs have formed a weathering surface and de-lamination is prominent. This inherently adds difficulty in the observation of larger structures due to the highly irregular expression of this sandstone and thus no lateral accretion surfaces are observed, nor evidence for this channel being component to a stacked complex. This channel body represents a large trunk river channel, following the interpretation of Klausen and Mørk (2014). This is based on the large channel geometry, its lateral extent and despite no visual evidence for lateral accretion surfaces, the log shows that the body is comprised of multiple packages trough cross and planar cross bedded sandstones, suggesting a component of lateral migration.

The sandstone channel body seen within the valley of Binnedalen in the northern end of Hopen is laterally discontinuous; 7 m in thickness and featuring a clear erosional scour (Fig. 5D). The width is undetermined as scree inhibits lateral tracing of this channel body. The sandstone lies 24 m below the base of the Hopen Member within heterolithic, laminated shale and thin sandstones. Beds below the base of this body consist of siltstones, with minor root beds and loading structures. The internal architecture of the sandstone shows pronounced large scale trough cross bedding with an abundance of rip up mud clasts and organic material observed at the base of the troughs. Internal bed packages show a tendency for gentle fining upwards and the uppermost parts of these are dominated by uni-directional current ripples. The channel is topped by a minor upwards fining package of sand to silt, featuring coalified root structures and desiccation cracks. These characteristics suggest a delta top environment in a fluvial dominated system. The channel lack marine or tidal influence and the internal architecture of the sandstone, suggest that this channel body represents a fluvial distributary channel.

On the western cliff section, on the NW flank of Braastadskaret (Braastadskaret NW, Fig. 5E), a channel scour is seen to erode into the underlying strata some 25 m below the base of the Hopen Member. Measurements indicate that this feature is 7 m thick and 100 m wide. The internal architecture of this channel is seen to display a series of laterally accreting, dipping bedding planes that terminate at the base of the scour. This channel may represent a laterally accreting body similar to several others observed on the island. In addition, interpretation from the model suggests the channels features a mud plug suggesting that the dipping beds may represent a migrating point bar within the bend of a fluvial distributary channel, which has then been abandoned.

On Blåfjell a channel scour estimated at approximately 13-19 m thick and 325 – 475 m in width is observed at approximately 28 m below the base of the Hopen Member (Blåfjell, S Fig. 5F). The internal architecture of this channel scour is dominated by a series of gently dipping sandstone beds intermittently dispersed with finer grained material, suggesting that this channel is multilateral in nature. Furthermore, observations made from the model show evidence for sand lenses within the scour and there is also potential for this channel being part of a stacked channel complex, with a younger channel scouring into an older channel body at the same stratigraphical interval. This is interpreted as representing a fluvial distributary channel, showing evidence of abandonment with potential reactivation of the watercourse at a later time.

The uppermost channel on the western coastline of Lyngefjellet (Lyngefjellet W, Upper) is situated approximately 29 m below the base of the Hopen Member and its dimensions are 11 m in thickness and 210 m in lateral extent (Fig. 5G). The channel is present in the log taken at Lyngefjellet (J: Lyngefjellet, S), on the eastern side of Hopen. This channel features a scouring base into soft underlying sediments and its internal architecture is also well defined in the 3D geological model. A series of laterally dipping beds of medium grained sandstone can be seen. The presence of fine grained material suggests that this channel has undergone abandonment at some stage and subsequent filling by fine grained flood deposits. The sandier accretion packages were deposited by the migration of a point bar. This is interpreted as a fluvial distributary channel.

In the upper sections of Iversenfjellet in southern Hopen features a sandstone channel body of 12 m thickness and an undetermined width, lying 29 m below the Hopen Member. The channel is homogeneous, composed of medium grained sandstone featuring trough and planar cross bedding. The uppermost of this body is defined by minor upwards coarsening packages. This channel is interpreted as representing a fluvial distributary channel. At Nørdstefjellet, 30 m below the base of the Hopen Member a channel sandstone body is observed, (Nørdstefjellet Upper, Fig. 5H). This channel is not logged but does appear at a similar interval to that in Binnedalen and appears isolated within the surrounding strata. It is laterally extensive with no noticeable internal architecture. The thickness is determined to be some 10-15 m whilst the lateral extent is unknown. Given the relative homogeneity of this sandstone body, with no evidence for lateral accretion surfaces or obvious fines formed during abandonment, this channel is interpreted as being a fluvial distributary channel.

On the SW flank of Nørdstefjellet a laterally discontinuous, lenticular shaped sandstone channel body is observed to be down cutting some 8 m into underlying sediments. Stratigraphically, it occurs 42 m below the base of the Hopen Member at a similar interval to the fluvial channel observed in the coastal cliff section at NE Nørdstefjellet. The sandstone has a thickness of 15 m and a width of 200 m. This deep scour and symmetrical geometry suggest that this channel represents a major watercourse, with no evidence for lateral migration being seen. The channel is interpreted as representing a major fluvial channel, possibly a trunk river.

The lowermost channel on the western coastline of Lyngefjellet (Lyngefjellet W, Lower) occurs some 50 m below the base of the Hopen Member and its geometry forms a laterally discontinuous scour, of 6 m in thickness and 145 m in lateral extent (Fig. 5I). The channel displays two prominent characteristics with regards to its internal architecture. First and foremost, a series of notable, sandy accretion surfaces are observed dipping laterally within the channel scour. Alongside, a series of fine grained sediments are observed. These are interpreted as the accreting planes of point bar deposits within a meandering river system, with fine grained sediments representing the ultimate abandonment of this channel and subsequent filling by sediments over time, suggesting this river is a fluvial distributary channel branching from a major watercourse.

On the western side of the mountain of Kvasstoppen (Kvasstoppen W) on southern Hopen, a 30 m thick sandstone body has been observed (Fig. 5J). Its lateral extent is undetermined due to fault displacement. Its position in the stratigraphy is 50 m below the Hopen Member. Despite Kvasstoppen not being capped by the Hopen Member, the position has been determined by laterally tracing prominent beds across the fault to Iversenfjellet. This places the body within delta plain sediments seen in the upper parts of the De Geerdalen Formation, beneath the Hopen Member. Although not logged, subtle bed packages are observed. Given its stratigraphical position, thickness and homogeneity, this sandstone might represent a fluvial, distributary channel deposit.

At Nørdstefjellet in the northern end of the island is a 36 m high and 1000 m wide sandstone body evident in the lower cliff section, shown in log N: Nørdstefjellet 2, (Fig. 5K). This single storey, multilateral channel body shows a clear lateral pinch out to fine grained sediments and a scour of some 17-20 m. It is present on both sides of the island as a notable cliff and is subject to minor oblique fault displacement. Within this channel body, the sandstone is relatively homogeneous with trough cross bedding surfaces being visible. The base is sharp, with an irregular contact into the underlying shale, which comprise minor, laterally discontinuous coals and coalified root structures. This channels stratigraphical position is determined to be approximately 60 m below the base of the Hopen Member. Given the multilateral nature, geometry and sheer size of this channel it is interpreted as representing a trunk river.

A channel scour is observed on the southern side of Blåfjell, named as Blåfjell, W (Fig. 5L). Within this scour, lateral accretion surfaces are observed in the 3D geological model, with a discontinuous layer of darker and presumably more mud rich deposits being evident. The position in the stratigraphy and extrapolation of the level to nearby logs, suggest this channel lies within delta top sediments and therefore it may represent a minor, formerly meandering fluvial distributary channel, with a mud plug formed as a result of channel abandonment.

The Middle Channel Zone

Fluvial, Tidal and Estuarine Channels in the Middle Zone

The upper cliff section on the western side of Kollerfjellet (Kollerfjellet W Upper, Fig. 5M) is seen to enclose a laterally discontinuous cliff forming sandstone body. Its position in the stratigraphy is measured as being 179 m below the base of the Hopen Member. This channel is determined to be 20 m thick and with an estimated width of 915 m (which cannot be accurately determined due to faulting). The cliff section of the channel itself is seen to be highly vegetated and weathered, thus no internal characteristics can be observed. This channel is interpreted as being a fluvial channel, however given its stratigraphical position, the potential remains for this to represent a tidally dominated or estuarine channel.

Within the narrow and steep sided gully of Djupskaret, a 5 m thick and 150 m wide channel occurs at a stratigraphic level some 135 m below the base of the Hopen Member. A section slightly north of this is logged at Djupsalen (Log E: Djupsalen), where a minor component of this channel body has been observed at the same stratigraphic level. The logged strata display a clear palaeosol horizon with intermittent current ripple laminated sandstones and root structures. Within the De Geerdalen Formation at various locations throughout Svalbard, most noticeably on the eastern island Edgeøya, palaeosols are common and they are characterised by bleached zones (Miall, 2006). On Hopen, however, they are observed to primarily be thin oxidised beds often seen in conjunction with coal shale, minor coal beds and coalified roots. Palaeosols can also be defined as a common flood plain facies (Miall, 2006; Kraus and Aslan, 1993), which suggests that this channel is deposited within a delta plain environment. Analysis of the internal architecture shows evidence for lateral accretion surfaces, indicating the lateral migration of a point bar. The heterolithic composition shows evidence for a mud plug. The relatively small lateral extent and minor thickness of this body, alongside the associated facies, indicate that this channel is representative of a relatively minor fluvial distributary channel. Given the position in the stratigraphy which is dominated by marine influenced facies it is likely this channel was initially flowing in a very near shore environment, where major channel paths have branched into smaller systems.

Along the coastline at Blåfjell two channels are observed to form a stacked channel system, where one is seen to scour into one below as shown in Figure 5N. The uppermost channel forms a vertical cliff of 30 m height, with an overall width of 415 m. This prominent sandstone body incising into the channel beneath it and its approximate stratigraphical position is c. 175 m below the base of the Hopen Member. The internal architecture of this channel body displays a series of prominent erosional scours along individual bed boundaries, which are observed to be of thicknesses between 3-5 m. They are interpreted as representing the amalgamation of small channels, with a minor lateral extent of some 10-15 m. This channel system has been logged (Blåfjell, E) and the upper part of this section reveals the presence of mud drapes along wave ripple crests, loading structures in the form of flame casts and Klausen and Mørk (2014) report the presence of tidal bundles within the lower packages of the channel body. This package is defined by Klausen and Mørk (2014) to be the deposits of an estuarine system where dune migration within a confined channel system represents scour and fill.

The lowermost channel of this stacked system and also this channel zone occurs some 180 m below the base of the Hopen Member and is seen to scour into underlying sediments. This channel body is 7 m thick and is documented in the stratigraphical log I: Blåfjell, E and in Figure 5N. The width is measured at some 100 m despite this channel being incised by an overlying channel body. The internal channel architectures, observed in the 3D geological model, shows that the channel contains a series of beds, where multiple erosional scours form their basal geometry. This can thus be considered as a stacked channel system, composed of minor stacked and amalgamated channels. Further information is provided from the sedimentological log Blåfjell, E where the lowest exposures of this channel have been logged along with the overlying channel body. The log shows a gentle upwards fining trend of fine to medium grained sandstone with an erosional base. Internal structures show the presence of large scale trough-cross stratification and mud-drapes. Mud drapes are common features in tidally influenced environments (Bhattacharya, 2006). Based on the presence of mud drapes, suggesting a bi-directional flow, this lower channel body is interpreted as being deposited within a tidally influenced environment and is defined as a tidal channel.

The Lower Channel Zone

Fluvial Channels in the Lower Zone

The basal sections of the mountain of Iversenfjellet in southern Hopen are seen to contain a sandstone channel body of 15 m thickness. The extent of this channel is undetermined due to extensive cover in the lower slopes of the mountain in this area. The channel consists of medium grained trough and planar cross bedded sandstone, seen to fine upwards into siltstone. This upwards fining trend suggests a slow abandonment of this channel. No evidence for a multilateral architecture is observed and no erosional surfaces are seen within the channel itself. This channel is within a zone dominated by delta top sediments and is interpreted as representing a fluvial distributary channel.

The cliff section on the western side of Kollerfjellet is seen to enclose a laterally discontinuous cliff forming sandstone body (Table 1, Fig. 5O). Its position in the stratigraphy is measured as being 179 m below the base of the Hopen Member. This channel is determined to be 20 m thick and with an estimated width of 915 m. The cliff section of the channel itself is seen to be highly vegetated and weathered, thus no internal characteristics can be observed. This channel appears to have a homogeneous composition, its geometry and scale suggests it represents a very large channel system and is thus interpreted as representing a trunk river.

At the SE tip of Hopen, a prominent cliff forming sandstone is present in the section at Vesterodden, approximately 183 m below the base of the Hopen Member (Table 1, Fig. 5P). This channel has been subject to faulting thus its lateral extent is undetermined; its thickness is measured to be 15 m. No sedimentological logs cover this channel; however neighbouring strata show that this interval is dominated by fine grained sediments with current ripple lamination. The stratigraphical interval here also contains an upwards fining sandstone bed with an erosional base, interpreted in this case to be a crevasse splay. The channel body is interpreted to be a fluvial trunk river, within a delta top setting.

The western flank of Werenskioldfjellet, to the SW of the Hopen meteorological station contains a 22 m thick and 210 m wide channel sandstone body, clearly eroding into the underlying sediments (Fig. 5Q). The channel body is present in the stratigraphy approximately 190 m below the base of the Hopen Member and correlates well to the stratigraphical level of the log taken at Iversenfjellet SE (Fig. 4). Strata in this interval consist of fine grained sediments containing wave and current ripple laminations, along with minor bioturbation. No direct environment indicators are evident; however the presence of symmetrical wave ripples and the occurrence of bioturbation suggest that this channel has been deposited in an environment with close proximity to wave or potentially tidal influence, such as a lower delta plain environment. This channel is thus interpreted as representing fluvial distributary channel at a point in the delta system where rivers have branched or anastomosed into smaller channels.

To the NE of the Hopen meteorological station a channel scour is present in the stratigraphy, approximately 200 m below the base of the Hopen Member (Fig. 5R). Its dimensions are measured to be 15 m in thickness and 232 m in overall width, however, a potential pinch out laterally to the north cannot be determined due to the presence of a deeply incised gully. The internal architecture as observed in the geological model shows the presence of an 8 m thick package of dark, fine grained sediments forming what is interpreted to be a mud plug. This channel was presented in Nystuen et al. (2008) although with no additional interpretation. No other prominent internal structures are noted. It is interpreted that this channel represents an abandoned fluvial distributary channel.

Sandstone channel bodies are also evident on the beach section at Russevika in central east Hopen, where a 13 m thick channel is observed to scour into soft underlying shales. Field observations show that this underlying stratum contains wave rippled siltstone with mud drapes, minor coals, root beds and small stream scours (see Figs. 5S and 6A-C). The channel consists entirely of sandstone, with large scale trough and cross-trough bedding present. Due to cover the full lateral extent is undetermined. The stratigraphical position of this channel body is 200 m below the base of the Hopen Member. The channel facies is representative of a fluvial channel with no evidence for any tidal influence being seen within the channel body itself; however wave ripples and bioturbation is seen in the underlying beds in addition to a minor coal bed and coalified root structures. The channel is interpreted to be a fluvial distributary channel based on the primarily heterogenic composition of the sand and lack of evidence for external environmental influences being present.

A further sandstone that is classified as fluvial in origin is observed to protrude from the island as a shallow, wave cut platform beneath the channel at Russevika (Fig. 5T), termed 'Russevika Reef' in Table 1. The exact geometries are unknown, yet it is laterally discontinuous in the order of ca. 75-100 m, and lithiologically homogenic (when observed at low tide). This sandstone is considered to have similarity with those channels seen at Nørdstefjellet and Johan Hjortfjellet. It is suggested on this basis that this sandstone is almost certainly representative of a fluvial channel, possibly representing a trunk river. Furthermore, field observations show that this channel is seen to be transporting large trees (Fig. 6D), a feature also seen in the trunk river channel at Johan Hjortfjellet.

Discussion

The nature of channel sandstone bodies on the island of Hopen can be interpreted as being indicative of three different depositional environments. Fluvial trunk river channels and fluvial distributary channels are seen to be present within delta top dominated sediments, whilst tidal and estuarine channels are seen within sediments dominated by a delta front environment. The geometry of these bodies and their architectures also vary in this regard. Fluvial trunk rivers are seen to be homogeneous in composition and form either lenticular or near symmetrical sandstone bodies, that typically feature a greater width to thickness ratio (Gibling, 2006). Fluvial distributary channels are in comparison characterised by their asymmetric geometry. At some locations, such as those seen at Lyngefjellet SW, Braastadskaret NW or Blåfjell S (Figs. 5A, E, L) the potential for the presence of a channel wing is evident. This is observed by the noticeable thinning of the channel's form laterally away from the scour, however this has only been observed in photomosaics. Both types of fluvial channels are seen to be isolated within the stratigraphy and do not form stacked systems or lateral sheets (Fig. 3). Channels of both types however, show evidence for lateral accretion surfaces, with these being most evident in the heterolithic sediments seen in fluvial distributary channels.

Fluvial channels can be seen to represent both meandering rivers systems and also anastomosed systems, based on the presence of lateral accretion surfaces seen in distributary channels. Fluvial trunk channels are suggested to represent a moderate sinuosity, multi-channel system flowing through an area characterised by extensive vegetation with a large proportion of overbank deposits. A number of channels also display abandonment features, characterised by their overall heterolithic composition, internal architecture and evidence for abandonment based on the presence of mud plugs. This is most evident in the channels at Lyngefjellet SW, Braastadskaret NW and Blåfjell W (Figs. 5A, E, L). These channel features are suggested to have formed on or near the apex of a bend in a meandering river system. Meanders are eroded through leaving an oxbow lake or meander scar that is later in-filled with fine grained sediments, through lake like deposition (Collinson, 1996).

The lowermost exposures present on the island of Hopen are dominated by terrestrial floodplain sediments, in which 7 channels incising into heterolithic sediments have been identified. These channels are shown within the lower channel zone in Table 1, which corresponds to interval 1a of Klausen and Mørk (2014) and is determined to occur approximately 180-200 m below the Hopen Member. These channels are located at Hopen Meteo NE, Kollerfjellet W (Lower), Iversenfjellet (Lower), Vesterodden, Werenskioldfjellet W, Russevika and protruding out to sea at Russevika Reef (Fig. 4). Only the channels at Hopen Meteo NE and the two at Russevika have been observed in the field, the remainder are identified in the 3D geological model.

This lower zone is of unknown thickness, as the De Geerdalen Formation continues in the subsurface. The presence of the fluvial Russevika Reef channel coupled with the Iversenfjellet SE and Hopen Radio N logs in Figure 4 suggest that the interval remains predominantly within a delta-top to delta front environment continuing in the immediate subsurface. A minor marine incursion of unknown lateral extent is interpreted within this zone (as shown in Figure 4), however, channels in this lower zone are dominantly distributary channels.

***Figure 6. A**, Mud draped wave ripples seen in the tidally dominated delta front sediments below the channel at Russevika. **B**, Minor coal seam directly beneath the Russevika channel. **C**, Cross stratified micro channels seen in wave rippled, tidal sediments underlying the Russevika channel. **D**, Excellently preserved tree trunk trapped in the outer edge of the trunk river at Russevika Reef.*

The strata dominating the middle section of the stratigraphy, between c. 70 and 180 m below the Hopen Member, is interpreted as being dominated by facies that display a marine influence. This ca. 100 m thick interval consists primarily of shallow marine and delta front facies associations. Here abundant bioturbation, wave ripples and laterally discontinuous sandstone beds featuring hummocky cross-stratification are prevalent. This is a visually discrete interval and corresponds closely to interval 1b of Klausen and Mørk (2014). It is considered laterally extensive, spanning the entirety of the island; however, fault displacement and scree cover make facies correlation difficult.

The middle zone is also interspersed with minor occurrences of delta front and delta top facies as show in Figure 4. Here channels are interpreted to be influenced to a greater extent by marine processes, given the individual channel architecture, geometries and sediment characteristics. Two primarily marine channels are observed at Blåfjell, where a lower tidally dominated channel is present, which is seen to be subsequently eroded into by an estuarine channel system. The two remaining channels seen in the middle zone are deemed to be fluvial distributary channels. They feature internal characteristics inherent of a fluvial system and in the case of the channel at Djupskaret are in close relation to delta top sediments. Given their stratigraphical position, however, an aspect of marine influence cannot be ruled out, as this interval is dominated by marine processes, suggesting fluvial channels are a result of delta switch.

The uppermost strata of the De Geerdalen Formation on Hopen, below the Hopen Member, are interpreted as being dominated by delta top and delta plain sediments, with minor marine influenced intervals being present where delta front facies are observed. This is defined as the upper channel zone (Table 1) which corresponds to intervals 2b and 2c of Klausen and Mørk (2014). Within this zone a total of 14 fluvial channels are observed. Of these 14 channels, 6 have been logged and their depositional facies has been determined through direct observation whilst the remaining channels are interpreted with evidence from photographs and the 3D geological model.

The De Geerdalen Formation on Svalbard was reported as a shallow marine to fluvial succession by Buchan et al. (1965) and Mørk et al. (1982). Deltaic conditions were reported from Barentsøya and western Edgeøya (Knarud, 1980; Lock et al., 1978; Mørk et al., 1982) and fluvial to delta top with coal beds further east on Edgeøya (Lock et al., 1978). Sedimentological data from Hopen was not presented, but the general depositional conditions as reported on the other main Svalbard islands were assumed to continue also to Hopen. In the Barents Sea, the correlative Snadd Formation was also reported as shallow marine to deltaic, however it is more fluvial in nature, especially in its upper part and this is noted by many authors (e.g. Høy and Lundschien, 2011; Klausen and Mørk, 2014; Riis et al., 2008; Glørstad-Clark et al., 2010).

The abundant presence of channels, within the De Geerdalen Formation on Hopen was first reported by Mørk et al. (2013) and these channels was compared with channels detected by seismic methods in the southern Barents Sea in the Snadd Formation by Klausen and Mørk (2014). Observations supported by shallow drilling data in the northern Barents Sea (Lundschien et al., 2014) show that this area was covered by extensive paralic deposits from mainland Norway through to Hopen. Authors interpreting seismic data demonstrated that during the Carnian four seismic sequences, up to 400 m thick, were progressing across the Barents Sea and passed Hopen in the uppermost sequence (e.g. Lundschien et al., 2014). The Hopen exposures thus display the nature of these prograding sequences with its arrangement of different channel belts.

The exposed Hopen succession as a whole is younger than the section at Edgeøya (Riis et al., 2008; Lord et al., 2014; Lundschien et al., 2014) and together they give a view of the total Late Triassic succession on the eastern Svalbard Islands. Hopen provides excellent exposures along a near perpendicular plane to the major palaeoflow direction of rivers during the Carnian. Klausen and Mørk (2014) show a clear trend of channels seen in seismic migrating to the W and NW. The perpendicular aspect of the island to this palaeoflow and the steep sections allow for excellent studies to be made. On Edgeøya, outcrops are generally oblique to the orientation of channels and thus their abundance may be under reported as their presence is not evident as with channels seen on Hopen.

On Spitsbergen; the Triassic succession is mostly complete (Buchan et al., 1965; Mørk et al., 1982, 1999), although the uppermost part (Wilhelmøya Subgroup) is quite condensed, especially in the central and western areas. Detailed facies studies by Rød et al. (2014) demonstrate that the paralic nature of the De Geerdalen Formations extends from Edgeøya into central Spitsbergen. Delta front sediment is, however, more abundant in these areas than distinct channels as seen on Hopen.

In comparison to the wider extent of the De Geerdalen Formation in Svalbard, the facies seen at Hopen is comparable to that on Edgeøya, despite being younger in age. Rød et al. (2014) document a paralic environment in the upper parts of the De Geerdalen Formation seen in western Edgeøya. A significantly greater extent of delta front and shore face facies is observed in central Spitsbergen with an inherently greater abundance of inter-distributary facies. In addition, a greater tidal influence is seen within distributary channels in Spitsbergen. Rød et al. (2014) report mud drapes and herringbone structures in distributary channels found in Spitsbergen, while distributary channels on Edgeøya lack diagnostic features that suggest any tidal influence (Rød et al., 2014) has been overprinted by a stronger fluvial signal.

The Triassic of western Spitsbergen cannot be correlated directly with the units of eastern Svalbard due to a different development of these sediments. This shows a clear regressive development of a paralic environment into the latter part of the Triassic, both on Spitsbergen, Edgeøya and Hopen. The depositional environment seen on Hopen represents the most regressive stage of this development seen in Svalbard, but similar to observations in cores from the Northern Barents Sea (Lundschien et al., 2014), and seismic data in the southern Barents Sea (Klausen and Mørk, 2014).

The offshore development of the Late Triassic is also well documented by Klausen and Mørk (2014), who present the De Geerdalen Formation at Hopen as an analogue to the Triassic Snadd Formation in the subsurface. The clear evidence for the development of meandering river systems in the Carnian (Klausen and Mørk, 2014) provides good evidence for a regressive deltaic system at this time. Hopen features sandstone channel bodies, of similar scale to those observed in the Barents Sea Snadd Formation and thus provides a good analogue to the Late-Triassic in the Barents Sea. Palaeoflow indicators also suggest a primarily westwards direction, with a provenance source to the east (Mørk, 1999; Rød et al., 2014) consistent with the trend of deltaic progradation seen in seismic (Høy and Lundschien, 2011; Riis et al., 2008; Glørstad-Clark et al., 2010).

The creation of the Hopen Member (Mørk et al., 2013; Lord et al., 2014) and its evident correlation to the Isfjorden Member in central Spitsbergen, displays one of the regional sequence stratigraphic intervals within the De Geerdalen Formation. The gentle onset of a transgression, shown by the development of marine influenced strata overlying the paralic sediment, further highlights the fact that the sediments in the De Geerdalen Formation at Hopen are the youngest and most regressive stage of this Carnian deltaic system.

Conclusions

25 sandstone channel bodies are observed on the island of Hopen. Stratigraphical positioning of channels show they form discrete intervals, dominated by a particular depositional style. The channels are dispersed throughout the stratigraphy and are numerous in the upper part of the De Geerdalen Formation, below the Hopen Member. Channels observed lower in the succession are less frequent and estuarine and tidal influence is observed for some of these channels.

Channels are isolated within the stratigraphy, forming individual bodies or multilateral/ stacked systems. Internal architecture and heterogeneities of channels vary considerably; from massive or highly cross-stratified, laterally accreting sandstone bodies deposited within a terrestrial fluvial environment, to more heterolithic stacked channel systems indicative of a tidally influenced system.

The upper channel zone occurs at 0-60 m below the base of the Hopen Member, the middle channel zone occurs 130-145 m, whilst the lower channel zone occurs 180-200 m. These zones are interpreted as representing a fluctuating sea level, inherent within a paralic environment (Klausen and Mørk 2014; Riis et al., 2008; Glørstad-Clark et al., 2010; Lundschien et al., 2014; Rød et al., 2014). The middle and upper zones together represent an overall shallowing upwards sequence, overlain by the Hopen Member.

The presence of trunk river and distributary channels on Hopen indicates a fluvially influenced setting, for the De Geerdalen Formation in this region. This is in contrast to central Spitsbergen where a stronger tidal signal is observed (Rød et al., 2014) and Edgeøya where diagnostic tidal features aresparse. In eastern Svalbard a paralic depositional environment is evident in the upper part of the succession (Lundschien et al., 2014; Rød et al., 2014). This allows for a composite of the stratigraphy of these locations to give a strong indication of the overall nature of the Triassic succession in the northern Barents Sea.

The depositional environment for the De Geerdalen Formation on Hopen is a fluvial dominated and tidally influenced delta plain, given the highly heterolithic nature of sediments and rapid fluctuations between terrestrial and marginal marine facies. The De Geerdalen Formation is present throughout Svalbard, becoming increasingly distal towards the NW. This gradual development is controlled by the W and NW direction of delta progradation as defined by Riis et al. (2008), Høy and Lundschien (2011), Glørstad-Clark et al. (2010) and Lundschien et al. (2014).

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References

Bhattacharya, J.P. 2006: Deltas. *In* Posamentier, H.G., & Walker, R.G. (eds.): *Facies models revisited, Society of Sedimentary Geology, Special publication, 84*, 237-292.

Buchan, S.H., Challinor, A., Harland, W.B & Parker, J.R. 1965: The Triassic stratigraphy of Svalbard: *Norsk Polarinstituttt Skrifter, 135*, 92 pp.

Collinson, J.D., 1996: Alluvial sediments. *In* Reading, H.G. (ed.): *Sedimentary environments: Processes, Facies and Stratigraphy.* Blackwell Publishing, 5-57.

Doré, A.G. 1995: Barents Sea Geology, Petroleum Resources and Economic Potential. *Arctic, 48*, 3, 207-221.

Flood, B., Nagy, J. & Winsnes, T.S. 1971: The Triassic succession of Barentsøya, Edgeøya and Hopen (Svalbard). *Norsk Polarinstitutt Meddelelser, 100*, 20 pp.

Gibling, M.R. 2006: Width and thickness of fluvial channel bodies and valley fills in the geological record: A literature compilation and classification. *Journal of Sedimentary Research, 76*, 731-770.

Glørstad-Clark, E., Faleide, J.I., Lundschien, B.A. & Nystuen, J.P. 2010: Triassic seismic sequence stratigraphy and paleogeography of the western Barents Sea area. *Marine and Petroleum Geology, 27*, 1448-1475.

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 Barents Sea. *In* Fleet, A.J. & Boldy, S.A.R. (eds.): *Petroleum Geology of Northern Europe, Proceedings of the 5th Conference*, 247-259.

Høy, T. & Lundschien, B.A. 2011: Triassic deltaic sequences in the northern Barents Sea. *In* Spencer A.M., Embry, A F., Gautier, D.L., Stopakova, 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., Brunn Christensen, O., Cheredeev, S.I., Ignatenko, E.A. & Margulis, L.S. 1993: Hydrocarbon potential in the Barents Sea region: Play distribution and potential. *In* Vorren, T.O. et al. (eds.): *Arctic Geology and Petroleum Potential, NPF Special Publication no. 2*, Elsevier Scientific Publications, 273-320.

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

Knarud, R. 1980: *En sedimentologisk og diagenetisk undersøkelse av Kapp Toscana Formasjonens sedimenter på Svalbard.* Cand. Real thesis, University of Oslo, 208 pp.

Korčinskaya, M.V. 1980: Early Norian Fauna of the Archipelago of Svalbard. *In* Geologiya osadochnogo chekhla arkhipelaga Sval'bard (*Geology of the Sedimentary Cover of the Archipelago of Svalbard*), Leningrad: NIIGA, 30–43.

Kraus, M.J. & Aslan, A. 1993: Eocene hydromorphic paleosols; Significance for interpreting ancient floodplain processes. *Journal of Sedimentary Petrology, 63*, 453-463.

Launis, A., Pott, C. & Mørk, A. 2014: A glimpse into the Carnian: Late Triassic plant fossils from Hopen, Svalbard. *Norwegian Petroleum Directorate Bulletin, 11*, 129-136.

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 Polarinstitutt Skrifter, 168*, 64 pp.

Lord, G.S. Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W. & Paterson, N.W. 2014: The Hopen Member: A new lithostratigraphic unit on Hopen and equivalent to the Isfjorden Member of Spitsbergen. *Norwegian Petroleum Directorate Bulletin, 11*, 81-96.

Lundschien, B.A., Høy, T. & Mørk, A. 2014. Triassic hydrocarbon potential in the Northern Barents Sea; integrating Svalbard and stratigraphic core data. *Norwegian Petroleum Directorate Bulletin, 11*, 3–20.

Miall, A.D. 1985: Architectural-element analysis; a new method of facies analysis applied to fluvial deposits. *Earth Sciences Review, 22*, 261-308.

Miall, A.D. 1988: Reservoir heterogeneities in fluvial sandstones; lessons from outcrop studies. *American Association of Petroleum Geologists Bulletin, 12*, 682-697.

Miall, A.D. 1996: *The geology of fluvial deposits*. Springer-Verlag, New York, 582 pp.

Miall, A.D. 2006: *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology*. 4th Corrected Printing, Berlin, 582 pp.

Miall, A.D. 2013: *Fluvial Depositional Systems*, Springer Geology, Springer International Publishing Switzerland 2013, 316 pp.

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*, 371-398.

Mørk, A., Dallmann, W.K., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pčelina, T.M. & Worsley, D. 1999: Mesozoic Lithostratigraphy. *In* Dallmann, W.K. (ed.): *Lithostratigraphic Lexicon of Svalbard, Upper Palaeozoic to Quaternary Bedrock – Review and recommendations for nomenclature use.* Norwegian Polar Institute, Tromsø.

Mørk, A., Lord, G.S., Solvi, K.H. & Dallmann, W.K. 2013: *Geological Map of Svalbard 1:100 000, sheet G14G Hopen. Norsk Polarinstitutt Temakart No. 50.*

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

Nystuen, J.P., Mørk, A., Müller, R. & Nøttvedt, A. 2008: From desert to floodplain – from land to sea. *In* Ramberg, I., Solli, A. & Nordgulen, Ø. (eds.): *The Making of Land: Geology of Norway*, The Geological Society of Norway, Trondheim, 328-353.

Pózer Bue, E. & Andresen, A. 2013: Constraining depositional models in the Barents Sea region using detrital zircon U-Pb data from Mesozoic sediments in Svalbard. *Geological Society Special Publication, 386*, 261- 279.

Puchkov, V.N. 2009: The evolution of the Uralian orogeny. *Geological Society, London, Special Publications, 327*, 161-195.

Pčelina, T.M. 1972: Concerning the age of sedimentary strata on Hopen. *In* Sokolov, V.N. & Vasilevskaya, N.D. (eds.): *Mesozoic deposits in Svalbard*. Leningrad, 75-81.

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.

Rød, R.S., Hynne, I.B. & Mørk, A. 2014: Depositional environment of the Upper Triassic De Geerdalen Formation – An E-W transect from Edgeøya to Central Spitsbergen, Svalbard. *Norwegian Petroleum Directorate Bulletin, 11*, 21-40.

Smith, D.G., Harland, W.B. & Hughes, N.F. 1975: Geology of Hopen, Svalbard. *Geological Magazine, 112*, 1-23.

Solvi, K.H. 2013: *Visualize and interpret the geometry, heterogeneity and lateral continuation of channel bodies in the De Geerdalen Formation at Hopen*. Master Thesis, Norwegian University of Science and Technology, 122 pp.

Tozer, E.T., & Parker, J.R. 1968: Notes on the Triassic biostratigraphy of Svalbard. *Geological Magazine, 105*, 526-542.

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

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

Paper 3

A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway.

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A multidisciplinary biofacies characterisation of the Late Triassic (late Carnian–Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway

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ABSTRACT

A multidisciplinary study of the Kapp Toscana Group (De Geerdalen, Flatsalen and Svenskøya formations) on Hopen, Svalbard, provides an enhanced palaeoenvironmental interpretation for the Upper Triassic succession on the island. The biofacies of the formations were characterised using a combination of palynological, palynofacies and micropalaeontological analyses. Micropalaeontological, palynofacies and $\delta^{13}C_{org}$ data are presented from Hopen for the first time. Six distinct biofacies assemblages were recognised: (I) Lower undifferentiated De Geerdalen Formation, characterised by a dominance of fern spores, and low abundance assemblages of foraminifera and ostracods, interpreted to reflect deposition in a deltaic environment during maximum marine regression; (II) Upper De Geerdalen Formation, Hopen Member, rich in bisaccate gymnosperm pollen and the alga *Plaesiodictyon mosellaneum*, consistent with deposition in a brackish marginal marine setting; (III) Lower Flatsalen Formation, characterised by microforaminiferal linings, marine phytoplankton and super-abundant agglutinated foraminifera, considered to reflect deposition in a shallow marine environment; (IV) Middle Flatsalen Formation, dominated by dinoflagellate cysts, radiolaria and ostracods, indicating deposition in a relatively distal, dysoxic–anoxic marine environment (a maximum flooding surface is inferred based on the acme of radiolarians and dominance of dinoflagellate cysts); (V) Upper Flatsalen Formation, corresponding to a decrease in marine palynomorphs, absence of radiolaria, agglutinated foraminifera and ostracods, and an increase in terrestrial organic matter; and (VI) Svenskøya Formation, characterised by a dominance of terrestrial palynomorphs and deposited in a fluvio-deltaic environment. The biofacies units are integrated with the established litho-, chrono- and palynostratigraphic framework for the island and contribute to an enhanced palaeogeographic understanding of the Barents Sea region during the Late Triassic.

1. Introduction

During the Late Triassic, a vast northwesterly prograding delta-complex gradually infilled a shallow gulf on the northern coastline of Pangaea, in an area now occupied by the Svalbard Archipelago and Barents Sea (Cocks and Torsvik, 2007; Riis et al., 2008; Glørstad-Clark et al., 2010, 2011; Høy and Lundschien, 2011; Lundschien et al., 2014). Upper Triassic strata are well exposed over large areas of the Svalbard Archipelago and are widespread in the subsurface of the Barents Shelf (Vigran et al., 2014) where they are petroliferous (Henricksen et al., 2011; Ryseth, 2014). The Upper Triassic to Middle Jurassic succession in the region is assigned to the Kapp Toscana Group, which is over 1000 m thick in the southern Barents Shelf, thinning to approximately 650 m on the eastern islands of the Svalbard Archipelago, and to 200–300 m on Spitsbergen (Lord et al., 2014b). Historically, the dating of Upper Triassic strata in the region has been problematic. Age-diagnostic marine macrofossils are rare, and there is a consequent lack of biostratigraphic control. The thickness of the succession, lateral variability of lithofacies and diachroneity of the succession further complicate matters. However, the paralic facies are well suited for palynology, which has proved to be a useful dating method. Several palynological studies have been conducted since the 1970s (e.g., Smith, 1974; Smith et al., 1975;

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0031-0182/

Bjærke, 1977; Bjærke and Dypvik, 1977; Bjærke and Manum, 1977; Hochuli et al., 1989; Ask, 2013; Vigran et al., 2014; Paterson and Mangerud, 2015), but few previous investigations have integrated palynology and micropalaeontology, and almost all have focused on biostratigraphy rather than palaeoenvironmental interpretation. The recent studies of the Upper Triassic on Spitsbergen by Nagy et al. (2011) and Mueller et al. (2014) have demonstrated the utility of using an integrated approach for palaeoenvironmental reconstruction.

In this investigation, the biofacies of the De Geerdalen, Flatsalen and Svenskøya formations (Kapp Toscana Group) on the island of Hopen were characterised through the integration of palynology, palynofacies analysis and micropalaeontology. The analyses build upon the previous sedimentological studies of the island (Mørk et al., 2013; Klausen and Mørk, 2014; Lord et al., 2014a,b) and provide new insights into the depositional environments and the palaeogeography of the region during the Late Triassic. Micropalaeontological, palynofacies and $\delta^{13}C_{org}$ data are presented from Hopen for the first time.

2. Geological setting

Hopen is a relatively small island (32 km long, 0.5–2.5 km wide) situated in the southeastern corner of the Svalbard Archipelago (N 76°35′, E 25°20′; Fig. 1). The island rests on a structural high (Doré, 1995; Grogan et al., 1999) and represents a unique uplifted analogue of the correlative Upper Triassic succession from the Barents Sea. Strata on Hopen comprise a succession of paralic–shallow marine deposits, which are collectively dated as late Carnian to Rhaetian age by palynology (Paterson and Mangerud, 2015). Subsurface data to the east of the island, in the northern Barents Sea, indicates the presence of a large northwesterly prograding clinoform belt of Late Triassic age (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy and Lundschien, 2011; Lundschien et al., 2014).

The lithostratigraphic succession on Hopen is assigned to the Kapp Toscana Group (Buchan et al., 1965; Worsley, 1973; Smith, 1974) and is subdivided into the De Geerdalen, Flatsalen and Svenskøya formations (Mørk et al., 1999, 2013) (Figs. 2 and 3). Preliminary sedimentological studies of the island were conducted by authors including Flood et al. (1971), Pčelina (1972), Worsley (1973) and Smith et al. (1975), while more detailed investigations were presented by Lord et al. (2014a,b) and Klausen and Mørk (2014). The palynostratigraphy of the succession is also reasonably well documented (e.g., Smith, 1974; Smith et al., 1975; Bjærke and Manum, 1977; Ask, 2013; Vigran et al., 2014; Paterson and Mangerud, 2015) but has yet to be fully integrated with the available sedimentological data.

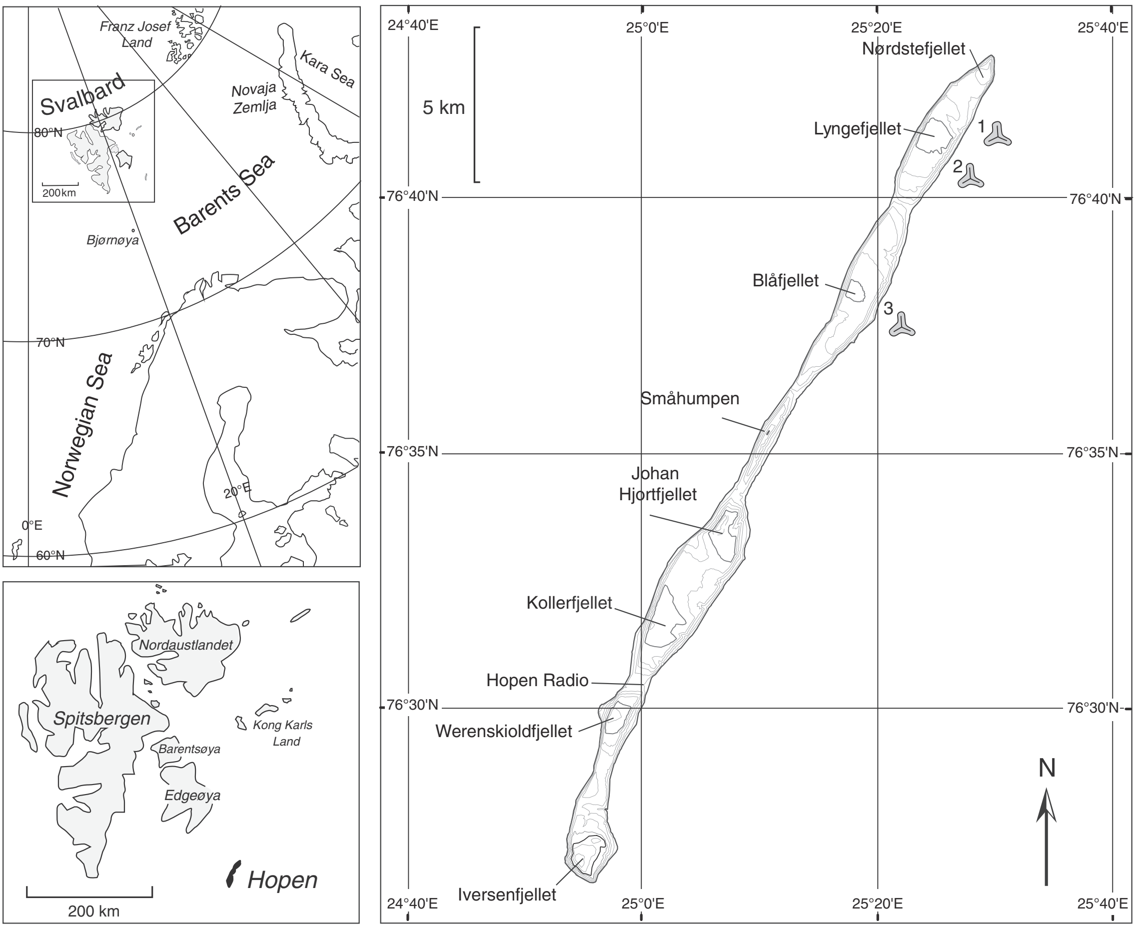

Fig. 1. Location map for sample localities on Hopen: (1) Binnedalen, (2) Lyngefjellet, (3) Blåfjellet.

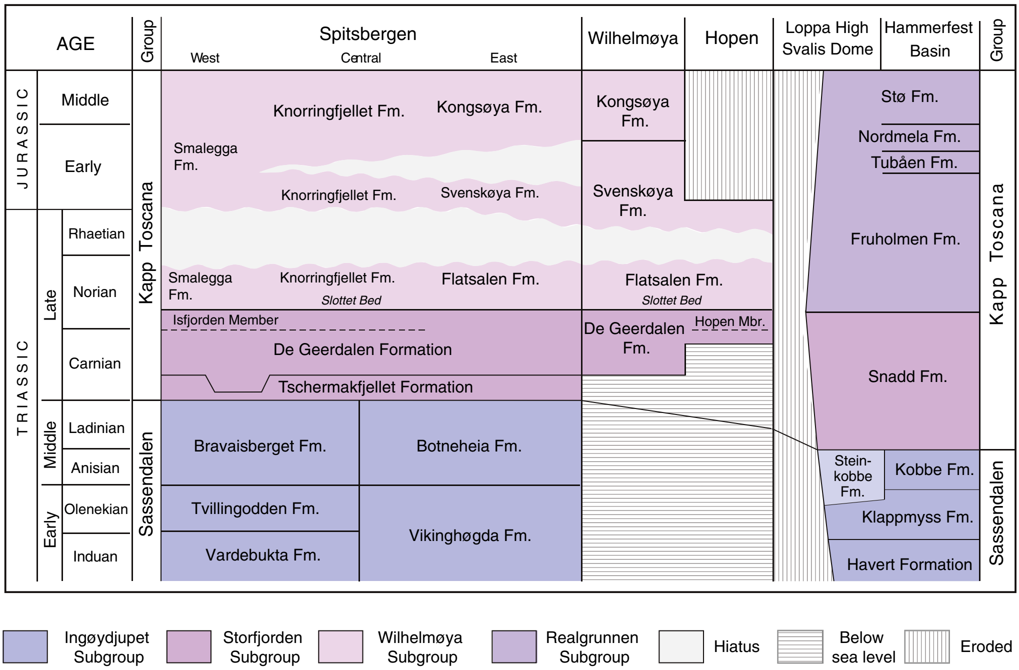

Fig. 2. Lithostratigraphy of the Sassendalen and Kapp Toscana groups, modified from Mørk et al. (1999).

2.1. De Geerdalen Formation

Sedimentological studies on Hopen indicate that the De Geerdalen Formation was deposited in a paralic setting (Mørk et al., 2013; Lord et al., 2014a,b), in a dynamic suite of sub-environments ranging from shallow marine to coastal plain (Smith et al., 1975; Mørk et al., 2013; Klausen and Mørk, 2014; Lord et al., 2014a,b; Rød et al., 2014; Vigran et al., 2014). Subsurface data from the Hopen 2 well, drilled by Norsk Fina Group in 1973, show an approximate cumulative thickness of 650 m for the formation on the island (Lord et al., 2014a,b). Since the base of the unit is below sea level on Hopen, the lowermost exposures on the island probably represent the middle of the formation as exposed elsewhere in Svalbard (Fig. 2). The unit is widespread throughout the Svalbard Archipelago, although it is significantly eroded on the eastern islands of Edgeøya and Barentsøya (Mørk et al., 1982; Lord et al., 2014b; Rød et al., 2014). The formation is characterised by repeated coarsening-upward units on a 5–10 m scale (Flood et al., 1971; Pčelina, 1972; Smith et al., 1975; Mørk et al., 2013; Lord et al., 2014a) (Fig. 3e). Lithologies range from silty, nodular mudstone to texturally and compositionally immature sandstone (Mørk et al., 1999; Mørk, 2013). A late Carnian (Tuvalian 2–3) age is inferred for the De Geerdalen Formation on Hopen based on palynological (Paterson and Mangerud, 2015), palaeobotanical (Pott, 2014) and magnetostratigraphic evidence (Lord et al., 2014b), calibrated by ammonoid data from the overlying Flatsalen Formation (Korčinskaya, 1980). The formation is subdivided into two units on Hopen, a lower undifferentiated member and an overlying unit, defined as the Hopen Member (Mørk et al., 2013; Solvi, 2013; Lord et al., 2014b) (Fig. 3e). The latter unit is considered to represent a lateral equivalent of Pčelina's (1983) Isfjorden Member from central Spitsbergen (Mørk et al., 1999, 2013; Lord et al., 2014b) (Fig. 2).

In the lower exposures of the formation, thin palaeosols, root beds and coals are present and have been noted at several localities on the island (Flood et al., 1971; Pčelina, 1972; Strullu-Derrien et al., 2012; Lord et al., 2014b) (Fig. 3b), often capping the upward coarsening units. Numerous channel sandstones are also evident (Smith et al., 1975; Smelror et al., 2009; Mørk et al., 2013; Solvi, 2013; Lord et al., 2014a,b) and have been interpreted as fluvial and tidal channel deposits, restricted to distinct zones within the stratigraphy (Solvi, 2013; Klausen and Mørk, 2014; Lord et al., 2014a,b). Fossil wood fragments and leaves have been observed in the formation at several localities on Hopen and throughout the region (Buchan et al., 1965; Flood et al., 1971; Pčelina, 1972; Smith et al., 1975; Launis et al., 2014; Lord et al., 2014a; Pott, 2014) and fossilised tree trunks several metres in length have been noted (Lord et al., 2014a, Fig. 6d). Collectively, these deposits are considered to represent the maximum regressive stage of the prograding De Geerdalen/Snadd Formation delta-system.

The Hopen Member comprises the upper 70 m of the De Geerdalen Formation on Hopen (Figs. 2 and 3), above the last occurrence of rootlets, palaeosols and coal beds (Lord et al., 2014b). The unit is characterised by dark mudrock, interbedded with subordinate fine-grained sandstone (Lord et al., 2014a,b). The presence of thin yellow-brown marls containing bivalves, dark shales and ironstone concretions in the upper part of the member (Flood et al., 1971; Pčelina, 1972; Smith et al., 1975; Lord et al., 2014a,b) indicates that the unit was deposited in a marine environment. Upwards-coarsening packages persist, grading from shale to siltstone and ripple-marked sandstone (Smith et al., 1975; Lord et al., 2014b). A latest Carnian (Tuvalian 3) age is inferred for the unit on the basis of palynology (Paterson and Mangerud, 2015) and magnetostratigraphy (Lord et al., 2014b).

2.2. Flatsalen Formation

The Flatsalen Formation on Hopen consists of a 62 m thick interval of dark-coloured laminated mudrock above the De Geerdalen Formation (Mørk et al., 2013) (Figs. 2 and 3). The formation is assigned an early Norian age on the basis of ammonoid, bivalve (Flood et al., 1971;

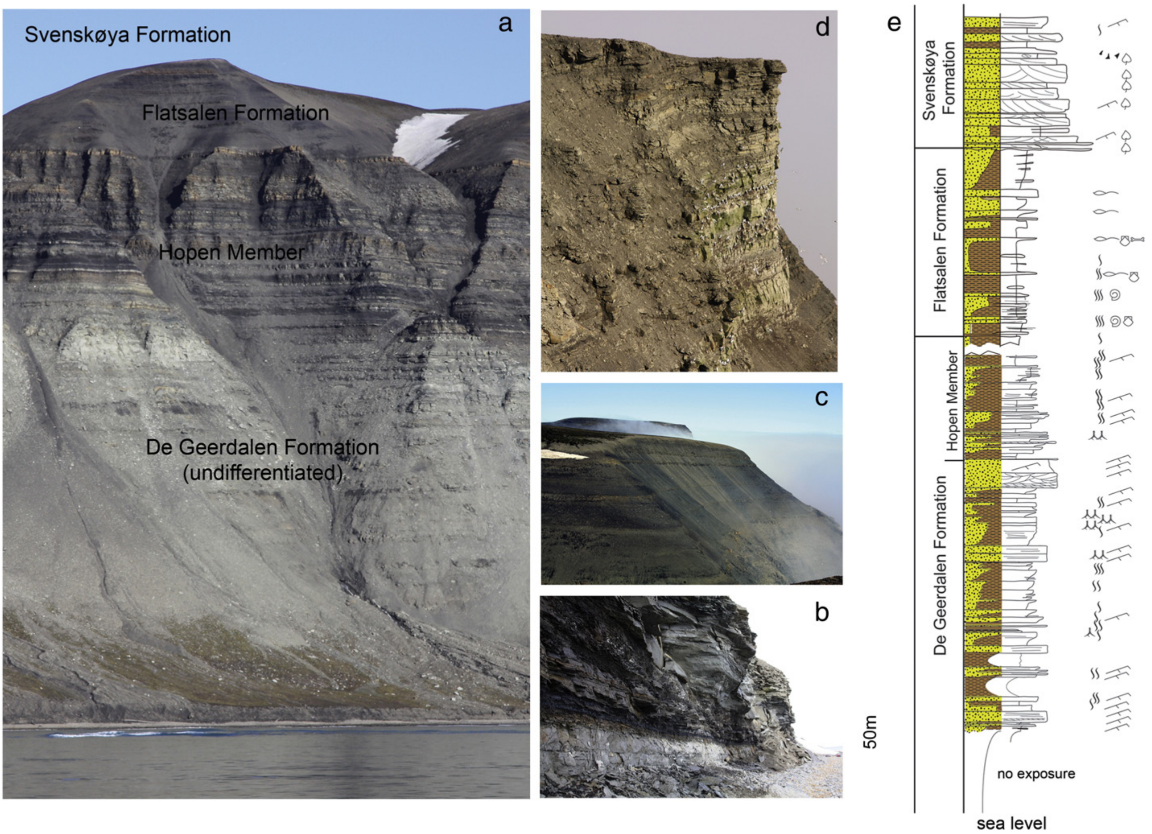

Fig. 3. Summary of the lithostratigraphic subdivision of the Kapp Toscana Group on Hopen: (a) annotated photograph of the Binnedalen section, (b) lower exposures of the De Geerdalen Formation, (c) Flatsalen Formation, (d) Svenskøya Formation, (e) Sedimentary log for the Lyngefjellet section.

Korčinskaya, 1980) and palynological evidence (Paterson and Mangerud, 2015). The base of the Flatsalen Formation is marked by the Slottet Bed, a prominent carbonate-cemented, conglomeratic mudrock, which is considered to represent a transgressive lag deposit (Klausen and Mørk, 2014). Regionally, the Slottet Bed is recognised as a distinctive marker horizon, delineating the base of the Wilhelmøya Subgroup, and of the laterally equivalent Flatsalen, Knorringfjellet and Smalegga formations (Mørk et al., 1999) (Fig. 2).

Above the Slottet Bed, the formation is composed of minor upwards-coarsening packages of shale to wave-rippled sandstone beds (Fig. 3e), which together constitute a larger upwards-coarsening succession (Mørk et al., 2013). The presence of ammonoid, bivalve, ichthyosaur remains (Flood et al., 1971; Smith et al., 1975; Korčinskaya, 1980; Mørk et al., 2013) and a dominance of marine microplankton in palynological assemblages (Smith et al., 1975; Bjærke and Manum, 1977; Vigran et al., 2014; Paterson and Mangerud, 2015) indicate that the formation was deposited under fully marine conditions.

2.3. Svenskøya Formation

The white and grey coloured cliff forming sandstone of the Svenskøya Formation disconformably overlies the Flatsalen Formation (Figs. 2 and 3). The unit extends from Kong Karls Land, approximately 300 km to the north northeast, and is interpreted to represent fluvial to deltaic facies (Smith et al., 1975; Mørk et al., 1999; Mørk et al., 2013; Lord et al., 2014b). The base of the formation on Hopen is marked by a thin conglomeratic unit, passing upwards into an interval of grey massive trough and planar to sigmoidal cross-bedded sandstone, which is overlain by a white trough and planar cross-bedded sandstone (Mørk et al., 2013). Palaeocurrent indicators in the lower part of the formation trend to the southwest and southeast, becoming progressively more eastwardly directed in the upper layers. The sandstones are mostly medium to coarse grained and contain occasional pebbles and mud clasts; fragmentary plant remains are abundant, and the lower package of sandstones is capped by a thin silty coal of allochthonous origin. The upper exposures of the Svenskøya Formation are characterised by thin heterolithic packages of siltstone and fine to medium grained sandstones, with abundant mud clasts and siderite nodules, fining-upwards into siltstone with siderite nodules.

The Svenskøya Formation is restricted to the highest point on Hopen, Lyngefjellet, on the northern tip of the island (Figs. 1 and 3). The formation attains a thickness of approximately 36 m on Hopen; however, the upper part of the unit has been removed by erosion. No marine macrofossils have been recorded in the formation during previous field expeditions to Hopen; however, fragmentary macroplant remains have been noted within the sandstone beds (Smith et al., 1975; Mørk et al., 2013). In the absence of independent biostratigraphic evidence, a tentative Norian–Rhaetian age has been proposed for the

Table 1
Botanical affinity of selected Late Triassic spore and pollen taxa from Hopen.

Spore taxon	Botanical affinity
Annulispora folliculosa	Bryophyta; Sphagnales (Koppelhus, 1991; Martin et al., 2013a, 2013b)
Apiculatasporites spp.	Pteridophyta; Filicopsida (Balme, 1995)
Apiculatisporis spp.	Pteridophyta; Filicopsida (Balme, 1995)
Aratrisporites spp.	Lycopodiophyta; Pleuromeiaceae; Isoetaceae (Balme, 1995); *Cyclostrobus*, *Lycostrobus* (Helby and Martin, 1965) and *Annalepsis zeilleri* (Grauvogel-Stamm and Düringer, 1983)
Baculatisporites spp.	Pteridophyta; Filicopsida (Polypodiopsida); Filicales (Van Konijnenburg-Van Cittert, 2000)
Calamospora spp.	Sphenopsida (Equisetopsida); Equisetales (Balme, 1995; Mander et al., 2010)
Camarozonosporites spp.	Lycopodiophyta; Lycopsida; Lycopodiaceae (Scholtz, 1985; Bonis, 2010)
Carnisporites spiniger (=*Anapiculatisporites spiniger*)	Lycopodiophyta; *Carinostrobus* spp. (Balme, 1995; Kustatscher et al., 2012)
Cingulizonates rhaeticus	Lycopodiophyta; Lycopsida (Mander et al., 2010)
Clathroidites papulosus	Pteridophyta; Filicopsida; Filicales; *Clathropteris meniscoides* (Bai et al., 1983)
Conbaculatisporites spp.	Pteridophyta; Filicopsida; Filicales (Mander et al., 2010)
Concavisporites spp.	Pteridophyta; Filicopsida; Filicales (Mander et al., 2010)
Deltoidospora spp.	Pteridophyta; Filicopsida; Filicales (Balme, 1995; Mander et al., 2010)
Dictyophyllidites mortonii	Filicopsida; Dipteridaceae and Matoniaceae (Balme, 1995)
Gordonispora spp.	Bryophyta (Petersen and Lindström, 2012)
Ischyosporites spp.	Pteridophyta; Filicopsida (Polypodiopsida); Schizaeaceae (Martin et al., 2013a,b)
Krauselisporites spp.	Lycopodiophyta; Lycopsida; Lycopodiales (Balme, 1995)
Kyrtomisporis spp.	Pteridophyta (Bonis, 2010)
Leschikisporis aduncus	Pteridophyta; Marattiopsida; Marattiales; *Asterotheca meriani* (Balme, 1995; Kustatscher and Van Konijnenburg-Van Cittert, 2011)
Limbosporites lundbladii	Lycopodiophyta; Lycopsida (Balme, 1995)
Limatulasporites limatulus	Bryophyta (McLoughlin et al., 1997)
Lycopodiacidites rugulatus	Pteridophyta; Filicopsida; Filicales (Balme, 1995; Mander et al., 2010)
Lycopodiumsporites semimuris	Lycopodiophyta; Lycopsida (Mander et al., 2010)
Neoraistrickia taylori	Lycopodiophyta; Lycopsida; Lycopodiales (Gary et al., 2009)
Osmundacidites spp.	Pteridophyta; Filicopsida (Polypodiopsida); Osmundaceae (Van Konijnenburg-Van Cittert, 1978)
Polycingulatisporites spp.	Bryophyta; Sphagnales (Koppelhus, 1991)
Porcellispora longdonensis	Hepatophyta (Bonis and Kürschner, 2012)
Retitriletes austroclavatidites	Lycopodiophyta; Lycopsida (Mander et al., 2010; Martin et al., 2013a, 2013b)
Rogalskaisporites spp.	Bryophyta; Sphagnales (Koppelhus, 1991)
Striatella spp.	Pteridophyta; Filicopsida (Polypodiopsida); Pteridaceae (Filatoff, 1975; Filatoff and Price, 1988)
Stereisporites spp.	Bryophyta; Sphagnopsida; Sphagnales (Filatoff, 1975; Boulter and Windle, 1993; Martin et al., 2013a, 2013b)
Trachysporites spp.	Pteridophyta; Filicopsida; Filicales (Mander et al., 2010)
Uvaesporites argentaeformis	Lycopodiophyta; Isoetopsida; Selaginellales (Balme, 1995; Mander et al., 2010)
Velosporites cavatus	? Lycopodiophyta; Lycopsida
Zebrasporites spp.	Pteridophyta; Filicopsida; Filicales; Cyatheaceae (Bonis, 2010; Bonis and Kürschner, 2012)
Pollen taxon	**Botanical affinity**
Araucariacites australis	Coniferopsida; Coniferales; Araucariaceae (Mander et al., 2010)
Aulisporites astigmosus	Cycadophyta; Spermatopsida; Bennettitales; found *in situ* in *Williamsonianthus keuperianus* (Kräusel and Schaarschmidt, 1966; Balme, 1995)
Cerebropollenites macroverrucosus	Coniferopsida; Coniferales; Taxodiaceae (Bonis, 2010; Mander et al., 2010)
Chasmatosporites spp.	Cycadopsida; Cycalades (Mander et al., 2010) Ginkgopsida; Ginkgoales (Mander et al., 2010)
Classopollis torosus	Coniferopsida; Coniferales; Cheirolepidiaceae (Bonis, 2010; Mander et al., 2010)
Cycadopites spp.	Cycadopsida; Cycalades (Mander et al., 2010) Ginkgopsida; Ginkgoales (Mander et al., 2010) Pteridospermopsida; Peltaspermales (Mander et al., 2010) Bennetitopsida; Bennettitales (Mander et al., 2010)
Eucommiidites spp.	Cycadopsida;? Cycalades (Balme, 1995)
Illinites chitinoides	Coniferopsida; Voltziales; *Willsiostrobus acuminatus* (*Aethophyllum*, Grauvogel-Stamm, 1978; Balme, 1995)
Lunatisporites spp. *	Coniferopsida; Coniferales; Voltziaceae (Bonis, 2010)
Parvisaccites radiatus	Coniferopsida; Voltziales (Balme, 1995)
Ovalipollis spp.	? Coniferopsida (Petersen and Lindström, 2012)
Protodiploxypinus spp.	Conifer (Samoilovich, 1953); Pinaceae or Podocarpaceae (Scheuring, 1970); *in situ* in *Sertostrobus laxus*, *Darneya peltata* and *D. mougeoutii* (Grauvogel-Stamm, 1978)
Quadraeculina anellaeformis	Coniferopsida; Coniferales; Podocarpaceae (Bonis, 2010; Mander et al., 2010)
Ricciisporites spp.	Gymnospermae (Mander et al., 2012; Kürschner et al., 2014)
Striatoabieites spp.	Pteridospermatophyta (Bonis, 2010)
Triadispora verrucata	Coniferopsida; Coniferales; Voltziaceae (Balme, 1995); *in situ* in *Sertostrobus*, *Darneya* (Grauvogel-Stamm, 1978)
Vesicaspora fuscus	Pteridospermatophyta; Pteridospermopsida (Mander et al., 2010)
Vitreisporites pallidus	Pteridospermatophyta; Caytoniales (Bonis, 2010)

Svenskøya Formation on Hopen based on palynological data (Paterson and Mangerud, 2015).

3. Materials and methods

3.1. Sampling

This study was based on the analysis of 105 outcrop samples from Hopen collected during a Norwegian Petroleum Directorate expedition in 2011. Samples from three localities were analysed for palynofacies, micropalaeontology and $\delta^{13}C_{org}$; the three sections are Binnedalen, Lyngefjellet and Blåfjellet (Fig. 1). Both the Binnedalen and Lyngefjellet sections are located on the northern tip of Hopen, approximately 1 km apart, around the highest point on the island, Lyngefjellet. These sections are well illustrated by Lord et al. (2014a, Figs. 1 and 5), where they are termed “Binnedalen” and “Lyngefjellet NE”. The Blåfjellet section is located approximately 7 km south southwest of Lyngefjellet, and was previously referred to as “Blåfjell E” by Lord et al. (2014a, Fig. 1).

3.2. Processing and analysis

Approximately 10 g of rock was processed per sample for palynology, using standard HCl and HF maceration techniques (see Traverse, 2007, pp. 632–647). Palynological slides were prepared by Palynological Laboratory Services (PLS), UK. Figured specimens are curated at the Natural History Museum, University of Oslo, Norway.

Supplementary palynological data was based on range charts presented by Paterson and Mangerud (2015). Selected palynomorph taxa are illustrated in plates I and II. As a palaeoenvironmental proxy, palynomorphs were grouped according to their presumed botanical affinity (Table 1), and assigned to Sporomorph Eco Groups (SEGs) (Table 2) following Abbink (1998) and Abbink et al. (2004). SEGs reflect the following ecological and environmental associations: (1) marine, (2) brackish–freshwater, (3) pioneer plant, (4) coastal pioneer, (5) wet lowland, (6) dry lowland, (7) river and (8) hinterland/upland. These SEGs were originally established to accommodate Jurassic and Cretaceous palynomorphs from the North Sea region (Abbink, 1998; Abbink et al., 2004). However, since many of the same palynomorph genera are present in the Upper Triassic succession in the Barents Sea region, we consider usage of the scheme appropriate in this instance. In the case of taxa, which are absent in Jurassic assemblages, SEGs have been allocated based on the inferred palaeoenvironmental tolerances and preferences of their parent plants following the rationale outlined by Abbink (1998).

Relative palynomorph abundance was plotted as spore–pollen–microplankton (SPM) ternary diagrams (after Federova, 1977;

Table 2
Ecological grouping of selected Late Triassic palynomorph taxa from Hopen. Fern spores are attributed to the Wet Lowland SEG but may also be attributed to the River SEG; bryophyte spores placed in the River SEG may also be attributed to the Lowland SEG. Groupings based on Abbink (1998), Kustatscher et al. (2012) and Petersen and Lindström (2012).

Sporomorph ecogroup (SEG)	Species	Environmental remarks
Marine	*Rhaetogonyaulax* spp.	
	Sverdrupiella spp.	
Brackish–freshwater	*Botryococcus* spp.	
	Plaesiodictyon mosellanum	
Coastal pioneer	*Cerebropollenites macroverrucosus*	
	Protodiploxypinus spp.	Xerophytic–tidal flats (Brugman, 1986)
Coastal	*Aratrisporites* spp.	
	Araucariacites australis	
	Carnisporites spiniger	
	Cingulizonates rhaeticus	
	Classopollis torosus	
	Illinites chitinoides	Conifer forming reed-like vegetation on delta plain (Brugman et al., 1994)
	Ischyosporites spp.	
	Krauselisporites spp.	
	Retitriletes austroclavatidites	
	Striatella spp. (=*Asseretospora* spp.)	
	Velosporites cavatus	
Wet lowland	*Apiculatasporites* spp.	
	Apiculatisporis spp.	
	Baculatisporites spp.	Mire (Petersen and Lindström, 2012)
	Clathroidites papulosus	
	Conbaculatisporites spp.	
	Concavisporites spp.	
	Leschikisporis aduncus	
	Ricciisporites spp.	? Mire (Petersen and Lindström, 2012)
	Trachysporites spp.	
	Vitreisporites pallidus	
	Zebrasporites spp.	Mire (Petersen and Lindström, 2012)
Dry lowland	*Aulisporites astigmosus*	
	Chasmatosporites spp.	
	Cycadopites spp.	
	Deltoidospora spp.	
	Dictyophyllidites mortonii	
	Eucommiidites spp.	
River	*Annulispora folliculosa*	
	Calamospora spp.	River banks (Petersen and Lindström, 2012)
	Gordonispora spp.	
	Limatulasporites limatulus	
	Lycopodiacidites rugulatus	
	Lycopodiumsporites semimuris	
	Neoraistrickia taylori	
	Osmundacidites spp.	
	Polycingulatisporites spp.	
	Porcellispora longdonensis	
	Rogalskaisporites spp.	
	Stereisporites spp.	
	Uvaesporites argentaeformis	
Hinterland/Upland	Alete bisaccate pollen	
	Lunatisporites spp.	Well-drained (Petersen and Lindström, 2012)
	Ovalipollis spp.	Well-drained, habitat unknown (Petersen and Lindström, 2012)
	Parvisaccites radiatus	
	Quadraeculina anellaeformis	Habitat unknown (Petersen and Lindström, 2012)
	Striatoabieites spp.	
	Triadispora verrucata	
	Vesicaspora fuscus	

Chronostratigraphy (Paterson & Mangerud, 2015)	**Lithostratigraphy** (Mørk et al., 2013)	**Palynostratigraphy** (Paterson & Mangerud, 2015)	**Biofacies unit**	**Palynology**	**Palynofacies**	**Micropalaeontology**	**Macropalaeontology**
Rhaetian ? Norian - Rhaetian	Svenskøya Fm.	*Rogalskaisporites ambientis* *Limbosporites lundbladii*	VI	Terrestrial palynomorph dominanted assemblages consisting of fern, bryophyte and lycopsid spores, and conifer pollen. "Coastal", "River" and "Wet Lowland" SEGs.	Phytoclast and sporomorph dominanted.	Interval barren of microfossils	Fragmentary plant remains
disconformity							
early Norian	Flatsalen Fm.	*Rhaetogonyaulax rhaetica*		Increase in terrestrial and freshwater palynomorphs coupled with a decrease in marine microplankton.	Phytoclasts dominant.	Interval barren of microfossils	Interval barren of macrofossils
			IV	Assemblages dominated by dinoflagellate cysts (*Rhaetogonyaulax rhaetica*) and acritarchs; terrestrial palynomorphs rare.	AOM dominant; sporomorphs and phytoclasts rare.	Acme of Radiolaria. Low abundance and low diversity assemblages of foraminifera in basal part. Assemblages dominated by deep infauna. Silicified ostracod moulds common. Increase in agglutinated foraminifera abundance and diversity in upper part, with dominance of opportunistic taxa (e.g. *Glomospira).*	Bivalves: *Anodontophora* cf. *ovalis*, *Halobia aotii*, *H.* cf. *maximiliani*, *H. zitteli*, *H.* cf. *obruchevi*, *'Gryphaea' sp.* Icthyosaur remains
		Classopollis torosus	III	Microforaminiferal linings and acritarchs, dinoflagellate cysts and prasinophytes common. Terrestrial palynomorphs rare, mostly bisaccate pollen.	AOM mixed with phytoclasts and sporomorphs.	Superabundant agglutinated foraminifera. Dominance of epifaunal species.	Ammonoids: *Arctosirenites* spp, *Argosirenites* cf. *obručevi*, *Sirenites, Sirenites nelgehensis* Bivalves: *Anadontophora* cf. *ovalis*
late Carnian	De Geerdalen Fm. — Hopen Mbr.	*Protodiploxypinus* spp.	II	Conifer pollen-rich assemblages, particularly *Protodiploxypinus* spp.; influx in taxa belonging to "Hinterland/Upland" SEG; freshwater alga *Plaesiodictyon mosellanum* common.	Phytoclast and sporomorph dominated.	Rare agglutinated foraminifera and fish remains.	Bivalves: *Anadontophora* cf. *lettica*, *A.* cf. *sublettica*, *A. cf. griesbachi Anadontophora* sp., *Myticus* cf. *nasai*, *Pteurophorus* (?) sp. Conchostraca: *Euesthesia minuta*, *Howellites princetonensis*, *Pseudoestheria ovata*
	De Geerdalen Fm.	*Leschikisporis aduncus*	I	Fern spore dominanted assemblages assignable to the "Wet Lowland" and "River" SEGs. Interval characterised by an acme of *Leschikisporis aduncus.* Acritarchs and dinocysts rare.	Phytoclast and sporomorph dominated.	Rare agglutinated foraminifera and fish remains.	Macroplant fossils: Pteridophytes *Clathropteris* sp., *Dictyophyllum* sp., *Neocalamites merianii* Pteridosperms *Paratatarina ptchelinae;* Cycadophytes *Pterophyllum filicoides P. brevipenne*, *P.* cf. *firmifolium*, *Nilssoniopteris angustior*, Ginkgophytes *Arberophyllum spetsbergensis*, *A. substrictum ?. Sphenobaiera* sp., *Ginkgoites* sp. Bivalves: *Anadontophora* sp. Conchostraca: *Euesthesia minuta*

Fig. 4. Outline of the biofacies units for the Kapp Toscana Group on Hopen and a summary of palynological, palynofacies and micropalaeontological observations. Macrofossil occurrences summarised from: ammonoids (Flood et al., 1971; Smith et al., 1975; Korčinskaya, 1980); bivalves (Flood et al., 1971; Pčelina, 1972); ichthyosaur remains (Cox and Smith, 1973); conchostracans (Pčelina, 1972); macroplant fossils (Flood et al., 1971; Pčelina, 1972; Smith et al., 1975; Launis et al., 2014; Pott, 2014).

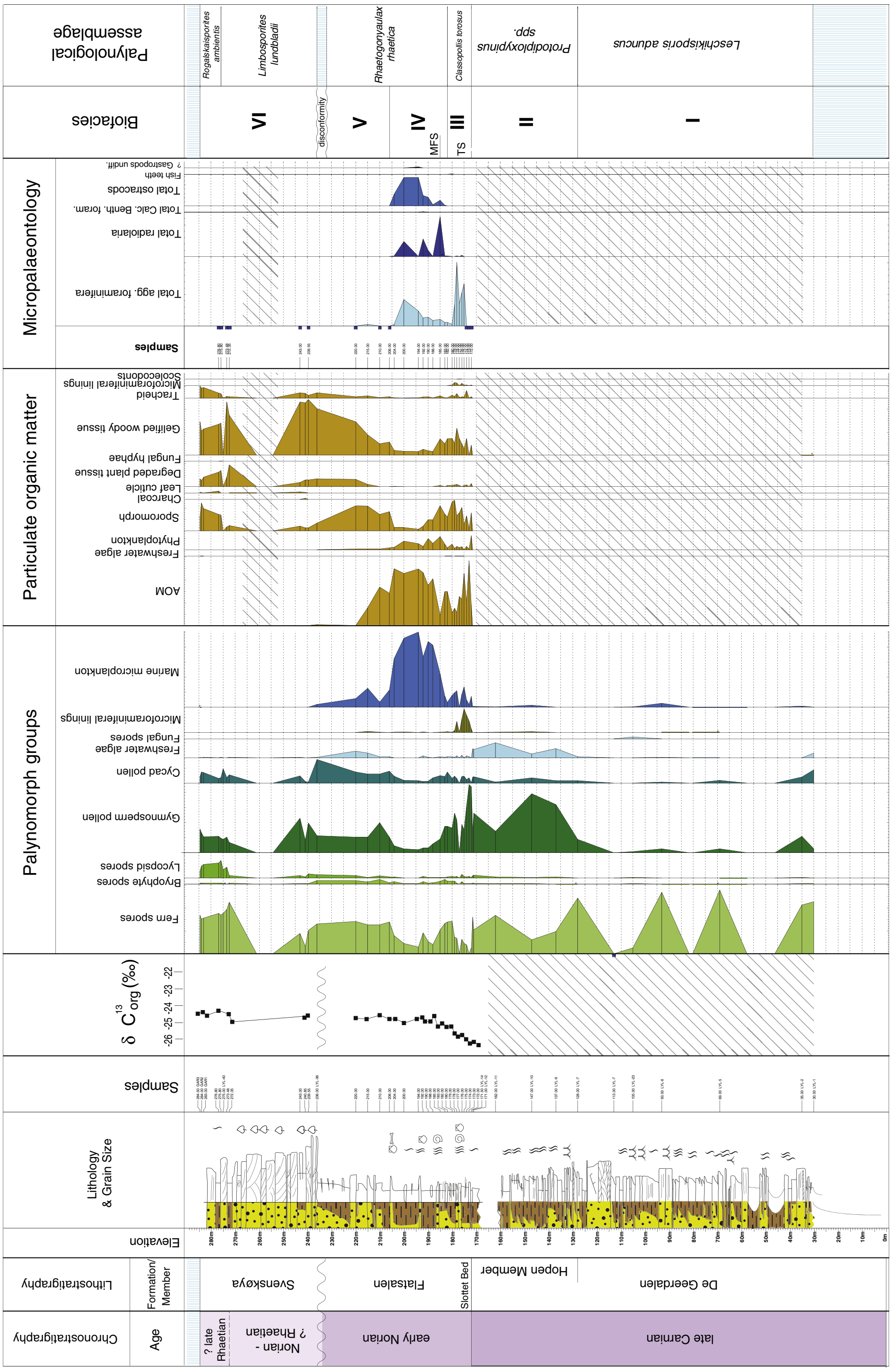

Fig. 5. Organic carbon, relative abundance of palynomorph groups, particulate organic matter and microfossils from Lyngefjellet, Hopen. Palynological assemblages are from Paterson and Mangerud (2015).

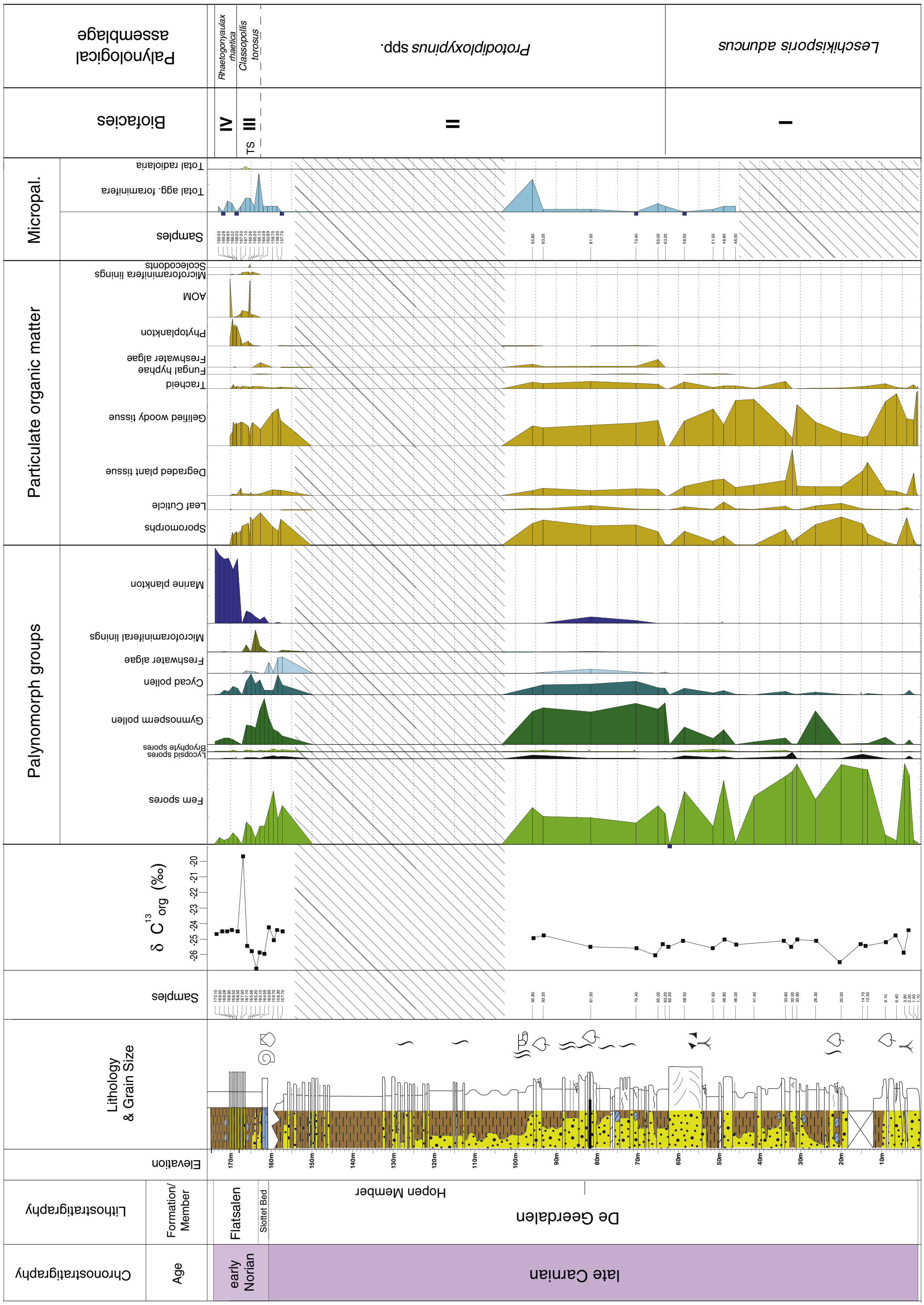

Fig. 6. Organic carbon, relative abundance of palynomorph groups, particulate organic matter and microfossils from Binnedalen, Hopen. Palynological assemblages are from Paterson and Mangerud (2015).

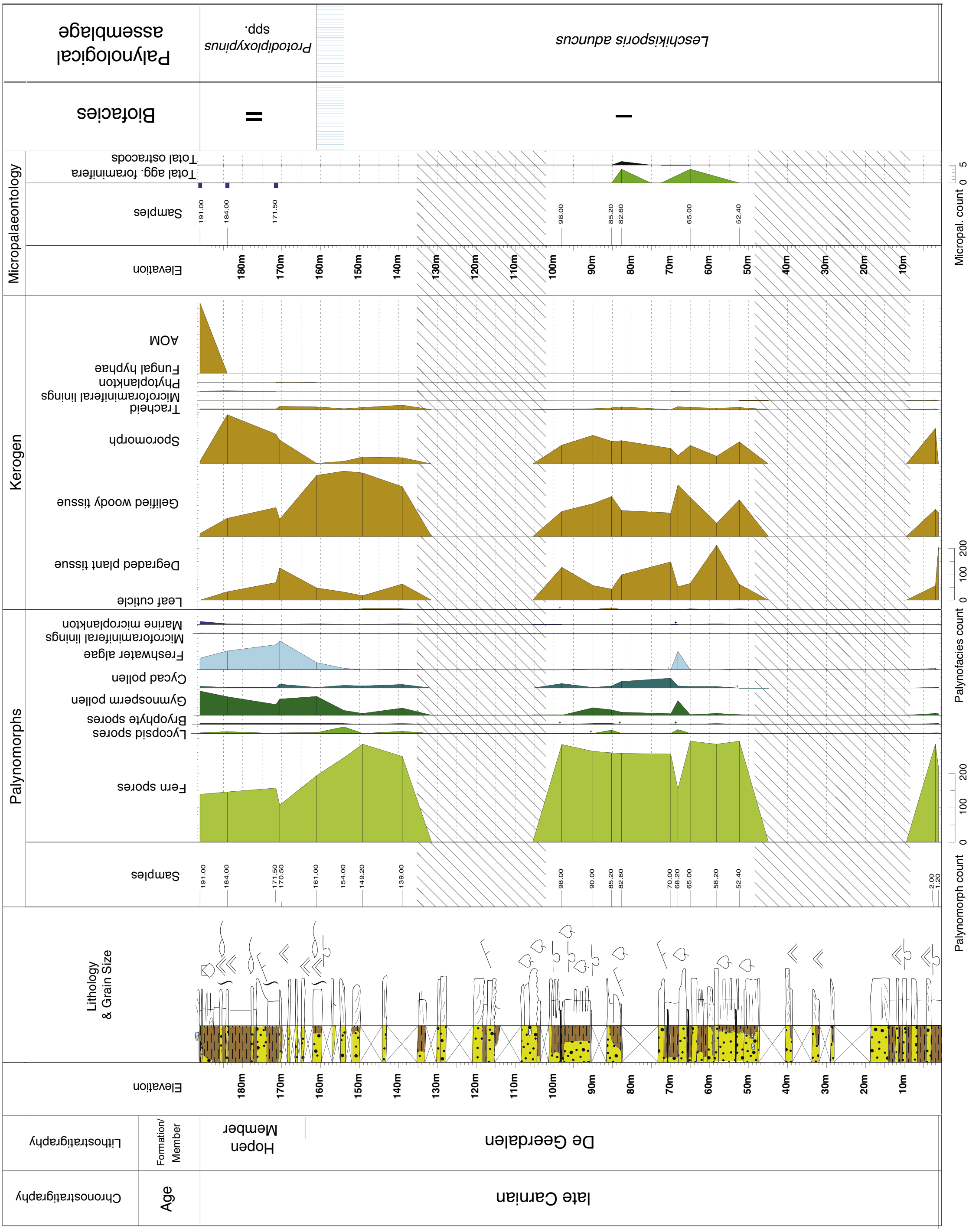

Fig. 7. Relative abundance of palynomorph groups, particulate organic matter and microfossils from Blåfjellet, Hopen. Palynological assemblages are from Paterson and Mangerud (2015).

Traverse, 1988; Duringer and Doubinger, 1985) to show transgressive–regressive trends. Palynofacies analysis was conducted by counting a minimum of 300 particles per sample; palynofacies analysis was performed using un-oxidised and un-sieved palynological preparations. Particulate organic matter (POM) was classified according to the scheme outlined by Tyson (1995, p.341–365) and plotted as AOM–phytoclast–palynomorph ternary diagrams.

Quantitative micropalaeontological analysis was conducted on 63 samples from the three investigated sections; 29 samples from Lyngefjellet, 25 samples from Binnedalen and 8 from Blåfjellet. No sample material was available for micropalaeontological study from the De Geerdalen Formation from the Lyngefjellet section; however, this interval was covered by samples from the correlative interval at the Binnedalen and Blåfjellet sections. Selected microfossil taxa are

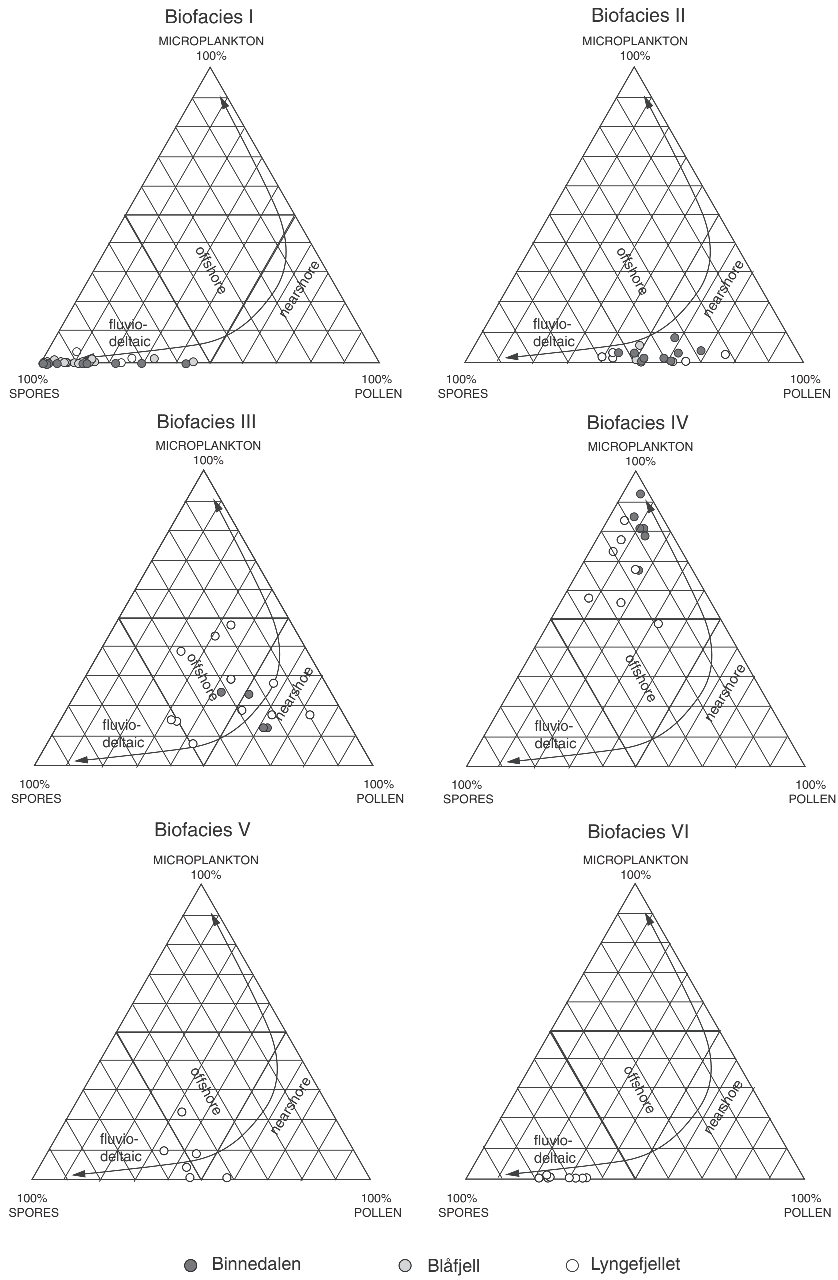

Fig. 8. Spore–pollen–microplankton ternary plots for biofacies units (I–VI) at Blåfjellet, Binnedalen and Lyngefjellet (after Federova, 1977; Traverse, 1988, p. 32; Duringer and Doubinger, 1985, p. 27). Curved arrow indicates a smoothed theoretical transgressive–regressive trend.

Table 3
Microfossil occurrences from Lyngefjellet.

Age (from Paterson & Mangerud submitted)	Formation	Sample depth (m)	Barren	Agglutinated Foraminifera																															Radiolaria			Access. Fossils		Total Agglutinated Foraminifera	Total Ostracoda	Total Radiolaria
				Verneuilinoides aff. *subvitreus*	*Spiroplectammina* spp.	*Gaudryina adoxa*	*Eobigenerina* spp.	*Verneuilinoides* spp.	? *Verneuilinoides* spp.	*Trochammina* sp. 1 *sensu* Nagy et al. 2010	*Trochammina* aff. *eoparva*	*Recurvoides* spp.	*Kutsevella* spp.	*Ammobaculites* spp.	*Verneuilinoides* aff. *kirillae*	*Kutsevella* aff. *haplophragmoides*	*Reophax* / *Nodulina* spp.	*Reophax metensis*	*Lagenammina* aff. *inanis*	*Glomospora gordialis*	*Ammodiscus* aff. *yonsnabensis*	*Trochammina* spp.	*Thuramina* spp.	*Lituotuba perplexa*	Indet. agg. foraminifera	*Glomospirella* spp.	*Ammolagena clavata*	*Ammodiscus incertus*	Agg. foram fragments	*Glomospira irregularis*	*Trochammina eoparva*	*Saccammina* spp.	*Nodulina liassica*	*Dentalina* spp. (pyr.)	Radiolaria (non-pyritised)	Radiolaria (pyritised)	*Cenosphaera* spp. (pyr.)	Fish teeth	? Gastropods undiff.			
Rhaetian	Svenskøya	276.6	B																																							
		275.88	B																																							
		273.48	B																																							
		272.35	B																																							
Early Norian		243	B																																							
		233.55	B																																							
	Flatsalen	220	B																																							
		215																													1	1	1								3		
		210	B																																							
		206	B																																							
		204																												2		1					1			3	28	1
		200																					9	2	3	5	1	1?	1	2	9		22					24			42	68	24
		194																	1	2	2	4	1		4					1	1	5		3	1						p	24	68	
		192															7	2				1	1			2									1?			28			13	25	28
		190														1		3				2	2			1			4		1							8			14	21	10
		188																		1		3				1					3			1							9	3	
		185																6	1				1											3				63			11	14	63
		183															1						1			3							1			1					6	2	1
		182																	1			2	2			1											1				6		1
		180																		1				1		1				1									p		3		
		179																	7	1		3	10	1		7				7	1	3	1								34		
		178							1	1	1	1	1	1	1	2		3	2		2	37			27				1	4	15	2			1					101		1
		177						1?			1			1		1		4			2	12			14															36		
		176			1	1	1	1			1			3				5	1		4	10			19						6				2					53		2
		175		1		2						1		3	3			1	2		4	27			18				1		4	1								67		
		174	B																																							
		173	B																																							
		172	B																																							

illustrated in Plate III. Micropalaeontological residues are curated at the Department of Earth Sciences, University of Bergen, Norway.

Seventy-one samples from Binnedalen and Lyngefjellet were analysed for bulk $\delta^{13}C_{org}$. Approximately 1 g of rock was crushed and treated with 15 ml of 1 M HCl for 24 h to dissolve carbonates. The acid was removed with repeated centrifugation and rinsing with deionised water until neutralised. Samples were dried overnight and homogenised by crushing before analysis. Carbon isotope ratios were measured using a Thermo Finnigan Flash EA elemental analyser connected to a Thermo Scientific Delta V isotope ratio mass spectrometer. One standard deviation of replicate analyses ($n = 3$ to 6) was 0.2‰ or lower. Carbon isotope ratios are expressed in delta notation relative to the Vienna Peedee Belemnite.

4. Results

Six biofacies units were recognised based on the integration of palynology, palynofacies analysis and micropalaeontology (Fig. 4). The biofacies units correspond closely with the established lithological and palynological subdivisions; they are as follows.

Table 4
Microfossil occurrences from Binnedalen.

Age (from Paterson & Mangerud submitted)	Formation	Member	Sample depth (m)	Barren	Agglutinated Foraminifera														Radiolaria	Total Agglutinated Foraminifera	Total Radiolaria
					Reophax spp.	*Psammosphaera* spp.	*Reophax ? metensis*	*Thurammina* spp.	*Ammodiscus* aff. *yonsnabensis*	*Ammodiscus* cf. *peruvianus*	Agg. foram fragments	*Trochammina* aff. *eoparva*	*Trochammina eoparva*	*? Ammobaculites* spp.	*Reophax metensis*	*Trochammina* spp.	Indet. agg. Foraminifera	*Saccammina* spp.	*Cenosphaera* spp. (non pyr.)		
Early Norian	Flatsalen		169.50															2		2	
			169.28	B																	
			168.95													1	1	2		4	
			168.82												2	1				3	
			168.50																		
			167.50												2					2	
			167.10											1	2	2			1	5	1
			165.56									1	2		1	1				5	
			165.20								1				1	1				2	
			165.10					1	4	2	3		3		1	3				14	
			164.59												1			1		2	
Late Carnian	De Geerdalen	Hopen	162.69				2													2	
			159.70												1		1			2	
			158.30													1		1		2	
			157.70	B																	
			95.80														3	6		12	
			93.20													1				1	
		undiff.	81.50															1		1	
			70.40	B																	
			65.00													2				2	
			63.20													2				3	
			58.50	B																	
			51.50													1?				1	
			48.80			1									1					2	
			46.00		1													1		2	

4.1. Biofacies unit I (lower undifferentiated De Geerdalen Formation)

Palynological assemblages from the lower exposures of the De Geerdalen Formation on Hopen were dominated by fern spores, particularly *Leschikisporis aduncus* (Figs. 5–8), representing >90% of the total assemblage in some samples. Marine palynomorphs including acritarchs and dinoflagellate cysts were a rare but consistent feature of the assemblages and were recorded in samples corresponding with the "lower", "middle" and "upper" channel zones of Lord et al. (2014b). Micropalaeontological samples from the De Geerdalen Formation at Binnedalen and Blåfjellet yielded poorly preserved, low abundance/low diversity assemblages of agglutinated foraminifera (Figs. 6 and 7; Tables 4 and 5). The poor preservation of foraminifera from this interval precluded the identification of taxa to species level, and only one species, *Reophax metensis*, was confidently identified. Five genera were recorded: *Caudammina* spp., *Psammosphaera* spp., *Reophax* spp., *Saccammina* spp. and *Trochammina* spp. Samples from Blåfjellet also contained rare ostracods and fish remains (Table 5). Particulate organic matter assemblages from the lower part of the formation were dominated by phytoclasts, especially gelified wood (Figs. 6, 7 and 9; Plate IV). Palynomorphs, primarily fern spores, were also a common constituent of POM assemblages. The $\delta^{13}C_{org}$ data from this interval at Binnedalen (Fig. 6) show a slight negative trend upwards to 20 m followed by a shift to more positive values around −25.5‰ from 26.3 m to the lower Hopen Member at 81.5 m.

4.2. Biofacies unit II (Hopen Member)

Palynological assemblages from the Hopen Member contained a relatively high abundance of bisaccate gymnosperm pollen (Figs. 5–8), particularly *Protodiploxypinus* spp. Very few specimens of *Leschikisporis aduncus* were recorded in this interval in comparison to the samples from the lower exposures of the De Geerdalen Formation. Many spore taxa present in Biofacies unit I were recorded but in lower relative abundance due the increased abundance of gymnosperm and cycad pollen. A slight increase in the abundance of marine microplankton was observed, and the freshwater alga *Plaesiodictyon mosellaneum* was noted as a characteristic feature of assemblages at all localities. Micropalaeontological samples from the Hopen Member at Blåfjellet were barren (Fig. 7; Table 5), but samples from the equivalent interval at Binnedalen yielded poorly preserved, low diversity assemblages of agglutinated foraminifera. The same taxa recorded in Biofacies unit I were recorded in similar low abundance (Fig. 6; Table 4). Particulate organic matter assemblages from the Hopen Member were similar to those from the undifferentiated De Geerdalen formation below (Figs. 6, 7 and 9; Plate II) and consisted mainly of gelified wood and terrestrial palynomorphs; marine microplankton was a relatively rare component of the POM assemblages throughout this interval. In the basal Hopen Member at Binnedalen, a slight positive shift (~1‰) in $\delta^{13}C_{org}$ values was noted (Fig. 6), which contrasts with the values obtained from the lowermost exposures of the De Geerdalen Formation.

4.3. Biofacies unit III (lower Flatsalen Formation)

Palynomorph assemblages from the basal Flatsalen Formation were similar to those from the Hopen Member but were distinguished by the appearance and common occurrence of microforaminiferal test linings and an increase in the relative abundance of marine microplankton, including the dinoflagellate cysts *Rhaetogonyaulax arctica*, *R. rhaetica* and various acritarchs (Figs. 5 and 6). Bisaccate gymnosperm pollen was also noted as being relatively abundant in this interval. Particulate organic matter assemblages were dominated by amorphous organic matter (AOM), with lesser amounts of sporomorphs and marine palynomorphs (Figs. 5, 6 and 9; Plate II).

Table 5
Microfossil occurrences from Blåfjellet.

Age (from Paterson & Mangerud submitted)	Formation	Member	Sample depth (m)	Barren	Agglutinated Foraminifera					? Ostracods - gen. undiff. (casts)	Access. Fossils							Total Agglutinated Foraminifera	Total ostracods
					Indet. agg. Foraminifera	*Trochammina* spp.	*Reophax metensis*	*Caudammina* spp.	*Saccammina* spp.		Wood frag. (pyr.)	Pyrtisised worm tubes	Fish teeth	Fish scales	Fish bones	Wood fragments	Megaspores indet.		
Late Carnian	De Geerdalen	Hopen	190.80	B															
			184.00	B															
			171.50	B															
		undiff.	98.00													p	p		
			85.20	B															
			82.60				1	2	1	1	p	p	p	p	p			4	1
			65.00		1	1	2									p		4	
			50.40								p								

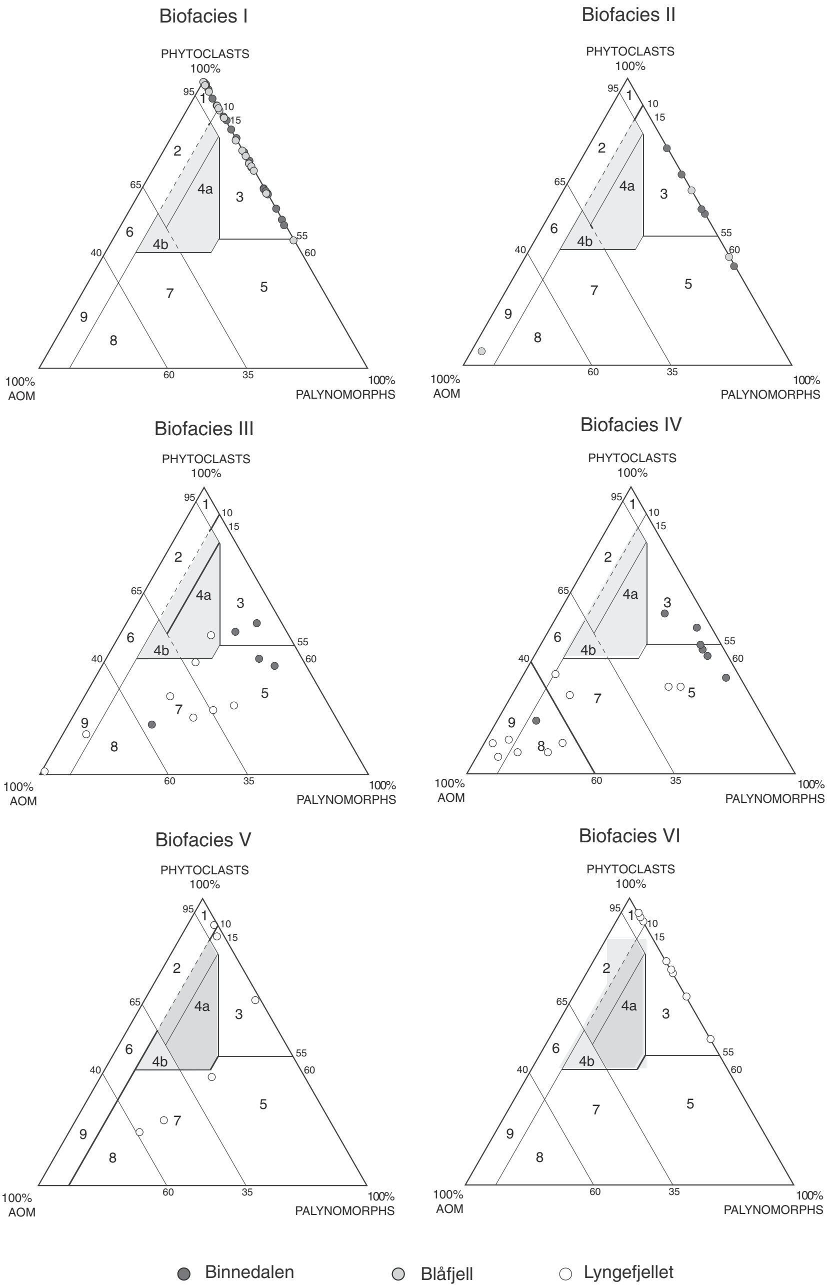

Fig. 9. "AOM"-Palynomorph-Phytoclast (APP) ternary plots for biofacies units (I–VI) at Blåfjellet, Binnedalen and Lyngefjellet, with inferred depositional environments (after Tyson, 1985, 1989, 1993). Field 1 = Highly proximal shelf or basin; Field 2 = Marginal dysoxic–anoxic basin; Field 3 = Heterolithic oxic shelf (proximal); Field 4 = Shelf to basin transition; Field 5 = Mud dominated oxic shelf (distal); Field 6 = Proximal suboxic-anoxic shelf; Field 7 = Distal suboxic-anoxic shelf; Field 8 = Distal dysoxic-oxic shelf; Field 9 = Distal suboxic-anoxic basin.

Micropalaeontological assemblages from this interval were comprised exclusively of agglutinated foraminifera (Figs. 5 and 6; Tables 3 and 4). At the Lyngefjellet section, samples from the base of the formation (172–174 m) were barren, followed by the sudden first super-abundant occurrence of agglutinated foraminifera, which was recorded at 175 m. The highest abundance and diversity of foraminifera was recorded in the interval between 175 and 179 m where the assemblage was characterised by a dominance of small specimens of epifaunal taxa including *Ammodiscus* aff. *yonsnabensis*, *Trochammina* aff. *eoparva* and *Trochammina* spp. (Table 3). The absence of calcareous forms in the assemblage may be attributed to post-depositional carbonate dissolution.

The $\delta^{13}C_{org}$ data from the lower part of the Flatsalen Formation at Binnedalen show a negative trend in values from −25.5‰ at 162.69 m to −27‰ at 165.2 m (Fig. 6). This is consistent with similar $\delta^{13}C$ values in samples from the lower Flatsalen Formation at Lyngefjellet (Fig. 5). However, at Binnedalen, a large positive excursion of ~6‰ was recorded in a single sample 167.5 m, which was not

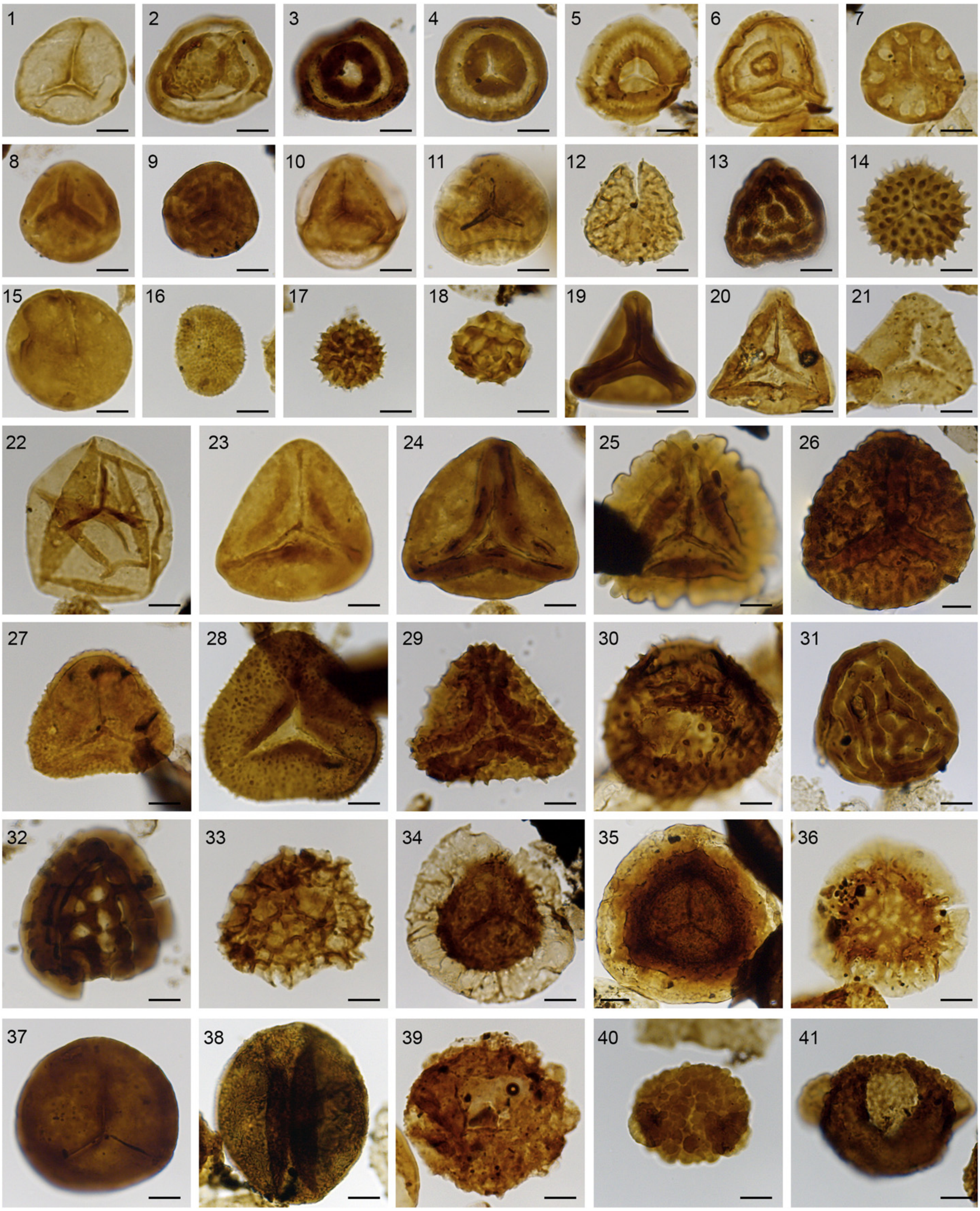

Plate I. *(caption on page 32)*

observed in the equivalent interval at Lyngefjellet, possible due to differences in sample density.

4.4. Biofacies unit IV (middle Flatsalen Formation)

Palynological assemblages from the middle part of the Flatsalen Formation from the Lyngefjellet and Binnedalen sections were dominated by dinoflagellate cysts (Figs. 5–6 and 8), particularly *Rhaetogonyaulax rhaetica*. The abundance of terrestrial palynomorphs was noted as relatively low within this interval due to the dominance of marine taxa. Particulate organic matter assemblages were dominated by AOM (Figs. 5 and 6). In micropalaeontological samples from Lyngefjellet an abrupt decrease in the abundance and diversity of agglutinated foraminifera was recorded at 180 m, corresponding to a transition from epifaunal to deep infaunal taxa such as *Reophax metensis* and *Saccammina* spp., and preceding an acme of radiolaria (pyritised *Cenosphaera* spp.) recorded at 185 m (Fig. 5; Table 3). Two smaller abundance peaks of radiolaria were observed at 192 m and 200 m. Between 183 and 204 m, silicified ostracod moulds were also recorded. The abundance of ostracods was observed to increase from 190 m, with peak abundances recorded in samples 194 m and 200 m. An increase in the diversity and abundance of agglutinated assemblages was noted in the upper Flatsalen Formation from 190 m upwards, with a dominance of opportunistic taxa such as *Glomospira* spp. (Table 3).

Some differences are evident between assemblages from Binnedalen and Lyngefjellet sections (Figs. 4 and 5; Tables 3 and 4). For instance, the acmes of radiolaria and ostracods observed in samples from Lyngefjellet are both absent in the Binnedalen preparations. However, since more samples were collected at Lyngefjellet over several metres of section, such differences probably relate to sampling bias rather than to palaeoenvironmental control. At both sections a shift to more positive $\delta^{13}C$ values (~25‰) was recorded, from 168.5 m at Binnedalen and 179 m at Lyngefjellet (Fig. 5).

4.5. Biofacies unit V (upper Flatsalen Formation)

This unit is characterised by an increase in the relative abundance of terrestrial and freshwater palynomorphs, coupled with a decrease in marine phytoplankton (Fig. 5). This corresponds with an increase in terrestrial palynomorphs, and an increase in sporomorphs and phytoclast noted in POM assemblages from the same stratigraphic interval. Marine palynomorphs were found to be increasingly rare approaching the top of the Flatsalen Formation (Fig. 5), and a brief reappearance of the freshwater alga *Plaesiodictyon mosellaneum* was recorded. Micropalaeontological samples from this interval were barren. The $\delta^{13}C_{org}$ curve from Lyngefjellet remains consistent above 185 m between −25 and −24.5‰ (Fig. 5).

4.6. Biofacies unit VI (Svenskøya Formation)

The six samples processed for micropalaeontology from the Svenskøya Formation at Lyngefjellet were barren of microfossils (Fig. 5; Table 3). In contrast, palynology samples yielded abundant and relatively well preserved assemblages consisting almost exclusively

Plate I. Palynomorph taxa from Hopen. Following the taxon name is the sample number, England Finder Slide coordinates, locality, formation and Palaeontological Museum of Oslo numbers. Scale bars equal 10 μm. (see on page 31)

1. *Stereisporites* spp. GAR 284m b F36-4, Lyngefjellet, Svenskøya Fm, PMO 229.184/1
2. *Limatulasporites limatulus* BIN-11-11 V48-2, Binnedalen, De Geerdalen Fm., PMO 229.165/1
3. *Annulispora folliculosa* BIN-11-36 W57-4, Binnedalen, De Geerdalen Fm., PMO 229.171/1
4. *Gordonispora* spp. BIN-11-36 V60-3, Binnedalen, De Geerdalen Fm., PMO 229.171/2
5. *Polycingulatisporites bicollateralis* LYN-11 40.35m F58-1, Lyngefjellet, Svenskøya Fm., PMO 229.177
6. *Polycingulatisporites mooniensis* LYN-11 41.48m J57, Lyngefjellet, Svenskøya Fm., PMO 229.178
7. *Rogalskaisporites ambientis* GAR 284m b M59-3, Lyngefjellet, Svenskøya Fm., PMO 229.184/2
8. *Camarozonosporites laevigatus* LYN-11 43.80m V61-4, Lyngefjellet, Svenskøya Fm., PMO 229.179/1
9. *Camarozonosporites rudis* BIN-11-36 E61-1, Binnedalen, De Geerdalen Fm., PMO 229.171/3
10. *Zebrasporites laevigatus* LYN-11 41.48m V45, Lyngefjellet, Svenskøya Fm., PMO 229.178/2
11. *Zebrasporites interscriptus* LYL-40 d P36-3, Lyngefjellet, Svenskøya Fm., PMO 229.182/1
12. *Lycopodiumsporites semimuris* LYL-40 b P23-4, Lyngefjellet, Svenskøya Fm., PMO 229.181
13. *Striatella parva* SLO-11 206m V35 Lyngefjellet, Flatsalen Fm., PMO 229.176/1
14. *Carnisporites spiniger* SØY-11 192.5m E46-4, Iversenfjellet, De Geerdalen Fm., PMO 229.187/1
15. *Leschikisporis aduncus* SØY-11 121.35m E38, Iversenfjellet, De Geerdalen Fm., PMO 229.186
16. *Apiculatisporis parvispinosus* HGOS-11 12m K39-3, Hugosøkket, De Geerdalen Fm., PMO 229.188/1
17. *Apiculatasporites hirsutus* HGOS-11 12m D57-3, Hugosøkket, De Geerdalen Fm., PMO 229.188/2
18. *Apiculatasporites lativerrucosus* HGOS-11 12m N53-4, Hugosøkket, De Geerdalen Fm., PMO 229.188/3
19. *Dictyophyllidites mortonii* SØY-11 192.5m F49, Iversenfjellet, De Geerdalen Fm., PMO 229.187/2
20. *Concavisporites crassexinus* SLO-11 206m V35, Lyngefjellet, Flatsalen Fm., PMO 229.176/2
21. *Lophotriletes novicus* BIN-11-12 V36, Binnedalen, De Geerdalen Fm., PMO 229.166/1
22. *Calamospora tener* HGOS-11 21m N48-3, Hugosøkket, De Geerdalen Fm., PMO 229.190
23. *Deltoidospora* spp. GSK-11 96.3m F40, Gåskaret, De Geerdalen Fm., PMO 229.191/1
24. *Kyrtomisporis laevigatus* BIN-11-36 H58-4, Binnedalen, De Geerdalen Fm., PMO 229.171/4
25. *Kyrtomisporis gracilis* LYL-40 d E35, Lyngefjellet, Svenskøya Fm., PMO 229.182/2
26. *Lycopodiacidites rugulatus* LYL-40 d P64-4, Lyngefjellet, Svenskøya Fm., PMO 229.182/3
27. *Trachysporites asper* LYN-11 43.80m L57-2, Lyngefjellet, Svenskøya Fm., PMO 229.179/2
28. *Conbaculatisporites hopensis* BIN-11-12 C55, Binnedalen, De Geerdalen Fm., PMO 229.166/2
29. *Clathroidites papulosus* BIN-11-28 D34, Binnedalen, De Geerdalen Fm., PMO 229.169
30. *Porcellispora longdonensis* BIN-11-11 N41, Binnedalen De Geerdalen Fm., PMO 229.165/2
31. *Striatella seebergensis* LYN-11 43.80m L57-2, Lyngefjellet, Flatsalen Fm., PMO 229.179/3
32. *Ischyosporites* spp. LYN-11 43.80m C51, Lyngefjellet, De Geerdalen Fm., PMO 229.179/4
33. *Retitriletes austroclavatidites* SLO-11 194m K61, Lyngefjellet, Flatsalen Fm., PMO 229.175/1
34. *Velosporites cavatus* BIN-11-36 X52-3, Binnedalen, De Geerdalen Fm., PMO 229.171/5
35. *Cingulizonates rhaeticus* LYL-40 d H29-2, Lyngefjellet, Svenskøya Fm., PMO 229.182/4
36. *Limbosporites lundbladii* GAR 283m F45-4, Lyngefjellet, Svenskøya Fm., PMO 229.183/1
37. *Punctatisporites fungosus* BIN-11-34 O36-4, Binnedalen, De Geerdalen Fm., PMO 229.170/1
38. *Chasmatosporites* sp. BIN-11-36 E45, Binnedalen, De Geerdalen Fm., PMO 229.171/6
39. *Cerebropollenites macroverrucosus* LYN-11 43.80m G40, Lyngefjellet, Svenskøya Fm., PMO 229.179/5
40. *Protodiploxypinus minutus* BIN-11-12 J45-3, Binnedalen, De Geerdalen Fm., PMO 229.166/3
41. *Protodiploxypinus decus* BIN-11-34 P45-1, Binnedalen, De Geerdalen Fm., PMO 229.170/2.

of terrestrial palynomorphs, particularly fern and lycopsid spores (Figs. 5 and 8). Freshwater and marine palynomorphs were exceedingly rare and poorly preserved in this interval and may be reworked from the Flatsalen Formation below. The recorded palynomorph taxa represent various plants groups, including cycads (*Chasmatosporites* spp., *Cycadopites* spp.), gymnosperms (*Protodiploxypinus* spp.) and ferns (*Deltoidospora* spp. and *Kyrtomisporis* spp.) (Table 1).

A slight change in the palynological assemblages was observed in samples from the uppermost Svenskøya Formation with an increase in the abundance and diversity of lycopsid spores, including *Aratrisporites* spp., *Cingulizonates rhaeticus* and *Limbosporites lundbladii*. Fern spores such as *Deltoidospora* spp. were abundant. The pollen assemblage includes cycads (*Chasmatosporites* spp.) and gymnosperms (*Cerebropollenites* spp., *Quadraeculina anellaeformis* and *Ricciisporites annulatus*). Particulate organic matter assemblages from the Svenskøya Formation were dominated by phytoclasts, mostly gelified wood and various degraded plant tissues (Figs. 5 and 9; Plate II), contrasting with the AOM-rich assemblages of the underlying Flatsalen Formation.

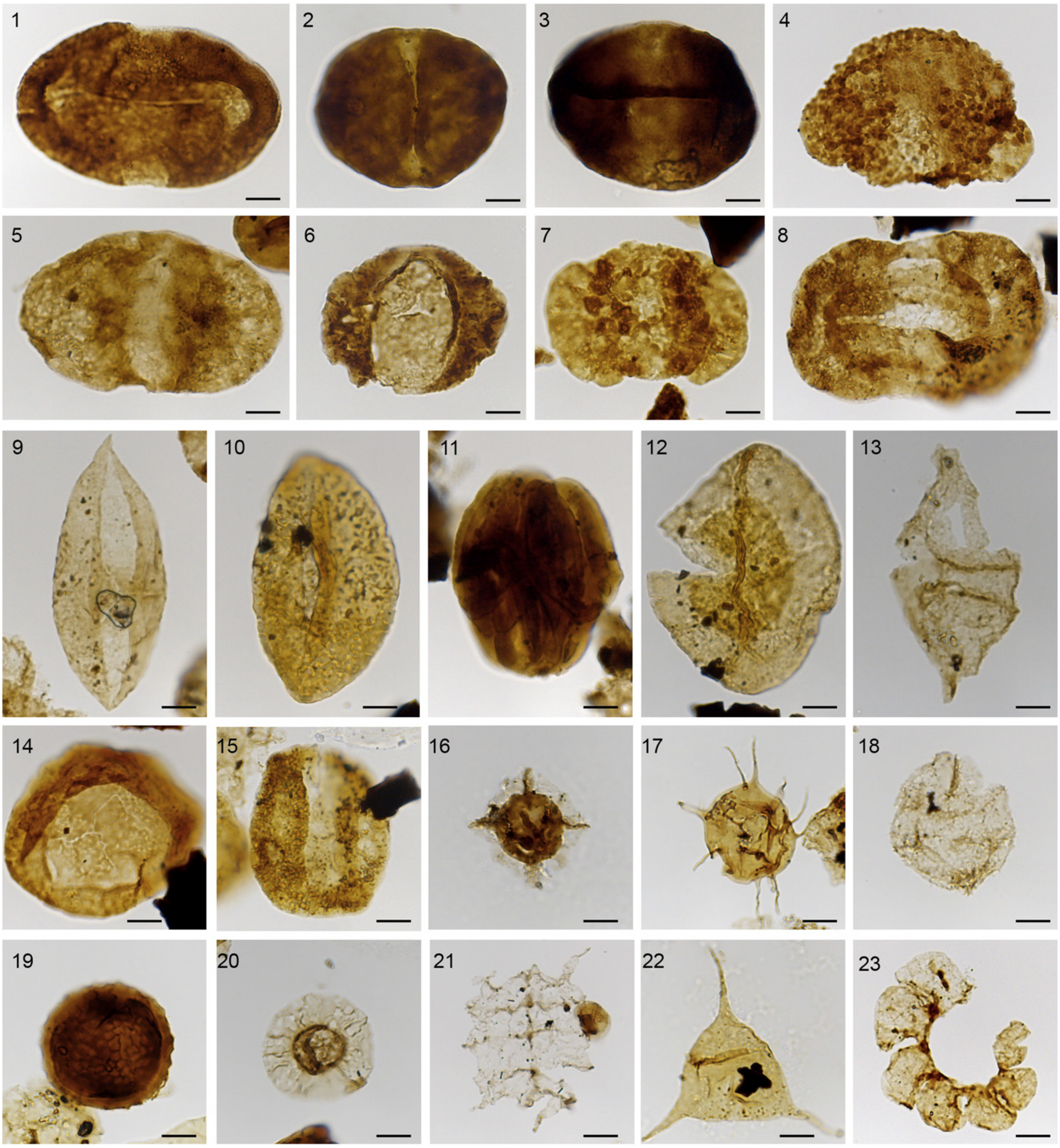

Plate II. *(caption on page 34)*

Amorphous organic matter was generally absent except for minor quantities recorded in the lowermost two samples from the Svenskøya Formation. The $\delta^{13}C_{org}$ curve from the Svenskøya Formation is consistent with that from the uppermost Flatsalen Formation with values between −25 and −24.5‰ (Fig. 5).

5. Discussion

5.1. Biofacies unit I (lower undifferentiated De Geerdalen Formation)

The integrated biofacies evidence indicates that the lower undifferentiated De Geerdalen Formation on Hopen was deposited in a paralic environment, under minor and episodic marine influence. Assemblages from this interval are characterised by the dominance of fern spores (Fig. 8), particularly *Leschikisporis aduncus*. Comparable assemblages have been described previously from the De Geerdalen Formation on Hopen (Bjærke and Manum, 1977; Ask, 2013; Vigran et al., 2014; Paterson and Mangerud, 2015) and on Spitsbergen (Nagy et al., 2011; Ask, 2013; Mueller et al., 2014; Vigran et al., 2014), as well as in the correlative Snadd Formation of the Barents Sea (Hochuli et al., 1989; Hochuli and Vigran, 2010; Holen, 2014). The wide geographical distribution of such assemblages suggests that the regional palaeoflora was comprised principally of ferns during this time interval.

The spore taxon *Leschikisporis aduncus* is known to have been produced by the marattialian fern parent plant *Asterotheca meriani* (Balme, 1995; Kustatscher and Van Konijnenburg-Van Cittert, 2011). Therefore, the high abundance and wide distribution of *L. aduncus* throughout the region suggests that the parent plant was a dominant element of the local palaeoflora. Palaeobotanical evidence from De Geerdalen Formation (Pott, 2014) confirms that *A. meriani* is indeed the most common macroplant fossil in several localities across Svalbard. However, it should be noted that this particular species has yet to be documented from fossil material collected on Hopen. *L. aduncus* and its parent taxon are considered to be indicative of swamp habitats (Roghi et al., 2010). This interpretation is corroborated by the dominance of the taxon within coal samples from the De Geerdalen Formation (Bjærke and Manum, 1977; Vigran et al., 2014; Paterson and Mangerud, 2015), although this and previous studies (e.g., Paterson and Mangerud, 2015) have demonstrated that the species is also present in high abundance in other lithologies such as mudrock and siltstone, and is therefore not facies restricted.

Other spore taxa present in the lower exposures of the De Geerdalen Formation have presumed filicopsid (*Apiculatasporites* spp., *Apiculatisporis* spp., *Clathroidites papulosus*, *Conbaculatisporites* spp.), lycopsid (*Aratrisporites* spp., *Krauselisporites* spp.), sphenopsid (*Calamospora tener*) and bryophyte (*Porcellispora longdonensis*) affinities (Table 1). Collectively, this taxonomic association coupled with the absence of xerophytic species is considered indicative of persistent humid climatic conditions for this stratigraphic interval throughout the region (Abbink, 1998; Abbink et al., 2004; Hochuli and Vigran, 2010). We assign this palynofloral association to the Wet Lowland and River SEGs (Table 2).

We consider the dominance of fern spores to be indicative of deposition in a deltaic environment (Fig. 8) and a basinward expansion of the lowland coastal habitat (Abbink, 1998; Abbink et al., 2004), such as would accompany a marine regression (Batten, 1975). Despite the overall dominance of terrestrial palynomorphs, the sporadic occurrence of acritarchs in lower exposures of the De Geerdalen Formation on Hopen indicates episodic marine influence. This is supported by the occurrence of low diversity, low abundance assemblages of foraminifera and ostracods (this study) and the presence of thin horizons of bivalve and echinoderm fossils observed by previous workers (Flood et al., 1971; Pčelina, 1972), and it is consistent with the reported occurrence of acritarchs and agglutinated foraminifera from the De Geerdalen Formation elsewhere in the region (e.g., Nagy et al., 2011; Mueller et al., 2014; Vigran et al., 2014).

The dominance of phytoclasts and sporomorphs in POM assemblages (Fig. 7b; Plate II) suggests a close proximity to a fluvio-deltaic source. Assemblages plot in fields I and III of the AOM–Palynomorph–Phytoclast (APP) diagram (Fig. 9), suggesting deposition in a "highly proximal" to "heterolithic oxic shelf" setting (Tyson, 1995, p. 446). Comparable POM assemblages were described by Mueller et al. (2014) from the De Geerdalen Formation at Juvdalskampen on Spitsbergen, as "Palynofacies J-C". The dominance of phytoclasts and absence of AOM in POM assemblages is further consistent with deposition during a marine regression (Tyson, 1995, p. 426).

The slight negative trend in $\delta^{13}C_{org}$ values recorded in the lower part of the De Geerdalen Formation at Binnedalen may be tentatively attributed to the Carnian Pluvial Event (CPE), a humid climatic phase well documented in the Tethyan Realm (Hochuli and Frank, 2000; Roghi, 2004; Hornung et al., 2007; Rigo et al., 2007; Breda et al., 2009; Kolar-Jurkovšek and Jurkovšek, 2010; Kozur and Backman, 2010; Roghi et al., 2010; Dal Corso et al., 2012; Muttoni et al., 2014; Dal Corso et al., 2015). In the Tethyan Realm, the onset of the CPE has been dated to the late early Carnian (Julian 1–2), corresponding with the *Austrotrachyceras austriacum* ammonoid zone (Hornung et al.,

Plate II. Palynomorph taxa from Hopen. Following the taxon name is the sample number, England Finder Slide coordinates, locality, formation and Palaeontological Museum of Oslo numbers. Scale bars equal 10 μm. (see on page 33)

1. *Ovalipollis ovalis* BIN-11-16 D43-2, Binnedalen, De Geerdalen Fm., PMO 229.167/1
2. *Vesicaspora fuscus* BIN-11-36 G39-2, Binnedalen, De Geerdalen Fm., PMO 229.171/7
3. *Parvisaccites radiatus* BIN-11-16 D32-1, Binnedalen, De Geerdalen Fm., PMO 229.167/2
4. *Protodiploxypinus ornatus* BIN-11-36 H58-3, Binnedalen, De Geerdalen Fm., PMO 229.171/8
5. *Alisporites* spp. BIN-11-19 T54-2, Binnedalen, De Geerdalen Fm., PMO 229.168
6. *Triadispora plicata* BLF-11 191 m C32-3, Blåfjellet, De Geerdalen Fm., PMO 229.185
7. *Triadispora verrucata* HGOS-11 16m Q35-4, Hugosøkket, De Geerdalen Fm., PMO 229.189
8. *Lunatisporites rhaeticlus* BIN-11-36 J58-3, Binnedalen, De Geerdalen Fm., PMO 229.171/9
9. *Cycadopites* spp. GSK-11 96.3m J42, Gåskaret, De Geerdalen Fm., PMO 229.191/2
10. *Chasmatosporites hians* LYL-40 d H36-4, Lyngefjellet, Svenskøya Fm., PMO 229.182/5
11. *Ricciisporites annulatus* (tetrad) LYN-11 44.6m K M60-1, Lyngefjellet, Svenskøya Fm., PMO 229.180
12. *Aratrisporites macrocavatus* LYL-40 d R63, Lyngefjellet, Svenskøya Fm., PMO 229.182/6
13. *Rhaetogonyaulax rhaetica* SLO-11 194m E49, Lyngefjellet, Flatsalen Fm., PMO 229.175/2
14. *Chasmatosporites apertus* LYN-11 41.48m N41-3, Lyngefjellet, Svenskøya Fm., PMO 229.178/3
15. *Quadraeculina anellaeformis* GAR 283m M52, Lyngefjellet, Svenskøya Fm., PMO 229.183/2
16. *Cymatiosphaera* spp. SLO-11 206m C63-4, Lyngefjellet, Flatsalen Fm., PMO 229.176/3
17. *Micrhystridium* spp. SLO-11 206m T36-2, Lyngefjellet, Flatsalen Fm., PMO 229.176/4
18. *Rhaetogonyaulax arctica* SLO-11 176m X63-3, Lyngefjellet, Flatsalen Fm., PMO 229.173
19. *Crassosphaera* spp. SLO-11 194m X49-1, Lyngefjellet, Flatsalen Fm., PMO 229.175/3
20. *Pterospermella* spp. SLO-11 192m D54-4, Lyngefjellet, Flatsalen Fm., PMO 229.174
21. *Plaesiodictyon mosellaneum* BIN-11-36 E39-3, Binnedalen, De Geerdalen Fm., PMO 229.171/10
22. *Veryhachium* spp. SLO-11 206m Y57-1, Lyngefjellet, Flatsalen Fm., PMO 229.176/5
23. Microforaminiferal test lining BIN-11-110 Q62-2, Binnedalen, Flatsalen Fm., PMO 229.172.

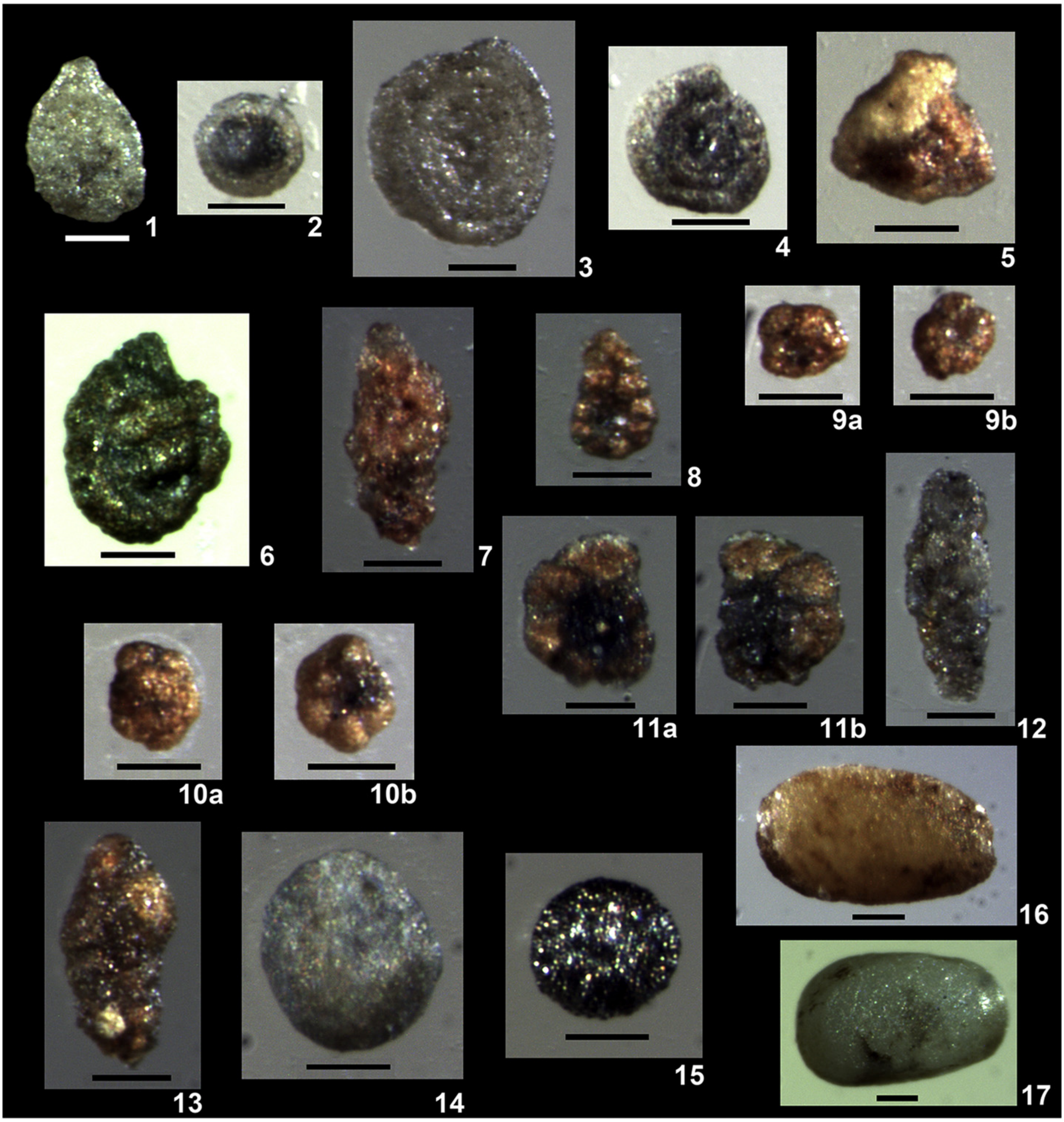

Plate III. Selected microfossil taxa from Hopen. All scale bars equal 100 μm. All illustrated microfossils from the Flatsalen Formation, sampled at the Lyngefjellet section.

1.	*Lagenammina* aff. *inanis*, 194 m
2.	*Saccammina* spp., 200 m
3.	*Ammodiscus* aff. *yonsnabensis*,188 m
4.	*Ammodiscus incertus*, 200 m
5.	*Glomospira irregularis*, 178 m
6.	*Lituotuba perplexa*, 200 m
7.	*Reophax metensis*, 175 m
8.	*Spiroplectammina* spp., 176 m
9a,b.	*Trochammina* aff. *eoparva*, 178 m
10a,b.	*Trochammina* aff. *eoparva*, 178 m
11a,b.	*Trochammina eoparva*, 176 m
12.	*Eobigenerina* spp., 176 m
13.	*Gaudryina adoxa*, 175 m
14–15.	Pyritised *Cenosphaera* spp., 14–176 m, 15–185 m
16–17.	Ostracoda casts, 16–200 m, 17–194 m.

2007; Kozur and Backman, 2010; Dal Corso et al., 2012, 2015) and to a transition in palynofloral assemblages from a dominance of xerophytes to hygrophytes (Hochuli and Frank, 2000; Roghi, 2004; Rigo et al., 2007; Roghi et al., 2010). However, since the De Geerdalen Formation on Hopen has been previously dated to the late Carnian (Tuvalian 2–3) (Lord et al., 2014b; Paterson and Mangerud, 2015), it is possible that primary CPE isotopic excursion is present lower in the stratigraphy, and is below sea level on Hopen.

In their study of the Juvdalskampen section in central Spitsbergen, Mueller et al. (2014) described an interval in the mid De Geerdalen Formation (Palynofacies J-C) dominated by *Leschikisporis aduncus* and corresponding to a negative CIE of 2.5‰. In a study of Triassic strata in the Southern Barents Sea, Hochuli and Vigran (2010) described a switch from palynofloras dominated by xerophytic forms, to hygrophyte dominated assemblages from the mid Carnian, corresponding to their Floral Phase 12. They attributed this to an increase in precipitation in the region, which they considered consistent with the CPE. However, it should be noted that the change in the bisaccate pollen: spore (xerophyte: hygrophyte) ratio recorded by Hochuli and Vigran (2010) corresponds closely to the lithological changes associated with the progradation and maximum regressive phase of the De Geerdalen/Snadd Formation deltaic system, and thus most likely facies controlled. Nonetheless, the dominance of *L. aduncus* in both Palynofacies J-C (Mueller et al., 2014) and in Floral Phase 12 (Hochuli and Vigran, 2010) undoubtedly corresponds to the *L. aduncus* assemblage of Paterson and Mangerud (2015) and to Biofacies I (this study) on Hopen.

5.1.1. Biofacies unit II (Hopen Member)

Integrated biofacies evidence from the Hopen Member suggests deposition occurred in a nearshore marine environment, as inferred on the basis of sedimentological evidence by Klausen and Mørk (2014) and Lord et al. (2014b). The transition to assemblages rich in bisaccate gymnosperm pollen recorded near the base of the Hopen Member (Figs. 5–8) has been noted previously at other sections on Hopen (Bjærke and Manum, 1977; Vigran et al., 2014; Paterson and Mangerud, 2015). The taxon *Protodiploxypinus* spp. is particularly common in this interval. In terms of palaeoecology, the parent plant of *Protodiploxypinus* spp. has been suggested to represent a xerophytic coastal pioneer plant with a preference for tidal flat environments (Brugman, 1986) and is thus assigned to the Coastal pioneer SEG (Table 2).

Similar bisaccate pollen-rich assemblages have been described from the upper De Geerdalen Formation on Svalbard (Vigran et al., 2014) and from the correlative Snadd Formation in the Barents Sea (Hochuli et al., 1989; Hochuli and Vigran, 2010; Vigran et al., 2014), suggesting a regionally significant transition in the palynoflora from spore-rich to pollen-rich assemblages. The increased abundance of bisaccate pollen recorded in the uppermost Snadd Formation by Hochuli and Vigran (2010) was interpreted by those authors to reflect the onset of drier conditions during the mid to late Carnian. However, the increased abundance of conifer pollen is also a feature commonly noted in marine deposits due to the "Neves effect" and hydrodynamic sorting of palynomorphs (Chaloner and Muir, 1968; Tyson, 1995, p. 451; Traverse, 2007; Gary et al., 2009). The corresponding increase in acritarch abundance and the sedimentological (Klausen and Mørk, 2014; Lord et al., 2014a,b) and palaeontological evidence (Flood et al., 1971; Pčelina, 1972; Smith et al., 1975) are consistent with the latter interpretation. The occurrence of the alga *Plaesiodictyon mosellaneum* is characteristic of assemblages from the Hopen Member, as previously noted by Lord et al. (2014b) and Paterson and Mangerud (2015). *P. mosellaneum* is considered to have inhabited fresh to brackish water environments (Brenner, 1992; Brenner and Foster, 1994; Brugman et al., 1994; Wood and Miller, 1998; Wood and Benson, 2000); therefore, its high abundance is perhaps indicative of close proximity to, or redeposition from, areas of freshwater input (Hauschke and Heunisch, 1990; Tyson, 1995, p. 451). Alternatively, this may also suggest the formation of freshwater–brackish lagoons on the coastal plain in response to rising sea levels, consistent with the inferred transgression in the upper part of the correlative Snadd Formation in the Barents Sea region (Klausen and Mørk, 2014; Ryseth, 2014; Klausen et al., 2015). This interpretation seems consistent with the increased relative abundance of *Protodiploxypinus* spp. given the inferred tidal flat habitat of its parent plant (Brugman, 1986). The low diversity and abundance of foraminiferal assemblages from the De Geerdalen Formation at Binnedalen and Blåfjellet, and the dominance of infaunal agglutinated foraminifera species indicates a highly stressed palaeoenvironment, such as a brackish marginal marine setting.

The increased abundance of pollen relative to spores suggests that deposition took place in a "nearshore" to "offshore" setting (Fig. 8), contrasting with the deltaic setting implied for the underlying part of the De Geerdalen Formation. Particulate organic matter assemblages from the Hopen Member contain more sporomorphs and less phytoclast than assemblages from the undifferentiated De Geerdalen Formation below, implying a higher degree of sorting. Particulate organic matter assemblages plot in fields III and V of the APP diagram (Fig. 9), indicating that deposition occurred within a "heterolithic oxic shelf" to "mud dominated oxic (distal) shelf" environment. This assemblage probably corresponds to "Palynofacies J-D" described by Mueller et al. (2014) from the upper De Geerdalen Formation at Juvdalskampen, Spitsbergen.

The slight shift to more positive carbon isotope values in the Hopen Member at Binnedalen (Fig. 6) is comparable to that observed by Mueller et al. (2014), Fig. 5) in the upper De Geerdalen Formation at Juvdalskampen on Spitsbergen. This may perhaps also be correlatable to the post Carnian Pluvial Event rebound reported by Dal Corso et al. (2012) from the Milieres–Dibona section in the Southern Alps.

5.2. Biofacies unit III (lower Flatsalen Formation)

The high abundance of microforaminiferal linings and marine microplankton in palynological assemblages from the basal Flatsalen Formation indicate that it was deposited in a shallow marine environment (Tyson, 1995, p. 453; Stancliffe, 1996; Sturrock, 1996, p. 43). The sudden first occurrence of super-abundant agglutinated foraminifera in the corresponding micropalaeontological samples supports this interpretation (Figs. 5 and 6; Tables 3 and 4). Our foraminiferal Fisher α and informational function H(S) values (Fig. 10) suggest that deposition occurred in a hyposaline, marginal marine to normal shelf setting (Murray, 1973, 1991, 2006). Similar low diversity assemblages dominated by small specimens of *Ammodiscus* aff. *yonsnabensis* and *Trochammina* spp. were documented by Nagy and Berge (2008) and Nagy et al. (2010) from the correlative Tverrbekken Member of the Knorringfjellet Formation on Spitsbergen. Such assemblages have been interpreted to be characteristic of shallow delta-influenced shelves to deltaic environments, between the fair weather and storm wave base (Nagy and Berge, 2008; Nagy et al., 2010; Hess et al., 2014).

The superposition of fully marine biofacies upon a more terrestrial one is indicative of a marine transgression (Sturrock, 1996, p. 101) and is consistent with the interpretation of the underlying Slottet Bed as a transgressive lag deposit (Klausen and Mørk, 2014). The Slottet Bed meets the criteria of a transgressive lag as defined by the Van Wagoner et al. (1990, p. 10–11) as "a sedimentary deposit, commonly less than 2 ft. (0.6 m) thick, of relatively coarse grained material composed of shells, shell fragments, clay rip-up clasts, calcareous nodules, siliciclastic gravel or pebbles". Such deposits are thought to form during marine transgressions when fair weather wave base encroaches on the shoreline, winnowing fine-grained sediment and concentrating coarser material as a discrete bed above the transgressive surface (Van Wagoner et al., 1990; Arnott, 1995). We therefore postulate that the base of the Slottet Bed represents a transgressive surface of regional extent.

Unfortunately there are no published carbon isotope curves for the basal Flatsalen Formation interval in the Barents Sea region with which to compare our data. Mueller et al. (2014) studied two samples from approximately 20 m above the base of the correlative Knorringfjellet Formation on Spitsbergen but the base of the unit was not sampled. Based on comparisons with the Alpine Realm the negative CIE recorded in the basal Flatsalen Formation in this study can perhaps be correlatable with the early Norian (Lacian) CIE reported by Muttoni et al. (2014).

5.3. Biofacies unit IV (middle Flatsalen Formation)

The increase in dinoflagellate cysts and the decrease in the abundance of microforaminiferal linings in the middle Flatsalen Formation (Fig. 5) are both consistent with deposition in an increasingly distal shelfal environment. In micropalaeontological samples from

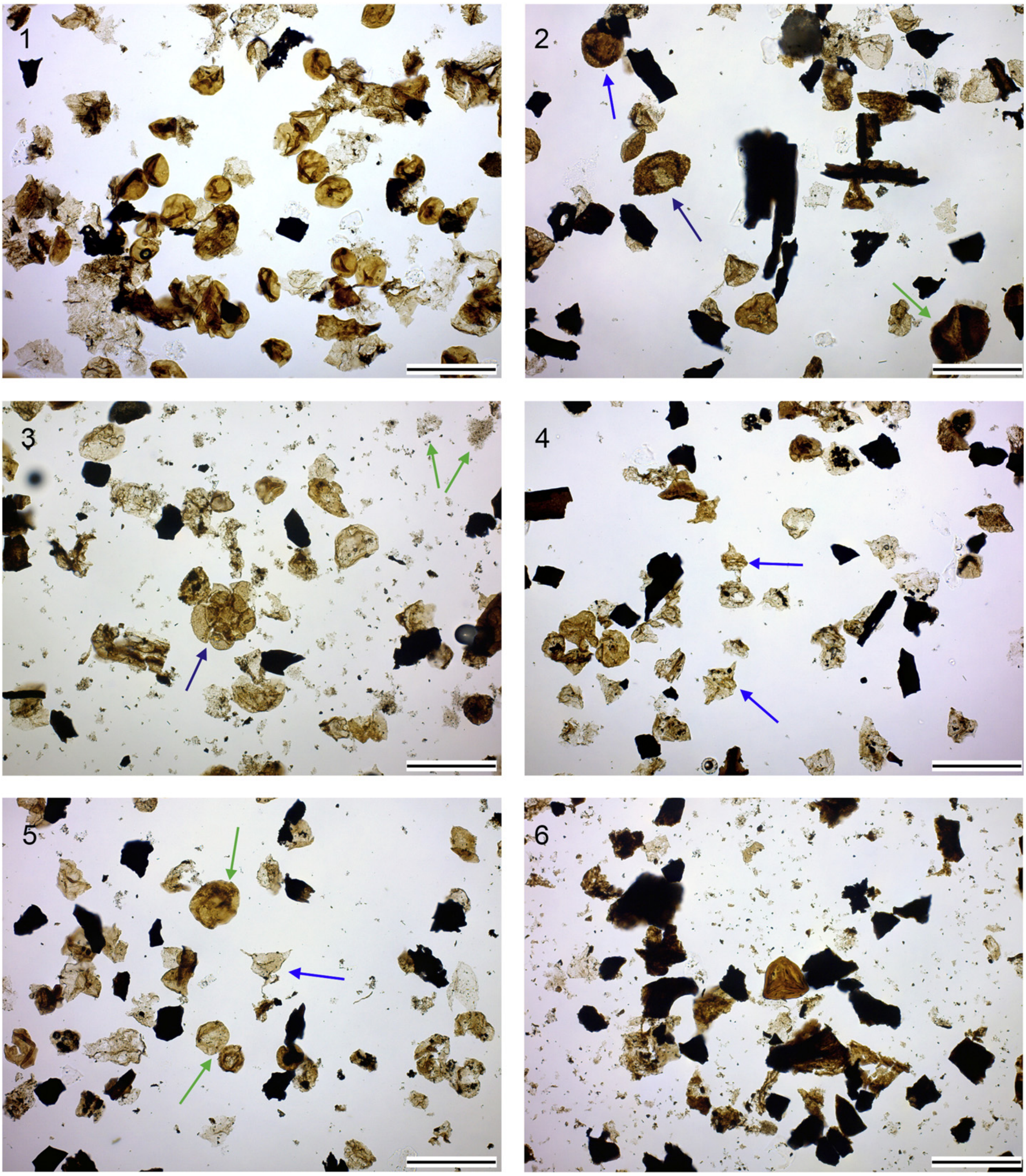

Plate IV. *(caption on page 38)*

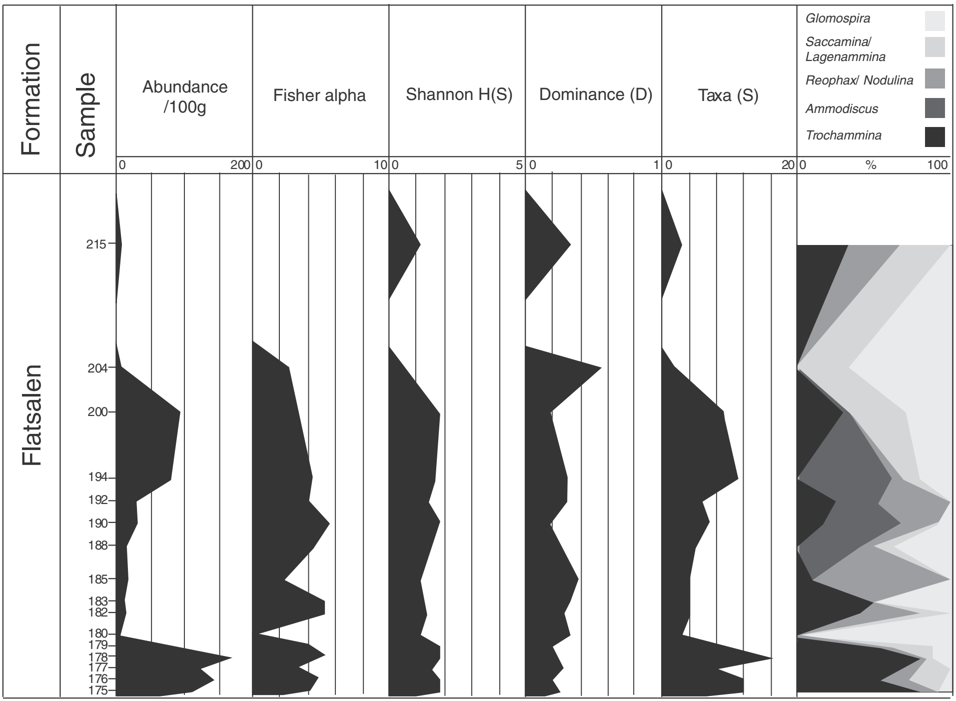

Fig. 10. Abundance (per 100 g), Fisher alpha (Fα), information function H(S), dominance (D), species richness (S) and generic relative abundance of foraminifera at Lyngefjellet, Hopen.

Lyngefjellet, a corresponding decrease in the abundance and diversity of foraminifera was observed between 180 and 185 m (Fig. 5; Table 3). The accompanying transition from epifaunal species to assemblages dominated by deep infaunal taxa including *Reophax*, *Saccammina* and *Lagenammina* spp. suggests increasingly hypoxic bottom waters. The acme of *Cenosphaera* spp. recorded at Lyngefjellet indicates the establishment of fully marine conditions (Sturrock, 1996, p.43). The observed dissociation between the abundance peaks of the marine benthonic and planktonic microfossils may be a consequence of a stratified water column. The occurrence of ammonoids and marine reptile remains within this interval (Cox and Smith, 1973; Worsley, 1973; Smith et al., 1975; Korčinskaya, 1980; Smith, 1982) provides further evidence of pelagic deposition.

Collectively, the biofacies evidence is consistent with a maximum flooding surface (MFS), which by definition represents the most landward extension of open marine plankton and deep water benthos within a sedimentary sequence (Loutit et al., 1988; Allen et al., 1991; Armentrout and Clement, 1991; Armentrout et al., 1991). At Lyngefjellet, the highest abundance of dinoflagellate cysts was recorded between 185 m and 204 m, with the maximum abundance observed at 194 m. The peak in dinoflagellate cysts is offset from the highest abundance of radiolaria, recorded at 185 m (Fig. 5). However, as noted by Tyson (1995, p. 421), cyst-forming dinoflagellates are meroplankton and spend only a portion of their life cycle in the water column. For this reason, the highest abundance of dinoflagellate cyst is not necessarily correlatable with the most pelagic phase of deposition. Since radiolaria are holoplanktonic and live in the water column for their entire life cycle, we therefore take the more discrete peak in radiolaria recorded at 185 m to be a more reliable indicator of the MFS in this instance. The MFS candidate is dated as early Norian age on the basis of previously reported macrofossil (Korčinskaya, 1980) and palynological evidence (Paterson and Mangerud, 2015), and presumably represents the early Norian age third order flooding surface described by Glørstad-Clark et al. (2010) at the base of the Fruholmen Formation in the subsurface of the Barents Sea.

Similar assemblages of dinoflagellate cysts have been documented from the Flatsalen Formation throughout the region, including on Hopen (Smith et al., 1975; Bjærke and Manum, 1977; Vigran et al., 2014; Paterson and Mangerud, 2015), various localities on Spitsbergen (Bjærke and Dypvik, 1977; Nagy et al., 2010; Mueller et al., 2014; Vigran et al., 2014) and in exploration wells from the southern Barents Sea (Hochuli et al., 1989; Vigran et al., 2014). Comparable assemblages have also been recorded in Norian age beds in the Alaskan (Wiggins, 1973) and Canadian Arctic (Felix, 1975; Fisher and Bujak, 1975; Bujak

Plate IV. Particulate organic matter assemblages from Hopen. All scale bars equal 100 µm. (see on page 37)

1. Biofacies I: Coastal plain swamp environment. Lower De Geerdalen Formation, Binnedalen. All circular orange-coloured palynomorphs in the image are assigned to the fern spore taxon *Leschikisporis aduncus*.
2. Biofacies II: Marginal marine environment. De Geerdalen Formation (Hopen Member), Binnedalen. Note the large black phytoclasts, presence of *Protodiploxypinus* spp. (blue arrows) and other bisaccate pollen grains (green arrow) and the absence of *Leschikisporis aduncus*.
3. Biofacies III: Hyposaline shallow marine environment. Lower Flatsalen Formation, Lyngefjellet. Note the presence of diffuse particles of AOM (green arrow) and microforaminiferal test linings (blue arrow).
4. Biofacies IV: Hypoxic-anoxic marine environment. Middle Flatsalen Formation, Lyngefjellet. Note the presence of dinoflagellate cysts (blue arrow).
5. Biofacies V: Terrestrially influenced shallow marine environment. Upper Flatsalen Formation, Lyngefjellet. Note the increase in terrestrial palynomorphs (green arrows), presence of acritarchs (blue arrow); dinoflagellate cysts are absent.
6. Biofacies VI: Fluvio-deltaic environment. Svenskøya Formation, Lyngefjellet. Note the dominance of black phytoclasts; acritarchs and dinoflagellate cysts are totally absent.

and Fisher, 1976; Staplin, 1979; Suneby and Hills, 1988). The similarity and age equivalency of these assemblages to those recorded in the Barents Sea region is consistent with a circum-arctic transgression during the early Norian, as suggested by Embry (1997).

Particulate organic matter assemblages from this interval are characterised by common to abundant particles of AOM (Figs. 5 and 9). In modern marine settings, AOM has been observed to collect as temporary flocculent layers in both oxic and anoxic environments following phytoplankton blooms (Thiel et al., 1989; Turley and Lochte, 1990; Wishner et al., 1990; Bochdansky and Herndl, 1992). Such material typically degrades rapidly in oxic settings but has a higher preservation potential in anoxic locations (Wishner et al., 1990; Jannasch, 1991; Pilskaln, 1991; Pacton et al., 2011). Thus, the high abundance of AOM observed within this interval of the Flatsalen Formation provides clear evidence of a dysoxic–anoxic environment. Similarly, the pyritisation of palynomorphs within Biofacies unit VI is suggestive of oxygen-depleted bottom waters (Pross et al., 2006; Candel et al., 2013; Ţabără et al., 2015).

The high relative abundance of marine phytoplankton (Figs. 5 and 8) indicates deposition occurred on a shelf area away from an active fluvial deltaic source (Tyson, 1995, p. 450); however, the variability in the abundance of terrestrial palynomorphs (Figs. 8 and 9), mainly fern spores and gymnosperm pollen (Fig. 5), suggests fluctuations in freshwater input. A comparable POM assemblage was recorded by Mueller et al. (2014) as "Palynofacies J-E" from the coeval Knorringfjellet at Juvdalskampen on Spitsbergen. The increased abundance of opportunistic *Glomospira* species observed in micropalaeontological samples from 190 m and upwards at Lyngefjellet (Table 3) suggests environmental perturbation and coincides with an increase in the sand–silt ratio (Fig. 3e).

5.4. Biofacies unit V (upper Flatsalen Formation)

The increase in terrestrial and freshwater palynomorphs, the decrease in marine microplankton and the absence of agglutinated foraminifera, radiolaria and ostracods are all indicative of an upward-shallowing succession, as postulated on the basis of sedimentological evidence (Mørk et al., 2013). This is consistent with the increase in the relative abundance of terrestrial palynomorphs and phytoclast in POM assemblages in the same interval.

5.5. Biofacies VI (Svenskøya Formation)

The dominance of spores (Fig. 5) in palynological assemblages from the Svenskøya Formation is indicative of deposition in a fluvio-deltaic environment (Fig. 8) as suggested by Lord et al. (2014b). The rarity of marine palynomorphs and the absence of marine microfossils in samples from the Svenskøya Formation at Lyngefjellet (Fig. 5) are consistent with this interpretation.

The dominance of various spore types implies damp and humid conditions, such as those found in coastal mire setting (Abbink, 1998; Abbink et al., 2004; Hochuli and Vigran, 2010). The increase in lycopsid spores such as *Aratrisporites* spp., *Cingulizonates rhaeticus* and *Limbosporites lundbladii* and the high abundance of the coastal conifer pollen *Araucariacites australis* are consistent with the Coastal SEG (Table 2). Bryophyte spores constitute a small but distinctive component of the assemblage and several species have been noted, including *Annulispora folliculosa*, *Gordonispora* spp., *Limatulasporites limatulus*, *Stereisporites* spp. and *Rogalskaisporites* spp., and are assigned to the River SEG (Table 2). Fern spores such as *Apiculatasporites hirsutus*, *A. lativerrucosus*, *Apiculatisporis parvispinosus*, *Baculatisporites* spp., *Concavisporites* spp. and *Trachysporites* spp. are representative of the Wet Lowland SEG (Table 2). Collectively, the dominance of forms attributable to the Coastal, River and Wet Lowland SEGs are suggestive of a fluvio-deltaic depositional environment. The presence of *Cerebropollenites* spp. (Paterson and Mangerud, 2015) is consistent with deposition immediately following a marine regression (Couper, 1958; Abbink et al., 2004). The occurrence of pollen such as *Quadraeculina anellaeformis* probably implies mixing of the upland/hinterland palynomorphs (Table 2) with the near autochthonous coastal assemblage. The overall dominance of phytoclast and palynomorphs in POM assemblages suggests that very little sorting took place prior to deposition in a highly proximal setting (Fig. 9).

6. Conclusions

Biofacies evidence from the Kapp Toscana Group on Hopen is interpreted to reflect deposition in a series of palaeoenvironments ranging from fluvio-deltaic through paralic, open marine and back to fluvio-deltaic. The exposed part of the De Geerdalen Formation on Hopen was likely deposited in a fluvial-dominated, fluctuating coastal plain to marginal marine setting during a period of regressive sedimentation in the late Carnian. The lower part of the formation on Hopen was deposited close to extensive, fern-dominated coastal mire, under prevailing humid conditions and episodic marine influence. The overlying Hopen Member was deposited in a nearshore, brackish marginal marine setting in the latest Carnian. The Slottet Bed is interpreted as a transgressive lag deposit delineating a transgressive surface of early Norian age. The Flatsalen Formation was deposited under fully marine conditions in an extensive shallow sea, which formed in response to rising relative sea levels during the Norian. A regionally significant maximum flooding surface is recognised within the Flatsalen Formation based on an acme of radiolaria. The overlying Svenskøya Formation was deposited in a fluvio-deltaic environment during the subsequent marine regression; the erosive base of the formation may represent a sequence boundary, formed in response to a drop in relative sea level during the Norian–Rhaetian. The upper and lower limits of the biofacies units defined herein are broadly equivalent to the palynological assemblages described by Paterson and Mangerud (2015). This indicates a strong palaeoenvironmental control upon the development of the palynological assemblages, and perhaps some degree of diachroneity in their distribution. However, since the *Rhaetogonyaulax rhaetica* assemblage of Paterson and Mangerud (2015) coincides with a maximum flooding surface, it can be presumed to be time equivalent across the region and thus represents an excellent correlation surface.

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Appendix A. Micropalaeontology taxa list

A.1. Agglutinated foraminifera

Ammobaculites spp.
? *Ammobaculites* spp.
Ammodiscus incertus
Ammodiscus aff. *peruvianus*
Ammodiscus aff. *yonsnabensis*
Ammolagena clavata
Caudammina spp.
Eobigenerina spp.
Gaudryina adoxa
Glomospira gordialis

Glomospira irregularis
Glomospirella spp.
Kutsevella aff. *haplophragmoides*
Kutsevella spp.
Lagenammina aff. *inanis*
Lituotuba perplexa
Nodulina liassica
Psammosphaera spp.
Recurvoides spp.
Reophax metensis
Reophax/*Nodulina* spp.
Saccammina spp.
Spiroplectammina spp.
Thurammina spp.
Trochammina eoparva
Trochammina aff. *eoparva*
Trochammina sp. 1 *sensu* Nagy et al., 2010
Trochammina spp.
Verneuilinoides aff. *kirillae*
Verneuilinoides aff. *subvitreus*
Verneuilinoides spp.
? *Verneuilinoides* spp.

A.2. Ostracods

? *Asciocythere* spp.
? *Darwinula* spp.
? Ostracoda undiff. (casts)

A.3. Radiolaria

Cenosphaera spp. (pyritised)
Radiolaria undiff. (non-pyritised)
Radiolaria undiff. (pyritised)

A.4. Accessory fossils

Fish bones
Fish scales
Fish teeth
? Gastropods undiff.
Megaspores indet.
Wood fragments
Worm tubes (pyritised)

References

Abbink, O.A., 1998. Palynological investigations in the Jurassic of the North Sea region. LPP Contributions Series 8 (192 pp.).
Abbink, O.A., Van Konijnenburg-Van Cittert, J.H.A., Visscher, H., 2004. A sporomorph ecogroup model for the Northwest European Jurassic–Lower Cretaceous: concepts and framework. Neth. J. Geosci. Geol. Mijnb. 83 (1), 17–38.
Allen, S., Coterill, K., Eisner, P., Perez-Cruz, G., Wornardt, W.W., Vail, P.R., 1991. Micropaleontology, well log and seismic sequence stratigraphy of the Plio-Pleistocene depositional sequences—offshore Texas. In: Armentrout, J.M., Perkins, B.F. (Eds.), Sequence Stratigraphy as an Exploration Tool: Concepts and Practices, Eleventh Annual Conference, June 2–5. Society of Economic Palaeontologists and Mineralogists, Texas Gulf Coast Section, pp. 11–13.
Armentrout, J.M., Clement, J.F., 1991. Biostratigraphic calibration of depositional cycles: a case study in High Island–Galveston–East Breaks areas, offshore Texas. In: Armentrout, J.M., Perkins, B.F. (Eds.), Sequence Stratigraphy as an Exploration Tool: Concepts and Practices, Eleventh Annual Conference, June 2–5. Society of Economic Palaeontologists and Mineralogists, Texas Gulf Coast Section, pp. 21–51.
Armentrout, J.M., Echols, R.J., Lee, T.D., 1991. Patterns of foraminiferal abundance and diversity: implications for sequence stratigraphic analysis. In: Armentrout, J.M., Perkins, B.F. (Eds.), Sequence Stratigraphy as an Exploration Tool: Concepts and Practices, Eleventh Annual Conference, June 2–5. Society of Economic Palaeontologists and Mineralogists, Texas Gulf Coast Section, pp. 53–58.
Arnott, R.W.C., 1995. The parasequence definition—are transgressive deposits inadequately addressed? J. Sediment. Res. B65 (1), 1–6.
Ask, M., 2013. Palynological dating of the upper part of the De Geerdalen Formation on central parts of Spitsbergen and Hopen (MSc. Thesis) University of Bergen, Norway, (I-XI), pp. 1–79 (URI: http://hdl.handle.net/1956/8263).
Bai, Y., Lu, M., Long, R., 1983. Mesozoic spores and pollen. In: Chengdu Institute of Geology and Mineral Resources (Ed.), Palaeontological Atlas of Southwest China: Volume of Microfossils. Geological Publishing House, Beijing, China.
Balme, B.E., 1995. Fossil in-situ spores and pollen grains: an annotated catalogue. Rev. Palaeobot. Palynol. 87, 81–323.
Batten, D.J., 1975. Wealden palaeoecology from the distribution of plant fossils. Proc. Geol. Assoc. 85, 433–458.
Bjærke, T., 1977. Mesozoic palynology of Svalbard—II. Palynomorphs from the Mesozoic sequence of Kong Karls Land. Nor. Polarinst. Aarb. 1976, 83–120.
Bjærke, T., Dypvik, H., 1977. Sedimentological and palynological studies of Upper Triassic–Lower Jurassic sediments in Sassenfjorden, Spitsbergen. Nor. Polarinst. Aarb. 1976, 131–150.
Bjærke, T., Manum, S.B., 1977. Mesozoic palynology of Svalbard—I. The Rhaetian of Hopen, with a preliminary report on the Rhaetian and Jurassic of Kong Karls Land. Nor. Polarinst. Skr. 135, 1–48.
Bochdansky, A.B., Herndl, G.J., 1992. Ecology of amorphous aggregations (marine snow) in the Northern Adriatic Sea. III. Zooplankton interactions with marine snow. Mar. Ecol. Prog. Ser. 87, 135–146.
Bonis, N.R., 2010. Palaeoenvironmental changes and vegetation history during the Triassic–Jurassic transition. LPP Contributions Series 29 (216 pp.).
Bonis, N.R., Kürschner, W.M., 2012. Vegetation history, diversity patterns, and climate change across the Triassic/Jurassic boundary. Paleobiology 38 (2), 240–264.
Boulter, M.C., Windle, T., 1993. A reconstruction of some Middle Jurassic vegetation in Northern Europe. Spec. Pap. Palaeontol. 49, 125–154.
Breda, A., Preto, N., Roghi, G., Furin, S., Meneguolo, R., Ragazzi, E., Fedele, P., Gianolla, P., 2009. The Carnian pluvial event in the Tofane Area (Cortina D'Ampezzo, Dolomites, Italy). Geol. Alps 6, 80–115.
Brenner, W., 1992. First results of Late Triassic palynology of the Wombat Plateau, Northwestern Australia. Proc. ODP Sci. Results 122, 413–426.
Brenner, W., Foster, C.B., 1994. Chlorophycean algae from the Triassic of Australia. Rev. Palaeobot. Palynol. 80 (3-4), 209–234.
Brugman, W.A., 1986. A palynological characterization of the Upper Scythian and Anisian of the Transdanubian Central Range (Hungary) and the Vicentinian Alps (Italy) (Ph.D. dissertation) State University of Utrecht.
Brugman, W.A., Van Bergen, P.F., Kerp, J.H.F., 1994. A quantitative approach to Triassic palynology: the Lettenkeuper of the Germanic Basin as an example. In: Traverse, A. (Ed.), Sedimentation of Organic Particles. Cambridge University Press, pp. 409–430.
Buchan, S.H., Challinor, A., Harland, W.B., Parker, J.R., 1965. The Triassic stratigraphy of Svalbard. Nor. Polarinst. Skr. 135 (92 pp.).
Bujak, J.P., Fisher, M.J., 1976. Dinoflagellate cysts from the Upper Triassic of Arctic Canada. Micropaleontology 22, 44–70.
Candel, M.S., Borromei, A.M., Martínez, M.A., Bujalesky, G., 2013. Palynofacies analysis of surface sediments from the Beagle Channel and its application as modern analogues for Holocene records of Tierra del Fuego, Argentina. Palynology 37 (1), 62–76.
Chaloner, W.G., Muir, M., 1968. Spores and floras. In: Murchison, D.G., Westall, T.S. (Eds.), Coal and coal-bearing Strata. Oliver and Boyd, Edinburgh, pp. 127–146.
Cocks, L.R.M., Torsvik, T.H., 2007. Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic. Earth-Sci. Rev. 82, 29–74.
Couper, R.A., 1958. British Mesozoic microspores and pollen grains. A systematic and stratigraphic study. Palaeontogr. Abt. B 103, 75–179.
Cox, C.B., Smith, D.G., 1973. A review of the Triassic vertebrate faunas of Svalbard. Geol. Mag. 110 (5), 405–418.
Dal Corso, J., Mietto, P., Newton, R.J., Pancost, R.D., Preto, N., Roghi, G., Wignall, P.B., 2012. Discovery of a major negative $\delta^{13}C$ spike in the Carnian (Late Triassic) linked to the eruption of Wrangellia flood basalts. Geology 40 (1), 79–82.
Dal Corso, J., Gianolla, P., Newton, R.J., Franceschi, M., Roghi, G., Caggiati, M., Raucsik, B., Budai, T., Haas, J., Preto, N., 2015. Carbon isotope records reveal synchronicity between carbon cycle perturbation and the "Carnian Pluvial Event" in the Tethys realm (Late Triassic). Glob. Planet. Chang. 127, 79–90.
Doré, A.G., 1995. Barents Sea Geology, Petroleum Resources and Economic Potential. Arctic 48 (3), 207–221.
Duringer, P., Doubinger, J., 1985. La palynology: un outil de characterisation des facies marins et continentaux a la limite Muschelkalk Supérieur–Lattenkohle. Sci. Géol. Bull. Strasbourg 38, 19–34.
Embry, A.F., 1997. Global sequence boundaries of the Triassic and their identification in the Western Canada sedimentary basins. Can. Pet. Geol. Bull. 45, 249–259.
Federova, V.A., 1977. The significance of the combined use of microphytoplankton, spores, and pollen for differentiation of multi-facies sediments. In: Samoilovich, S.R., Timoshina, N.A. (Eds.), Questions of Phytostratigraphy 398. Trudy Neftyanoi nauchno-issledovatelskii geologorazvedochnyi Institut (VNIGRI), Leningrad, pp. 70–88 (in Russian).
Felix, C.J., 1975. Palynological evidence for Triassic sediments on Ellef Ringes Island, Arctic Canada. Rev. Palaeobot. Palynol. 20, 109–117.
Filatoff, J., 1975. Jurassic palynology of the Perth Basin, Western Australia. Palaeontogr. Abt. B 154, 1–113.
Filatoff, J., Price, P.L., 1988. A pteridacean spore lineage in the Australian Mesozoic Memoir 5. Association of Australasian Palaeontologists, pp. 89–124 (ISSN 0810-8889).
Fisher, M.J., Bujak, J.P., 1975. Upper Triassic palynofloras from Arctic Canada. Geosci. Man 11, 87–94.
Flood, B., Nagy, J., Winsnes, T.S., 1971. The Triassic succession of Barentsøya, Edgeøya and Hopen (Svalbard). Nor. Polarinst. Med. 100, 5–20.
Gary, A.C., Wakefield, M.I., Johnson, G.W., Ekart, D.G., 2009. Application of fuzzy c-means clustering to palaeoenvironmental analysis: example from Jurassic, Central North

Sea, UK. In: Demchuk, T.D., Gary, A.C. (Eds.), Geological problem solving with microfossils: a volume in honor of Garry D. Jones. SEPM Special Publication 93, pp. 1–347.
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. 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.
Grauvogel-Stamm, L., 1978. La flora du Grès à Voltzia (Buntsandstein supérieur) des Vosges du Nord (France)—morphologie, anatomie, interprétations phylogénique et paléogéographique. Sciences Géologiques 50. Université Louis Pasteur de Strasbourg, Institut de Géologie (Mémoire).
Grauvogel-Stamm, L., Düringer, P., 1983. *Annalepsis zeilleri* FLICHE 1910 emend., un organe reproducteur de Lycophyte de la Lettenkohle de l'Est de la France. Geol. Rundsch. 72, 23–51.
Grogan, P., Ostvedt-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 Barents Sea. In: Fleet, A.J., Boldy, S.A.R. (Eds.), Petroleum Geology of Northern Europe, Proceedings of the 5th Conference, pp. 247–259.
Hauschke, N., Heunisch, C., 1990. Lithologie und Palynologie der Bohrung USB 3 (Horn–Bad–Meinberg, Ostwestfalen): ein Beitrag zur Faziesentwicklung im Keuper. Neues Jahrb. Geol. Palaontol. Abh. 181, 79–105.
Helby, R., Martin, A.R.H., 1965. *Cyclostrobus* n. g., cones of lycopsidean plants from the Narrabeen Group (Triassic) of New South Wales. Aust. J. Bot. 13, 389–404.
Henricksen, 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. Geol. Soc. Lond. Mem. 35, 163–195.
Hess, S., Nagy, J., Laursen, G.V., 2014. Benthic foraminifera from the Lower Jurassic transgressive mudstones of the south-western Barents Sea—a possible high latitude expression of the global Pliensbachian-Toarcian turnover? Polar Res. 33. http://dx.doi.org/10.3402/polar.v33.20206.
Hochuli, P.A., Frank, S.M., 2000. Palynology (dinoflagellate cysts, spore-pollen) and stratigraphy of the Lower Carnian Raibl Group in the Eastern Swiss Alps. Eclogae Geol. Helv. 93, 429–443.
Hochuli, P.A., Vigran, J.O., 2010. Climate variations in the boreal Triassic—inferred from palynological records from the Barents Sea. Palaeogeogr. Palaeoclimatol. Palaeoecol. 290, 20–42.
Hochuli, P.A., Colin, J.P., Vigran, J.O., 1989. Triassic biostratigraphy of the Barents Sea area. In: Collinson, J. (Ed.), Correlation in Hydrocarbon Exploration. Graham and Trotman, London, pp. 131–153.
Holen, L.H., 2014. Late Triassic (Carnian) palynology of the Northern Barents Sea (Sentralbanken High) (MSc. Thesis) I-VI. University of Bergen, Norway, pp. 1–96 (URI: http://hdl.handle.net/1956/8279).
Hornung, T., Brandner, R., Krystyn, L., Joachimski, M.M., Keim, L., 2007. Multistratigraphic constraints on the NW Tethyan "Carnian Crisis". Glob. Triassic 41, 59–67.
Høy, T., Lundschien, B.A., 2011. Triassic deltaic sequences in the northern Barents Sea. In: Spencer, A.M. (Ed.), Arctic Petroleum Geology. Geological Society Memoir 35, pp. 249–260.
Jannasch, H.W., 1991. Microbial processes in the Black Sea water column and top sediment: an overview. In: Idzar, E., Murray, J.W. (Eds.), Black Sea OceanographyNATO Advanced Studies Institute Series C351. Kluwer Academic, Dordrecht, pp. 271–281.
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. AAPG Bull. 98 (10), 1911–1941.
Klausen, T.G., Ryseth, A.E., Helland-Hansen, W., 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.
Kolar-Jurkovšek, T., Jurkovšek, B., 2010. New paleontological evidence of the Carnian strata in the Mežica area (Karavanke Mts., Slovenia): conodont data for the Carnian pluvial event. Palaeogeogr. Palaeoclimatol. Palaeoecol. 290, 81–88.
Koppelhus, E.B., 1991. Palynology of the Lower Jurassic Rønne Formation on Bornholm, eastern Denmark. Bull. Geol. Soc. Den. 39, 91–109.
Korčinskaya, M.V., 1980. Rannenorijskaja fauna arhipelaga Sval'bard (Early Norian fauna of the archipelago of Svalbard). Geologija osadočnogo čehla arhipelaga Sval'bard (Geology of the sedimentary platform cover of the archipelago of Svalbard). N.I.I.G.A., Leningrad, pp. 30–43 (In Russian).
Kozur, H.W., Backman, G.H., 2010. The Middle Carnian Wet Intermezzo of the Stuttgart Formation (Schilfsandstein), Germanic Basin. Palaeogeogr. Palaeoclimatol. Palaeoecol. 290, 107–119.
Kräusel, R., Schaarschmidt, F., 1966. Die Keuperflora von Neuewelt bei Basel. IV. Pterophyllen und Taeniopteriden. Schweiz. Palaeontol. Abh. 84, 4–66.
Kürschner, W.M., Mander, L., McElwain, J.C., 2014. A gymnosperm affinity for *Ricciisporites tuberculatus* Lundblad: implications for vegetation and environmental reconstructions in the Late Triassic. Palaeobiodivers. Palaeoenviron. 94 (2), 295–305. http://dx.doi.org/10.1007/s12549-014-0163-y (ISSN 1867-1594.).
Kustatscher, E., Van Konijnenburg-Van Cittert, J.H.A., 2011. The ferns of the Middle Triassic flora from Thale (Germany). N. Jb. Geol. Paläont. (Abh.) 261, 209–248. http://dx.doi.org/10.1127/0077-7749/2011/0174.
Kustatscher, E., Heunisch, C., Van Konijnenburg-Van Cittert, J.H.A., 2012. Taphonomical implications of the Ladinian megaflora and palynoflora of Thale (Germany). PALAIOS 27, 753–764.
Launis, A., Pott, C., Mørk, A., 2014. A glimpse into the Carnian: Late Triassic plant fossils from Hopen, Svalbard. Norw. Petrol. Direct. Bull. 11, 129–136 (ISBN 978-82-7257-117-6).
Lord, G.S., Solvi, K.H., Klausen, T.G., Mørk, A., 2014a. Triassic channel bodies on Hopen, Svalbard: their facies, stratigraphical significance and spatial distribution. Norw. Petrol. Direct. Bull. 11, 41–60 (ISBN 978-82-7257-117-6).
Lord, G.S., Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W., Paterson, N.W., 2014b. The Hopen Member: a new lithostratigraphic unit on Hopen and equivalent to the Isfjorden Member of Spitsbergen. Norw. Petrol. Direct. Bull. 11, 81–96 (ISBN 978-82-7257-117-6).
Loutit, T.S., Hardenbol, J., Vail, P.R., Baum, G.R., 1988. Condensed sections: the key to age determination and correlation of continental margin sequences. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), Sea Level Changes—An Integrated Approach Special Publication. Society of Economic Paleontologists and Mineralogists, Tulsa, pp. 183–213.
Lundschien, B.A., Høy, T., Mørk, A., 2014. Triassic hydrocarbon potential in the Northern Barents Sea; integrating Svalbard and stratigraphic core data. Norw. Petrol. Direct. Bull. 11, 3–20 (ISBN 978-82-7257-117-6).
Mander, L., Kürschner, W.M., McElwain, J.C., 2010. An explanation for conflicting records of Triassic–Jurassic plant diversity. Proc. Natl. Acad. Sci. U. S. A. 107 (35), 15351–15356.
Mander, L., Collinson, M.E., Chaloner, W.G., Brain, A.P.R., Long, D.G., 2012. The ultrastructure and botanical affinity of the problematic mid-Mesozoic palynomorph *Ricciisporites tuberculatus* Lundblad. Int. J. Plant Sci. 173, 429–440.
Martin, M.A., Wakefield, M., MacPhail, M.K., Pearce, T., Edwards, E., 2013a. Sedimentology and stratigraphy of an intra-cratonic basin coal seam gas play: Walloon Subgroup of the Surat Basin, eastern Australia. Pet. Geosci. 19, 21–38.
Martin, M.A., Wakefield, M., MacPhail, M.K., Pearce, T., Edwards, E., 2013b. Sedimentology and stratigraphy of an intra-cratonic basin coal seam gas play: Walloon Subgroup of the Surat Basin, eastern Australia. Erratum for Martin et al. 2013a. Petroleum Geoscience 19, p. 200.
McLoughlin, S., Lindström, S., Drinnan, A.N., 1997. Gondwanan floristic and sedimentological trends during the Permian–Triassic transition: new evidence from the Amery Group, northern Prince Charles Mountains, East Antarctica. Antarct. Sci. 9 (3), 281–298.
Mørk, M.B.E., 2013. Diagenesis and quartz cement distribution of low-permeability Upper Triassic–Middle Jurassic reservoir sandstones, Longyearbyen CO_2 lab well site in Svalbard, Norway. Am. Assoc. Pet. Geol. Bull. 97. http://dx.doi.org/10.1306/10031211193.
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., Dallmann, W.K., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pčelina, T.M., Worsley, D., 1999. Mesozoic Lithostratigraphy. In: Dallmann, W.K. (Ed.), Lithostratigraphic lexicon of Svalbard, Upper Palaeozoic to Quaternary Bedrock: Review and recommendations for nomenclature use. Committee on the Stratigraphy of Svalbard/Norwegian Polar Institute, Tromsø, pp. 127–214.
Mørk, A., Lord, G.S., Solvi, K.H., Dallmann, W.K., 2013. Geological map of Svalbard 1: 100000, sheet G14G Hopen. Norsk Polarinstitutt Temakart No. 50.
Mueller, S., Veld, H., Nagy, J., Kürschner, W.M., 2014. Depositional history of the Upper Triassic Kapp Toscana Group on Svalbard, Norway, inferred from palynofacies analysis and organic geochemistry. Sediment. Geol. 310, 16–29.
Murray, J.W., 1973. Distribution and ecology of living benthic foraminiferids. Crane Russak and Co., New York (274 pp.).
Murray, J.W., 1991. Ecology and palaeoecology of benthic foraminifera. Longman Scientific and Technical, Harlow, UK, p. 402.
Murray, J.W., 2006. Ecology and applications of benthic foraminifera. Cambridge University Press (440 pp.).
Muttoni, G., Mazza, M., Mosher, D., Katz, M.E., Kent, D.V., Balini, M., 2014. A Middle-Late Triassic (Ladinian-Rhaetian) carbon and oxygen isotope record from the Tethyan Ocean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 399, 246–259.
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.
Nagy, J., Hess, S., Alve, E., 2010. Environmental significance of foraminiferal assemblages dominated by small-sized *Ammodiscus* and *Trochammina* in Triassic and Jurassic delta-influenced deposits. Earth Sci. Rev. 99, 31–49.
Nagy, J., Hess, S., Dypvik, H., Bjærke, T., 2011. Marine shelf to paralic biofacies of Upper Triassic to Lower Jurassic deposits in Spitsbergen. Palaeogeogr. Palaeoclimatol. Palaeoecol. 300, 138–151.
Pacton, M., Gorin, G.E., Vasconcelos, C., 2011. Amorphous organic matter—experimental data on formation and the role of microbes. Rev. Palaeobot. Palynol. 166, 253–267.
Paterson, N.W., Mangerud, G., 2015. Late Triassic (Carnian–Rhaetian) palynology of Hopen, Svalbard. Rev. Palaeobot. Palynol. 220, 98–119.
Pčelina, T.M., 1972. K voprosu o vozraste osadočnoj tolšči ostrova Nadeždy (Sval'bard), (On the question of the age of sedimentary succession of the island of Hopen (Svalbard)). In: Sokolov, V.N., Vasilevskaya, N.D. (Eds.), Mezozoiskie otloženija Sval'barda (Mesozoic deposits of Svalbard). N.I.I.G.A., Leningrad, pp. 75–81 (In Russian).
Pčelina, T.M., 1983. Novye dannye po stratigrafi mezozoja archipelago Špicbergena. Geologija Špicbergena. PGO "Sevmorgeologija", Leningrad, pp. 121–141 (In Russian).
Petersen, H.I., Lindström, S., 2012. Synchronous wildfire activity rise and mire deforestation at the Triassic–Jurassic boundary. PLoS ONE 7 (10), e47236. http://dx.doi.org/10.1371/journal.pone.0047236.
Pilskaln, C.H., 1991. Biogenic aggregate sedimentation in the Black Sea. In: Idzar, E., Murray, J.W. (Eds.), Black Sea Oceanography, NATO Advanced Studies Institute Series C351. Kluwer Academic, Dordrecht, pp. 293–306.
Pott, C., 2014. The Upper Triassic flora of Svalbard. Acta Palaeontol. Pol. 59 (3), 709–740.
Pross, J., Link, E., Ruf, M., Aigner, T., 2006. Delineating sequence stratigraphic patterns in deeper ramp carbonates: quantitative palynofacies data from the Upper Jurassic (Kimmeridgian) of Southwest Germany. J. Sediment. Res. 76, 524–538.

Rigo, M., Preto, N., Roghi, G., Tateo, F., Mietto, P., 2007. A rise in the carbonate compensation depth of western tethys in the Carnian (Late Triassic): deep-water evidence for the Carnian Pluvial Event. Palaeogeogr. Palaeoclimatol. Palaeoecol. 246, 188–205.
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, 317–337.
Rød, R.S., Hynne, I.B., Mørk, A., 2014. Depositional environment of the Upper Triassic De Geerdalen Formation—an E-W transect from Edgeøya to Central Spitsbergen, Svalbard. Norw. Petrol. Direct. Bull. 11, 89–107.
Roghi, G., 2004. Palynological investigations in the Carnian of the Cave del Predil area (Julian Alps, NE Italy). Rev. Palaeobot. Palynol. 132, 1–35.
Roghi, G., Gianolla, P., Minarelli, L., Pilati, C., Preto, N., 2010. Palynological correlation of Carnian humid pulses throughout western Tethys. Palaeogeogr. Palaeoclimatol. Palaeoecol. 290, 89–106.
Ryseth, A., 2014. Sedimentation at the Triassic–Jurassic boundary, south-west Barents Sea: indication of climatic change. 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 46. International Association of Sedimentary Sedimentologists, Special Publication, pp. 187–214. http://dx.doi.org/10.1002/9781118920435.ch9.
Samoilovich, S.R., 1953. Pollen and spores from the Permian deposits of the Cherdyn and Aktyubinsk areas, Cis-Urals. Oklahoma Geol. Surv. 56, 1–103.
Scheuring, B., 1970. Palynologische und palynostratigraphische Untersuchungen des Keupers im Bölchentunnel (Solothurner Jura). Schweiz. Palaeontol. Abh. 88, 1–119.
Scholtz, A., 1985. The palynology of the upper lacustrine sediments of the Arnot Pipe, Banke, Namaqualand. Ann. S. Afr. Mus. 95 (1) (109 pp.).
Smelror, M., Petrov, O.V., Larssen, G.B., Werner, S., 2009. ATLAS—Geological History of the Barents Sea. Geological Survey of Norway, Trondheim, Norway, pp. 1–135 (ISBN 978-82-7385-137-6).
Smith, D.G., 1974. Late Triassic pollen and spores from the Kapp Toscana Formation, Hopen, Svalbard—a preliminary account. Rev. Palaeobot. Palynol. 17, 175–178.
Smith, D.G., 1982. Stratigraphic significance of a palynoflora from ammonoid-bearing Early Norian strata in Svalbard. Newsl. Stratigr. 11 (3), 154–161.
Smith, D.G., Harland, W.B., Hughes, N.F., 1975. Geology of Hopen, Svalbard. Geol. Mag. 112 (1), 1–23.
Solvi, K.H., 2013. Visualize and interpret the geometry, heterogeneity and lateral continuation of channel bodies in the De Geerdalen Formation at Hopen (MSc. thesis) Norwegian University of Science and Technology, Norway, p. 114 (URN:nbn:no:ntnu:diva-21287).
Stancliffe, R.P.W., 1996. Chapter 13D. Microforaminiferal linings. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: principles and applications vol. 1. American Association of Stratigraphic Palynologists Foundation, pp. 373–379.
Staplin, F.L., 1979. Triassic microplankton, Sverdrup Basin, Arctic Canada. J. Palynol. 14 (1), 1–11.
Strullu-Derrien, C., McLoughlin, S., Philippe, M., Mørk, A., Strull, D.G., 2012. Arthropod interactions with bennettitalean roots in a Triassic permineralized peat from Hopen, Svalbard Archipelago (Arctic). Palaeogeogr. Palaeoclimatol. Palaeoecol. 348-349, 45–58.
Sturrock, S.J., 1996. Biostratigraphy. In: Emery, D., Myers, K. (Eds.), Sequence Stratigraphy. Blackwell Science, Oxford, UK, pp. 89–107 (Chapter 6).
Suneby, L.B., Hills, L.V., 1988. Palynological zonation of the Heiberg Formation (Triassic–Jurassic) Eastern Sverdrup Basin, Arctic Canada. Bull. Can. Petrol. Geol. 36 (4), 347–361.
Ţabără, D., Pacton, M., Makou, M., Chirilă, G., 2015. Palynofacies and geochemical analysis of Oligo-Miocene bituminous rocks from the Moldavidian Domain (Eastern Carpathians, Romania): implications for petroleum exploration. Rev. Palaeobot. Palynol. 216, 101–122.
Thiel, H., Pfannkuche, O., Schriever, G., Lochte, K., 1989. Phytodetritus on the deep-sea floor in a central oceanic region of the Northeast Atlantic. Biol. Oceanogr. 6, 203–239.
Traverse, A., 1988. Paleopalynology. 1st edition. Unwin Hyman, Boston (600 pp.).
Traverse, A., 2007. Paleopalynology. 2nd edition. Springer, Dordrecht (813 pp.).
Turley, C.M., Lochte, K., 1990. Microbial response to the input of fresh detritus to the deep-sea bed. Palaeogeogr. Palaeoclimatol. Palaeoecol. 89, 3–23 (Global and Planetary Change Section).
Tyson, R.V., 1985. Palynofacies and sedimentology of some Late Triassic sediments from the British Isles and northern North Sea (PhD thesis) The Open University, Milton Keynes (623 pp.).
Tyson, R.V., 1989. Late Jurassic palynofacies trends, Piper and Kimmeridge Clay Formations, UK onshore and offshore. In: Batten, D.J., Keen, M.C. (Eds.), Northwest European Micropalaeontology and PalynologyBritish Micropalaeontological Society Series. Ellis Horwood, Chichester, pp. 135–172.
Tyson, R.V., 1993. Palynofacies analysis. In: Jenkins, D.J. (Ed.), Applied Micropalaeontology. Kluwer, Dordrecht, pp. 153–191.
Tyson, R.V., 1995. Sedimentary Organic Matter: Organic Facies and Palynofacies. Chapman and Hall, London, p. 615.
Van Konijnenburg-Van Cittert, J.H.A., 1978. Osmundaceous spores in situ from the Jurassic of Yorkshire, England. Rev. Palaeobot. Palynol. 26, 125–141.
Van Konijnenburg-Van Cittert, J.H.A., 2000. Osmundaceous spores throughout time. In: Harley, M.M., Morton, C.M., Blackmore, S. (Eds.), Pollen and Spores: Morphology and Biology. Royal Botanic Gardens, Kew, pp. 435–449.
Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops: concepts for high-resolution correlation of time and facies. AAPG Methods in Exploration Series. 7 pp. 1–55.
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. 14. Geological Survey of Norway Special Publication, p. 247.
Wiggins, V.D., 1973. Upper Triassic dinoflagellates from arctic Alaska. Micropaleontology 19 (1), 1–17.
Wishner, K., Levin, L., Gowing, M., Mullineaux, L., 1990. Involvement of the oxygen minimum in benthic zonation on a deep seamount. Nature 346, 57–59.
Wood, G.D., Benson Jr., D.G., 2000. The North American occurrence of the algal coenobium *Plaesiodictyon*: paleogeographic, paleoecologic, and biostratigraphic importance in the Triassic. Palynology 24, 9–20.
Wood, G.D., Miller, M.A., 1998. Stratigraphic, paleoecologic and petroleum generating significance of Chlorophyta (chlorococcalean algae) in the Cretaceous of Western Africa and South America. Afr. Geosci. Rev. 4, 499–510.
Worsley, D., 1973. Wilhelmøya Formation—a new lithostratigraphic unit from the Mesozoic of eastern Svalbard. Nor. Polarinst. Aarb. 1971, 7–16.

Paper 4

Facies development of the Upper Triassic Succession on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard.

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Facies development of the Upper Triassic succession on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard

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Field data collected from the northeasternmost Triassic exposures on the islands of Spitsbergen, Wilhelmøya and Barentsøya during 2015 are used for sedimentological facies analysis to improve our understanding of the stratigraphic development of the Upper Triassic strata. Results presented here build upon previous studies from the eastern areas of the Svalbard archipelago and seek to extend this understanding northward. Paralic deltaic sediments are recognised throughout the field area, and our analysis shows that the Upper Triassic De Geerdalen Formation is composed of three discrete units defined by the differences in gross depositional environments. The lower interval of early Carnian age is dominated by shallow-marine and delta-front/ shoreface deposits, the middle interval of mid Carnian age is dominated by delta-front to delta-top deposits, and the upper interval, corresponding to the Isfjorden Member, of a late Carnian to early Norian age, is dominated by delta-top deposits which include lagoonal and lacustrine deposits. These observations show that the De Geerdalen Formation represents a more distal depositional setting, than the depositional environments previously reported from the islands of Edgeøya and Hopen. We also document the presence of the Tschermakfjellet Formation and Isfjorden Member on Wilhelmøya, thus increasing our understanding of the northwestward development of the Upper Triassic succession in Svalbard.

Keywords: Facies Development; Upper Triassic; Eastern Svalbard; Sedimentology

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Introduction

The Upper Triassic stratigraphy in Svalbard (Figs. 1A–B & 2A) was first described by Buchan et al. (1965). Preliminary facies studies were given for eastern Svalbard by Flood et al. (1971a) and Lock et al. (1978), whilst Mørk et al. (1982) covered much of the archipelago. Rød et al. (2014) provide the most extensive sedimentological study covering Edgeøya and central Spitsbergen. The succession has largely been regarded as a useful analogue to the Triassic in the Barents Sea, and particularly the comparison to the fluvio-deltaic Snadd Formation, known for its reservoir potential, has received some attention (e.g., Klausen & Mørk, 2014; Klausen et al., 2014, 2015). Recent sedimentological studies in the Upper Triassic of Svalbard have thus focused primarily on fluvial sandstone bodies seen in the southeastern areas of the archipelago (Solvi, 2013; Klausen & Mørk, 2014; Lord et al., 2014b), as analogues to potential reservoirs in the Snadd Formation. Mørk (2013) and Anell et al. (2014a, b) discussed the Upper Triassic succession in relation to its potential as a CO_2 storage reservoir in central Spitsbergen. However, in these cases the northernmost parts of the Storfjorden area in eastern Spitsbergen have been somewhat disregarded.

In the study area (Fig. 1B), the Carnian succession has not been studied in detail since the earlier works of

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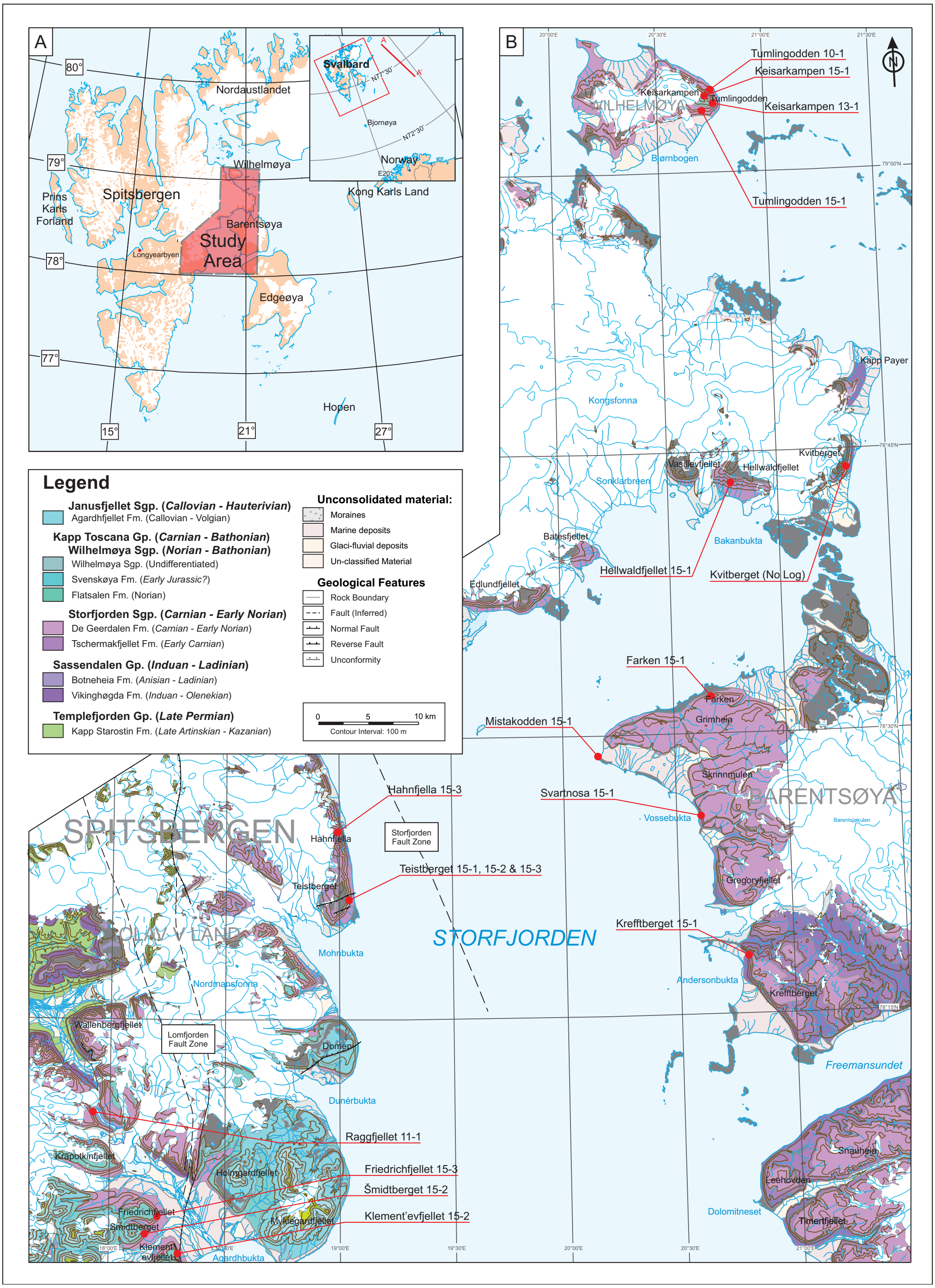


Figure 1. (A) Inset map showing an overview of the high Arctic position of Svalbard in relation to the Barents Sea and Norway. The study area is highlighted in red. Note the location of the seismic line, shown in Fig. 3B. (B) Geological map of the study area featuring the major stratigraphic units, structures and position of measured sections. The map is modified after Dallmann & Elvevold (2015).

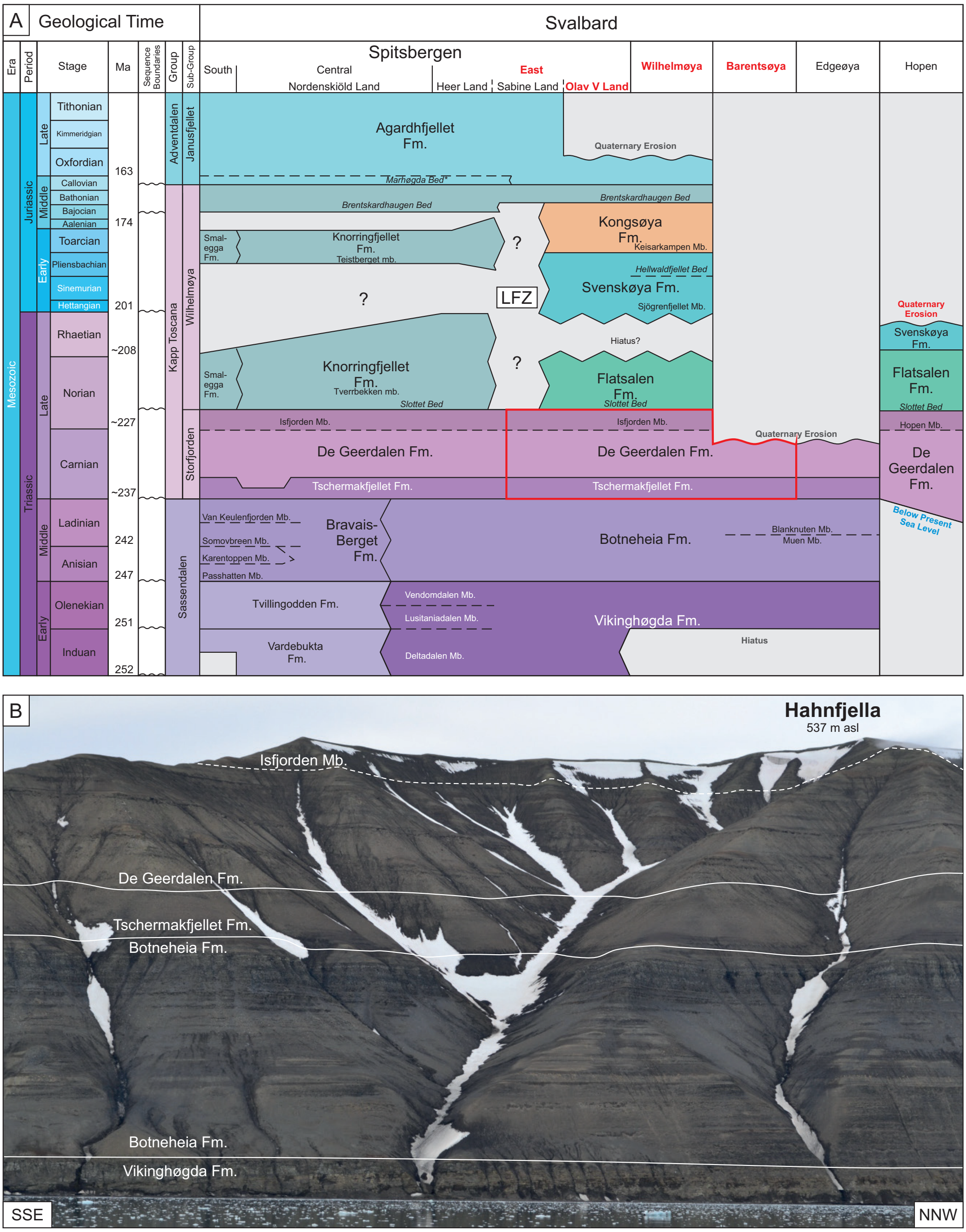


Figure 2. (A) Stratigraphic chart of the Triassic to Middle Jurassic successions at various locations throughout Svalbard (modified after Mørk et al., 1999a, 2013). (B) An overview picture of the mountain of Hahnfjella (Fig. 1B) in eastern Spitsbergen with a well exposed section of the Middle–Upper Triassic succession. The Middle Triassic shales of the Vikinghøgda and Botneheia formations form steep cliffs along the base of the mountain. These are overlain by small upward-coarsening packages in the De Geerdalen Formation. The Isfjorden Member is partially exposed in the upper part of the mountain.

Flood et al. (1971a), Lock et al. (1978) and Pčelina (1983). These studies primarily focused on the establishment of a stratigraphic scheme and detailed dating. The work by Flood et al. (1971a) covered the main eastern islands of Barentsøya, Edgeøya and Hopen, defining the Vardebukta, Kongressfjellet, Tschermakfjellet and De Geerdalen formations. A brief sedimentological description of each formation is also provided. Importantly, this study recognised the correlation of units from Spitsbergen to the eastern islands.

The stratigraphic terminology for Barentsøya, Edgeøya, Wilhelmøya and Hopen of Flood et al. (1971a, b), Worsley (1973), Smith et al. (1975), Lock et al. (1978), Winsnes (1981), Winsnes & Worsley (1981), Mørk et al. (1982) and Pčelina (1983) was replaced by the nomenclature now in use by Mørk et al. (1999a), representing a more coherent stratigraphical scheme (Fig. 2A).

Pčelina (1983) proposed the names Hahnfjella and Isfjorden 'suita' (formation), recognising the distinctive change seen in the upper part of the De Geerdalen Formation. The Isfjorden suita was retained, but lowered to member rank, by Mørk et al. (1999a).

This study builds upon the existing stratigraphic and facies frameworks defined for other eastern islands of Svalbard and extend these to the northernmost Upper Triassic exposures. The sedimentological understanding from Hopen (Klausen & Mørk, 2014; Lord et al., 2014a, b) and Edgeøya (Rød et al., 2014) provide the base framework for this study. Vigran et al. (2014) provided regional biostratigraphic dating that aids in positioning logged sections accurately within the stratigraphy.

The aim of this article is to present findings from recent fieldwork in Svalbard, conducted on the Upper Triassic in easternmost Spitsbergen, Barentsøya and Wilhelmøya (Fig. 1A). The focus has been primarily on the Upper Triassic Tschermakfjellet and De Geerdalen formations. The primary objective is to understand facies distributions within these two formations and relate these to the development of a major deltaic system that has been well documented in other areas in the archipelago and the Barents Sea (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011; Klausen & Mørk, 2014; Rød et al., 2014; Klausen et al., 2014, 2015).

Regional geological setting

Svalbard is a 61,000 km^2 archipelago in the European high arctic and consists of eight main islands with Spitsbergen being the largest (Fig. 1A). The archipelago represents an uplifted corner of the Barents Sea Shelf (Worsley, 2008) and is bound to its north and west by continental margins. The western part of Spitsbergen is dominated by a Cenozoic orogenic belt, whilst the eastern areas, including the study area, are part of a Palaeozoic–Mesozoic platform area (Riis et al., 2008; Worsley, 2008). The eastern areas of Spitsbergen are dominated by flat-lying strata of Permian to Palaeocene age, intruded by Cretaceous (124.5 Ma; Corfu et al., 2013) dolerite sills and dykes (Dallmann & Elvevold, 2015). The study area is located in this eastern platform area. Some tectonic features of Palaeozoic and Cenozoic age are present; however, the majority of the study area is undeformed.

In the study area, the Lomfjorden Fault Zone (Fig. 1B) dissects eastern Spitsbergen, in a near north–south orientation from northern Spitsbergen through part of the study area in Agardhbukta. This fault zone comprises a main thrust fault, a dextral strike-slip fault component, and a series of small thrust sheets (Dallmann & Elvevold, 2015; Dallmann et al., 2015). The Storfjorden Fault Zone (Eiken, 1985), a NNW–SSE lineament, trends through Storfjorden approximately 40 km to the east of Agardhbukta. The faulting is defined as Permian age or older and is present as normal faulting with a westward dip and throws of up to 1 km (Eiken, 1985).

In eastern Svalbard, Triassic strata overlie the Upper Permian Kapp Starostin Formation (Mørk et al., 1999a; Dallmann & Elvevold, 2015). The units of the Lower to Middle Triassic Sassendalen Group are the Vikinghøgda (Induan–Olenekian) and Botneheia (Anisian–Ladinian) formations (Mørk et al., 1999a, b). The Upper Triassic Storfjorden Subgroup is divisible into the Tschermakfjellet and De Geerdalen formations (Buchan et al., 1965; Mørk et al., 1999a). The overlying Upper Triassic to Middle Jurassic Wilhelmøya Subgroup (Worsley, 1973; Mørk et al., 1999a) consists of the Flatsalen, Svenskøya and Kongsøya formations. The Storfjorden and Wilhelmøya subgroups together form the Kapp Toscana Group (Mørk et al., 1999a).

The shales of the Induan to Olenekian Vikinghøgda Formation (Fig. 2B) were deposited in a shallow shelf setting (Mørk et al., 1999a; Dallmann & Elvevold, 2015). The Middle Triassic Botneheia Formation (Fig. 2A, B), formed of marine shale, is one of the major organic-rich units present in Svalbard with a high total organic content of *c.* 8–10% (Mørk & Bjorøy, 1984).

The Botneheia Formation is overlain by the early Carnian Tschermakfjellet Formation (Figs. 2B, 3A), which is a succession of prodelta shale and siltstone. Offshore, this shale-dominated unit is incorporated into the lower part of the Snadd Formation (Lundschien et al., 2014).

The De Geerdalen Formation in Svalbard represents deposition of sediments in a shallow shelf and deltaic environment in an overall paralic setting (Mørk et al., 1982, 1999a, Klausen & Mørk, 2014; Rød et al., 2014). The base of the unit is defined by the first prominent sandstone above the Tschermakfjellet Formation (Mørk et al., 1999a). The formation largely consists of stacked

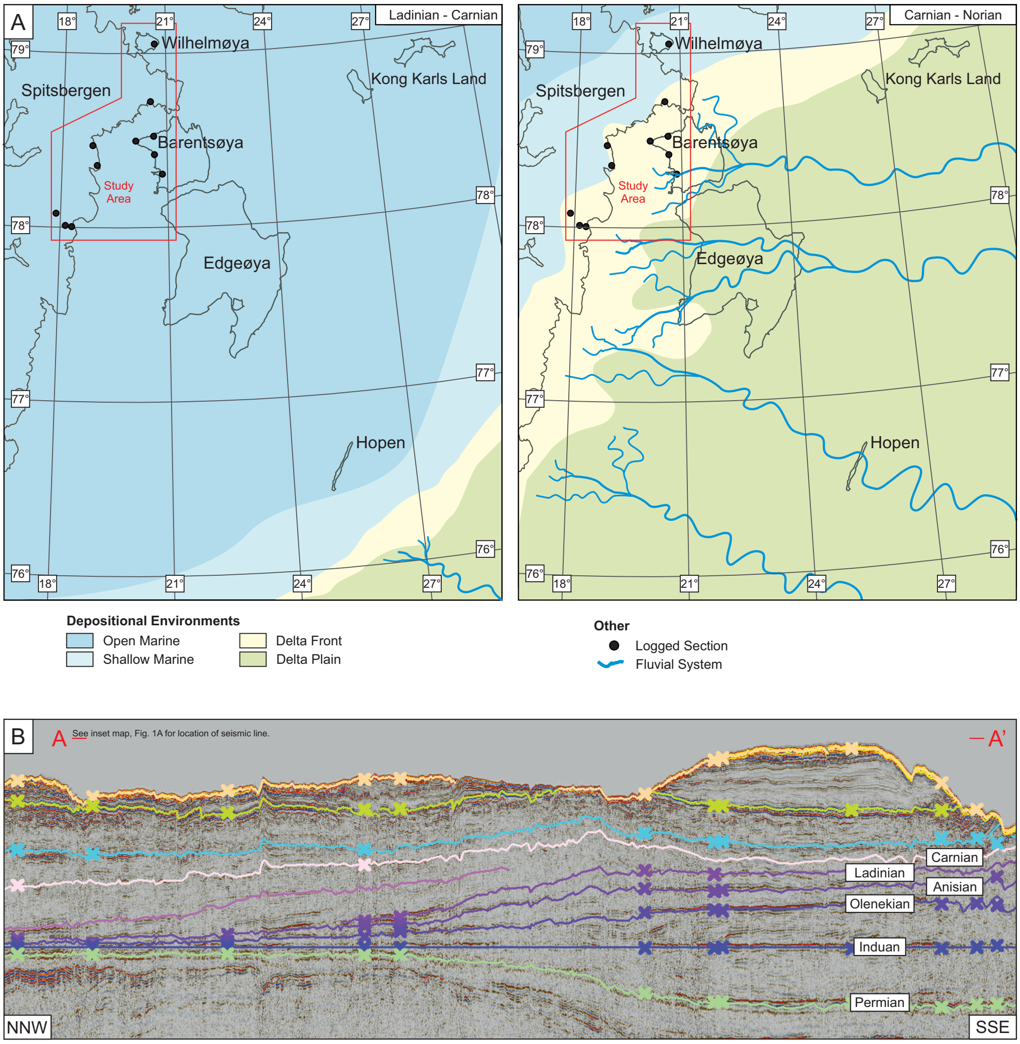


Figure 3. *(A) Depositional environments of the southeastern area of Svalbard and the northern Barents Sea showing the infill of sediment throughout the Middle–Late Triassic, after Riis et al. (2008), Lundschien et al. (2014) and Klausen et al. (2015). Open marine conditions prevailed in the study area throughout the Middle Triassic prior to a rapid deltaic advance from the east and southeast during the Carnian. (B) The seismic line (courtesy of NPD) shot to the east of Svalbard, has been flattened on the Induan reflector. The position of the line is marked on the inset map in Fig. 1A. The section shows Middle to Late Triassic clinoforms prograding to the NNW throughout the northern Barents Sea and is in agreement with the studies of Riis et al. (2008), Glørstad-Clark et al. (2010) and Anell et al. (2014a).*

upward-coarsening units (parasequences) of deltaic origin (Mørk et al., 1982, 1999a; Rød et al., 2014) and is seen to be most proximal in the area around Hopen, where fluvial trunk channels are observed (Mørk et al., 2013; Klausen & Mørk, 2014; Lord et al., 2014b). Distal deltaic facies are evident throughout parts of Edgeøya, becoming more dominant in central Spitsbergen (Knarud, 1980; Mørk et al., 1982; Rød et al., 2014). The interpretation of well-defined clinoforms in the northern Barents Sea (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011; Anell et al., 2014a, b; Lundschien et al., 2014; Klausen et al., 2015) supports the interpretation of a large deltaic system prograding north-westwards over a shallow shelf.

The upper 70 m of the De Geerdalen Formation is defined as the Isfjorden Member (Fig. 2A, B; Pčelina, 1983; Mørk et al., 1999a; Haugen, 2016). This member is dominated by siltstone and thin sandstone beds, with red and green nodular clays in its upper part. The unit is correlative to the Hopen Member in easternmost Svalbard (Mørk et al., 2013; Lord et al., 2014a). On Spitsbergen and Wilhelmøya, the Isfjorden Member represents deposition in shallow shelf, lagoonal and delta-plain environments (Pčelina, 1983; Mørk et al., 1999a; Haugen, 2016). This part of the succession is eroded on Barentsøya and Edgeøya (Mørk et al., 1999a; Lundschien et al., 2014; Rød et al., 2014).

The base of the early Norian Flatsalen Formation (Wilhelmøya Subgroup) is marked by the Slottet Bed (Fig. 2A; Worsley, 1973; Mørk et al., 1999a), a 2–3 m-thick unit consisting of phosphate conglomerate and carbonate cemented siltstone. The remainder of the Flatsalen Formation is composed of deep-marine shelf shales, which include several minor upward-coarsening units. Marine vertebrate fossils are present throughout (Vigran et al., 2014) and abundant at one interval on Wilhelmøya; and dating by palynology, ammonoids and magnetostratigraphy indicates that the unit is of Norian age (Mørk et al., 1999a; Lord et al., 2014a). The remaining Upper Triassic to Middle Jurassic stratigraphy is represented by the Svenskøya and Kongsøya formations, overlain by the Upper Jurassic Agardhfjellet Formation (Fig. 2A).

Carnian–Norian infill patterns of the Barents Sea

The deposits of the Carnian De Geerdalen Formation (Figs. 2B, 3A) represent the northwestward progradation of a deltaic system across the Barents Shelf, with its primary source area being the Uralide Mountains in the southeast (Riis et al., 2008; Høy & Lundschien, 2011; Lundschien et al., 2014; Støen, 2016).

Mineralogical provenance (Mørk, 1999) and detrital zircon studies (Bue & Andresen, 2013; Fleming et al., 2016) collectively indicate that major portions of Uralian derived sand originate from the northern part of the Ural Mountains, with a minor contribution originating from either the Timanides or another northeastern source in the Taimyr region. Chromium-spinel provenance studies suggest that sandstones in the De Geerdalen Formation are partly derived from volcanic rocks and indicate a source to the northeast or east of Svalbard (Mørk, 1999; Flemming et al., 2016; Harstad, 2016).

The orogenic processes that formed the Uralide Mountains occurred during the Late Devonian to Late Permian (Puchkov, 2009). The mountain belt stretched along the continental margin of the Siberian Terrane, accompanied by a shallow foreland basin. This basin formed an epicontinental sea situated between the Siberian Terrane and the Greenland–American plate (Torsvik & Cocks, 2004; Riis et al., 2008; Torsvik et al., 2012).

The area of Svalbard was positioned in the northwestern margin of this shelf during the Triassic at approximately 55–60°N (Elvevold et al., 2007). A slow northward migration of the northern part of Pangea occurred throughout the Mesozoic, resulting in a shift from subtropical to temperate climates (Elvevold et al., 2007; Worsley, 2008).

The Uralide and Timanide mountains provided sediment to this basin, from the east and southeast (Mørk, 1999; Riis et al., 2008; Glørstad-Clark et al., 2010; Miller et al., 2013). Throughout the Triassic, large rivers and deltaic depositional environments (Fig. 3A) became prominent along the margins of this seaway (Nystuen et al., 2008; Riis et al., 2008, Eide et al., in press), extending northwards to the Svalbard area by the Carnian. The sediment yield was significant enough to infill the basin with large volumes of siliciclastic material and resulted in extensive tidal, deltaic and fluvial deposits forming the Snadd and De Geerdalen formations (Mørk et al., 1982, 1999a; Glørstad-Clark et al., 2010; Klausen & Mørk, 2014; Lord et al., 2014b; Rød et al., 2014; Enga, 2015).

Progradation of this delta system can be viewed in seismic lines shot to the east and southeast of Svalbard as shown in Fig. 3B (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien, 2011; Anell et al., 2013, 2014a, b; Lundschien et al., 2014). Several studies have interpreted and mapped a succession of clinoform belts that can be seen to be gently dipping to the northwest. Within this series, Anisian, Ladinian and Carnian age clinoforms have been reported.

Methods

New field data have been collected during a summer field campaign in 2015, during two separate expeditions. The first expedition was conducted by students and researchers from the Norwegian University of Science and Technology (NTNU), working in the region of Agardhdalen in eastern Spitsbergen. The second was undertaken by the same group throughout eastern Spitsbergen, Wilhelmøya and Barentsøya, in cooperation with geologists from the Norwegian Petroleum Directorate (NPD).

Contemporary sedimentological field studies form the bulk of the data collected during the 2015 field season in the Storfjorden area (Fig. 1B). Sedimentary logs were measured bed-by-bed, and include descriptions of rock type, grain size, sorting, sedimentary structures and the presence of body and trace fossils. Sections were measured at centimetre scale and drawn to 1:100 or 1:50 in the field. Logs have been redrawn to 1:1250 scale for ease of presentation. Relevant sections collected from earlier expeditions in 2010, 2011 and 2013 are also included.

The Wilhelmøya Subgroup was not the primary target of the present field studies. Nevertheless, where present, the subgroup has been measured for the key purpose of correlation. The lower parts of the De Geerdalen

Formation are often scree covered and underlying stratigraphic units are either below the surface or sea level. Throughout Barentsøya the uppermost part of the De Geerdalen Formation has been eroded by Cenozoic uplift and erosion as well as by Quaternary glaciation. Sections without the underlying Botneheia or Tschermakfjellet formations present are thus correlated tentatively. In order to correlate facies correctly in the De Geerdalen Formation, it is necessary to 'flatten' sections on a well-defined datum surface. The basal Slottet Bed to the Wilhelmøya Subgroup (Mørk et al., 1999a) has been chosen for this purpose, as it is seen extensively throughout the study area. Where this unit is not present the boundaries between the Botneheia and Tschermakfjellet formations have been used.

Results

Facies analysis conducted in this study has subdivided measured sections into individual facies and combined genetically related groups of facies into facies associations (FA) reflecting various subenvironments of deposition. These are then grouped to form an overall depositional environment (DE) that may be recognised at various levels in the stratigraphy and thus correlated across the study area.

Facies

In total, 14 sedimentary facies are defined within the study area and are summarily presented in Table 1. The observed facies are an extension of those presented by Klausen & Mørk (2014) and Rød et al. (2014) in areas farther to the south and east. Facies analyses mainly focus on the Tschermakfjellet and De Geerdalen formations; deposits in the underlying and overlying units are only briefly described.

Facies associations

The De Geerdalen Formation consists of recurring coarsening- and shallowing-upward successions (Mørk et al., 1982, 1999a), which may be defined as parasequences (*sensu* Van Wagoner et al., 1990), where delta lobe-switching and subsequent abandonment and transgression have been suggested mechanisms (Mørk et al., 1982; Vigran et al., 2014). In the study area, 11 facies associations have been defined and are constructed from the facies presented. These are summarised in Table 2.

FA 1 – Open shelf deposits

Description: Units consisting entirely of laminated, normal-graded, fissile shales composed entirely of facies A (Table 1; Fig. 4A). Dolomite and calcite-cemented beds may be present and abundant ammonoids or marine vertebrate fossils are found. A high total organic content is evident, with reported values up to 10% (Mørk & Bjorøy, 1984). Phosphate nodules are abundant both as distinctive beds or individual nodules. Septarian concretions are also present.

Interpretation: This facies association is restricted to the Botneheia and Flatsalen formations (Fig. 2A, B) which represent deep-marine shelf and offshore mudstones deposited in the deepest parts of the basin (Mørk et al., 1999a; Krajewski, 2008). Preservation of organic matter, phosphate nodules and ammonoid imprints are interpreted as suggesting dysoxic to anoxic bottom-water conditions (Mørk & Bjorøy, 1984; Krajewski, 2008; Mørk & Bromley, 2008). These formations underlie and overlie the Storfjorden Subgroup (Fig. 2A), respectively.

FA 2 – Prodelta slope deposits

Description: This facies association is composed of normal-graded mudstones and siltstones (Facies A, Table 1; Fig. 4B), sets of upward-coarsening heterolithic bedding (Facies B) and thin (10–20 cm), normal-graded, sandstone beds with hummocky cross-stratification (Facies C). Siderite concretions are common. Normal-graded, fine-grained, plane parallel-laminated sandstones in thin beds with bioturbation are also seen (Facies H). This facies association typically displays an overall upward-coarsening trend with silt and sandstone beds becoming thicker and more extensive in the upper part.

Interpretation: This facies association is typically restricted to the Tschermakfjellet Formation. The unit is commonly regarded to represent the prodeltaic counterpart to the De Geerdalen Formation (Mørk et al., 1982, 1999a; Lundschien et al., 2014; Rød et al., 2014) and this interpretation is maintained for the study area. The bulk of the mudstone component represents a settling of fine-grained background sediments. A proportion may be derived from far-travelled hypopycnal sediment, which originates from the delta front as diluted, low-density flows (Bhattacharya & MacEachern, 2009; Olariu et al., 2010). Thin hummocky cross-stratified and plane parallel laminated sandstones are interpreted as representing sediment introduced to the delta slope by storm events.

FA 3 – Offshore deposits

Description: Offshore deposits (Fig. 4C) consist primarily of normal-graded, grey mudstone and siltstone or heterolithic beds (Facies A and B). Beds of 20–30 cm-thick, normal-graded, low-angle cross-laminated sandstone, or tabular cross-laminated sandstone (Facies I and J), are also seen to be interbedded within the fine-grained facies. Plant fragments may be found in some sandstone beds and bioturbation is common. This facies association gradually passes laterally into FA 4.

Interpretation: This facies association is dominated by fine-grained material with sand introduced from the shoreline (Reading & Collinson, 1996; Myrow et al.,

Table 1. Overview of the 14 facies defined for the Upper Triassic succession on Wilhelmøya, Barentsøya and eastern Spitsbergen, expanded from Rød et al. (2014). Log examples are provided as a key for logs displayed in the correlation panel (Fig. 6).

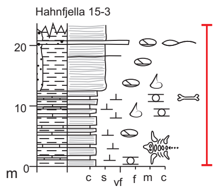
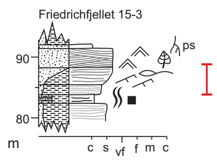
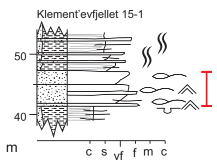
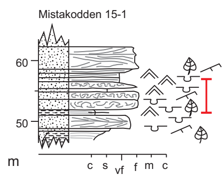
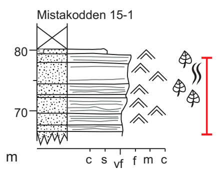
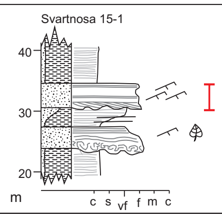
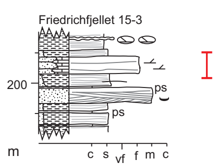
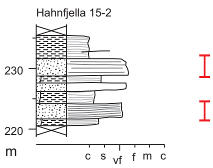
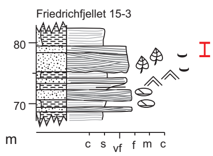
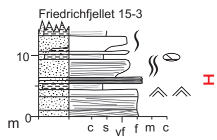
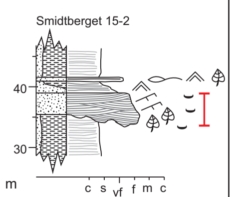
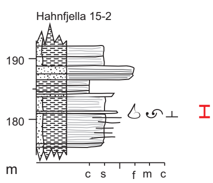
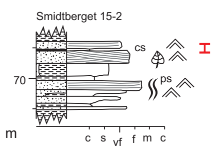
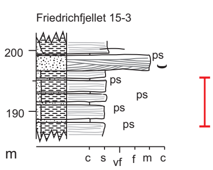
Facies	Log Example	Description	Interpretation
A		**Mudstone (0.1 - 10's m)** Clay and silt, laminated (shale) or non-laminated (mudstone). Thickness varies from a few centimetres to tens of metres. Laminated mudstones are most common and may encase thin beds of silty to very-fine sandstone. Colour is dominantly grey or black, but may also be yellow, white or purple colour with weathering of siderite cement. Facies is characterised by horizontal and gently undulating laminae. Load structures and irregular lamination are occasionally observed. Concretions of calcite or siderite are common. Organic content may be high at some intervals. Ammonoids and marine vertebrate fossils are common.	Pelagic shale and mudstone deposited from suspension in low-energy environments where clay and silt flocculate and settle on the sea floor (Boggs, 2011; Collinson et al., 2006). Also forms background sedimentation in shallow-marine environments closer to the shoreline.
B		**Heterolithic Bedding (0.01 - 10's m)** Heterolithic bedding is observed as thin beds of very-fine to fine sandstone and siltstone alternating with mudstones often forming coarsening-upwards units. The thickness of mud and sand layers generally range from 1 mm to a few centimetres, however thicker packages are evident. Units are up to 10-15 m thick. Sedimentary structures preserved in the sandstones of heterolithic successions are commonly hummocky cross-stratification and ripple cross-stratification. Bioturbation is common towards the top of units and *Skolithos* may be present.	Heterolithic bedding indicates alternating flow regime where sand and mud is available (Davis, 2012). Mud is deposited from suspension, while sand is deposited during current or wave activity (Reineck & Singh, 1980). This facies can form in the transition zone when mud interacts with sand introduced by periods of higher flow and sedimentation.
C		**Hummocky Cross-Stratified VF-F Sandstone (0.1 - 1 m)** Very-fine to fine-grained sandstones featuring hummocky and swaley cross-stratification. Consists of 10 cm to 1 m thick sandstone beds and are characterised by cross-laminae in undulating sets. Individual laminae sets are commonly between 5 and 20 cm thick. The sandstones are typically grey to yellow or orange to reddish brown colour. Beds are usually moderately to intensely bioturbated with *Skolithos* and *Diplocraterion*. Hummocky cross-stratified sandstones are common in upwards coarsening sequences in the lower part of the De Geerdalen Formation throughout the study area.	Hummocky cross-stratification shows a distinct undulating geometry of lamination formed by the migration of low-relief bed forms in one direction due to wave surge and unidirectional currents (Nøttvedt & Kreisa ,1987). This facies is widely recognised as being characteristic of tempestite deposition in shallow marine, storm-dominated inner shelf, to lower shoreface settings (Midtgaard, 1996; Yang et al., 2006). Hummocks form below the fair weather wave base and above, but are most common near storm weather wave base (Dumas & Arnott, 2006).
D		**Sandstone with Soft Sediment Deformation (0.3 - 1.5 m)** Erosive based, very-fine to fine-grained sandstones characterised by abundant soft-sediment deformation. Units can be laterally restricted but also extensive thickness ranges from 0.3 to 1.5 m. Irregular lamination seen within the sandstone bodies are also present in the upper parts of the underlying, deformed, mudstones. Sandstones are typically green-grey in colour and lack bioturbation. Soft-sediment deformed beds are relatively rare throughout the study area, with the most extensive beds occurring at the locality of Mistakodden.	Soft-sediment deformation structures typically generate from gravitational processes such as downslope sliding and slumping or rapid loading of sediment (Reineck & Singh, 1980; Bhattacharya & MacEachern, 2009). Likely form the base of distributary mouth bar deposits, where large volumes of sediments are deposited rapidly in front of distributary systems and reworked by wave or fluvial processes.
E		**Wave Rippled Sandstone (0.1 - 4 m)** Very-fine to fine-grained sandstone with symmetrical ripple lamination. Thicknesses range from tens of cm up to ca. 4 m, individual beds can be 10 to 30 cm in thickness. Sandstones have grey, yellow or red weathering colour. Fresh surfaces are light grey. Carbonate cement (calcite/ dolomite) or siderite is common. Sandstone beds of this facies are normally graded and wave ripples are often observed on the upper surfaces in coarsening-upwards successions. The crests tend to be continuous and straight. Mud drapes are common and expose ripple foresets. Facies is commonly found interbedded with heterolithic bedding or overlying horizontally bedded sandstone. Moderate bioturbation and *Rhizocorallium* or *Skolithos* trace fossils are present.	Wave ripples are commonly found in shallow-marine settings. They are formed by the oscillatory movement of currents at normal wave base (upper shoreface) where swash and backwash currents produce symmetrically shaped ripples (Boggs, 2011). Mud drapes on the foresets of ripples indicate a tidal influence.
F		**Current Rippled Sandstone (0.1 - 4 m)** Very-fine to fine-grained sandstone with asymmetric ripples forming individual beds or units composed entirely of ripple cross stratification up to 4 m in thickness. Sandstone is yellow, orange and brownish colour. Sandstone beds in this facies are typically normally graded and have sharp lower contacts, whereas contacts to upper facies are gradual. In some instances this facies may fine upwards. Facies is often observed to overlay large-scale cross-bedded and small-scale cross-bedded, normally graded sandstones and itself is overlain by fining-upwards beds of horizontally bedded sandstone.	Current ripples occur with the aggradation of ripples under contemporary downstream migration during unidirectional flow. Sets arranged into climbing ripples form under the same regime but with the angle of climb reflecting rate of aggradation (Collinson et al., 2006). Current ripples are commonly found in environments such as fluvial floodplains, with sub-environments such as; crevasse splays and point bars. They are also present in seasonally flooded river deltas (Reading & Collinson, 1996; Boggs, 2011). In marine environments they are usually formed in the shoaling wave zone.
G		**Carbonate Cemented Sandstone (0.2 - 2 m)** Very-fine to fine-grained, normally graded, sandstones characterised by structures formed during diagenesis. Sandstone units are commonly hard and heavily cemented with calcite, dolomite or siderite, making observations of primary sedimentary structures difficult, thickness is typically 0.2 – 2 m. Secondary sedimentary structures include cone-in-cone, siderite beds and calcareous concretions. Colour variation between grey, brown and red are observed. Scarce to heavy bioturbation is noticed. Cemented sandstone forms benches in the topography or distinctive layers, that may be laterally continuous for several tens of metres prior to pinching out.	Sources of calcite cement may be dissolved bivalves and coquinas. Recent studies by Tugarova & Fedyaevsky (2014) suggests a genesis driven by micro-organisms and a biochemical precipitation of carbonates during early diagenesis in a shallow-marine environment. Siderite occurs in organic-rich brackish to meteoric pore-waters depleted of SO_2 and is commonly found in fine-grained deltaic to coastal sediments (Morad, 1998). Siderite concretions and layering might indicate a continental influence on marine sedimentation with organic-rich stagnant waters close to the delta front (Pettijohn et al., 1987).

Table 1. Cont.

Facies	Log Example	Description	Interpretation
H		**Plane Parallel Laminated Sandstone (0.3 - 2 m)** Sandstones with horizontal, plane parallel lamination or plane parallel stratification. Mostly very fine to fine grained sand, but can also be silty and medium grained. Units range between 30 cm and 2 m in thickness, with mm-thin lamina and cm-thick beds. Parting lineation (primary current lineation), is present on bedding surfaces. Stratification varies from lamination to bedding. Colour is grey to pale yellow, but weathers brown to red. Lower boundaries are typically sharp, while the upper are commonly more gradual. Units are often observed towards the top of sandstone benches. Bioturbation is rare in lower parts, but occurs towards the upper part of units. *Skolithos, Diplocraterion* and *Rhizocorallium* also observed.	Plane parallel stratification occurs in various environments and is not a unique environmental indicator (Boggs, 2011). The structure form by settling of fine grains from suspension or traction of sand as bed-load in the upper flow regime (Collinson et al., 2006; Boggs, 2011). Laminae are defined by grain size variations or assembling of mica, representing subtle variations in depositional environment (Collinson et al., 2006). It is commonly found in rivers and streams with a high flow (Boggs, 2011), but it can also result from settling of sand grains from suspension.
I		**Low Angle Cross-Stratified Sandstone (0.1 - 1.5 m)** Very fine to fine grained sand, forming gently inclined sets of planar parallel stratification or lamination, with wedge-shaped set boundaries. The colour is usually grey to red-brown when weathered and grey on fresh surfaces. Unit thickness is usually between tens of cm to 1.5 m, while set thickness range between 5 and 15 cm. Individual sets are composed of both beds and lamina, where the former is the most common. These sandstones are commonly bioturbated and contain plant fragments and rare fish remains. It is frequently found overlying or interbedded with wave rippled sandstones, or heterolithic bedding.	Low angle cross-stratification is not considered a diagnostic sedimentary structure as it can be seen occurring in a range of depositional environments. However, the presence of bioturbation and plant fragments are interpreted as indicators of a proximal position in the shallow marine environment, most likely the upper shoreface or beach foreshore (Reading & Collinson, 1996). Low angle cross-stratified sandstones typically exhibit a gentle dip seawards when found in foreshore and backshore settings (Reading & Collinson, 1996)
J		**Tabular Cross-Stratified Sandstone (0.1 - 1.5 m)** Very fine to fine grained sandstones with tabular cross-stratification or cross-lamination, arranged in foresets with bedforms of 2 to 10 cm thickness and stacked in units that are up to 1.5 m thick. Calcite cementation is common and varies from vague to pervasive resulting in differences in appearance within facies. Sparse bioturbation is occasionally observed towards the top of units and plant fragments are common. Grey, yellow, brown and reddish colours are observed. Weathering of finer material on sandstone bounding surfaces is interpreted as draping mud or finer sand. Facies is commonly found overlying large-scale cross bedded sandstones in fining upwards units. It is also often found within heterolithic bedded units.	Tabular cross-stratification forms by unidirectional currents of the lower flow regime in shallow waters (Collinson et al., 2006; Boggs, 2011). Environments of formation are fluvial and shallow marine where rip-currents, longshore currents, tidal currents and breaking waves creates unidirectional currents (Reading & Collinson, 1996). Plant fragments, low abundance of trace fossils and close proximity to palaeosols in upper sections indicates that this facies is most likely associated with terrestrial depositional environments.
K		**Trough Cross-Stratified Sandstone (0.2 - 4 m)** Fine to medium grained trough cross-stratified sandstones with sharp erosive base, displaying a fining upwards trend. Cross set thicknesses range from 20 to 80 cm, whereas stacking of sets results in unit thicknesses of 0.2 to 4 meters. Rip-up clasts and plant fragments are frequent in the basal parts of units and scours. Observed colours are grey, yellow and brown, with reddish and dark colours appearing occasionally on weathered surfaces. Upper parts of sandstones may be sparsely bioturbated, whereas lower parts are essentially free of traces. Trace fossils observed within this facies are *Skolithos* and *Diplocraterion*.	Formed by migration of 3D dunes, in unidirectional currents in the lower flow regime (Reading & Collinson, 1996; Boggs, 2011). Complexity of dune morphology is thought to increase at higher current velocities and shallower waters (Collinson et al., 2006; Boggs, 2011) and stacking of co-sets represent superimposed bed-forms (Reineck & Singh, 1980). Facies is interpreted as migrating dunes in a subaqueous environment due to unidirectional current. Mud drapes are attributed to slight changes in current velocity, possibly implemented by tidal activity or seasonal changes in stream discharge.
L		**Bioclastic Sandstone and Mudstone (0.1 - 0.5 m)** The unit consists mainly of disarticulated and fragmented bivalves (coquina), lacking sedimentary structures. Thickness is from 10 to 50 cm. All the observed units are cemented and display orange and purple weathering colours. Bioclastic beds are found as discrete laterally continuous layers sandwiched between mud and locally as minor shell accumulations within sandstone bodies. Bioclastic beds are typically restricted to the lower parts of the Isfjorden Member, but are also seen at some localities in the lower part of the De Geerdalen Formation.	Fragmented shells indicate a relatively high energy environment. Mass erosion and transportation of shells can lead to concentration of shell fragments in beds where the hydrodynamic energy is low enough for deposition (Reineck & Singh, 1980). The Isfjorden Member is interpreted to be deposited in a shallow marine and lagoonal environment. Based on associated facies, field observations also point towards a proximal shallow marine origin, and coquina beds may represent wave reworked shallow marine shell banks accumulated by currents or waves.
M		**Coal and Coal Shale (0.1 - 0.2 m)** Units of coal and coal shale are from 1 to 20 cm thick. The units often appear laterally continuous over tens of metres. Coal and coal shales are usually found in close proximity to the top of larger sandstones. Coals are distinguished from coal shales by being more consolidated and vitrinous, reflecting a higher proportion of organic material. Coal and coal shales are commonly associated with underlying palaeosols, but coal shale surrounded by grey shale is observed on Wilhelmøya and Hahnfjella. Rhizoliths are also commonly observed in the coals. The facies is found at all localities, but only in the middle and upper parts of the De Geerdalen Formation.	Coal seams found in the De Geerdalen Formation typically overlie palaeosols, indicating they are formed in place (histic epipedons) (Retallack, 1991). Coal and coal shale beds found in the De Geerdalen Formation are thin and laterally discontinuous. Coal and coal shales are here interpreted to originate from mires on a dynamic delta plain setting in a humid palaeoclimate with seasonal variations in precipitation, following the conclusions of Enga (2015).
N		**Palaeosols and Calcrete (0.2 - 1 m)** Palaeosols are found at all localities. The thickness is in the range of 0.2 to 1.0 metres. Roots and wood fragments up to 20 cm in diameter can be found. The colour varies from brown to reddish brown and yellow. Non-calcareous palaeosols are composed of mudstone and weather red or green and are 0.2 to 1 m in thickness. The structure of these mudstones is blocky or gravelly with weathering and mottles being common. Palaeosols occur both in grey mudstone and on top of sandstone beds. A gradual contact at the base and sharper contact at the top is typical for palaeosols (Boggs, 2011) and is frequently observed in the outcrops. The palaeosols are commonly overlain by coal or coal shale.	Palaeosols form due to physical, biological and chemical modification of soil during periods of subaerial exposure. Palaeosols are continental (Boggs, 2009), but can form in marine strata following sea level fall and sub-aerial exposure (Webb, 1994). Palaeosols represent an unconformity, formed in a degrading landscape (Kraus, 1999). Red mudstone beds are interpreted as calcrete horizons formed in a semi-arid environment. Calcretes also imply periods of non-deposition. Red and green colours may result from fluctuations in groundwater and shifts between oxic to anoxic conditions.

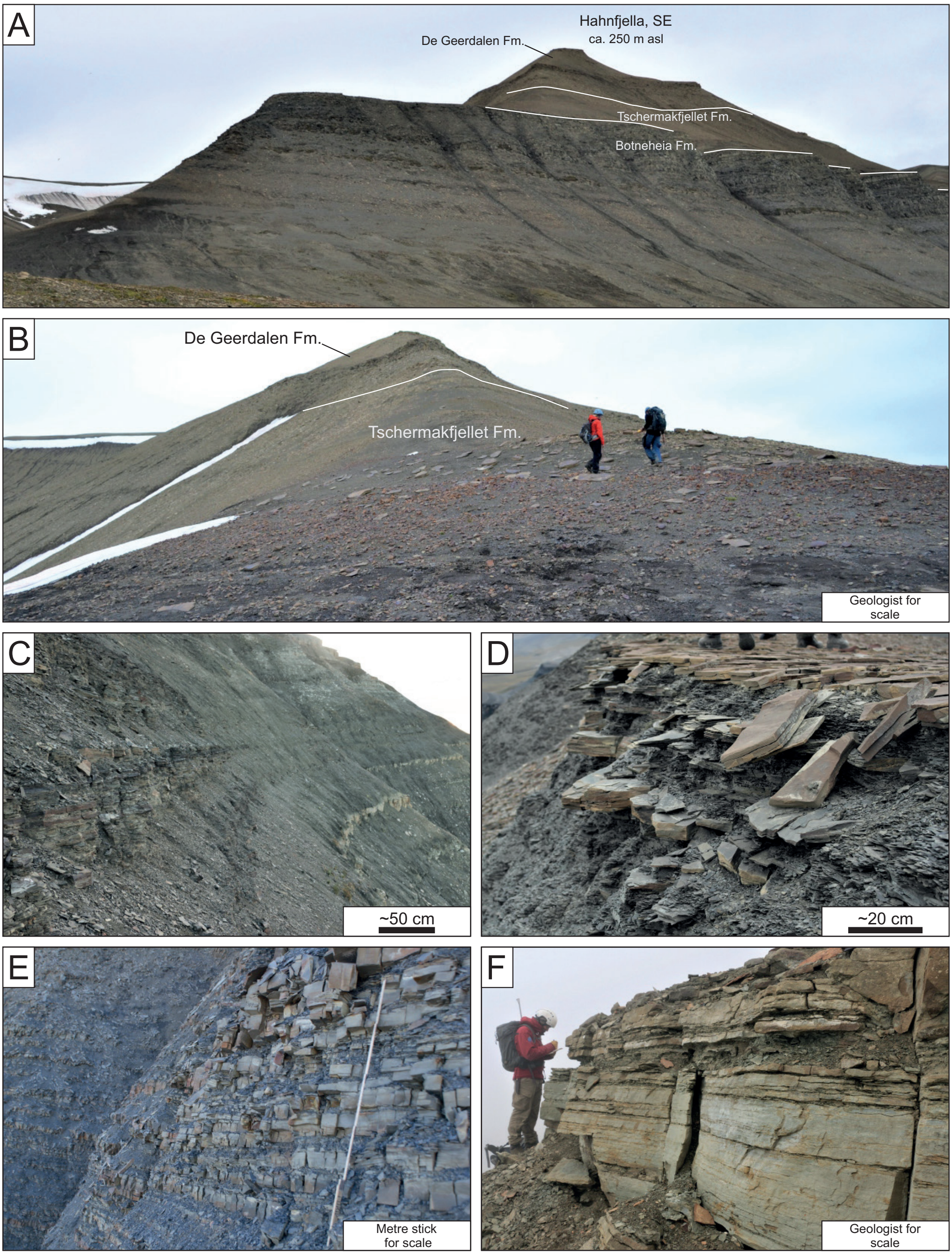


Figure 4. *(A) Overview photo of the western ridge of Hahnfjella (Fig. 1B) showing the thick and laterally extensive deposits of FA 1 (Table 2) that typically characterise the Botneheia Formation. (B) FA 2, prodelta shales of the Tschermakfjellet Formation at Hahnfjella. The unit typically consists of facies A, B, C and H (Tables 1, 2). (C) Offshore deposits (FA 3) observed in the upper part of Friedrichfjellet, Agardhbukta (Fig. 1B). This interval represents sedimentation in a shallow-marine environment in a distal setting with dark-grey shales (Facies A) being the dominant lithology. (D) Offshore transition deposits (FA 4) showing thin beds of carbonate-cemented sandstone in the upper part, bearing hummocky cross-stratification (Facies C), with dark-grey shales (Facies A) representing background sedimentation. (E) Heterolithic bedding observed in lower shoreface deposits (FA 4); this facies association represents deposition of sand and silt in a periodically turbulent environment. This periodic turbidity has resulted in heterolithic coarsening-upward units, composed of mudstone and sandstone. Hummocky cross-stratified and wave-rippled sandstones are common. (F) Upper shoreface deposits (FA 6) featuring sandstone with low-angle, cross-stratification overlain by beds of wave-rippled sandstone (Facies I). Mud drapes are common in the upper parts of these units and are seen to drape ripple crests.*

Table 2. *Summary of facies associations (FAs) recognised in the De Geerdalen Formation. The subenvironments are further classified according to their gross depositional environment (DE).*

DE	Facies Association (FA)	Facies Incorporated	Description	Geometry / Form
DE 1 - Open Marine Shelf & Prodelta	FA 1 - Open Marine Shelf Deposits	A	Pelagic, organic rich shales and marine shale deposits. Abundant fossils and bone fragments and thin interlaminae of silt.	Extensive in thickness and areal extent. Forms major units.
	FA 2 - Prodelta Slope Deposits	A, B, C & H	Marine shales and siltstones, minor sand and bioturbation. Tempestites may be present with minor hummocky cross-stratification and ripples.	Areally extensive throughout Svalbard. Forms stratigraphic unit with variable thickness. (10 - 130 m).
DE 2 - Shallow Marine	FA 3 - Offshore Deposits	A, I & J	Mud and silt dominated distal deltaic sediments. Forms dark mudstone and heterolithic bedded units with minor storm induced sandtsones and thin offshore bars.	1 - 10's of metres thick. Laterally extensive and grade into offshore transition or lower shoreface deposits.
	FA 4 - Offshore Transition Deposits	A, B, C & E	Thin beds of hummocky cross-stratificatied sandstone in fine-grained shale and stiltstones. Wave and symmetrical ripples common. Bioturbation and shell fragments also present.	1-10 m thick, laterally extensive for 100's m. Grades laterally into offshore or lower shoreface deposits
	FA 5 - Lower Shoreface Deposits	A, B, C, E, G & H	Below normal wave base deposits dominated by mudstone and siltstone, with storm induced sandstone beds. Wave rippled, carbonate cemented or plane parallel laminated sandstone beds are common.	1 - 5 m thickness and laterally extensive. Grades laterally into upper shoreface deposits or fluvial distributary deposits.
DE 3 - Delta Front	FA 6 - Upper Shoreface Deposits	C, E, F, I & K (also G & L)	Sandstone and siltstone, showing re-working of sediment in a turbulent environment. Wave structures indicate marine processes. Mud drapes suggest tidal influence. Forms prominent sandstone benches.	1 - 5 m thick and laterally extensive. Overlies lower shoreface or offshore transition deposits.
	FA 7 - Distributary Mouth Bar Deposits	D, F, H, I, J & M	Soft sediment deformed sandstone with trough, low-angle and tabular cross-stratified sandstones. Erosive base indicate rapid deposition. Reworking of sediment by wave or tide processes evident. Also amalgamated.	Laterally extensive sheets for 100's of m. Thickness varies but is in the order of 1 - 4 m. Grades into distributary facies.
	FA 8 - Barrier Bar Deposits	E,F, H, I & K	Upwards coarsening facies, with trough or low angle cross-stratified sandstone, with current or wave rippled sandstone. Tidal indicators and bioturbation suggest a marine origin.	Laterally extensive. Thickness ca. 1 - 2 m. Grades laterally into shoreface or inter distributary deposits.
DE 4 - Delta Plain	FA 9 - Distributary Channel Deposits	F, H, J, K, M & N	Sharp erosive base, contains trough and tabular cross-stratified sandstone facies. Mud-flakes are common in this association. Often underlies palaeosol facies. Can also form lateral sheets with amalgamated channels.	Extensive sandstone bodies. Often less than 10 m in thickness. Grades laterally into floodplain deposits.
	FA 10 - Floodplain Deposits	A, E, F, J, M & N	Fine-grained floodplain deposits, or overbank fines. Silt with sandstone laminae common. Coal,coal shale and palaeosols present in this FA.	Laterally extensive with variable thickness, ca. 0.2 - 1.5 m. Overlies or insciced by fluvial distributary deposits.
	FA 11 - Inter-distributary Areas	A, L, M & N (with E, F & H)	Fine-grained facies. Some rare sandstone incursions with hummocks or ripples may be present, facies generally suggest a low energy marine or lacustrine environment. Bioturbation and palaeosols common.	1 - 10's of metres thick, laterally extensive, grading laterally into shoreface or barrier bar deposits.

2008; Ichaso & Dalrymple, 2009; Boggs, 2011). The offshore zone is defined as shelf areas below storm wave base and is primarily the site of deposition of fine mud and silt settling from suspension (Bhattacharya, 2006; Nichols, 2009). Bioturbation occurs, and may be locally intense. The offshore zone is well oxygenated, resulting in a typically grey colour of the sediments, partly due to preservation of some organic matter in the mud (Nichols, 2009). Sandstone beds within this FA may represent storm-induced deposits where coarser clastic sediment has been reworked from proximal areas.

This facies association is commonly seen to occur at the base of shallowing-upward parasequences that are common in the De Geerdalen Formation (Mørk et al., 1982). Beds composed of FA 3 mark the onset of flooding (flooding surface) during transgressive episodes. FA 3 can commonly be seen to overlie FAs 9 and 10.

FA 4 – Offshore transition deposits

Description: Offshore transition deposits in the study area (Fig. 4D) typically consist of normal-graded mudstone (Facies A) or upward-coarsening heterolithic bedding (Facies B), hummocky cross-stratification (Facies C) and wave-rippled sandstones (Facies E). This facies association generally forms an overall upward-coarsening unit, with an increasing thickness of sandstone beds. Heterolithic beds usually feature fine-grained sandstone with hummocky cross-stratification. Wave ripples are commonly preserved on the upper bed surface. The mudstones and sandstones commonly display evidence for bioturbation in the form of vertical or semihorizontal burrows (e.g., *Skolithos*, *Diplocraterion* or *Rhizocorallium*). This facies association is typically underlain by offshore zone deposits (FA 3) and overlain by lower shoreface deposits (FA 5), or passes laterally into these FAs.

Interpretation: Due to the overall heterolithic character of deposits in this FA, the presence of hummocky cross-stratification and marine trace fossils, this facies association is interpreted to be representative of the offshore transition zone. This zone extends from the offshore zone, below storm wave base, to depths where storm waves begin to agitate sediments. It is more sand-rich compared to the offshore zone and is dominated by alternating energy conditions (Reading & Collinson, 1996; Dashtgard et al., 2012). Storms generally control sediment distribution in the offshore transition zone by erosion of the coastline. Fine sediments (background sedimentation) are deposited from suspension during fair weather conditions. Typical signatures of storm deposits are a basal lag of coarse sediments, hummocky cross-stratification, wave-rippled cross-lamination and burrowed intervals (Johnson & Baldwin, 1996; Dashtgard et al., 2012). Bioturbation tends to decrease from proximal to distal settings.

FA 5 – Lower shoreface deposits

Description: The lower shoreface deposits (Fig. 4E) typically feature normal-graded mudstone in the lower part (Facies A) with an upwards increase of siltstone and sandstone into heterolithic beds (Facies B). Thin, normal-graded sandstone beds, featuring hummocky cross-stratified, wave-rippled and plane parallel stratified, very fine-grained sandstones are present (Facies C, E and H). Wave-rippled sandstones (Facies E) and plane parallel stratified sandstones (Facies H) cap upward- coarsening units and are seen to be laterally discontinuous and interfinger with heterolithic beds or mudstone (Facies A and B). Top surfaces may also show eroded wave crests. Wave-ripple troughs are commonly mud draped and slight bioturbation is present. Calcite-cemented sandstones with cone-in-cone structures (Facies G) are also found. This facies association commonly forms the middle part of upward-coarsening parasequences in the lower part of the De Geerdalen Formation.

Interpretation: The lower shoreface deposits feature a higher sand content than in the offshore transition deposits (FA 4) due to the constant reworking of finer grain sizes by oscillatory currents, under fair weather conditions (Clifton, 2006). Wave ripples shallow into current ripples, but can be reworked by storm events resulting in hummocky cross-stratification (Reading & Collinson, 1996; Dumas & Arnott, 2006). Interbedded mudstones and mud drapes are indicative of alternating energy conditions and could also be attributed to a tidal influence (Davis, 2012).

FA 6 – Upper shoreface deposits

Description: Upper shoreface deposits (Fig. 4F) typically include very fine and fine-grained, normal-graded sandstones, dominated by low-angle and trough cross-stratified fine-grained sandstone (Facies I and K). Units typically coarsen upwards from the heterolithic part of FA 5. The upper parts of sandstone units feature wave and current ripples (Facies E and F). Bioturbation is also common. Fragmented and disarticulated bivalves and shell fragments may also be found forming thin bioclastic sandstone and mudstone beds (Facies L). Carbonate-cemented sandstone beds (Facies G) may be present and form laterally extensive sandstone beds that form prominent 'benches' in the topography.

Interpretation: The upper shoreface is dominated by wave processes with deposition of sediment occurring above normal wave base. Wave-agitated sediment forms beaches and berms, while fragmented shell beds indicate a high-energy environment. These wave processes typically form seaward-dipping cross-stratification (Scholle & Spearing, 1982). Shell banks are often located on beaches subjected to intense wave reworking. Massive erosion and transportation of shells can lead to concentration of shell fragments in beds where the hydrodynamic energy is low enough for deposition (Reineck & Singh, 1980). Individual beds of bioclastic mudstone and sandstone are observed throughout the study area and may represent shell banks (coquina beds) deposited under high-energy conditions.

FA 7 – Distributary mouth bar deposits

Description: The distributary mouth-bar facies (Fig. 5A) association consists of normal-graded, fine to medium-grained sandstones, arranged into coarsening-upward units up to 10 m thick, typically overlying or incising into the heterolithic facies associations of FAs 2 to 5. Soft-sediment deformed sandstone (Facies D) can be observed to scour into underlying shale beds (FA 3). Low-angle cross-stratified sandstone (Facies I) and tabular cross-stratified sandstones (Facies J) are common in the middle and upper parts of these units. Plane parallel laminated sandstones (Facies H) and occasional interbedded wave-rippled and current-rippled sandstones (Facies E and F) are commonly found in the upper parts of sandy units. Abundant plant fragments and coal drapes are found in this facies association. Bioturbation is rarely observed. The sandstone bodies of this FA can also be seen to form amalgamated and laterally extensive sandstone sheets (Fig. 5A) or lenticular sandstone bodies. These are often incised by FA 9 (Distributary channel deposits) or are directly overlain by coaly and coal shale (Facies M, delta-plain deposits FA 10).

Interpretation: Rapid deposition rates are common for distributary mouth bars (Reineck & Singh, 1980), with this illustrated by ripple-laminated sandstones and loading structures. Plane parallel laminated, low-angle cross-stratified and wave-rippled sandstones are commonly found in the upper part of this facies association. This indicates wave reworking of deposits. A marine affiliation is supported by marine trace fossils, the low abundance being explained by a rapid influx of fresh water and turbid waters rich in suspended fines. Abundant plant fragments and coal-draped foresets indicate a proximal terrestrial influence, while beds of mudstone forming the heterolithic component of this facies association are likely a result of variations in fluvial discharge. Coal and coaly shale caps indicate an extended period with a high water table, resulting in mires and wetlands and may represent the onset of a transgressive regime.

Distributary mouth bars form at the seaward limit of distributary channels as the flow decelerates, depositing sandy shoals (Reading & Collinson, 1996; Tye, 2004; Olariu & Bhattacharya, 2006). Laterally extensive sheets form as waves straighten and elongate the mouth bar alongshore (Reynolds, 1999; Bhattacharya & Giosan, 2003). Down-cutting of the associated distributary channel commonly erodes the upper parts of mouth-bar sediments (Reading & Collinson, 1996).

FA 8 – Barrier bar deposits

Description: Barrier bar deposits (Fig. 5A) can be observed above the heterolithic deposits of FA 2 to 6. Fine to medium-grained sandstone is found in large-scale, trough cross-stratified units (Facies K) in the upper part of parasequences. Low-angle cross-stratified sandstone (Facies I) and plane parallel laminated sandstone (Facies H) may also be present. Small-scale current-rippled sandstones (Facies F) and wave-rippled sandstones (Facies E) are also found in this interval, but compose finer sandstone fractions with minor inclusions of intercalated mud. Tidal signatures such as mud-draped foresets and double mud drapes are observed. Calcite cementation is common and *Skolithos* and *Diplocraterion* trace fossils are found within this facies association.

Interpretation: The presence of laterally extensive sandstone benches overlying heterolithic deposits, with low-angle cross-stratification and extensive bioturbation suggests that they represent barrier bar deposits formed in an open clastic coastline (e.g., Clifton, 2006). The units exhibit an upward-shallowing succession of sandstone-dominated deposits, overlying distal marine offshore to lower shoreface deposits (FA 1) and underlying proximal nonmarine facies. On the upper shoreface, fair-weather waves set up longshore and onshore currents, leading to migration of bars and current ripples.

Barrier island formations have traditionally been associated with low sediment supply and relative sea-level rise, e.g., a transgressed and submerged delta lobe after upstream avulsion (Reading & Collinson, 1996; Olariu, 2014). This interpretation can be debated (e.g., Bhattacharya & Giosan, 2003; Li et al., 2011) as barrier islands can also be attributed to significant delta asymmetry, and are common elements in wave-dominated deltas, characterised by strong longshore drift. Mechanisms such as autogenic process change from fluvial to wave-dominated have previously been suggested to explain the coarsening-upward parasequences seen in the De Geerdalen Formation (Mørk et al., 1982). Recurrent barrier bars are seen to form vertically stacked parasequences in the lower parts of measured sections.

FA 9 – Distributary channel deposits

Description: Distributary channel deposits (Fig. 5C) form prominent sandstone units, either as thin and laterally extensive sheets, or amalgamated into channel complexes that form the upper parts of lenticular sandstone bodies typically incising into FA 7. Rarely, isolated channel deposits may be observed but only in the Isfjorden Member. Sandstones of this facies association feature an erosive base, commonly containing a mud-flake conglomerate lag and abundant plant fragments. Lower parts are dominated by trough cross-stratified intervals (Facies K, Table 1), while tabular cross-stratified sandstones (Facies J, Table 1) and current-rippled sandstones (Facies F, Table 1) are found in the uppermost beds. Mud-draped foresets are occasionally seen in trough cross-stratified intervals and on ripple crests, but generally mud is restricted to interbedded clay laminae in plane parallel laminated sandstone (Facies H). Rootlets, coal and palaeosols (Facies M and N, Table 1) are found at the very tops of sequences.

Interpretation: Distributary channels carry sediment and water discharge from trunk rivers over the delta plain, to the sea. Distributary channels merge with coastal waters on the delta front and become shallower, branch into sub-channels and lose competence (Reineck & Singh, 1980; Olariu & Bhattacharya, 2006). Distributary channels are prone to avulsion, bifurcation and anastomose due to the lower slope gradient on the delta plain. Their base is typically erosive with a lag that gradually fines upwards from cross-stratified sandstone to ripple-laminated fine sandstone with alternating silt and clay. Observed rootlets or palaeosols on the top indicate emergence of the channel (Reading & Collinson, 1996) and likely abandonment of the fluvial system at that location. The width to depth ratio is also small for distributary channels because of their relatively short lifetime and limited time to migrate laterally (Reading & Collinson, 1996).

Distributary channel deposits tend to be laterally restricted, displaying relatively modest dimensions (height around 2 to 3 metres, width around 10 m). However, amalgamated channel deposits show extensive

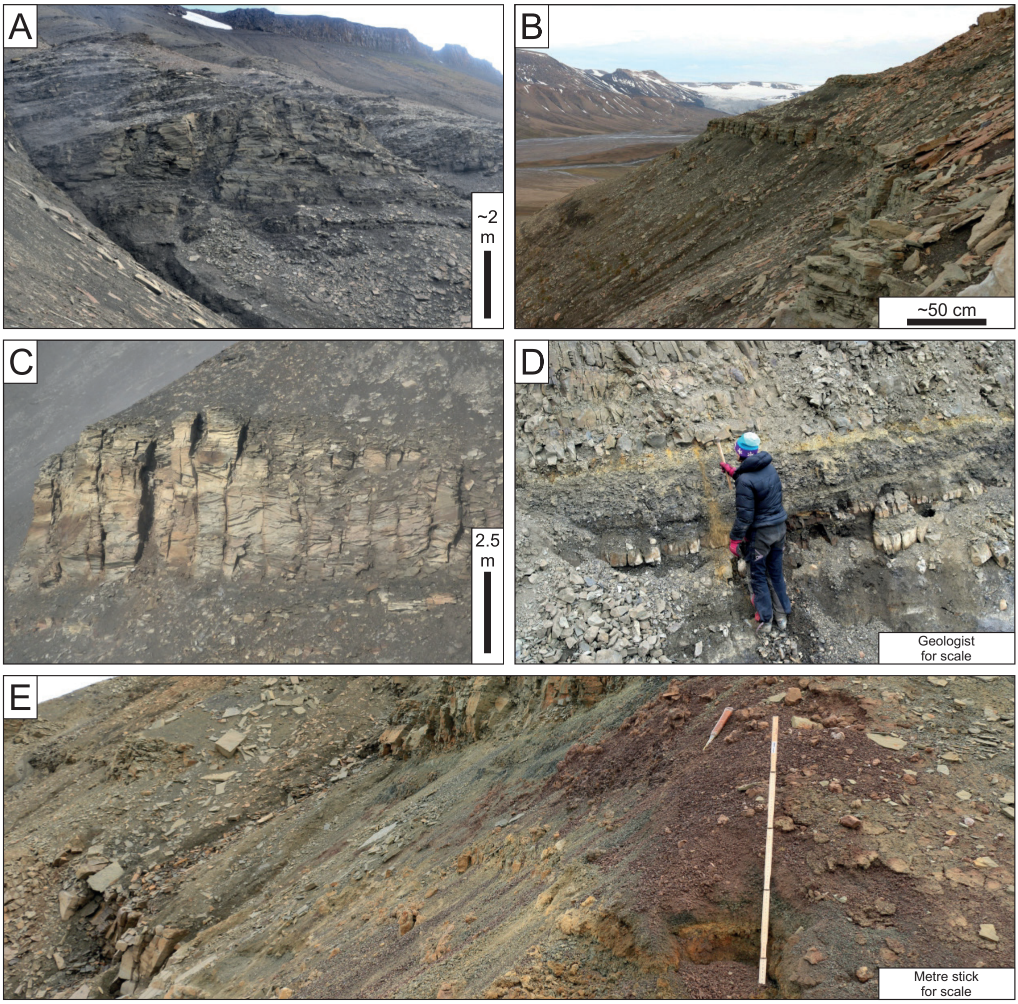


Figure 5. *(A) Distributary mouth-bar deposits (FA 7) observed in the lower part of the mountainside at Svartnosa, Barentsøya (Figs. 1B, 6, 9). These mouth-bar deposits feature a soft-sediment deformed base (Facies D), overlain by trough and low-angle cross-stratification with wave ripples in the upper part (Facies K, I, E). This sandstone body is interpreted as representing a series of amalgamated distributary mouth-bar deposits. (B) Laterally extensive sandstone bench observed at Šmidtberget, Agardhbukta (Figs. 1B, 6), interpreted as forming barrier-bar deposits (FA 8). The sandstone is composed of low-angle cross-stratified sandstone (Facies I) with laterally restricted beds of plane-parallel laminated and trough cross-stratified sandstone (Facies, K) overlain by wave-rippled sandstones (Facies E). (C) Distributary channel deposits (FA 9) observed at Svartnosa on Barentsøya (Figs. 1B, 6, 9). These sandstones form a laterally extensive sheet, extending across the mountain, interpreted as amalgamated distributary channels composed of tabular and trough cross-stratified sandstone (Facies J, K). This facies association is commonly overlain by FA 10 or 11. (D) Flood-plain deposits (FA 10) exposed at Friedrichfjellet, Agardhbukta (Figs. 1B, 6), showing a well developed palaeosol horizon (Facies N), over heterolithic flood-plain deposits. (E) Interdistributary deposits (FA 11) observed at Klement'evfjellet in Agardhbukta (Figs. 1B, 6). Here, well developed beds of alternating green and red clay are observed with mudstone and heterolithic units (Facies A, B). These beds are interpreted as soil horizons (Facies N).*

lateral continuity throughout the study area, forming sandstone 'benches' and are suggested to grade laterally into either distal or proximal facies associations (e.g., upper shoreface or mouth-bar deposits or floodplain deposits). Isolated distributary channel complexes are typically confined to the Isfjorden Member whilst amalgamated channel deposits are found in the middle part of the De Geerdalen Formation. The relatively modest dimensions characterising laterally restricted fluvial channel deposits could possibly be explained by frequent switching and abandonment on the delta plain (Reading & Collinson, 1996). The amalgamated deposits may represent periods of relatively stable base level, thereby allowing the extensive lateral migration as, for example, observed at Svartnosa (Fig. 5A).

FA 10 – Floodplain

Description: Floodplain deposits (Fig. 5D) are found extensively throughout the study area. The facies association is typically found in thin units overlying distributary channel deposits, or as thick and laterally extensive deposits in the upper part of the De Geerdalen Formation. These deposits are composed primarily of mudstones (Facies A) with thin, normal-graded beds of fine-grained sandstone with wave and current ripples (Facies E and F). Minor sandstone beds with tabular cross-stratification (Facies J) may be present. Coal, coaly shales and palaeosols (Facies M and N; Fig. 5D) are found both at the tops of distributary channels and extensively within floodplain deposits. Plant fragments and bioturbation in sandstone beds are common. Floodplain deposits typically range between two and twenty metres in thickness in the study area.

Interpretation: Distributary channels (FA 3) together with floodplains are the main areas of activity on the delta plain (Bhattacharya, 2006). Floodplains receive most of the sediments from distributary channels and the sediment load in most rivers contains as much as 85–95% mud (Schumm, 1972). Mud is primarily carried in suspension (Bhattacharya, 2006). Beds of mud on the floodplain may be interrupted by silt and sand sourced from levees and crevasse splays. During periods of flood, levees may breach and crevasses splays advance onto the delta plain, leading to deposition of silt and sand in lobes. Crevasse splays may form distinct layers of rippled sandstone and thin beds of siltstone that generally fine away from the source channel. Bioturbation is common.
Floodplains are commonly exposed during low water level, leading to pedogenesis. In humid conditions, the floodplain sediments may stay wet and peat may accumulate, resulting in the formation of coal (Fig. 5D; Collinson, 1996).

FA 11 – Interdistributary areas

Description: Interdistributary areas (Fig. 5E) are recognised by less sand content in comparison to distributary areas and floodplain deposits, with a greater marine influence. They are dominated by normal-graded mudstone (Facies A), in places interrupted by thin coal and coal shales (Facies M), or alternating red and green palaeosols (Facies N). Some exposures interpreted as this facies association contain beds of wave-rippled, symmetrical rippled or plane parallel laminated sandstone (Facies E, F and H). Palaeosols (Facies N) are commonly found underlying coal or coal shales (Facies M) and directly overlying mudstones (Facies M,) or distributary channels. In some sections palaeosols are found dispersed within mudstones (Facies M). Coquina beds (Facies L) are also abundant in this FA forming laterally extensive and relatively thin, bioclastic beds with abundant bivalve and shell fragments.

Interpretation: Interdistributary areas are herein considered as standing bodies of water such as lagoons and lakes, as well as marshes and swamps. Facies successions are in general seen as quite thin, coarsening or fining-upward units (Bhattacharya, 2006). Coal and coal shales found in the De Geerdalen Formation are thin and appear impure, leading to the interpretation that they originate in the lower delta-plain setting, in saline marshes. Thin coal seams with a limited lateral continuity support the relatively dynamic and unstable paralic regime interpreted for the De Geerdalen Formation (Klausen & Mørk, 2014; Rød et al., 2014; Paterson et al., 2016).

Coquina beds found in this FA could form due to very slow rates of deposition following a major avulsion, delta lobe or distributary switching, or eustatic sea-level rise, e.g., the 'Abandonment facies association' of Reading & Collinson (1996). These conditions are common in interfluvial areas where limestone, coals or highly condensed horizons bioturbated by plants or animals are present (Reading & Collinson, 1996). Abundant molluscs are found in interdistributary bay sediments in the modern Mississippi delta (Frazier, 1967).

Palaeosols indicate a time of subaerial exposure and only form if the sedimentation rate does not exceed the rate of pedogenesis (Kraus, 1999; Kraus & Aslan, 1999). Palaeosols are an indicator of periods with little or no sedimentation and are the clearest indicators of an interdistributary regime. Palaeosols above distributary channel facies typically indicate channel abandonment.
In the upper part of the De Geerdalen Formation, red and green, nodular palaeosols (Fig. 5E) and caliche horizons are common. These differ from grey and yellow palaeosols, coals and coal-shales seen in in the remainder of the formation. This change is documented in stratigraphical terms by the Isfjorden Member (Pčelina, 1983; Mørk et al., 1999a; Haugen, 2016). Red nodular clays are interpreted as representing an unaltered, oxidised soil profile, whilst green and grey suggests an environment with reducing conditions (Haugen, 2016). The alternating presence of these beds is useful for gaining insight into environmental fluctuations at the time of deposition. In addition, as they represent extended periods of subaerial exposure (Webb, 1994) and non-deposition, these beds can thus also be considered as a minor hiatus (Kraus, 1999).

Depositional environments

Due to the paralic nature of the Upper Triassic in eastern Svalbard (Mørk et al., 1999a; Klausen & Mørk, 2014; Lord et al., 2014a, b; Paterson & Mangerud, 2015; Paterson et al., 2016; this study), individual facies associations are difficult to correlate laterally over wide areas. To overcome this problem and to ease regional correlation, the facies associations have been grouped into four gross depositional environments (DE). These are: DE 1 – open marine shelf and prodelta, DE 2 – shallow marine, DE 3 – delta front, DE 4 – delta plain. The method builds

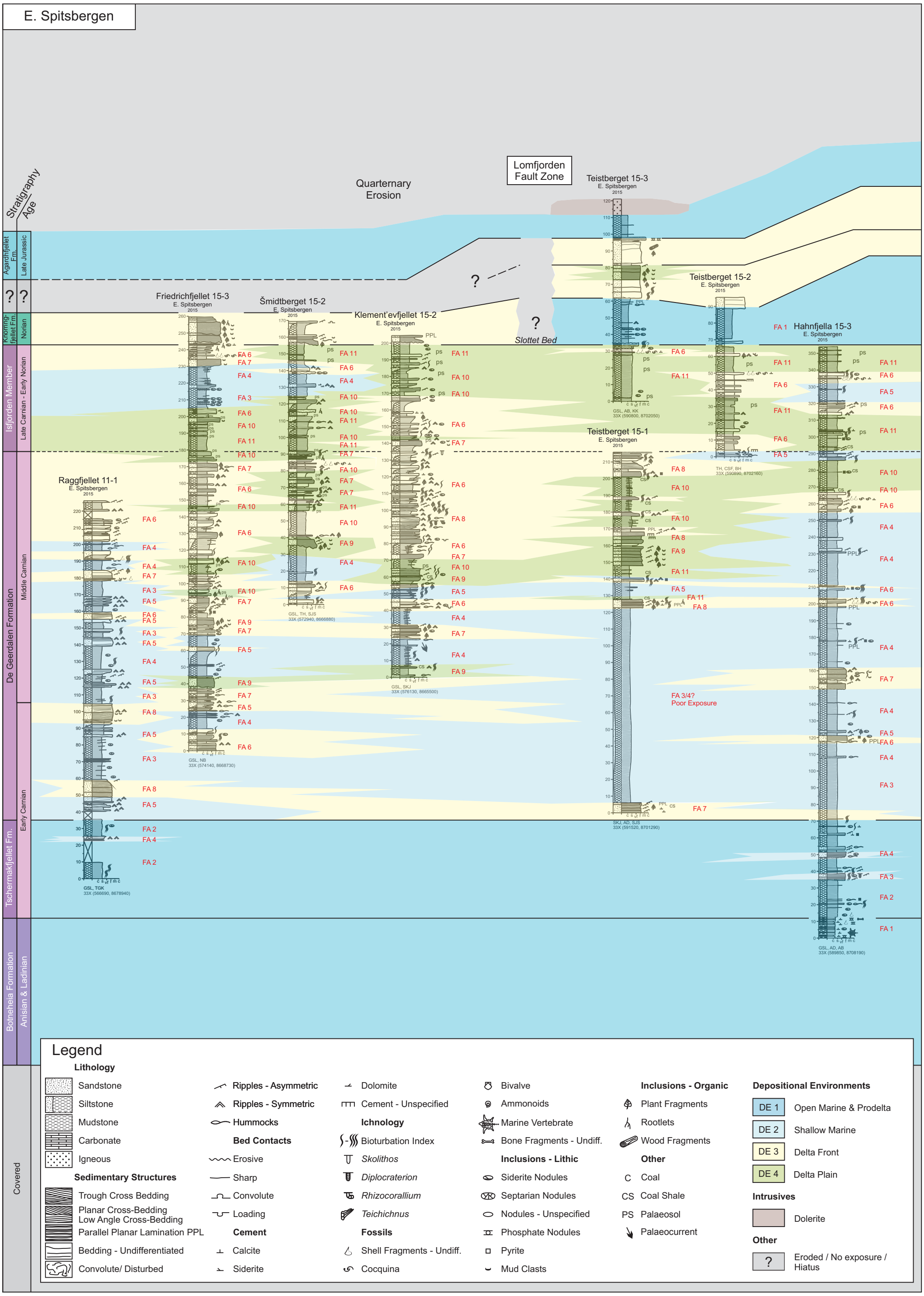
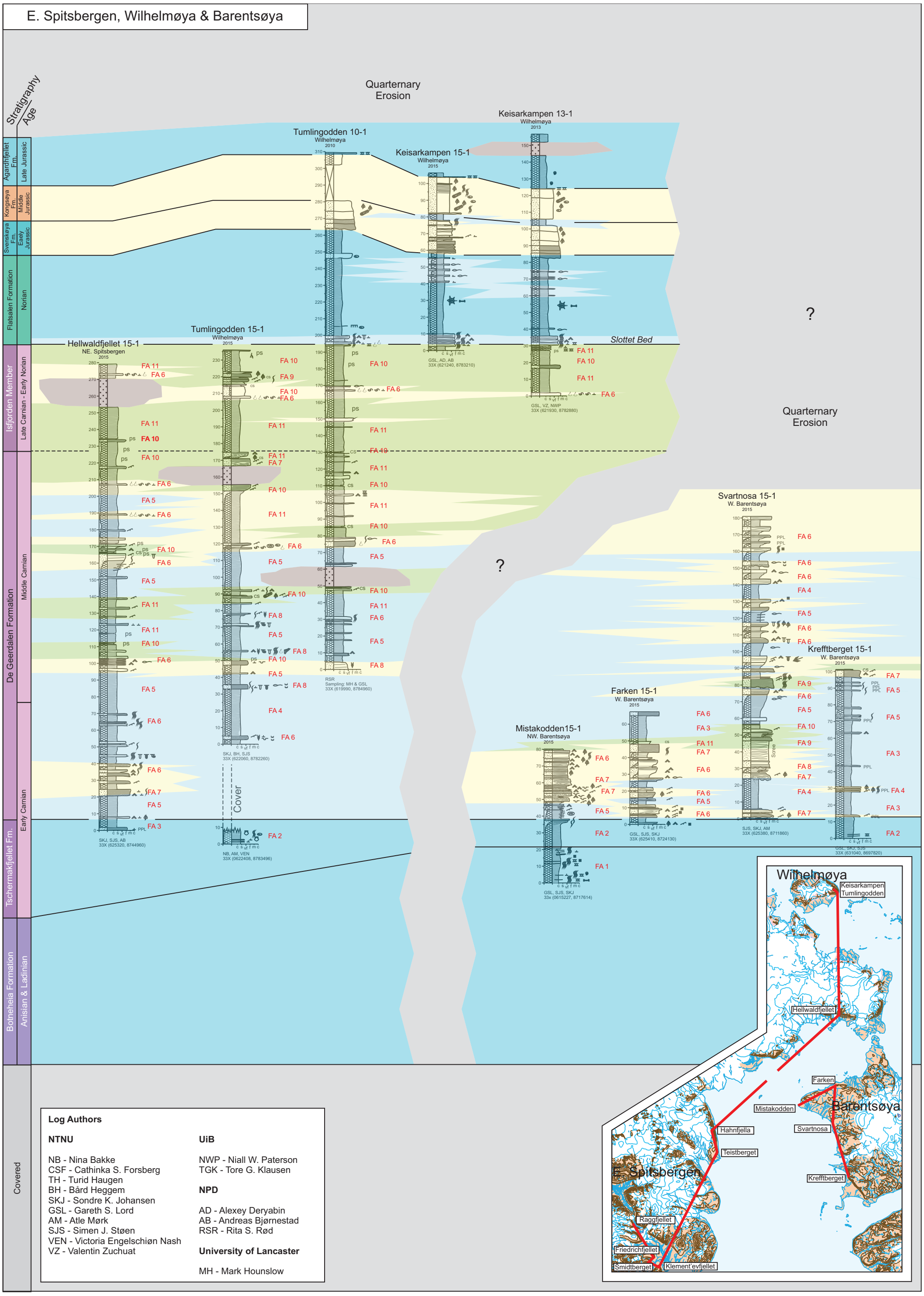


Figure 6. Log correlations for sections measured throughout eastern Spitsbergen, Barentsøya and Wilhelmøya. Positions of individual logs are marked on the locality map in Fig. 1B. Depositional environments are interpreted for various levels in the stratigraphy based upon the interpreted facies and facies associations. Units overlying and underlying the De Geerdalen Formation are also briefly interpreted.


E. Spitsbergen, Wilhelmøya & Barentsøya
Stratigraphy
Age
Quarternary Erosion
Tumlingodden 10-1
Keisarkampen 15-1
Keisarkampen 13-1
Tumlingodden 15-1
Hellwaldfjellet 15-1
Slottet Bed
Svartnosa 15-1
Farken 15-1
Mistakodden15-1
Krefftberget 15-1
Cover
Wilhelmøya
Barentsøya
E. Spitsbergen
Keisarkampen
Tumlingodden
Hellwaldfjellet
Farken
Mistakodden
Svartnosa
Hahnfjella
Teistberget
Krefftberget
Raggfjellet
Friedrichfjellet
Smidtberget
Klement'evfjellet
Agardhfjellet Fm.
Late Jurassic
Kongsøya Fm.
Middle Jurassic
Svenskøya Fm.
Early Jurassic
Flatsalen Formation
Norian
Isfjorden Member
Late Carnian - Early Norian
De Geerdalen Formation
Middle Carnian
Early Carnian
Tschermakfjellet Fm.
Botneheia Formation
Anisian & Ladinian
Covered
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on the principles used by Rød et al. (2014) in Edgeøya and central Spitsbergen (Table 2; Fig. 6). Subdivision according to the gross depositional environment has been applied to the full length of sections and the following descriptions of depositional environments relate to those shown in the log correlation panel in Fig. 6.

A generalised, conceptual depositional model for the Botneheia, Tschermakfjellet and De Geerdalen formations is presented in Fig. 7 and is based on concepts from Bhattacharya & Walker (1992), Reinson (1992), Howell et al. (2008), Glørstad-Clark et al. (2011) and Rød et al. (2014). The log from Hahnfjella (Figs. 1B, 2B, 6) is presented alongside as it shows a near complete succession of the De Geerdalen Formation, a complete succession of the Tschermakfjellet Formation and the upper part of the underlying Botneheia Formation.

Depositional environment 1 – open marine shelf & prodelta

Description: Open marine shelf deposits (FA 1; Figs. 4A, 7) are constrained to the Botneheia and Flatsalen formations overlying and underlying the Storfjorden Subgroup (Fig. 2A). The depositional environment consists almost exclusively of open marine shelf facies and organic rich shales (Fig. 7).
Prodeltaic shales of the Tschermakfjellet Formation (FA 2; Fig. 4B) are also included in this depositional environment as they represent the most distal portion of the deltaic deposits that make up the Storfjorden Subgroup. The upper part of the Tschermakfjellet Formation shows transitions to DE 2 with FA 3 and 4 (Table 2) being present at some localities where the Tschermakfjellet Formation is exposed (e.g., Raggfjellet and Hahnfjella, Fig. 1B).

Interpretation: This depositional environment represents a deep shelf basin, with pelagic sedimentation, occurring over an extended period of time (Mørk et al., 1982). The grey mudstones and siltstones of the Tschermakfjellet Formation represent the onset of a regressive deltaic system in the study area atop of the open marine Botneheia Formation.

Depositional environment 2 – shallow marine

Description: This depositional environment is characterised predominantly by shallow-marine facies within the De Geerdalen Formation or the very upper parts of the Tschermakfjellet Formation. FA 3 and 4 (Table 2; Fig. 4B, C) are common within this DE and appear as laterally continuous, upward-coarsening units that extend for several kilometres. Shallow-marine intervals within the De Geerdalen Formation generally form the bases of regressive parasequences (Fig. 5A, C) and mark repeated episodes of deltaic abandonments and shoreline retreats in an overall, long-term, regressive system. Parasequences are commonly composed of FA 3 and 4 (Table 2; Fig. 4C, D) with lower shoreface deposits of FA 5 (Table 2; Fig. 4E) in their lower part. These units grade upwards into DE 3, highlighting the regressive and shallowing trend.

Interpretation: This gross environment represents either the most proximal parts of the prodeltaic Tschermakfjellet Formation or marine incursions that are observed throughout the De Geerdalen Formation, predominantly in the lower parts of parasequences. The environment is easily recognised in the field as scree-forming slopes between prominent sandstone benches. The bases of these units commonly mark the onset of flooding surfaces that mark the bounding surface for shallowing-upward parasequences.

Depositional environment 3 – delta front

Description: This environment consists of upper shoreface deposits (FA 6; Figs. 4F, 7), distributary mouth-bar deposits (FA 7; Fig. 5A) and barrier-bar deposits (FA 8; Fig. 5B). The facies and facies associations within this environment are often laterally extensive and form prominent benches of sandstone, which represent the coarsest grained component of upward-shallowing parasequences seen throughout the study area.

Interpretation: This environment which is dominated by various sandstone facies is indicative of a delta-front environment. Sandstones within this environment often represent the coarsest part of upward-shallowing successions that form parasequences seen throughout the De Geerdalen Formation.

Depositional environment 4 – delta plain

Description: Facies associations assigned to this environment are typically fine-grained floodplain deposits and palaeosols (FA 10; Figs. 5D, E, 7). Sandstones are evident as distributary channel deposits (FA 9), or interpreted as overbank deposits, crevasse splays or bars (FA 10) within a distributive system on the delta top (Fig. 5). Intervals forming in this depositional environment are generally very thin. In the lower parts of the De Geerdalen Formation they are generally found to cap sandstone bodies. In the Isfjorden Member, deposits of DE 4 form extensive fine-grained deposits interspersed with palaeosols (FA 10). Interdistributary areas (FA 11; Fig. 5E), forming between distributary channel deposits, are also included within this DE.

Interpretation: The delta-plain environment has been confined to include facies on the delta plain that have been deposited outside the influence of marine processes as well as those forming in interdistributary areas that represent sedimentation in brackish waters (e.g., interdistributary bays or lagoonal settings). Units composed of facies that are assigned to this DE generally overlie facies and facies associations assigned to DE 3 and in many cases form the uppermost parts of shallowing upwards parasequences. Thicker deposits assigned to this DE are observed in the Isfjorden Member and are regarded as representing lagoon or lacustrine deposits

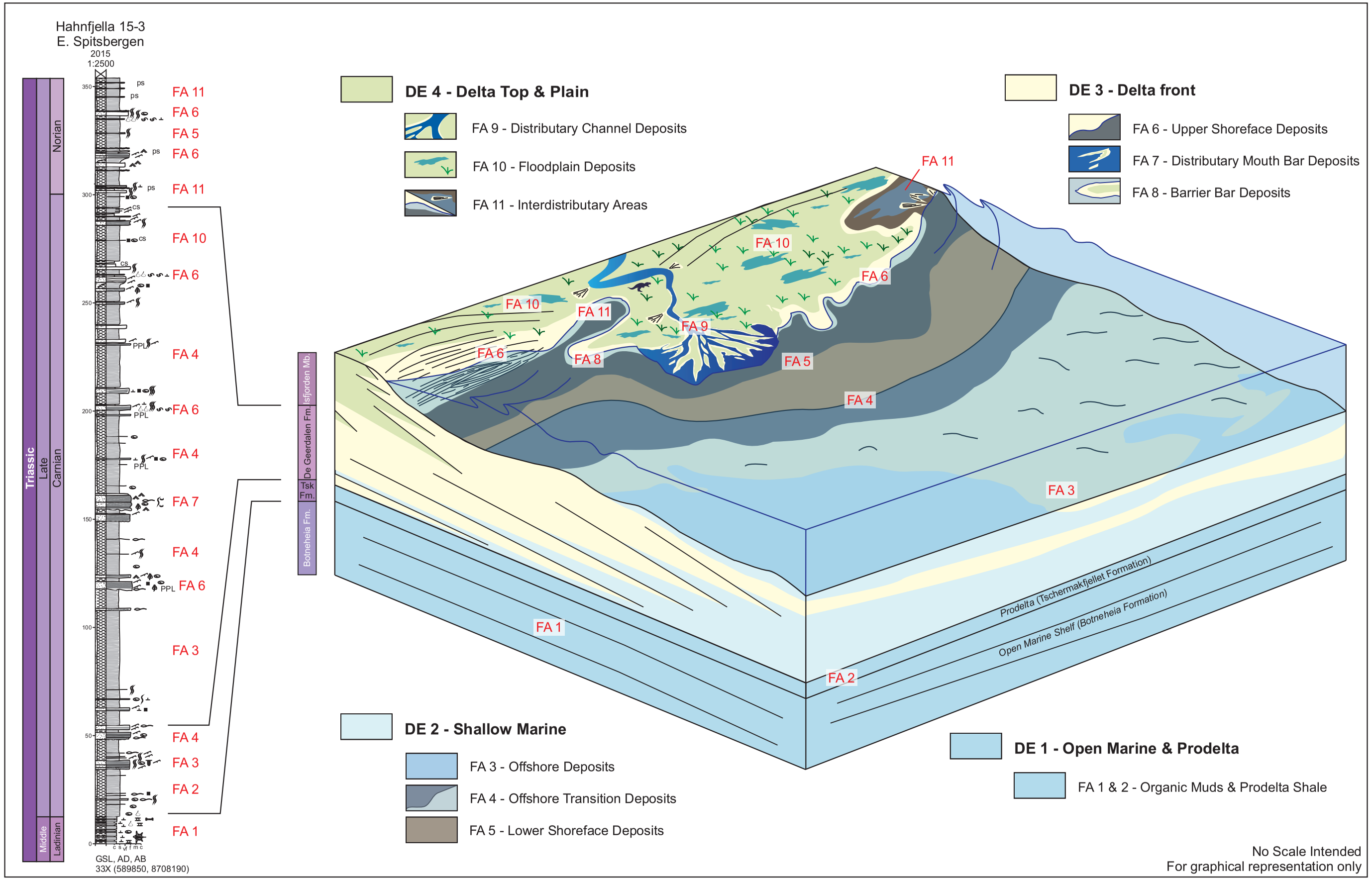

Figure 7. Conceptual depositional model (after Johansen, 2016) of the various environments and subenvironments interpreted to occur in the De Geerdalen Formation during Carnian to early Norian time in the study area. Fluvial, wave and tidal processes were important factors in governing coastline morphology and the resulting deposits are investigated in this study. These processes, in combination with wave action, are important factors in forming barrier island complexes. Suggested positions of the individual facies associations recognised in this study are denoted in the model. The legend of symbols in the Hahnfjella section is shown in Fig. 6. The figure is based on concepts from Bhattacharya & Walker (1992), Reinson (1992), Howell et al. (2008), Glørstad-Clark et al. (2011) and Rød et al. (2014).

(Pčelina, 1983; Mørk et al., 1999a; Haugen, 2016). The DE in the Isfjorden Member suggests prolonged periods of deposition in a restricted environment. A fluctuating climate and water-table is proposed for this unit, due to the presence of extensive palaeosols (Fig. 5E; Haugen, 2016).

Stratigraphic distribution and correlation of depositional environments

The depositional environments and their respective facies associations are discussed in the context of three stratigraphic units (subdivision shown in Fig. 6): 1) a lower Carnian, 2) a middle Carnian, and 3) an upper Carnian to lower Norian unit. The lower and middle Carnian units are represented by the Tschermakfjellet Formation and the bulk of the De Geerdalen Formation. The upper Carnian to lower Norian unit is represented by the Isfjorden Member. The use of the gross depositional environments for correlation solves the highly complex problem of facies distributions throughout the Tschermakfjellet and De Geerdalen formations.

It should be noted that despite well constrained palynological dating for most of the lithostratigraphic units in the Triassic succession of Svalbard (e.g., Vigran et al., 2014; Paterson & Mangerud, 2015; Paterson et al., 2016), the middle Carnian unit is poorly constrained and the present assignment should therefore be considered subjective. The middle Carnian age assignment is based entirely on indirect stratigraphic relationships between the middle Carnian unit, the underlying early Carnian Tschermakfjellet Formation and the overlying Isfjorden Member (late Carnian to early Norian).

Lower Carnian

Throughout the study area, prodeltaic shales (FA 2, Table 2) of the Tschermakfjellet Formation (Figs. 4B, 8) were deposited during earliest Carnian time, in advance of the delta-front and delta-top deposits that make up the De Geerdalen Formation. The unit consists of facies assigned to DE 1 throughout eastern Spitsbergen, with minor shallow-marine intervals (DE 2) being present (e.g., Raggfjellet and Hahnfjella, Fig. 1B).

The base of the De Geerdalen Formation is given as the first prominent sandstone above the Tschermakfjellet Formation. However, due to the widespread thickness variations in the Tschermakfjellet Formation as well as thickness variations in these basal sandstones, this definition is somewhat arbitrary. Throughout the study area, the first prominent sandstone generally represents lower or upper shoreface sandstones (FA 5 and FA6) or mouth-bar deposits (FA 7), displaying reworking by wave processes (Fig. 4F). These sandstone beds are often thin and laterally extensive, cemented either by calcite or siderite, and are generally considered to have been deposited in a delta-front environment. The lowermost sandstone exposures can be considered as the termination of an upward-shallowing transition, between the Tschermakfjellet and De Geerdalen formations.

On Barentsøya, the Svartnosa and Mistakodden sections (Figs. 1B, 6) feature thick units of sandstone interpreted as representing delta-front sandstones (DE 3) with upper shoreface, distributary mouth-bar and barrier-bar deposits (FA 6, 7 and 8) being the dominant facies associations recognised. The delta-front sandstone seen at Svartnosa (Fig. 9) forms a lenticular sandstone body that is *c.* 30 m in thickness and laterally extensive over hundreds of metres. The lenticular geometry and internal facies of this sandstone body suggest it represents a delta lobe, similar to that reported at Blanknuten on Edgeøya (Knarud, 1980; Rød et al., 2014). The sandstone body is subsequently overlain by FA 9 and 10, showing a transition to delta-plain deposits (DE 4), consisting of fine-grained floodplain and distributary channel deposits (FA 9, 10, Table 2). The remainder of the lower Carnian on Barentsøya is comprised of shallow-marine (DE 2) and delta-front (DE 3) deposits.

The lower Carnian throughout the eastern Spitsbergen and Wilhelmøya area is dominated by delta-front and shallow-marine deposits (DE 2 and 3; Fig. 6), as shown in the Hahnfjella (Fig. 8) and Hellwaldfjellet sections. On Wilhelmøya the basal beds of the Tumlingodden section (Fig. 6) at sea level contain the bivalve *Halobia* sp. which is an index fossil of the lower Carnian Tschermakfjellet Formation. Facies associations form upward-shallowing parasequences (in the order of 30–50 m in thickness) that typically show a coarsening-upward trend from fine-grained facies associations (FA 3, 4 and 5) to deltaic facies (FA 6, 7 and 8). This can be seen in the Raggfjellet section (Figs. 1A, 6) from *c.* 40 m to 100 m. Here, two vertically stacked shallowing-upward parasequences, formed of shallow-marine and deltaic facies (DE 2 and 3), are evident (Fig. 6).

Middle Carnian

Well exposed and prominent upward-shallowing units dominate the middle Carnian part of the succession throughout the study area (Fig. 6). The units are well defined and coarsen upwards from silt to medium-grained sandstones, forming parasequences of approximately 20–30 m thickness. The lower part of the middle Carnian is dominated by shallow-marine (DE 2) and delta-front (DE 3) environments typically composed of FAs 3, 4, 5, 6 and 7 (Table 2). Minor occurrences of delta-plain (DE 4) deposits are present as distributary channel deposits (FA 9), overlain by palaeosols and coal horizons, interpreted as representing floodplain deposits (FA 10), the most notable being observed at *c.* 20–50 m in the Friedrichfjellet section (Fig. 6). Here, a *c.* 30 m-thick parasequence is exposed composed of offshore transition deposits (FA 4) and lower shoreface deposits (FA 7; Fig. 4D, E) grading into distributary channel deposits (FA 9). This parasequence is subsequently

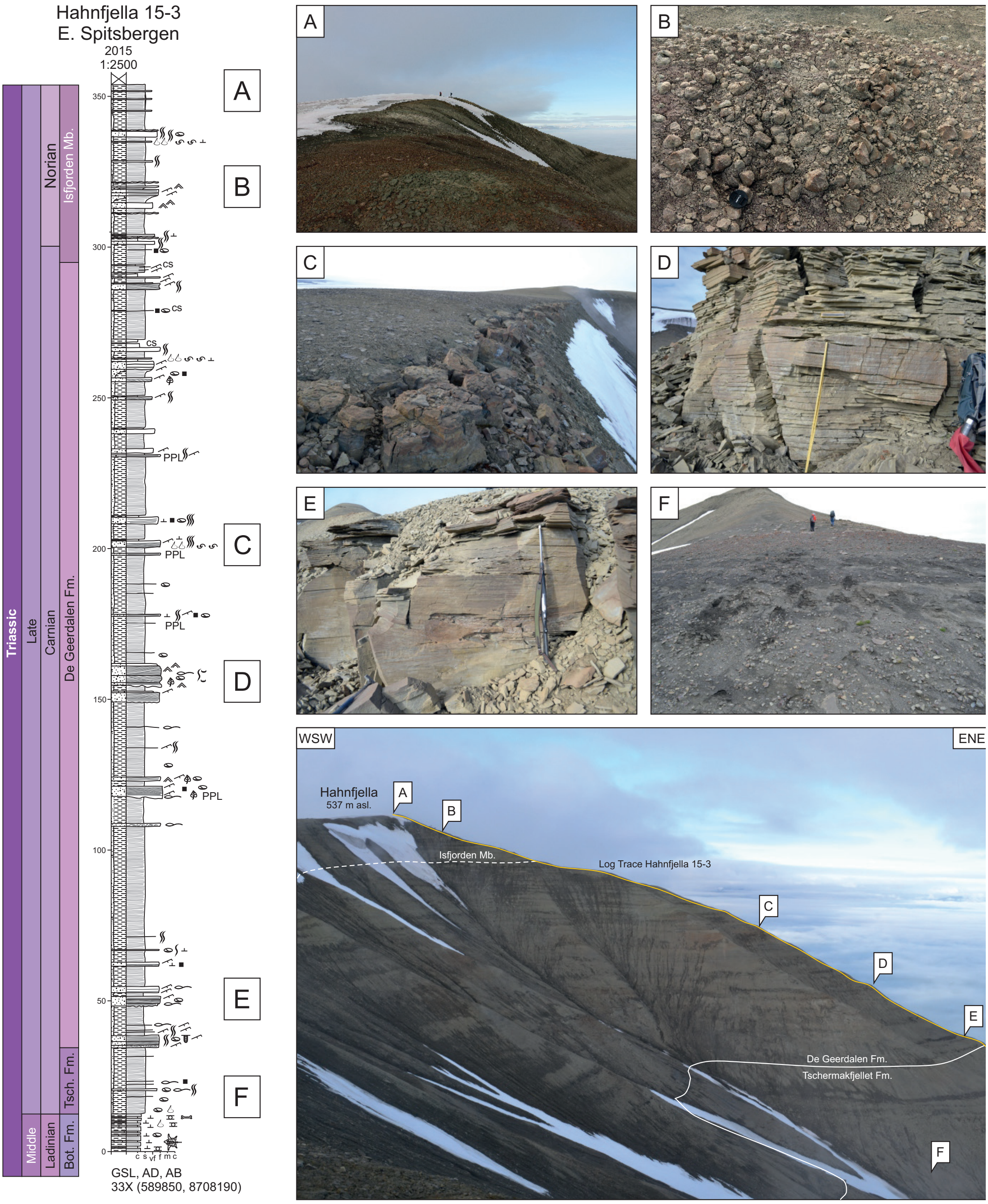

Figure 8. Sedimentological section and overview photo of Hahnfjella (Fig. 1B), eastern Spitsbergen, with accompanying photos (A–F) of prominent lithologies seen at this location. The overview photo shows the trace of the section measured in log Hahnfjella 15–3. (A) Green and red beds of the Isfjorden Member palaeosol horizons cap the mountain. (B) Detail photo showing the nodular nature of the red beds (lens cap for scale). (C) A thick and well exposed bed of fragmented shells (coquina bed) is well preserved due to cementation. (D) Low-angle trough cross-stratified sandstone with an erosive base observed in the lower part of the section. This sandstone is interpreted as representing a minor distributary channel. (E) Low-angle cross- and planar-stratified sandstone common to the De Geerdalen Formation; the beds are commonly cemented and weather red. (F) The prodelta shale of the Tschermakfjellet Formation is well exposed, as is the boundary to the Botneheia Formation (not shown). Siderite concretions (in places containing ammonoid imprints) are common. Legend to section in Fig. 6.

overlain by fine-grained sediments interpreted as lower shoreface deposits, with a minor flooding surface at the base.

Similarly, between 50 m and 115 m in the Friedrichfjellet section (Fig. 6), a *c.* 65 m-thick shallowing-upward succession from shallow-marine facies (FA 5) to delta-front and delta-plain facies can be observed. These relatively thick parasequence units can be seen throughout much of the remaining part of the middle Carnian, where delta-front and delta-plain facies interfinger with shallow-marine deposits throughout the study area. The De Geerdalen Formation is largely described as paralic (Klausen & Mørk, 2014; Lord et al., 2014a, b; Rød et al., 2014; Paterson et al., 2016) and this is reflected in the highly variable lateral distribution of facies and depositional environments.

Upper Carnian–Lower Norian

The upper part of the De Geerdalen Formation throughout eastern Svalbard is defined by the Isfjorden Member (Figs. 2A, 6), deposited during the latest part of the Carnian and early Norian (Pčelina, 1983; Mørk et al., 1999a; Vigran et al., 2014; Haugen, 2016). In the field, the basal beds of the Isfjorden Member are difficult to identify at outcrop level, but distinct visual changes can be observed from scree in mountainsides. The presence of alternating, green and red, nodular palaeosols (Figs. 5E, 8) is characteristic for the member (Facies N, FA 10 and 11) and such palaeosols are observed at most locations in eastern Spitsbergen and Wilhelmøya.

The most northern exposures of the Isfjorden Member are found on Wilhelmøya (Tumlingodden and Keisarkampen) and at Hellwaldfjellet (Figs. 1B, 6). Here, the member is dominated by siltstone, with thin sandstones and coquina beds in its lower part. The upper part consists of alternating green and red nodular clays, directly underlying the Wilhelmøya Subgroup. These alternating green and red beds are also apparent at Hahnfjella (Figs. 1B, 2B, 6, 8), where they are excellently exposed and dominate the upper exposures of the mountainside.

Alternating red and green palaeosol horizons are also observed in the Agardhbukta areas (e.g., Klement'evfjellet, Šmidtberget and Friedrichfjellet, see Figs. 1B, 6). On Wilhelmøya and at Teistberget, the Norian Flatsalen Formation directly overlies beds of palaeosol (Fig. 6). However, in the Agardhbukta area palaeosol horizons are overlain by an upper interval of marine shale (Fig. 4C), siderite beds and shoreface sandstones, uncommon for this part of the succession. This suggests that there was a transgression of the delta plain leading to a ravinement surface and eventually flooding covering the entire area with marine water and depositing FA 3. During the following regression, shallow-marine deposits (FA 4) were laid down. The coarsening-upward trend within the parasequences reflects progradation of the shallow-marine environments, and the thickness of the parasequence reflects the water depth at the time of progradation. Palynological dating of selected samples from Friedrichfjellet indicate a Carnian age for this marine interval. The overlying sandstone (240 m on the Friedrichfjellet log, Fig. 6) includes Norian palynomorphs suggesting that they belong of the Flatsalen or Knorringfjellet formations in the Wilhelmøya Subgroup (Niall Paterson, pers. comm., 2016).

Discussion

Palaeogeographic development

A subdivision into lower Carnian, middle Carnian and upper Carnian–Norian units means that it is possible to better infer the palaeogeography for the study area. The palaeogeography for these three intervals is discussed and presented in the series of palaeogeographic maps in Fig. 10. The maps are based on tentative correlations and are only meant to show one of many tenable solutions.

Lower Carnian: The lower Carnian unit is typically dominated by prodeltaic deposits of the Tschermakfjellet Formation throughout the study area. The lower Carnian part to the overlying De Geerdalen Formation is predominantly composed of shallow marine and shoreface deposits in the eastern Spitsbergen and Wilhelmøya areas (Fig. 10). Only minor fluvial influence and delta-front advances are interpreted, particularly in the uppermost part of a shallowing-upward parasequence at Friedrichfjellet. Agewise, this unit represents the onset of the middle Carnian in the area.

On Barentsøya, however, the lower Carnian at Svartnosa (Figs. 1B, 10) shows evidence for a deltaic advance in the form of an extensive lenticular sandstone body (Fig. 9), composed of delta-front and delta-plain sediments, interpreted as representing a delta lobe which likely prograded towards the west. In addition, a thick sandstone unit is observed at Mistakodden, whilst Farken is composed of predominantly deltaic facies (FA 7). The southern part of Barentsøya is considered as representing a shallow-marine to delta-front environment following interpretation of the succession at Krefftberget (Fig. 1B).

Middle Carnian: In contrast to the lower Carnian, the middle Carnian part of the succession shows major regressive deltaic advances, with distributive facies (FA7 and 9) becoming more common (Figs. 6, 10), as do delta-top sediments (Fig. 6). Interdistributary bay areas, or areas of marine incursion due to avulsion of the fluvial distributary systems, are also evident with minor intervals of shallow-marine facies being present in this unit, notably on Barentsøya.

The Agardhbukta area (Fig. 1B) is interpreted to have

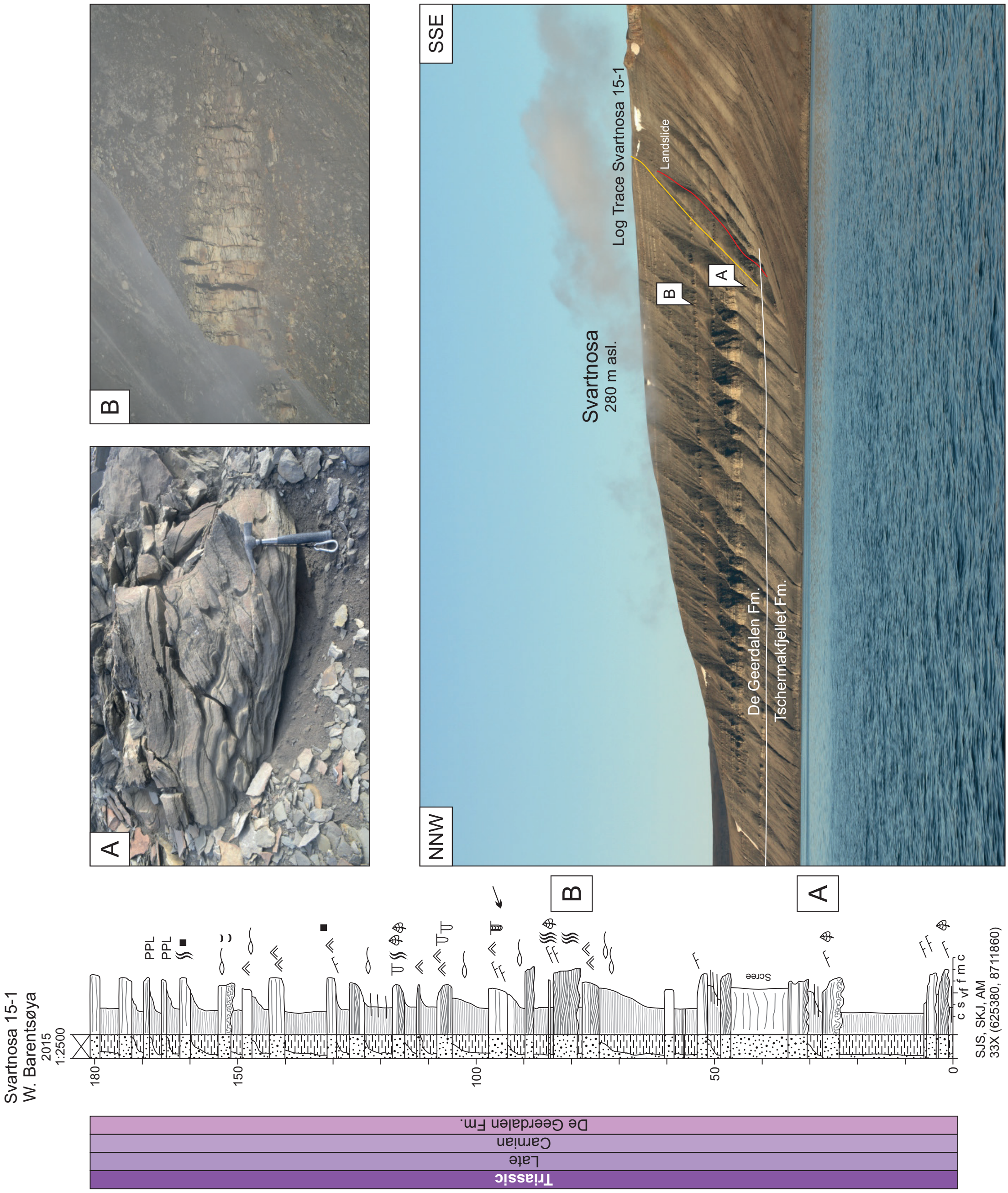

Figure 9. Sedimentological section and overview photo of Svartnosa (Fig. 1B), Barentsøya, with accompanying photos (A–B). The log trace is shown by the yellow line in the overview photo. (A) Soft-sediment deformed bedding, observed in the lower sandstone beds of the De Geerdalen Formation, interpreted as forming the base of an amalgamated distributary mouth-bar unit. (B) Fluvial distributary channel facies observed in the middle part of the mountain, consisting of trough cross-stratified, medium-grained sandstone forming a laterally extensive sandstone body with amalgamated fluvial distributary channel facies. Legend to section in Fig. 6.

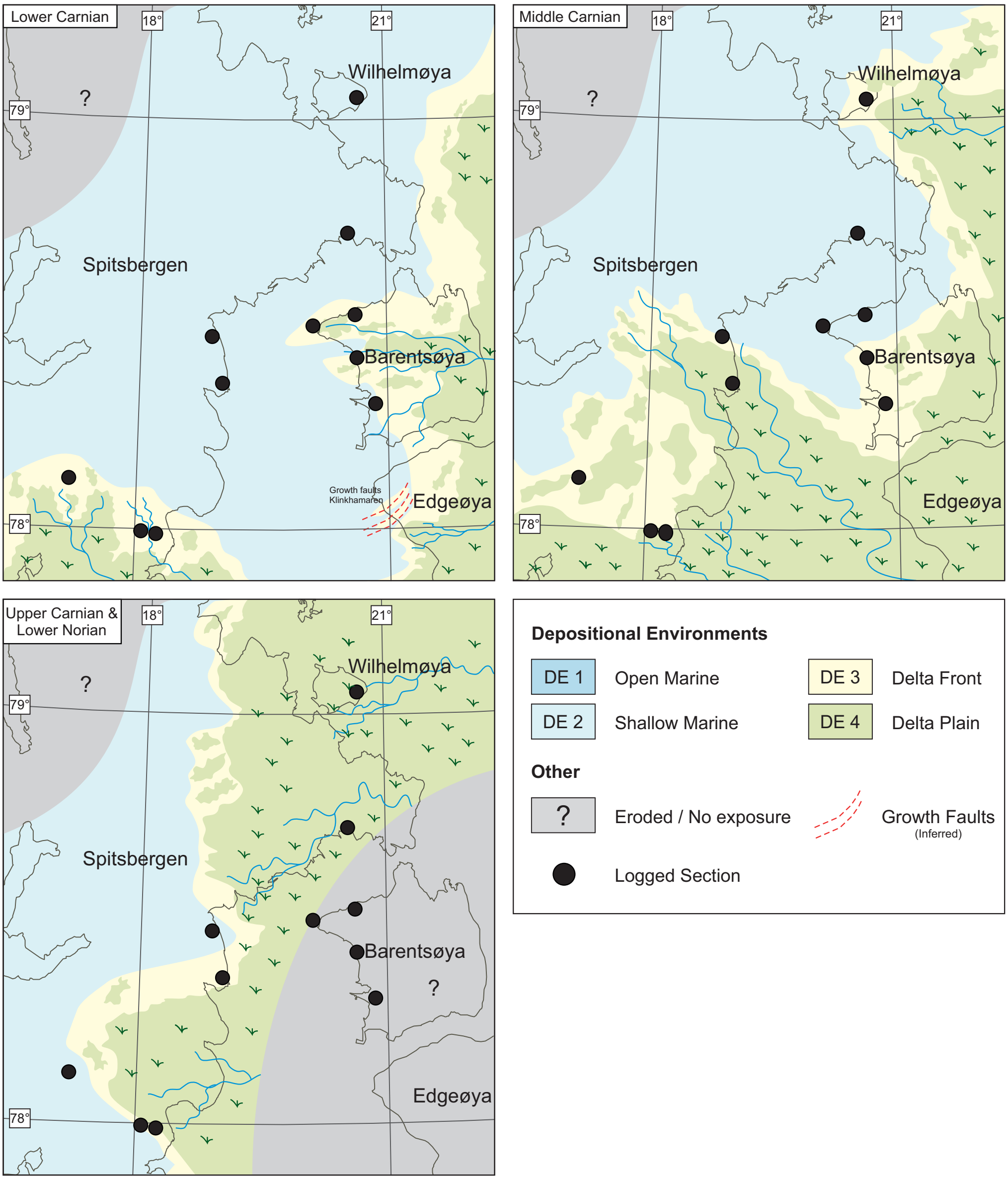

Figure 10 . *Conceptual palaeogeographic representations of the study area, showing a suggested palaeogeographical setting for the lower, middle and upper Carnian to lower Norian. Interpretations are based on outcrop data and log correlations (Fig. 6). The lower Carnian is represented by the deposition of prodeltaic shales (DE 2) and prominent delta-lobe advances (DE 3 and 4; Fig. 6) in the Svartnosa and Agardhbukta areas (see Figs. 1B, 6). The middle Carnian is dominated by the development of a paralic delta plain, with widespread delta-front (DE 3) and delta-plain deposits (DE 4). The late Carnian–early Norian (Isfjorden Member) suggests that a lagoonal environment was dominant, with only minor fluvial deposition occurring at this time. Finer-grained sediments are more common and parasequences become thinner. Palaeosols dominate the upper part of the Isfjorden Member during this time.*

been located in a paralic to near-shore setting dominated by delta-front and shallow-marine facies (Figs. 6, 10). Delta-plain environments are also evident with distributary channel deposits being present in the areas of Friedrichfjellet, Šmidtberget and Klement'evfjellet (Fig. 6). The localities of Teistberget and Hahnfjella are suggested as representing a terminal distributary system with limited lateral extent, due to the presence of deltaic and marine environments at Hahnfjella, at the same interval as fluvial facies are observed at Teistberget.

Sections on Wilhelmøya (Fig. 1B) display a paralic succession in the middle Carnian, with units of shallow-marine, delta-front and delta-plain deposits occurring locally. This area is interpreted as being a channellised minor delta-lobe system. Palaeosols, coal and coaly shales are typically found capping distributary channel and mouth-bar deposits within the middle Carnian part of the De Geerdalen Formation (Fig. 6). This may suggest an extended period of subaerial exposure, allowing for mature soil profile development (see Haugen, 2016), whilst coal and coal shale units indicate a humid climate and a waterlogged environment with rapid depletion of oxygen (Retallack, 1991). Shell beds seen in the middle Carnian on Wilhelmøya are typically isolated within either marine facies (FA 3 or 4) or interdistributary facies (FA 11) and may represent shell banks in a shallow-marine or lagoon setting.

The middle Carnian unit on Barentsøya is only observed at Svartnosa (Figs. 6, 9). The lower part of the middle Carnian is marked by a well-defined sandstone bench composed of FA 9; distributary channel deposits (Fig. 5C). This is potentially correlative to a sandstone bench observed in the upper part of the section at Farken (Fig. 6), which is interpreted as distributary mouth-bar deposits (FA 7) overlain by coal shale. The remainder of the middle Carnian succession on Barentsøya typically shows shallow-marine or delta-front facies (FA 4 and 5) suggesting the presence of an interdistributary lobe bay area; no continental deposits (palaeosols, coals or coal shales) have been observed. This suggests that a marine transgression took place in the Barentsøya area at this time. In contrast, a delta-lobe advance is interpreted to have taken place in the eastern Spitsbergen area (Fig. 10).

Upper Carnian and lower Norian: In the upper Carnian and lower Norian unit, facies typical of the Isfjorden Member became widespread throughout Spitsbergen and Wilhelmøya (Figs. 2A, 6, 10). Facies variability within the Isfjorden Member is relatively discrete, with thick intervals of delta-plain deposits interspersed with only thin units of shoreface deposits (Fig. 6). Limited fluvial distributary facies are observed and where present are generally thin, laterally inextensive beds within floodplain deposits. In the Agardhbukta area, a marine incursion is observed in the mountains of Friedrichfjellet and Klement'evfjellet. Facies are similar to those reported in central Spitsbergen by Mørk et al. (1982) and Rød et al. (2014). The upper part of the member is likely missing from the well exposed type-section at Storfjellet (Knarud, 1980). Towards the west the upper Carnian is inferred as being predominantly shallow marine, with offshore and tidal deposits dominating (Fig. 10; Knutsen, 2013; Husteli et al., 2014; Olaussen et al., 2015).

The upper Carnian and lower Norian succession in the study area is interpreted as representing an extensive delta plain (Fig. 10) dominated by lagoonal and lacustrine environments. The paralic systems that characterise the lower and middle Carnian succession throughout the study area appeared to have stabilised during late Carnian to early Norian times. The extensive delta plain with well developed palaeosols seen in this part of the succession indicate a more physically stable environment in comparison with the dynamic fluvio-deltaic environment seen in the underlying lower and middle Carnian units.

Regional comparison

This study provides important infill to the preliminary studies conducted throughout Svalbard by Knarud (1980), as presented in Mørk et al. (1982). It further builds on the early sedimentological studies in the region by Lock et al. (1978) from Barentsøya and Edgeøya, Rød et al. (2014) from Edgeøya and central Spitsbergen and work on Hopen (Klausen & Mørk, 2014; Lord et al., 2014a, b).

Field studies, supported by palynology (Niall Paterson, pers. comm., 2015), show that late Carnian sedimentary rocks are not present on Edgeøya and we interpret this to mean that Cenozoic uplift and Quaternary erosion has removed this part of the succession. Localities visited throughout this study typically feature the middle and upper part of the De Geerdalen Formation, with the Tschermakfjellet Formation and lower part of the De Geerdalen Formation being poorly exposed, due to scree cover.

On Edgeøya, the lower part of the Upper Triassic succession is composed of prodelta shales overlain by delta-front deposits and lagoonal to delta plain deposits in the upper part of exposed sections (Rød et al., 2014). Growth faulting is observed along the western side of the island (Figs. 3A, 10; Edwards, 1976; Anell et al., 2013; Osmundsen et al., 2014; Rød et al., 2014). The Carnian succession on Hopen is largely composed of fluvial delta-plain sediments with subordinate marine-influenced deposits (Klausen & Mørk, 2014; Lord et al., 2014a, b) and is late Carnian in age (Paterson & Mangerud, 2015; Patterson et al., 2016).

The Upper Triassic succession thins considerably throughout Svalbard, from southeast to northwest. In the southeast at Hopen, the 7626/5–1 well ('Hopen

2', see Mørk et al., 2013; Anell et al., 2014a; Lord et al., 2014a) shows the Tschermakfjellet and De Geerdalen formations to be some 1100 m in thickness, which is thicker than initially reported by Lord et al. (2014a). The De Geerdalen Formation on Wilhelmøya is complete and is minimum 350–400 m in thickness (the lower part was not logged in this study due to scree cover); as the Tschermakfjellet Formation is present at sea level.

Below sea level at Hopen, gamma-ray logs from the 7626/5–1 well indicate that the De Geerdalen Formation likely has a similar grain-size trend as in sections elsewhere, with a high sand content and multiple coarsening-upward parasequences. This indicates similar depositional environments as those seen elsewhere in eastern Svalbard and offshore in the Sentralbanken High area (Lundschien et al., 2014).

Throughout central Spitsbergen, the De Geerdalen and Tschermakfjellet formations together are approximately 300 m in thickness (Vigran et al., 2014), whilst in the Barents Sea, offshore from Svalbard, the units are up to 1400 m in thickness (Mørk et al., 1999a; Lundschien et al., 2014). Anell et al. (2014a, b) relate this thinning to the progression of the Carnian deltaic system onto the Svalbard Platform (Dallmann et al., 2015), where lack of accommodation space has resulted in a shallowing of the basin and a rapid advance of the delta (Riis et al., 2008; Anell et al., 2014b).

If true, this mechanism explains the variable facies distributions seen throughout the study area. Lenticular sandstone bodies, as seen at Svartnosa on Barentsøya (Fig. 9) and at Blanknuten on Edgeøya (Rød et al., 2014), are not seen farther west in Spitsbergen. Instead, thin, laterally continuous, distributary channel, mouth-bar or shoreface deposits are present in these areas. This is also interpreted by Rød et al. (2014) to be a result of lower accommodation space to the west (Fig. 10). Laterally extensive sandstones are typically composed of distributary channel deposits in the present study area, whilst in central Spitsbergen laterally extensive shoreface deposits dominate (Rød et al., 2014).

The middle Carnian succession seen in eastern Spitsbergen is likely the time equivalent and distal component to the lower parts of the exposed De Geerdalen Formation on Hopen. On the island of Hopen, the lower part of the De Geerdalen Formation has been interpreted as representing delta-plain deposition close to an extensive, fern-dominated coastal mire (Paterson et al., 2016) (the presence of fern fossils is documented by Launis et al., 2014), with fluvial trunk and distributary channels (Klausen & Mørk, 2014; Lord et al., 2014b). Paterson et al. (2016) have suggested that wet, humid conditions prevailed at this time, allowing for the accumulation of organic material and subsequent coal formation. Lord et al. (2014b) noted the presence of large tree remains. Whilst these may have been derived from much farther upstream, their presence suggests a well vegetated landscape, also indicated by the large volume of plant material seen in sandstone beds throughout the study area.

Similarly, Enga (2015) has documented the presence of palaeosols, coaly shale and coal horizons on Edgeøya, forming on top of delta-front and fluvial sandstones, or within fine-grained deposits in mud-dominated interdistributary or delta-plain settings. These palaeosols, which formed in delta-front and delta-plain settings, can be viewed as abandonment surfaces, marking a period of non-deposition after termination of sediment supply (Enga, 2015). Furthermore, in situ tree remains are present at a similar level in the stratigraphy at Blanknuten on Edgeøya (Enga, 2015).

The overall paralic setting seen elsewhere in Svalbard, with laterally discontinuous belts, suggests that the middle Carnian succession in the study area was deposited on a low-angle, delta plain (Knarud, 1980), with distributary channels bringing sediment to the delta shoreline where they were prone to wave reworking. The abandonment of delta lobes and fluvial systems resulted in local subaerial unconformities. Here, well developed palaeosols (Fig. 5D) formed above extensive sandstone bodies prior to being transgressed, as shown by a marine facies directly overlying palaeosols in the study area.

Additionally, the Isfjorden Member is laterally extensive throughout eastern Spitsbergen and on Wilhelmøya, where the alternating red and green palaeosols are seen to be directly overlain by the Slottet Bed, at the base of the Wilhelmøya Subgroup. Lord et al. (2014a) hypothesised that this part of the stratigraphy on Wilhelmøya may be the Hopen Member; however, this is not the case, and thus the Isfjorden Member has been extended to this area (Haugen, 2016) on the stratigraphic chart in Fig. 2A. The lateral extent of these two units offshore in the northern part of the Barents Sea is at present unknown.

The alternating red and green palaeosols of the Isfjorden Member (Figs. 5E, 8) are vastly different from those seen in the lower and middle Carnian parts of the De Geerdalen Formation throughout Svalbard, where they are characterised by yellow/grey clay with thin coal and coal shale (Fig. 5D). This may suggest either; (1) a climatic shift occurring during the late Carnian to early Norian, where palaeosols indicating a humid environment are replaced by those more indicative of an arid environment, or (2) a significant change in drainage pattern has resulted in a different type of pedogenesis (Haugen, 2016).

In southeastern Svalbard, the correlative Hopen Member features no palaeosols (Lord et al., 2014a), whilst the underlying De Geerdalen Formation displays thin, yet well developed coal beds and rootlets (Klausen & Mørk, 2014; Lord et al., 2014b). Studies of plant fragments and remains from the De Geerdalen Formation on Hopen show a dominance of ferns and conifer flora (Launis et al., 2014), suggesting a more temperate environment for the De Geerdalen Formation. This is also supported by palynofacies and palaeogeography studies from Hopen (Paterson & Mangerud, 2015; Paterson et al., 2016).

Summary and conclusions

In eastern Svalbard, the De Geerdalen Formation consists of multiple, discrete or indiscrete, upward-coarsening units, interpreted as parasequences formed as a result of the progradation of a large, fluvial dominated delta system. The overall depositional environment for the De Geerdalen Formation can be considered as paralic, with deposition of sediments occurring in three key environments; delta plain, delta front and shallow marine.

Due to the low progradation angle of this system, these environments are easily influenced by changes in the delta or sea-level, with the high level of lateral variability of facies observed in the study area reflecting this. We address the depositional environments seen in the De Geerdalen Formation with a three-fold subdivision of the Upper Triassic succession into; (1) a lower Carnian unit consisting of shallow-marine to shoreface deposition; (2) a middle Carnian unit dominated by delta-front and delta-top deposits; and an upper part, (3) a late Carnian to early Norian unit, consisting of delta-plain deposits.

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References

Anell, I., Braathen, A., Olaussen, S. & Osmundsen, P.T. 2013: Evidence of faulting contradicts quiescent northern Barents Shelf during the Triassic. *First Break 31*, 67–76. https://doi.org/10.3997/1365-2397.2013017.

Anell, I.M., Braathen, A. & Olaussen, S. 2014a: The Triassic – Early Jurassic of the northern Barents Shelf: a regional understanding of the Longyearbyen CO_2 reservoir. *Norwegian Journal of Geology 94*, 83–98.

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*, 167–179. https://doi.org/10.1016/j.marpetgeo.2014.03.005.

Bhattacharya, J.P. 2006: Deltas. *In* Posamentier, H.W. & Walker, R.G. (eds.): *Facies models revisited*, Society for Sedimentary Geology Special Publication 84, pp. 237–292. https://doi.org/10.2110/pec.06.84.0237.

Bhattacharya, J.P. & Giosan, L. 2003: Wave-influenced deltas: Geomorphological implications for facies reconstruction. *Sedimentology 50*, 187–210. https://doi.org/10.1046/j.1365-3091.2003.00545.x.

Bhattacharya, J.P. & MacEachern, J.A. 2009: Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America. *Journal of Sedimentary Research 79*, 184–209. https://doi.org/10.2110/jsr.2009.026.

Bhattacharya, J.P. & Walker, R.G. 1992: Deltas. *In* Walker, R.G. & James, N.P. (eds.): *Facies Models: Response to Sea Level Change*, Geological Association of Canada, pp. 157–177.

Boggs, S., Jr. 2009: *Petrology of sedimentary rocks, Second edition*. Cambridge University Press, Cambridge. 600 pp.

Boggs, S., Jr. 2011: *Principles of sedimentology and stratigraphy, Fifth Edition*. Pearson Prentice Hall, Upper Saddle River, New Jersey, 585 pp.

Buchan, S.H., Challinor, A., Harland, W.B. & Parker, J.R. 1965: The Triassic stratigraphy of Svalbard. *Norsk Polarinstitutt Skrifter 135*, 94 pp.

Bue, E.P. & Andresen, A. 2013: Constraining depositional models in the Barents Sea region using detrital zircon U-Pb data from Mesozoic sediments in Svalbard. *Geological Society of London Special Publication 386*, 261–279.

Clifton, H.E. 2006: A re-examination of facies models for clastic shorelines. *In* Posamentier, H.W. & Walker, R.G. (eds.): *Facies Models Revisited*, Society for Sedimentary Geology Special Publication 84, pp. 293–338.

Collinson, J.D. 1996: Chapter 3 – Alluvial sediments. *In* Reading, H.G. (ed.): *Sedimentary environments: processes, facies and stratigraphy, Third Edition*, Blackwell Science, Oxford, pp. 37–82.

Collinson, J.D., Mountney, N. & Thompson, D.B. 2006: *Sedimentary structures, Third Edition*. Terra Publishing, London, 304 pp.

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. https://doi.org/10.1017/S0016756813000162.

Dallmann, W.K. & Elvevold, S. 2015: Chapter 7 – Bedrock Geology. *In* Dallmann, W.K. (ed.): *Geoscience Atlas of Svalbard*, Report Series 148, Norsk Polarinstitutt, Tromsø, pp. 133–174.

Dallmann, W.K., Elvevold, S., Majka, J. & Piepjohn, K. 2015: Chapter 8 – Tectonics and tectonothermal events. *In* Dallmann, W.K. (ed.): *Geoscience Atlas of Svalbard*, Report Series 148, Norsk Polarinstitutt, Tromsø, pp. 175–224.

Dashtgard, S.E., MacEachern, J.A., Frey, S.E. & Gingras, M.K. 2012: Tidal effects on the shoreface: Towards a conceptual framework. *Sedimentary Geology 279*, 42–61. https://doi.org/10.1016/j.sedgeo.2010.09.006.

Davis, R.A. 2012: Tidal signatures and their preservation potential in stratigraphic sequences. *In* Davis R.A & Dalrymple, R.W. (eds.): *Principles of tidal sedimentology*, Springer Netherlands, Dordrecht , pp. 35–55. https://doi.org/10.1007/978-94-007-0123-6_3.

Dumas, S. & Arnott, R.W.C. 2006: Origin of hummocky and swaley cross-stratification – the controlling influence of unidirectional current strength and aggradation rate. *Geology 34*, 1073–1076. https://doi.org/10.1130/G22930A.1.

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

Eide, C.H., Klausen, T.G., Katkov, D., Suslova, A.A. & Helland-Hansen, W. in press: Linking an Early Triassic delta to antecedent topography: source-to-sink study of the southwestern Barents Sea margin. *Geological Society of America Bulletin.*

Eiken, O. 1985: Seismic mapping of the post-Caledonian strata in Svalbard. *Polar Research 3*, 167–176. https://doi.org/10.1111/j.1751-8369.1985.tb00505.x.

Elvevold, S., Dallman, W.K. & Bloomeier, D. 2007: *The Geology of Svalbard*. Norwegian Polar Institute, Tromsø, 38 pp.

Enga, J. 2015: *Paleosols in the Triassic De Geerdalen and Snadd formations*. MSc thesis, Norwegian University of Science and Technology, Trondheim, 127 pp.

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

Flood, B., Nagy, J. & Winsnes, T.S. 1971a: The Triassic succession of Barentsøya, Edgeøya and Hopen (Svalbard). *Norsk Polarinstitutt Meddeler Nr. 100*, 28 pp.

Flood, B., Nagy, J. & Winsnes, T.S. 1971b: Geological map of Svalbard, sheet 1G, Spitsbergen southern part, scale 1:500,000, *Norsk Polarinstitutt Skrifter 154 A*. (With short description).

Frazier D.E. 1967: Recent deltaic deposits of the Mississippi delta: their development and chronology. *Gulf Coast Association of Geological Societies Transactions 17*, 287–315.

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

Glørstad-Clark, E., Birkeland, E., Nystuen, J., Faleide, J.I. & Midtkandal, I. 2011: Triassic platform-margin deltas in the western Barents Sea. *Marine and Petroleum Geology 28*, 1294–1314.

Harstad, T. 2016: *Sandstone Provenance of the De Geerdalen Formation, Svalbard – Emphasis on Petrography and Chromium Spinel Compositions*. MSc thesis, Norwegian University of Science and Technology, Trondheim, 98 pp.

Haugen, T. 2016: *A Sedimentological Study of the De Geerdalen Formation with Focus on the Isfjorden Member and Palaeosols*. MSc thesis, Norwegian University of Science and Technology, Trondheim, 155 pp.

Howell, J.A., Skorstad, A., MacDonald, A., Fordham, A., Flint, S., Fjellvoll, B. & Manzocchi, T. 2008: Sedimentological parameterization of shallow-marine reservoirs. *Petroleum Geoscience 14*, 17–34. https://doi.org/10.1144/1354-079307-787.

Husteli, B., Boxaspen, M.A. & Rosseland Knutsen, E. 2014: Lateral variations in a tidally influenced Carnian to Early Norian transect in central Svalbard. *European Geosciences Union General Assembly Conference Abstracts 16, 27 April–2 May, Vienna, Austria*. http://meetingorganizer.copernicus.org/EGU2014/EGU2014-12654.pdf

Høy, T. & Lundschien B.A. 2011: Triassic deltaic sequences in the northern Barents Sea. *Geological Society of London Memoirs 35*, 249–260.

Ichaso, A.A. & Dalrymple, R.W. 2009: Tide- and wave-generated fluid mud deposits in the Tilje Formation (Jurassic), offshore Norway. *Geology 37*, 539–542. https://doi.org/10.1130/G25481A.1.

Johansen, S.K. 2016: *Sedimentology and facies distribution of the Upper Triassic De Geerdalen Formation in the Storfjorden area and Wilhelmøya, eastern Svalbard*. MSc thesis, Norwegian University of Science and Technology, Trondheim, 179 pp.

Johnson, H.D. & Baldwin, C.T. 1996: Chapter 7 – Shallow clastic seas. *In* Reading, H.G. (ed.): *Sedimentary environments: processes, facies and stratigraphy, Third edition*, Blackwell Science, Oxford, pp. 232–280.

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

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

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

Knarud, R. 1980: *En sedimentologisk og diagenetisk undersøkelse av Kapp Toscana Formasjonens sedimenter på Svalbard*. Cand. Real. thesis, University of Oslo, 208 pp.

Knutsen, E.R. 2013: *Sedimentology of the Offshore-to Tide-Dominated Upper Triassic De Geerdalen Formation on Central Spitsbergen and Examples of Comparable Facies in the Equivalent Snadd Formation.* MSc thesis, University of Bergen, 134 pp.

Krajewski, K.P. 2008: The Botneheia Formation (Middle Triassic) in Edgeøya and Barentsøya, Svalbard: lithostratigraphy, facies, phosphogenesis, paleoenvironment, *Polish Polar Research 29*, 319–364.

Kraus, M.J. 1999: Palaeosols in clastic sedimentary rocks: their geologic applications. *Earth-Science Reviews 47*, 41–70. https://doi.org/10.1016/S0012-8252(99)00026-4.

Kraus, M.J. & Aslan, A. 1999: Palaeosol sequences in floodplain environments: a hierarchical approach. *Special Publication, International Association of Sedimentologists 27*, 303–321.

Launis, A., Pott, C.P. & Mørk, A. 2014: A glimpse into the Carnian: Late Triassic plant fossils from Hopen, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 129–136.

Li, W., Bhattacharya, J.P. & Wang, Y. 2011: Delta asymmetry: concepts, characteristics, and depositional models. *Petroleum Science 8*, 278–289. https://doi.org/10.1007/s12182-011-0145-x.

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 Polarinstitutt Skrifter Nr.168*, 67 pp.

Lord, G.S., Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W. & Paterson, N.W. 2014a: The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 81–96.

Lord, G.S., Solvi, K.H., Klausen, T.G. & Mørk, A. 2014b: Triassic channel bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution. *Norwegian Petroleum Directorate Bulletin 11*, 41–49.

Lundschien, B.A., Høy, T. & Mørk, A. 2014: Triassic hydrocarbon potential in the Northern Barents Sea: Integrating Svalbard and stratigraphic core data. *Norwegian Petroleum Directorate Bulletin 11*, 3–20.

Midtgaard, H.H. 1996: Inner-shelf to lower-shoreface hummocky sandstone bodies with evidence for geostrophic influenced combined flow, Lower Cretaceous, West Greenland. *Journal of Sedimentary Research 66*, 343–353. https://doi.org/10.1306/d4268342-2b26-11d7-8648000102c1865d.

Miller, E.L., Soloviev, A.V., Prokopiev, A.V., Toro, J., Harris, D., Kuzmichev, A.B. & Gehrels, G.E. 2013: Triassic river systems and the paleo-Pacific margin of northwestern Pangea. *Gondwana Research 23*, 1631–1645. https://doi.org/10.1016/j.gr.2012.08.015.

Morad, S. 1998: Carbonate cementation in sandstones: distribution patterns and geochemical evolution. *In* Morad, S. (ed.): *Carbonate cementation in sandstones*, International Association of Sedimentologists Special Publication 26, pp. 1–26. https://doi.org/10.1002/9781444304893.ch1.

Myrow, P.M., Lukens, C., Lamb, M.P., Houck, K. & Strauss, J. 2008: Dynamics of a transgressive prodeltaic system; implications for geography and climate within a Pennsylvanian intracratonic basin, Colorado, USA. *Journal of Sedimentary Research 78*, 512–528. https://doi.org/10.2110/jsr.2008.061.

Mørk, A. & Bjorøy, M. 1984: Mesozoic source rocks on Svalbard. *In* Spencer A.M. (ed.): *Petroleum Geology of the North European Margin*, Norwegian Petroleum Society, Graham & Trotman, London, pp. 371–382. https://doi.org/10.1007/978-94-009-5626-1_28.

Mørk, A. & Bromley, R.G. 2008: Ichnology of a marine regressive systems tract: the Middle Triassic of Svalbard. *Polar Research 27*, 339–359. http://onlinelibrary.wiley.com/doi/10.1111/j.1751-8369.2008.00077.x/full.

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., Dallmann, W.K., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pčelina, T.M. & Worsley, D. 1999a: Mesozoic Lithostratigraphy. *In* Dallmann, W.K. (ed.): *Lithostratigraphic Lexicon of Svalbard, Upper Paleozoic to Quaternary Bedrock – Review and recommendations for nomenclature use*, Norwegian Polar Institute, 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. https://doi.org/10.3402/polar.v18i1.6558.

Mørk, A., Lord, G.S., Solvi, K.H. & Dallmann, W.K. 2013: Geological Map of Svalbard, sheet G14G Hopen, scale 1:100,000, *Norsk Polarinstitutt Temakart 50*.

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

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

Nichols, G. 2009: *Sedimentology and Stratigraphy, Second edition*. River Street, Hoboken, USA, 419 pp.

Nystuen, J.P., Andresen, A., Kumpulainen, R.A. & Siedlecka, A. 2008: Neoproterozoic basin evolution in Fennoscandia, East Greenland and Svalbard. *Episodes 31*, 35–43.

Nøttvedt, A. & Kreisa, R.D. 1987: Model for the combined-flow origin of hummocky cross-stratification. *Geology 15*, 357–361. https://doi.org/10.1130/0091-7613(1987)15<357:MFTCOO>2.0.CO;2.

Olariu, C. 2014: Autogenic process change in modern deltas. *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 46, pp. 149–166. https://doi.org/10.1002/9781118920435.ch7.

Olariu, C. & Bhattacharya, J.P. 2006: Terminal distributary channels and delta front architecture of river-dominated delta systems. *Journal of Sedimentary Research 76*, 212–233. https://doi.org/10.2110/jsr.2006.026.

Olariu, C., Steel, R.J. & Petter, A.L. 2010: Delta-front hyperpycnal bed geometry and implications for reservoir modeling: Cretaceous Panther Tongue delta, Book Cliffs, Utah. *American Association of Petroleum Geologists Bulletin 94*, 819–845. https://doi.org/10.1306/11020909072.

Olaussen, S., Husteli, B., Lord, G.S., Rismyhr, B., Johannessen, E.P. & Mørk, A. 2015: The Early Norian transition in Svalbard and the Barents Sea: A record of slowing down of basin subsidence, alteration of facies associations and shift of provenance and climate change. 2nd Boreal Triassic Conference 2015, Svalbard. *Abstract and proceedings Geological Society of Norway*, 39–42.

Osmundsen, P.T., Braathen, A., Rød, R.S. & Hynne, I. 2014: Styles of normal faulting and fault controlled deposition in the Triassic of Hopen and Edgeøya, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 61–80.

Paterson, N.W. & Mangerud, G. 2015: Late Triassic (Carnian – Rhaetian) palynology of Hopen, Svalbard. *Review of Paleobotany and Palynology 220*, 98–119. https://doi.org/10.1016/j.revpalbo.2015.05.001.

Paterson, N.W., Mangerud, G., Cetean, C.G., Mørk, A., Lord, G.S., Klausen, T.G. & Mørkved, P.T. 2016: A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway. *Palaeogeography Palaeoclimatology Palaeoecology 464*, 16–42. https://doi.org/10.1016/j.palaeo.2015.10.035.

Pčelina, T.M. 1983: Novye dannye po stratigrafii mezozoja arhipelaga Špicbergen. (New material on the Mesozoic stratigraphy of the Spitsbergen Archipelago.) *In* Krasil'ščikov, A.A. & Basov, V.A. (eds.): Geologija Špicbergena. (The geology of Spitsbergen.), Leningrad: Production–Geological Association Sevmorgeologija, pp. 121–141.

Pettijohn, F.J., Potter, P.E. & Siever, R. 1987: *Sand and Sandstone, Second Edition*. Springer-Verlag, New York, 553 pp. https://doi.org/10.1007/978-1-4612-1066-5.

Puchkov, V.N. 2009: The evolution of the Uralian orogen. *Geological Society of London Special Publications 327*, 161–195. https://doi.org/10.1144/SP327.9.

Reading, H.G. & Collinson, J.D. 1996: Chapter 6 – Clastic coasts. *In* Reading, H.G. (ed.): *Sedimentary environments: processes, facies and stratigraphy, Third edition*, Blackwell Science, Oxford, pp. 154–231.

Reineck, H.E. & Singh, I.B. 1980: *Depositional Sedimentary Environments, Second Edition*. Springer-Verlag, Berlin Heidelberg, 549 pp. https://doi.org/10.1007/978-3-642-81498-3.

Reinson, G.E. 1992: Transgressive barrier island and estuarine systems. *In* Walker, R.G. & James, N.P. (eds.): *Facies Models: Response to Sea Level Change*, Geological Association of Canada, Wiley & Sons, Hoboken, New Jersey, pp. 179–194. https://doi.org/10.1002/gj.3350290317.

Retallack, G.J. 1991: Untangling the effects of burial alteration and ancient soil formation. *Annual Review of Earth and Planetary Sciences 19*, 183–206. https://doi.org/10.1146/annurev.ea.19.050191.001151.

Reynolds, A.D. 1999: Dimensions of paralic sandstone bodies. *American Association of Petroleum Geologists Bulletin 83*, 211–229. https://doi.org/10.1306/00aa9a48-1730-11d7-8645000102c1865d.

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

Rød, R.S., Hynne, I.B. & Mørk, A. 2014: Depositional environment of the Upper Triassic De Geerdalen Formation – An E-W transect from Edgeøya to Central Spitsbergen, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 21–40.

Scholle, P.A. & Spearing, D. 1982: *Sandstone Depositional Environments*. The American Association of Petroleum Geologists, Yulsa, Oklahoma, 392pp.

Schumm, S.A. 1972: Fluvial paleochannels. *In* Rigby, J.K. & Hamblin, W.K. (eds.): *Recognition of Acient Sedimentary Environments*, Society for Sedimentary Geology Special Publication 16, pp. 98–107. https://doi.org/10.2110/pec.72.02.0098.

Smith, D.G., Harland, W.B. & Hughes, N.F. 1975: The Geology of Hopen, Svalbard. *Geological Magazine 112*, 1–23. https://doi.org/10.1017/S0016756800045544.

Solvi, K.H. 2013: *Visualize and interpret the geometry, heterogeneity and lateral continuation of channel bodies in the De Geerdalen Formation at Hopen*. MSc thesis, Norwegian University of Science and Technology, Trondheim, 122 pp.

Støen, S.J. 2016: *Late Triassic sedimentology and diagenesis of Barentsøya, Wilhelmøya and eastern Spitsbergen*. MSc thesis, Norwegian University of Science and Technology, Trondheim, 165 pp.

Torsvik, T.H. & Cocks, L.R.M. 2004: Earth geography from 400 to 250 million years: a paleomagnetic, faunal and facies review. *Journal of the Geological Society of London 161*, 555–572. https://doi.org/10.1144/0016-764903-098.

Torsvik, T.H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinburger, B., Doubrovine, P.V., van Hinsbergen, D.J.J., Domeier, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A. & Cocks, L.R.M. 2012: Phanerozoic polar wander, paleogeography and dynamics. *Earth Sciences Review 114*, 325–368. https://doi.org/10.1016/j.earscirev.2012.06.007.

Tugarova, M.A. & Fedyaevsky, A.G. 2014: Calcareous microbialites in the Upper Triassic succession of Eastern Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 137–152.

Tye, R.S. 2004: Geomorphology: An approach to determining subsurface reservoir dimensions. *American Association of Petroleum Geologists Bulletin 88*, 1123–1147. https://doi.org/10.1306/02090403100.

Van Wagoner, J.C., Mitchum, R., Campion, K. & Rahmanian, V. 1990: Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. *American Association of Petroleum Geologists Methods in Exploration Series 7*, 1–55.

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*, 1–269.

Webb, G.E. 1994: Paleokarst, paleosol, and rocky-shore deposits at the Mississippian-Pennsylvanian unconformity, northwestern Arkansas. *Geological Society of America Bulletin 106*, 634–648. https://doi.org/10.1130/0016-7606(1994)106<0634:PPARSD>2.3.CO;2.

Winsnes, T. 1981: Geological Map of Svalbard, sheet 2G, Edgeøya, scale 1:500,000, *Norsk Polarinstitutt Skrifter 154B* (map).

Winsnes, T. & Worsley, D. 1981: Geological Map of Svalbard, sheet 2G, Edgeøya, scale 1:500,000, *Norsk Polarinstitutt Skrifter 154B* (text).

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

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

Yang, B., Dalrymple, R.W. & Chun, S. 2006: The significance of hummocky cross-stratification (HCS) wavelengths; evidence from an open-coast tidal flat, South Korea. *Journal of Sedimentary Research 76*, 2–8. https://doi.org/10.2110/jsr.2006.01.

Paper 5

Sedimentology and Petrography of the Svenskøya Formation on Hopen, Svalbard: An analogue to sandstone reservoirs in the Realgrunnen Subgroup

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Sedimentology and Petrography of the Svenskøya Formation on Hopen, Svalbard: An analogue to sandstone reservoirs in the Realgrunnen Subgroup

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Abstract

The Svenskøya Formation on Hopen is a 35 m thick sandstone and mudstone interval, forming the youngest strata exposed on the island. Herein we present a sedimentological and petrographic study of the Svenskøya Formation sandstones, with a regional comparison to the formation in the Sentralbanken area of the northern Barents Sea and to exposures on Wilhelmøya and Kong Karls Land.

On Hopen, the formation is interpreted as representing sandstones deposited in a mixed fluvial and shoreface setting prior to being overlain by a thin interval composed of tidal channels and marine shales. Petrographic studies show the formation as being arkosic both on Hopen and in the Sentralbanken area. The sandstone reservoir quality at Hopen is somewhat reduced compared to Sentralbanken due to more extensive diagenetic impacts by compaction, mineral dissolution, and extensive precipitation of pore-filling clay minerals. Similar properties are observed in the Sentralbanken area and also on Wilhelmøya and Kong Karls Land.

Introduction

Hopen is a small elongate island, situated in the far south-eastern corner of the Svalbard archipelago (Fig. 1a), that is 32 km long and 0.5–3 km wide. Hopen is the southernmost exposure of Upper Triassic strata in Svalbard and has recently been regarded as an analogue to potential reservoir units in the greater Barents Sea area (e.g. Mørk et al. 2013; Klausen & Mørk 2014; Lord et al. 2014b). As a result, several expeditions to the island have been possible, with support from the industry and the Norwegian Petroleum Directorate (NPD).

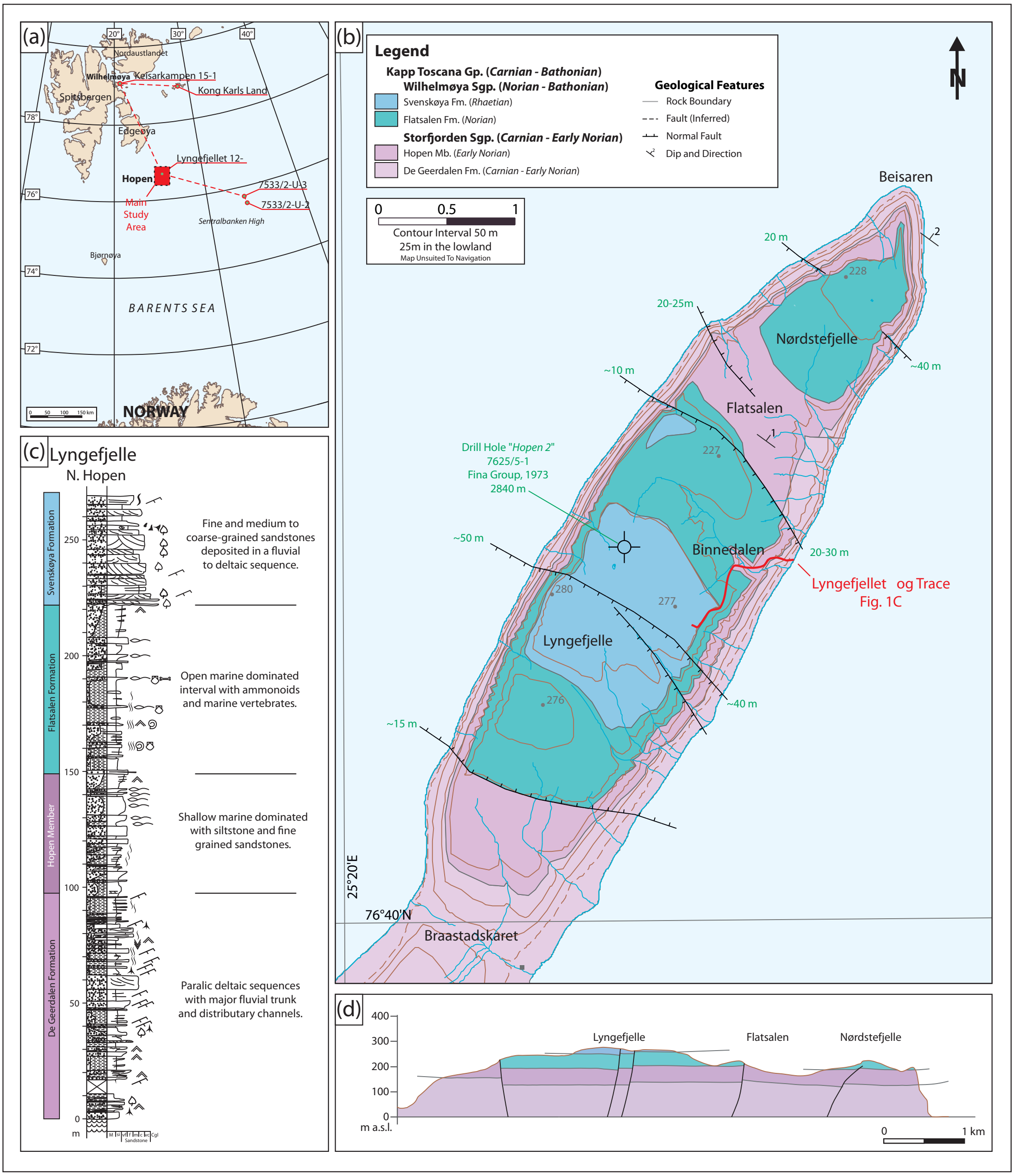


Fig. 1 *(a) Map of the Barents Sea showing the location of Svalbard and the main study area of Hopen in the south-east, Wilhelmøya is also highlighted. The position of wells and logged sections in used in this article are also denoted on the inset map. (b) Geological map of Hopen modified after Mørk et al. (2013), showing the northern part of the island. The log trace for Lyngefjellet Fig. 1c is marked by the red line and follows from the coastline, up Binnedalen to the summit of Lyngefjellet. (c) Log section for the De Geerdalen, Flatsalen and Svenskøya formations at Lyngefjellet, Hopen (from Mørk et al. 2013; Lord et al. 2014a). A general overview of sedimentary environments is given for each formation. (d) A SW–NE oriented cross section of the summits in northern Hopen modified from Mørk et al. (2013). The cross section shows the nature of faulting observed on the island, with minor fault throws (denoted on the geological map Fig. 1b).*

The Svenskøya Formation outcropping on Hopen is the primary target of this study. Although more developed deposits of the Svenskøya Formation and overlying Kongsøya Formation are present at the type sections in Kong Karls Land and Wilhelmøya (Worsley 1973; Smith et al. 1976; Mørk et al. 1999; Larssen et al. unpubl. ms.; Smelror et al. unpubl. ms.), environmental politics regarding Svalbard have made accessing Kong Karls Land challenging at present. Hence, Hopen becomes a viable alternative that can be visited in good weather and with the necessary permissions.

The well exposed Flatsalen and Svenskøya formations on Hopen is an obvious onshore analogue to the Fruholmen and lower part of the Tubåen formations, which are present exploration targets in the south-western Barents Sea. Recent hydrocarbon discoveries in the Realgrunnen Subgroup in the Hoop area of the Barents Sea (e.g. Wisting and Hanssen discoveries), have re-established the outcrops at Hopen as an important analogue. With the exception of palynological dating studies (Smith et al. 1974; Vigran et al. 2014; Paterson & Mangerud 2015; Paterson et al. 2016), the formation has received remarkably little attention in recent publications regarding its facies and petrography. Previous work on the Svenskøya Formation on Hopen was conducted by Smith et al. (1975) who described the formation briefly.

The aim of this paper is to provide an overview of the Svenskøya Formation on Hopen. We compare the lithostratigraphic, sedimentological and petrographic properties observed on Hopen, to localities on Wilhelmøya (ca. 287 km north-west), Kong Karls Land (the type section, ca. 230 km north) and to the Sentralbanken area of the Barents Sea (ca. 200 km to the south-east). Petrographic analysis has been performed, in order to determine potential reservoir properties and compare this with data from the same formation in the Sentralbanken area.

Geological background

During the 1960's and 1970's, the Norwegian Polar Institute (Flood et al. 1971; Worsley 1973), Russian groups (Pčelina 1972) and British expeditions from the Cambridge University Arctic Shelf Program (Smith 1974; Smith et al. 1975) studied the outcrops on Hopen. Two exploration wells were drilled on the island by Norsk Fina in 1971 and 1973. Hopen 1 (7625/7-1) was drilled in the south-western part of the island whilst Hopen 2 (7625/5-1) was drilled in the north at Lyngefjellet. The Hopen 2 well (7625/5-1) penetrates a ca. 1350 m succession of the Triassic (Harland & Geddes 1997; Anell et al. 2013) and was spudded high up in the Svenskøya Formation.

Earlier work in the eastern Svalbard region focused on establishing lithostratigraphic schemes or dating of strata, as opposed to detailed sedimentological studies. Smith et al. (1975) presented the first overview of the geology on the island of Hopen, establishing a tripartite stratigraphy. The three formations were defined as; the Iversenfjellet Formation (now De Geerdalen Formation), the Flatsalen Shale Formation, (now simply Flatsalen Formation) and the Lyngefjellet Sandstone Formation (now Svenskøya Formation). In this paper we follow the stratigraphic subdivision of Mørk et al. (1999), Figure 2a.

A large proportion of recent geological work relating to the island resulted from the requirement to conduct detailed geological mapping (Mørk et al. 2013). Several works have also established dating for the lithological units on Hopen (Vigran et al. 2014; Lord et al. 2014a; Paterson & Mangerud 2015; Paterson et al. 2016). Other studies have focused on the interpretation of Carnian channel bodies exposed in the De Geerdalen Formation (Solvi 2013; Klausen & Mørk 2014; Lord et al. 2014b), as analogues to the Snadd Formation in the Barents Sea.

The south-eastern part of the Svalbard archipelago is dominated by a series of ENE–WSW trending faults (Grogan et al. 1999; Osmundsen et al. 2014; Anell et al. 2016), which strike parallel to the island and down step from the Edgeøya Platform (Doré 1995; Mørk et al. 2013; Lord et al. 2014a, b; Dallmann et al. 2015). Extensional faulting dissects Hopen in a NW–SE manner (Fig. 1b, d) and form minor horst and graben structures (Mørk et al. 2013; Osmundsen et al. 2014; Dallmann & Elvevold 2015) and these are also seen offshore (Anell et al. 2013). Fault throws are relatively minor, with the largest being ca. 50 m. Beds dip gently to the north-east (Fig. 1b) and monoclines are also present in the middle and southern areas of the island. Minor anticlinal and synclinal structures with shallow limb dip of 1–2° (Mørk et al. 2013) are also evident. The area around Hopen has been recognised as one of the focal points for seismic activity in Svalbard, with a number of small earthquakes occurring since 1980 (Nasuti et al. 2015). Analysis shows activity along NW–SE oriented normal faults.

The stratigraphy of Hopen is dominated entirely by Upper Triassic rocks of the De Geerdalen, Flatsalen and Svenskøya formations (Fig. 1c, 2a, b). The De Geerdalen Formation is in the Storfjorden Subgroup. The Flatsalen and Svenskøya formations belong to the Wilhelmøya Subgroup in Svalbard, which was originally defined as a formation by Worsley (1973) and later promoted to subgroup, within the Kapp Toscana Group by Mørk et al. (1999). The Realgrunnen Subgroup, its offshore equivalent, has so far been proven to be the most important reservoir unit in the south-western Barents Sea (Henriksen, et al. 2011; Lundschien et al. 2014).

A complete section of the Wilhelmøya Subgroup (Worsley 1973; Mørk et al. 1999) is present on Wilhelmøya and has been defined as the type section (Mørk et al. 1999). Here the Svenskøya Formation is only partially exposed as it consists of nearly unconsolidated sandstone with good exposure being limited to a few small outcrops. Unconsolidated sandstones are typical for the Svenskøya Formation and this is also the case for the type-section on Kong Karls Land. Hopen is unique however, as the exposures are better consolidated.

The De Geerdalen Formation is Carnian to early Norian in age, based on ammonoid biostratigraphy, palynology and magnetostratigraphy (Tozer & Parker 1968; Pčelina 1972; Korčinskaja 1980; Lord et al. 2014a; Launis et al. 2014; Vigran et al. 2014; Paterson & Mangerud 2015; Paterson et al. 2016). The De Geerdalen Formation and its offshore counterpart, the Snadd Formation represents paralic deltaic facies, deposited in a shallow epicontinental sea (Mørk et al. 1982; Riis et al. 2008; Glørstad-Clark et al. 2010; Høy & Lundschien 2011; Lundschien et al. 2014).

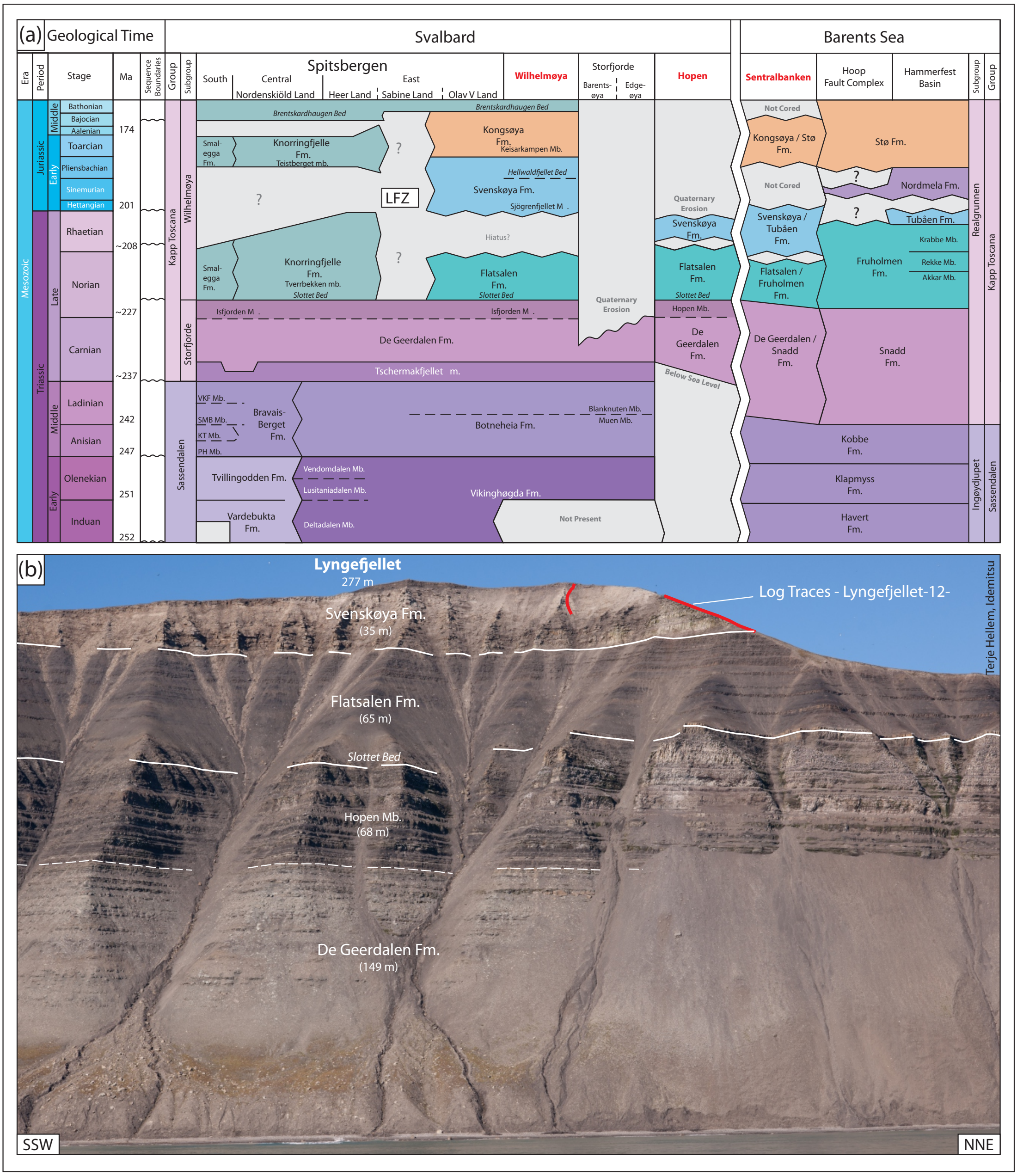


Fig. 2 *(a) Modified stratigraphic chart after Mørk et al. (2013) and Lord et al. (in press) showing the relationships between stratigraphic units in Svalbard and the Barents Sea. Main locations are highlighted in red. (b) A photograph of Lyngefjellet in northern Hopen, showing the distribution of stratigraphic units. The log trace for Lyngefjellet-12-1 (Fig. 4) is marked in red.*

The Flatsalen Formation (Fig. 2a, b) has a prominent, bioclastic carbonate bed at its base – the Slottet Bed. The overlying rocks consist of dark marine shales with minor coarsening upward successions grading into siltstones and very fine sandstone. The unit is dated as Norian in age based primarily on ammonoid biostratigraphy, magnetostratigraphy (Pčelina 1972; Korčinskaja 1980; Lord et al. 2014a) and palynology (Vigran et al. 2014; Paterson & Mangerud 2015; Paterson et al. 2016). The type section for this unit is defined on Hopen (Mørk et al. 1999) and its name originates from a topographic saddle-mountain in the north of the island.

The boundary between the Flatsalen Formation and the overlying Svenskøya Formation (Fig. 1c) is marked by an erosive contact. This is a key sequence stratigraphic surface in Svalbard and the Barents Sea (Gjelberg et al. 1987; Larssen et al. unpubl. ms.; Rismyhr et al. unpubl. ms.). These prominent cliff-forming white and grey beds (Fig. 3) represent an extension of the Svenskøya Formation, as defined on Kong Karls Land (Larssen et al. unpubl. ms.). The formation is correlative to the upper part of the Fruholmen and Tubåen formations of the Realgrunnen Subgroup (Worsley et al. 1988; Mørk et al. 1999), although it is not necessarily the chronostratigraphic equivalent.

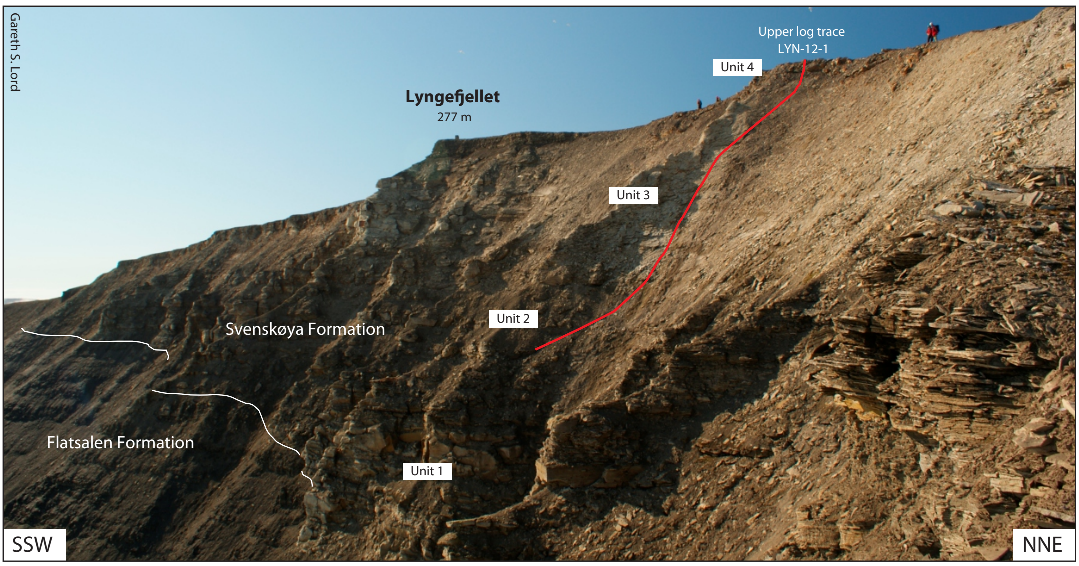


Fig. 3 Photograph of the Svenskøya Formation at Lyngefjellet, geologists for scale. Red line marks the log trace for the upper part of Lyngefjellet-12-1 accessible with rope; the lower part of the log is out of view. Note the visual changes from darker sandstone packages in the base to more grey - yellow sandstones in the upper part. The dark silt and sand interval is visible at the summit.

Earlier work by Smith et al. (1975) described the Svenskøya Formation on Hopen as being correlative to the Tumlingodden member of the Wilhelmøya Formation as defined by Worsley (1973). The Svenskøya Formation is described briefly as a cliff-forming sandstone that is weathering white and appears quartz rich. The main part of the cliff was described as massive, cross-stratified sandstones in the middle part, with plant fragments and thinner bedded sandstones at the top and base of the unit. The upper sandstones were observed as being thinly bedded, within silty shales. Sandstones described in the lower part by Smith et al. (1975) are now regarded as the uppermost part of the Flatsalen Formation and represent prodelta deposits. The Svenskøya Formation was defined as being fluvial in origin by Smith et al. (1975).

During revision of the Mesozoic stratigraphic nomenclature in Svalbard, Mørk et al. (1999) extended the definition of the Svenskøya Formation from the island of Svenskøya in Kong Karls Land, to Hopen and Wilhelmøya (Figs. 1a, 2a). The Flatsalen Formation was maintained, whilst the Iversenfjellet and Lyngefjellet Sandstone formations of Smith et al. (1975) were redefined as the De Geerdalen and Svenskøya formations, respectively.

On Hopen, the Svenskøya Formation is now regarded as Rhaetian in age (Paterson & Mangerud 2015; Paterson et al. 2016; Smelror et al. unpubl. ms.). However, this dating is somewhat tentative based on the lack of sufficient biostratigraphic evidence (Paterson & Mangerud 2015; Paterson et al. 2016). Palynological studies by Smith et al. (1975) regarded the Svenskøya Formation as Jurassic in age, with the upper part of the De Geerdalen Formation and Flatsalen Formation being dated as Rhaetian. Rocks of Rhaetian age have not been conclusively dated in Svalbard previously. Herein, however, we follow the ages suggested by Paterson and Mangerud (2015) and Paterson et al. (2016).

During the Neogene, Hopen (and Svalbard as a whole) experienced severe uplift, glacial rebound and erosion (Throndsen 1982; Dimikas et al. 1998; Henriksen et al. 2011). Estimates by Henriksen et al. (2011) suggest a net erosion of 2.2 to 2.3km in the Hopen area, while the wells in the Sentralbanken High likely experienced less than 1.5 km erosion. However, the general trend of a westward palaeo-temperature (Senger 2017) might influence those estimates. Previous deeper burial has likely influenced both mechanical and chemical compaction of the sandstones in the Svenskøya Formation.

Methods

The Svenskøya Formation on Hopen was studied in detail during mapping expeditions and petroleum license excursions organised by SINTEF Petroleum AS and the Norwegian Petroleum Directorate. The Lyngefjellet section (Fig. 3) features the most complete exposure of the Flatsalen and Svenskøya formations on the island. The transition from the Flatsalen Formation and the lower part of the Svenskøya Formation can be seen and easily accessed along the eastern ridge of Lyngefjellet (Fig. 2b, 3).

Sedimentological sections were measured at the Lyngefjellet locality (Lyngefjellet-12-1), at a scale of 1:50 in the field. In addition, sedimentological sections measured at Wilhelmøya (Keisarkampen-15-1) and Kong Karls Land are also included for regional, onshore, comparison. Core from the 7533/2-U-2 and 7533/2-U-3 wells, drilled by the NPD in the Sentralbanken area, were measured in detail at their core store in Stavanger and are included to create an offshore link.

Samples were collected for both petrography and palynology during these excursions to the island. Fine-grained samples provided for palynological dating were presented by Paterson and Mangerud (2015) and

Paterson et al. (2016). Thin sections were produced with blue dye to indicate porosity. Contemporary optical microscopy studies and SEM analysis have been employed to study the mineral, cement and porosity content. Point counting of each sample (300 points) has also been conducted to quantify the grain composition. Petrographic data from the 7533/2-U-2 well is also included in this paper, in order to discuss the petrographic development of the unit southwards into the Barents Sea and to support a regional onshore – offshore link.

The Svenskøya Formation in Eastern Svalbard

Hopen

At Lyngefjellet (Figs. 2b, 3), eight facies have been defined and are presented in Table 1. These facies are also presented on the sedimentological log, Lyngefjellet-12-1 shown in Fig. 4, with the legend to all logs in Fig. 5. On Hopen the Svenskøya Formation overlies the Flatsalen Formation which is a 75 m thick, well exposed, marine mudstone with subordinate very fine-grained sandstone, and carbonate cemented sandstone. The Flatsalen Formation marks the onset of a major marine transgression in the eastern areas of Svalbard (Fig. 1c) (Klausen & Mørk 2014), during the Norian. The base of the unit is defined at the Slottet Bed (Mørk et al. 1999; 2013) and on Hopen this is a bioclastic carbonate, likely representing a transgressive lag deposit (Klausen & Mørk 2014).

The remainder of the Flatsalen Formation is composed of dark mudstone with minor coarsening upwards units, grading from bioturbated open marine muds, to hummocky cross-stratified very fine sandstone (Facies A, B). These coarsening upwards units, likely represent open shelf deposits grading to offshore transition zone deposits. The uppermost beds of the Flatsalen Formation (Fig. 1c) form a well-defined coarsening and shallowing upwards unit. The amalgamated hummocky cross-stratified, very fine-grained sandstone in the uppermost part of the Flatsalen Formation suggests lower to middle shoreface deposits. Due to the shallowing and gradual coarsening upwards trend of the Flatsalen Formation, the unit can be regarded as a prograding succession, probably deposited during high-stand conditions (cf. Reading & Collinson 1996).

We have subdivided the Svenskøya Formation on Hopen into four informal units based on their lithological properties and facies (see Figs. 3, 4): Unit 1 consists of a lower conglomerate and medium to coarse-grained sandstones (2.5–10.2 m). Unit 2 is mostly composed of immature, fine to medium-grained sandstones (10.2–17.7). Unit 3 is a fine to medium-grained, mature sandstone with a white to light grey appearance (17.7–30 m). Unit 4 is a heterolithic sequence with mature, fine-grained sandstones and prominent mud-flake conglomerate, capped by dark grey mudstone at the summit of Lyngefjellet (30–37.5 m).

Facies	Facies Description	Geometry	Interpretation
A	**Laminated Claystone - Siltstone** Sharp based fine-grained claystone and siltstone beds with a uniform grain size throughout. Typically part of the Flatsalen Formation. Bioturbation is common and ammonoid fossils may be present. Formed in a stable and low energy marine environment, from low density hypopycnal sediments.	Laterally extensive over 100's of km.	Shallow marine / offshore mud and silt.
B	**Hummocky Cross-Stratified Sandstone** Sharp or erosive based, silt to very fine-grained sandstone beds featuring hummocky cross-stratification, erosive bases are common and upper surfaces may feature current ripples. Formed in a turbulent energy environment, often as storm deposits below normal wave base and above storm wave base in a shallow marine environment.	Laterally extensive deposits. Sandstone beds are lenticular and pinch out, but facies is widespread.	Shallow marine silt and storm deposits emplaced in an offshore transition zone to open shelf area below normal wave base.
C	**Planar Cross-Stratified Sandstone** Sharp based, fine to medium-grained planar cross-stratified sandstone. Foresets are defined by finer grained material and are typically 0.5 - 1 cm in thickness. Upper part may fine to ripples. These sandstone beds represent lateral migration of coarse clastic sediment in a uni-directional current, within a moderate flow regime.	Laterally extensive beds for several metres with discrete pinch out. Beds thickness' range from 20 cm to 2 m.	Upper shoreface or estuarine sands deposited as an advancing bar or as part of a prograding shoreline.
D	**Mud-Flake Conglomerate** Sharp or erosive based conglomerate, with a matrix of medium-grained sandstone containing abundant small to medium sized (1 - 10 cm) clasts of mud. Bed contact is often erosive into underlying beds. Siderite common. Formed in a high energy environment, where a flow carrying a large clastic load erodes into underlying beds of fine grained material which is subsequently incorporated into overlying beds.	Prominent beds with lateral discontinuity over several metres. Form as the base of troughs or individual beds of varying thickness between 20 cm and 1 m.	High energy, erosive, fluvial channel basal conglomerate, with clasts derived from underlying lithology.
E	**Trough Cross-Stratified Sandstone** Erosive based, fine to medium-grained sandstone featuring large scale trough cross-stratification. Bed contacts are erosive with mud-flake conglomerate being common. Mud-flakes are also common at the base of troughs/ scours. Upper part may fine to rippled sandstone. Beds are formed by the aggradation of coarse clastic sediment in a moderate energy environment with a uni-directional flow.	Laterally extensive beds for several metres with discrete or erosive pinch out. Beds thickness' range from 20 cm to 2 m.	Fluvial channel fill, migrating 3D dunes with separation at dune crests.
F	**Parallel Planar Stratified Sandstone** Sharp based, fine to medium-grained, horizontally bedded and planar laminated sandstone. Laminations are typically 0.5 - 1 cm in thickness. Planes are parallel and form tabular sets. Upper part may feature ripples. These sandstone beds represent deposition of clastic sediment in a shallow and low energy environment.	Laterally extensive beds for several metres with discrete pinch out. Beds thickness' range from 20 cm to 2 m.	Channel fill, in the upper flow regime.
G	**Current Rippled Sandstone** Gradual based, very fine to medium-grained sand with asymmetrical ripples, formed in a uni-directional flow regime. No mud drapes on ripple crests is evident and ripples are often seen to form in the upwards fining part of sandstone beds containing cross-stratification. Rippled sands represent the deposition of coarse clastic sediment in a low energy system, with a single flow direction.	Beds with current ripples are laterally discontinuous and typically found atop major sandstone beds.	Channel fill, rippled sandstones deposited in the lower flow regime.
H	**Claystones** Sharp based very fine grained beds in yellow, grey or orange with a uniform grainsize throughout. Often found capping sandstone horizons, with an erosive contact to overlying beds. Clay features no obvious lamination with or specific bedding. Siderite may be present. Formed in a delta top environment where sub-aerial exposure allows soil formation.	Laterally discontinuos within a few metres. Beds are 10 - 20 cm in thickness.	Delta plain deposits.

Table 1 *Summary of facies table, presenting the main facies observed in the Svenskøya Formation at Lyngefjellet, northern Hopen. References to facies in the text refer to this table.*

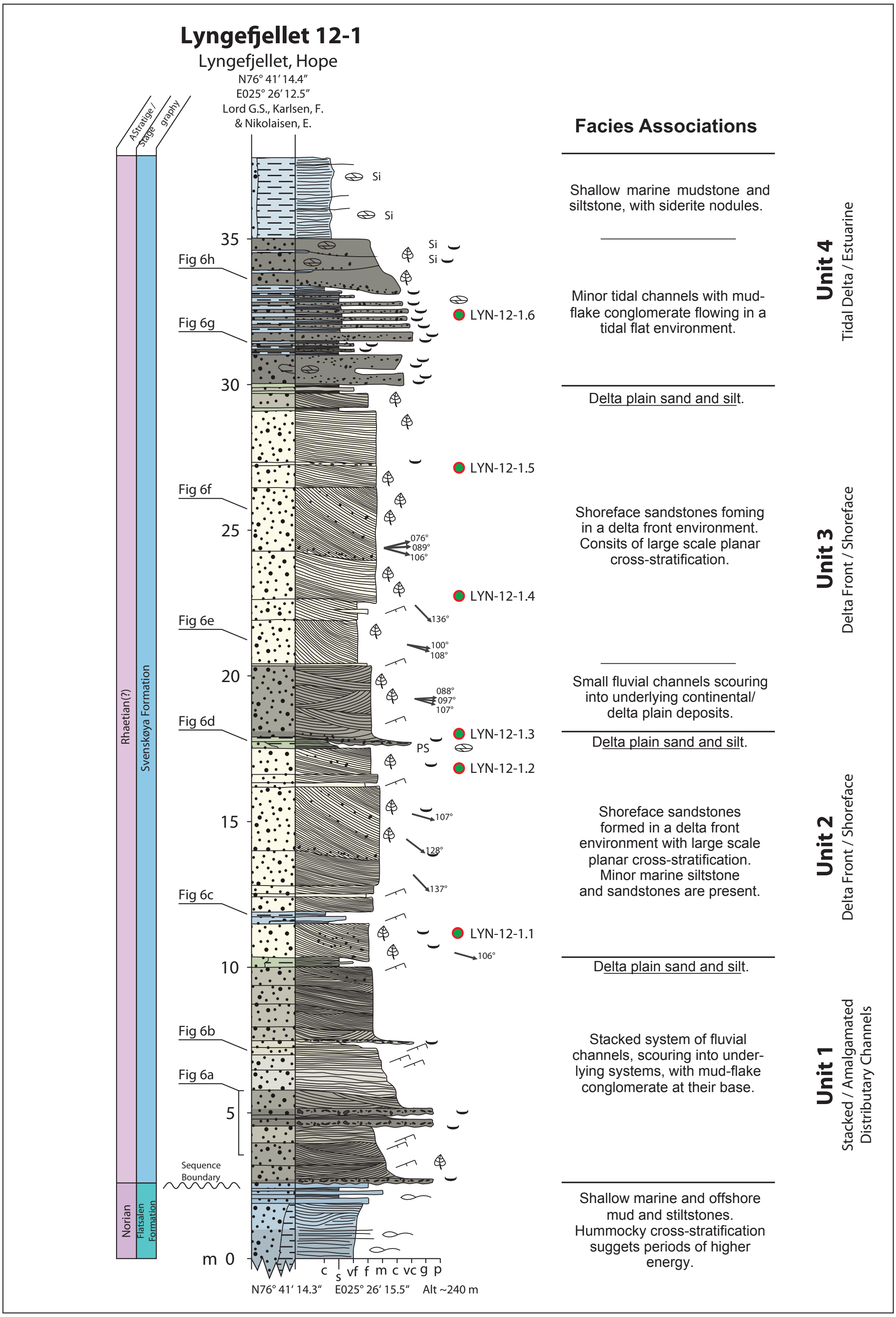


Fig. 4 *Log Lyngefjellet-12-1 (Lyn-12-1) recorded of the Svenskøya Formation at Lyngefjellet, Hopen. The lower 8 m is a composite of data after Larssen et al. (unpubl. ms., in Mørk et al. 1999), with additional observations included, see Fig.5 for symbol legend. Facies associations are provided and colours relate to those given in Fig. 5.*

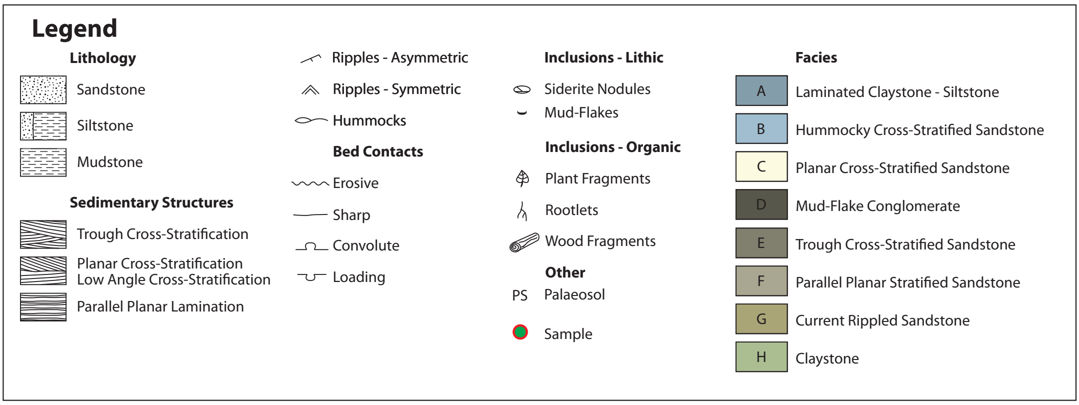


Fig. 5 *Legend to sedimentological logs presented in Figs. 4 and 8.*

Unit 1- Fluvial channel fill

Description: The lowermost unit of the Svenskøya Formation is 8.3 m in thickness (2.5–10.2 m on the log in Figs. 4, 6a). The boundary between Svenskøya and Flatsalen formations is erosive and is a key sequence stratigraphic surface in Svalbard (Rismyhr et al. unpubl. ms.; Larssen et al. unpubl. ms.) and Barents Sea (Gjelberg 1987; Klausen et al. 2016). Stacked cut-and-fill or channelised structures, which form Unit 1, are resting on this erosive surface. Each cut-and-fill structure is fining upwards with a mud-flake conglomerate (Facies D) as a lag deposit, which grades into trough and planar cross-stratified, fine to medium-grained sandstone beds (Facies C and E). The channel fills are vaguely organised by having trough cross-stratification in the middle part, which becomes more parallel planar in the upper part (Fig. 4, 6b).

Asymmetrical ripples are present (Facies G), in the upper part of sandstone beds and small, coalified plant fragments are also seen. Also a thin local and laterally discontinuous grey coloured claystone bed (Facies H) caps the upper part of Unit 1.

Interpretation: The fining upward, cut-and-fill structures, with unidirectional palaeo-current and lack of burrows and marine fossils suggest amalgamated channel fill (similar to those described in Olariu and Bhattacharya 2006) and correspond well to facies expected in the Fluvial Zone described by Dalrymple and Choi (2007). The presence of conglomerate lag, trough cross-stratification, planar stratification and current ripples, suggests rapid and high energy deposition of sediment in a uni-directional flow regime (Reading & Collinson 1996; Fielding 2006).

Troughs form as three dimensional dunes that migrate without separation at the dune crests in uni-directional flow regimes (Reading & Collinson 1996; Fielding 2006), while the planar stratified sandstone (Facies F) is thus suggested to represent flow in the upper flow regime (Fielding 2006).

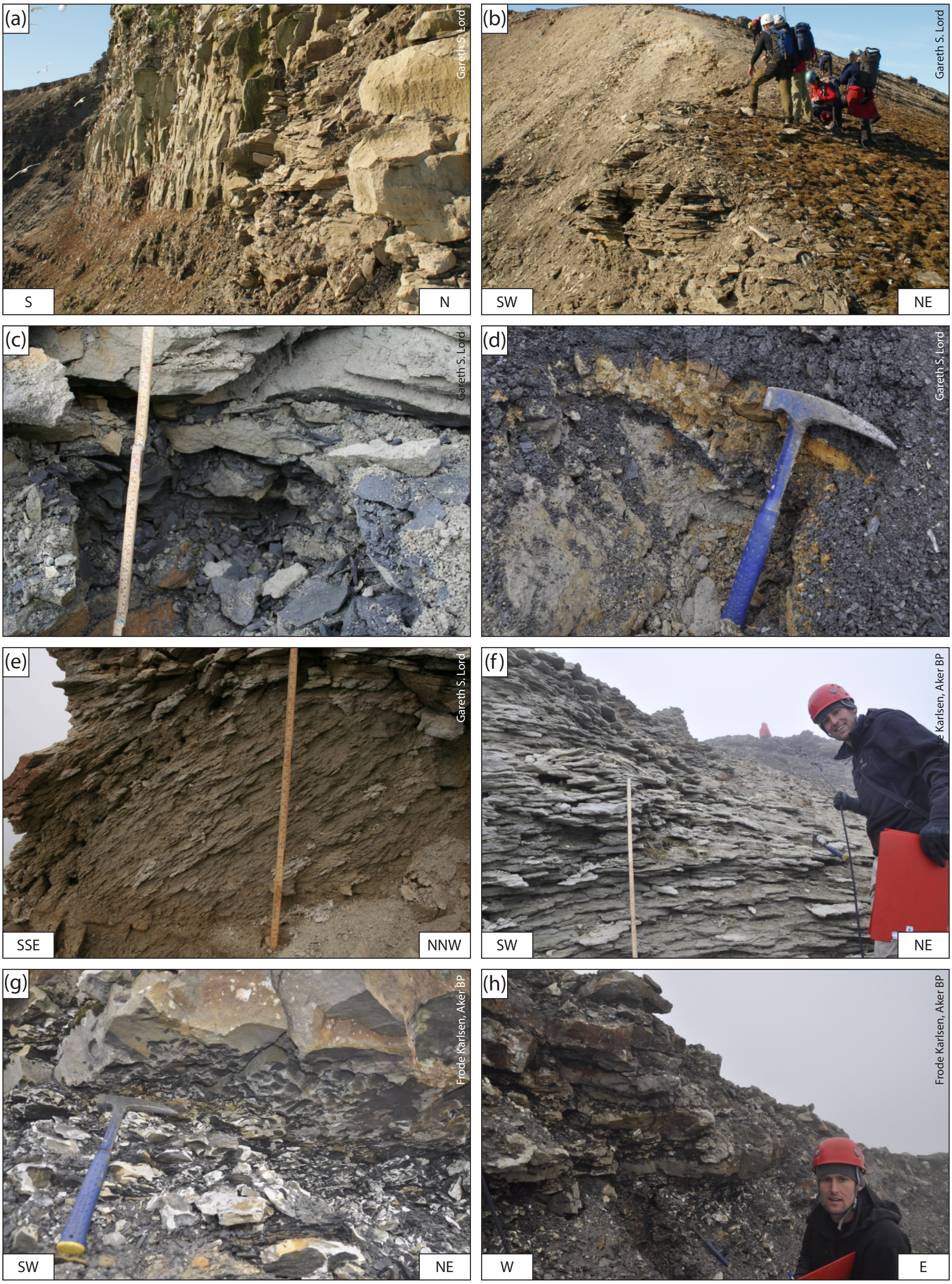


***Fig. 6** (a) The lower beds of the Svenskøya Formation consisting of mud-flake conglomerate and trough cross-stratified sandstones. (b) Parallel planar laminated sands at the top of the lower package. (c) Fine yellow and grey clay with orange weathered palaeosol and siderite. (d) Shallow marine siltstone. (e) Planar cross-stratified sandstone capped by parallel planar sandstone beds, note palaeo-current is to the east / south-east. (f) Large scale planar cross-stratification in the upper part of the Svenskøya Formation. (g) Mud-flake conglomerate beds that form the uppermost package of the Svenskøya Formation. (h) Dense mud-flake conglomerate*

with feint trough cross-stratification in the sandstone, interpreted as representing small channels flowing on a tidal flat. Note position of photographs is also denoted on Fig. 4.

We suggest the lower part of this unit represents small distributary channels scouring into the underlying formation, causing the presence of locally derived mud clasts. Amalgamated beds of mud-flake conglomerate grading into sandstone, scour into underlying beds, suggest stacking of small fluvial channels (Skelly et al. 2003). These mud-flakes may also be the cause for discrepancies in palynological dating as they are likely derived from the older Flatsalen Formation. The finer grained facies suggest over-bank deposits and the grey coloured mudstone may represent palaeosol development (Kraus 1999; Kraus & Aslan 1999).

Unit 2 - Distributary channel and shoreface delta front

Description: Unit 2 is 7.5 m in thickness (10.2–17.7 m on the log in Fig. 4), with a basal bed of cross-stratified fine-grained sandstone, that appears to erode the mudstone bed at the top of Unit 1. Above this basal bed, the remaining part of Unit 2 can be regarded as a coarsening upward unit, from clay to fine-grained sandstone, with a small upwards fining component in the uppermost part to facies F and G. The unit is cliff-forming and dominated by a thick planar cross-stratified, fine-grained and well sorted sandstone bed (Facies C), with mud-flakes on the foresets. Beds range in thickness from 1–3 m and show stacking with the superimposition of bed-forms. The basal lower sandstone beds are capped by a ca. 30 cm thick bed of siltstone with thin rippled sandstone lenses (Fig. 6c). Unit 2 can be observed as being darker in colour and more green / grey, which gives a clear contrast to the overlying sandstone beds of unit 3. Unit 2 is also capped by a thin yellow and orange clay bed with some organic content (Facies H, Fig. 4, 6d). Palaeo-current measurements in this unit suggest migration of foresets to the east and south-east.

Interpretation: The erosive basal bed to this unit may represent a shoreline ravinement unconformity (cf. Embry 2009), with a minor flooding surface marked by the overlying marine silt bed. The thin silt interval in the lower part of the unit is likely marine in origin, given the presence of shoreface deposits in the overlying sandstone beds. The large-scale, planar cross-stratified nature of the main sandstone bed, suggests deposition in lower flow velocities (Cant & Walker 1978; Berne et al. 1998), sporadic mud-flakes can represent periods of higher energy, current ripples are present in the upper part but wave ripples are absent. Bioturbation has not been observed in this unit but is likely present.

These planar cross-stratified sandstone beds and the coarsening upwards trend are interpreted as representing a shoreface environment (cf. Olariu & Bhattacharya 2006), on a delta front setting and are likely within the Fluvial-Tidal Transition Zone as described by Dalrymple and Choi (2007). The fining upwards trend seen in the upper part of the unit suggests back-stepping of the shoreline. The claystone and siltstone with organic content in uppermost bed (Fig. 6d) is interpreted as representing a delta coastal plain and may indicate the possible development of a palaeosol, suggesting subaerial exposure (Kraus, 1999; Kraus & Aslan, 1999).

Unit 3 - Delta front and shoreface

Description: Unit 3 is 12.3 m in thickness (17.7–30 m on the log in Fig. 4) is a mixture of facies as seen in units 1 and 2. The basal part appears to erode the top of Unit 2 and consists of a 3m thick fining upward bed, resembling the cut and fill channelised beds in Unit 1 with mud-flake conglomerate lag at the base (Facies D) passing upward to trough cross-stratified sandstone (Facies E). This bed is followed by a coarsening upwards unit capped by a fining upwards unit as in Unit 2. The coarsening upwards unit consists primarily of fine to medium-grained sandstone with large scale planar cross-stratification (Facies C). Sandstones here are lighter in colour and appear slightly loose in consolidation. Overlying beds of medium-grained sandstone are found within this interval with easily visible planar cross-stratification (Facies C; Fig. 6e, f). Foresets in thinner beds appear to contain fine sandstone or possibly silt. Plant fragments are abundant while mud-flakes are less common. Unit 3 is capped by a thin clay bed that may represent a palaeosol deposit. Palaeo-current measurements in this unit suggest, alike Unit 2 that foresets are migrating to the east and south-east.

Interpretation: The basal sandstone bed with Facies D and E as the cut and fill structures in Unit 1 represent channel fill deposits and may also represent a low order sequence boundary (cf. Embry 2009). As in Unit 1, the fining upward trend of this bed and the uni-directional flow of the channel fill, with trough cross-stratification, suggest an interval representing fluvial channel deposits. The coarsening upwards unit above this cut and fill bed, with better sorted planar cross-stratified sandstone suggests, as in Unit 2, a shoreface deposit with a minor flooding surface at its base. As in Unit 2, Unit 3 is also capped by thin clay and silt beds which are interpreted to represent palaeosol development (Kraus 1999).

Due to this lower channel deposit being sandwiched between two shoreface deposits, it is regarded as a small, nearshore distributary channel (cf. Reading & Collinson 1996; Olariu & Bhattacharya 2006). This unit is determined to represent part of a fluvial and destructive, wave dominated shoreline, representing a proximal delta front environment (Reading & Collinson 1996; Hampson et al. 2008).

Unit 4 - Tidal delta / estuarine deposits and offshore marine

Description: The upper part of the formation is subject to a notable change in its lithological characteristics and facies. Unit 4 (30–37.5 m on the log in Fig. 4) consists of a 7.5 m thick succession of dense mud-flake conglomerate (Facies D) interspersed with thin silt beds (Facies A). The unit overlies the clean sandstone of Unit 3 with a sharp and likely erosive boundary. The lower beds of unit 4 are abundant in mud-flake conglomerate (Facies D) and medium-grained sandstone, separated by thin, ca. 15 cm beds of mudstone (Facies A, Fig. 6g). The sandstone in Unit 4 is white to light grey in colour and has a uniform grain size, suggesting it has been well sorted. These sandstones and mud-flake conglomerate beds appear to have a lenticular geometry, which suggests scouring into underlying siltstone beds. Subtle trough cross-stratification (Facies E) or internal scours are observed. Laterally these sandstones with mud-flake conglomerate appear to disperse to the south-west on Hopen and vertically the unit fines upward to siltstone, with a 3 m thick mudstone (Facies A) with siderite concretions forming the summit of Lyngefjellet (Fig. 3).

Interpretation: The scouring characteristics of the sandstones in this unit, with feint trough cross-stratification and mud-flake conglomerate, in an overall heterolithic unit, suggest that this upper part represents the onset of a new fluvial or estuarine system (Fig. 6h). The sharp, potentially erosive boundary at the base of this unit may represent a tidal ravinement surface, however, no diagnostic tidal features are observed. The interpretation of an estuarine system is based on the apparent maturity of the sandstone, with mud-flake conglomerate and channel-like geometries, scouring into shallow marine siltstone and can be considered reasonable. The upper clay and siltstone is interpreted as being shallow marine, which suggests the presence of a flooding surface at its base. However, as this is the uppermost part of the section with a considerable portion likely being eroded, the extent or significance of this surface is unknown.

Wilhelmøya

On Wilhelmøya, the Svenskøya Formation is poorly exposed, due to its unconsolidated nature. At Keisarkampen (Fig. 7a, 8), the highest summit to Wilhelmøya, a moderately consolidated exposure is present (Fig. 7b), although limited to a small outcrop. The underlying Flatsalen Formation is also poorly exposed. The Svenskøya Formation is inferred to have a sharp or erosive contact with the Flatsalen Formation (Fig. 7a, 8) following previous observations (e.g. Worsley 1973). The exposures of the Svenskøya Formation on Wilhelmøya are composed of fine to medium-grained sandstone with parallel planar stratification and planar cross-stratification (Fig. 7c). Troughs do not appear evident. but may be present locally. Foresets to cross-stratified sandstones in the lower part of the Svenskøya Formation on Keisarkampen trend to the north-east. Field observations suggest these sandstones represent delta front sediments, with a minor fluvial component. No mud-flakes were noticed however plant material is abundant.

The remainder of the Svenskøya Formation is composed of loose sand, or poorly consolidated outcrops with much of the unit being completely covered. Excavated sections consist of relatively massive fine to medium-grained sandstone, where some beds exhibit bioturbation. Rootlets and plant fragments are abundant, but sedimentary structures are difficult to distinguish. The uppermost part is marked by a thin siltstone interval. The Svenskøya Formation on Wilhelmøya most likely consists of shoreface facies, where large scale cross-stratified sandstones may represent sequences of tidal sand sheets (Fichter & Poche 2001).

Kong Karls Land

In Kong Karls Land the boundary between the Flatsalen and Svenskøya formations is covered by a ca. 10 m thick unit of Quaternary to recent strandlines. The exposed part of the Flatsalen Formation is dated as being early Norian age, while the first exposed part of the Svenskøya Formations is possibly late Norian to Rhaetian age (Smelror et al. unpubl. ms.).

The lowermost exposed part of the Svenskøya Formation consists of the Rhaetian to Early Pliensbachian Sjøgrenfjellet Member and is ca. 160 m thick in Kong Karls Land. The lower part of the member is composed of a 12 m thick trough and planar cross-stratified medium-grained sandstone interpreted as fluvial or estuarine channel fill deposits (Larssen et al. unpubl. ms.). The lower part of the Sjøgrenfjellet Member features palaeo-current directions towards the north-east. In terms of facies, the succession shows distinctive similarity to the channelised beds seen in the lower part of the Svenskøya Formation on Hopen.

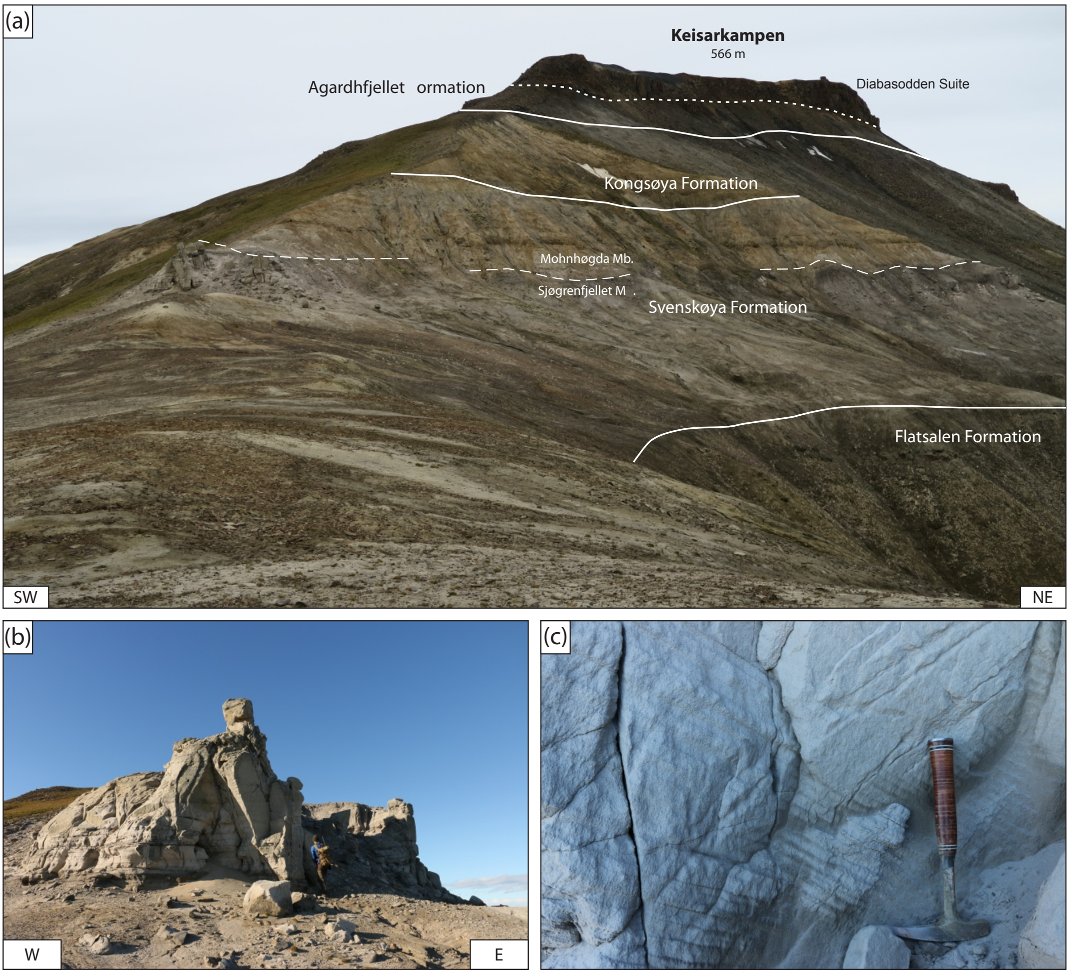


***Fig.** 7 (a) Photograph of the north-eastern flank of Keisarkampen, Wilhelmøya. Note the poorly exposed Flatsalen, Svenskøya and Kongsøya formations. The upper part of the mountain is formed of a dolerite sill of the Diabasodden Suite intruding into the marine shales of the Late Jurassic Agardhfjellet Formation. (b) The primary locality of the Svenskøya Formation on Wilhelmøya where poorly consolidated sands are exposed. (c) Planar cross-stratified fine to medium sand in the Svenskøya Formation on Wilhelmøya. Foresets are composed of finer grains suggesting tidal influence. The sandstones at this locality primarily represent upper shoreface facies deposited in a delta front environment.*

The remaining part of the member comprises heterolithic facies, intersected by channelised beds. Wedge-shaped planar cross-stratified sandstone beds with tidal bundles and reactivation surfaces are common features, both in the channelised and heterolithic beds. The heterolithic and more tabular units comprises 30–50 cm thick beds with organic rich claystone at the base and in ascending order passes to lenticular, wavy and finally flaser bedded sandstone suggesting tidal flat deposit, i.e. mudflat, mixed mud sandflat and sandflat respectively (cf. Reineck & Singh 1980). The channelised deposits often feature lateral accretion surfaces, which have cleaner sandstones at the base that fines upward to flaser and lenticular bedded sandstone suggest tidal channel-fill (Larssen et al. unpubl. ms.). Thicker, organic-rich mudstones represent lagoonal or estuarine basin-fill. The upper 25 m of the Sjøgrenfjellet Member has a well-defined coarsening upward unit, suggested to be a prograding bay head delta environment. The provenance of the Sjøgrenfjellet Member is suggested to be in north-east based on a dominant south-westwards palaeo-current trend in the majority of the Formation (Larssen et al. unpubl. ms.). In summary, the member is interpreted as having been deposited in an estuarine environment as defined by Dalrymple & Choi (2007). The Sjøgrenfjellet Member shows facies similarities to the Tubåen and Nordmela formations in southwestern Barents Sea petroleum province (Olaussen et al. 1984; Gjelberg et al. 1987; Henriksen et al. 2011; Ryseth 2014).

There is a sharp boundary between the Sjøgrenfjellet Member and the overlying 45–55 m thick late Pliensbachian to Toarcian Mohnhøgda Member in the Svenskøya Formation (Fig. 8). The base of the Mohnhøgda Member consists of a 0.5 m thick poorly sorted quartz gravel bed and shell fragments of ostracods representing a key sequence stratigraphic surface, which is also seen in Spitsbergen (Rismyhr et al. unpubl. ms.) and the south-western Barents Sea. Amalgamated hummocky cross-stratified fine-grained sandstone beds, are interbedded with thoroughly bioturbated very fine-grained sandstones with *Ophiomorpha* burrows.

This lower part is interpreted as shoreface depositional environment (Larssen et al. unpubl. ms.). The overlying heterolithic succession is composed of grey, dark grey and brownish clay and siltstones with an increase in marine palynomorphs (Smelror et al. unpubl. ms.), probably representing offshore or transition zone deposits. Of particular interest is the upper part of the member, with either a 6 m thick coarsening upwards unit, with 4 or 5 stacked 1–2 m thick coarsening upwards units, capped by channelised cross-stratified sandstone, with gravel along the channel thalweg. Lack of burrows in the channels with a dominance of bisaccate pollen in the mudstones (Smelror et al. unpubl. ms.), suggests brackish or freshwater conditions. The coarsening upwards units suggest fluvial discharge and likely represent minor mouth bars. The channelised body would then be a distributary channel, in a more fluvial deltaic environment or proximal bay head delta.

The upper boundary of the Svenskøya Formation is marked by the basal lag of the Late Toarcian-Aalenian Kongsøya Formation. This lag is a thin siderite and mudstone bed, with a 5 cm thick quartz and chert-rich gravel bed within, containing pieces of wood and siderite pebbles. The Mohnhøgda Member and Kongsøya Formation are near time equivalent to the lower and middle part of the Stø Formation in the south-western Barents Sea.

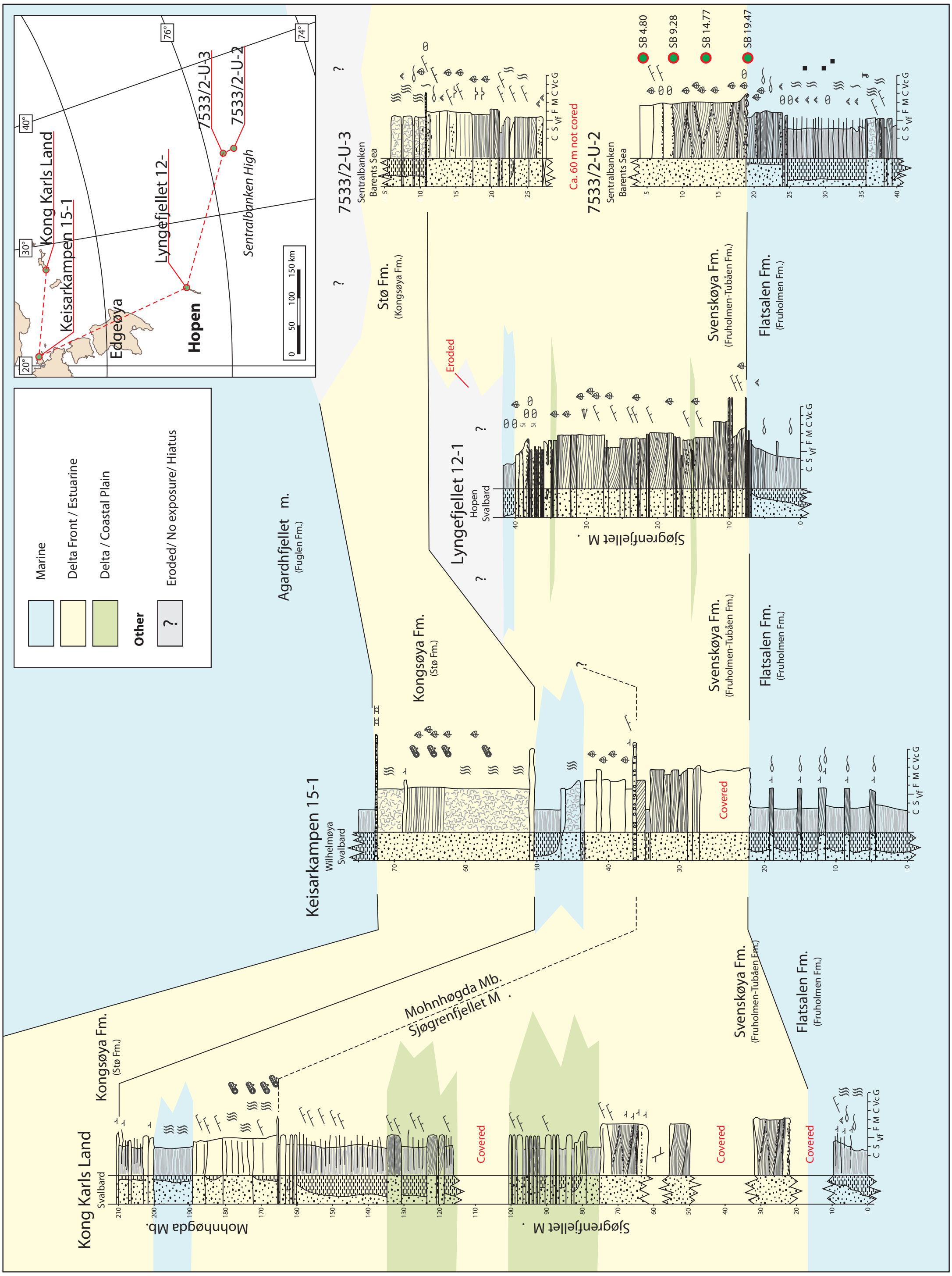


Fig. 8 *Correlation diagram showing the main depositional environments of the Svenskøya Formation. Note the extensive erosional unconformity at the base of the unit. Stratigraphic nomenclature for Svalbard and the Barents Sea is combined; comparative units are given in parenthesis.*

The Svenskøya Formation in Sentralbanken

The stratigraphic chart in Fig. 2a, shows the relationships between onshore stratigraphic units and those found offshore in the Barents Sea. The formations that form the Triassic stratigraphy of Svalbard, which may be correlated throughout the Barents Shelf area, are diachronous. Thus, correlation is based mostly on chronostratigraphic relationships, as opposed to purely litho-stratigraphic similarities. Fig. 8 presents sections from Svalbard and the correlation of lithological units to the Sentralbanken area. Stratigraphic nomenclature from Svalbard (Mørk et al. 1999) up to the Svenskøya Formation is maintained in the Sentralbanken area (with the exception of the Kongsøya – Stø formations), due to its close proximity and similarity to Svalbard.

An explanation of the relationships between individual stratigraphic units (See Figs. 2a, 8) and nomenclature can be given as: The Flatsalen Formation extends from the Svalbard area to Sentralbanken, and is termed the Fruholmen Formation in the south-western Barents Sea. The Svenskøya Formation is also maintained to Sentralbanken however is termed the Tubåen Formation in the south-western Barents Sea. The Kongsøya Formation is only defined for the Svalbard area at present and is termed the Stø Formation in the Sentralbanken and south-western Barents Sea area. The Nordmela Formation, present throughout the south-western Barents Sea, is not defined as a formation in itself in Sentralbanken and Svalbard, but does however have facies that correlate well in Kong Karls Land (cf. Gjelberg et al. 1987; Klausen et al. 2016). The surface marking the onset of marine shales in Agardhfjellet Formation throughout Svalbard is traceable into the Sentralbanken area where it is termed the Fuglen Formation. However, in the Barents Sea the base of this unit is unclear and is defined at the top of the Stø Formation (Worsley 2008).

Well 7533/2-U-2

In 1998 the NPD drilled well 7533/2-U-2 and cored 88 m of Upper Triassic to Lower Jurassic strata in the Sentralbanken area of the Barents Sea (Fig. 8). Above paralic deltaic deposits of the De Geerdalen (Snadd) Formation, 45.6 m of the Flatsalen (Fruholmen) Formation was penetrated with the entire formation being cored. The Flatsalen Formation is interpreted as representing shallow marine deposits. Supported by the presence of marine palynomorphs and is correlative to the Flatsalen Formation on Hopen, Wilhelmøya and Kong Karls Land (Vigran et al. 2014, Paterson & Mangerud 2015; Paterson et al. 2016; Smelror et al. unpubl. ms.). Only the uppermost part of the Flatsalen Formation is shown in the log of well 7533/2-U-2 (Fig. 8).

A 19 m thick sandstone unit (Fig. 8) is seen to rest sharply on top of the Flatsalen Formation in well 7533/2-U-2. Palynological studies indicate the age is the same as the underlying unit (Vigran et al. 2014). We regard the unit as correlative to the Svenskøya Formation (Tubåen Formation), as seen on Hopen. The top of the core is close to the seabed and thus the total thickness of the unit is not known for certain. The upper part of the Svenskøya Formation is seen in core 7533/2-U-3 (Fig. 8), this however is Jurassic in age and correlates to the upper part of the Svenskøya Formation on Kong Karls Land (Smelror et al. unpubl. ms.). This core is not discussed in detail further. However, approximately 60–80 m of the Svenskøya Formation is thought to be missing from the cored section, suggesting the unit is ca. 100 m thick in the Sentralbanken area.

The Svenskøya Formation in core 7533/2-U-2 has an erosional contact to the underlying Flatsalen Formation. The basal lag of the Svenskøya Formation shows a calcite cemented bed, containing mud-flakes and siderite fragments. This is followed by six meters of low-angle cross-stratified, very fine-grained and light grey sandstone. The middle part of the unit consists of 5–6 m of fining upwards sandstones with intra-formational conglomerates of siltstone and siderite clasts at the base as well as coal fragments and plant debris. The upper part of the core consists of fine sandstone. These fine upward to very fine-grained, grey sandstone, which appears massive with indistinct lamination. Mud-flakes and siltstone clasts are present, but sparse. There are neither macrofossils nor trace fossils observed in the sandstone.

The Svenskøya Formation, although lacking clear marine indicators may represent shoreface depositional environments with the fining upwards units in the middle part representing channels.

Petrography and reservoir properties

Petrographic analysis of samples from the Svenskøya Formation from Hopen, (marked on the Lyngefjellet-12-1 log, Fig.4) has been incorporated (Fig. 9a, b). Additionally, data from well 7533/2-U-2 in Sentralbanken (Fig. 9a, b) is included, allowing for a comparison of reservoir properties from a structural high in the northern Barents Sea. Samples from the 7533/2-U-2 well are derived from the following core depths in the Svenskøya (Tubåen) Formation; 4.80 m, 9.28 m, 14.77 m and 19.47 m (Fig. 8).

Permeability

A sample from Unit 3 on Hopen (25.7 m on log Lyngefjellet-12-1), was selected for permeability analysis using standard core plug analysis (3.8 cm in diameter and 1 cm long). The sample is representative for the fine to medium-grained sandstone with mud-flakes and plant material, common to Units 2 and 3. Analysis yielded a relatively low permeability value of 0.6 mD. This is in contrast to the permeability measured in the upper part of the Svenskøya Formation on the Sentralbanken High where permeability is measured to be 145 mD (sandstone from 7533/2-U-2, 5.65 m depth below sea-floor). Based on petrographic thin section observations, chemical compaction is the main porosity-reducing factor. A likely permeability reducing factor is presence of mud-flakes, which are common in the sandstones in the Svenskøya Formation on Hopen.

Sandstone compositions and impacts of diagenesis - Hopen

The sandstones from the Lyngefjellet profile (Fig. 4) are fine to medium-grained with sub-angular to sub-rounded grains (Fig. 10a, c). Petrographic modal analysis verifies a distinct increase in quartz content, from the relatively immature arkosic mineral composition in the three lower units (Units 1, 2 and 3), to the quartz-rich sandstone unit (Unit 4) in the uppermost part of the Svenskøya Formation (Fig. 4, 9a, b).

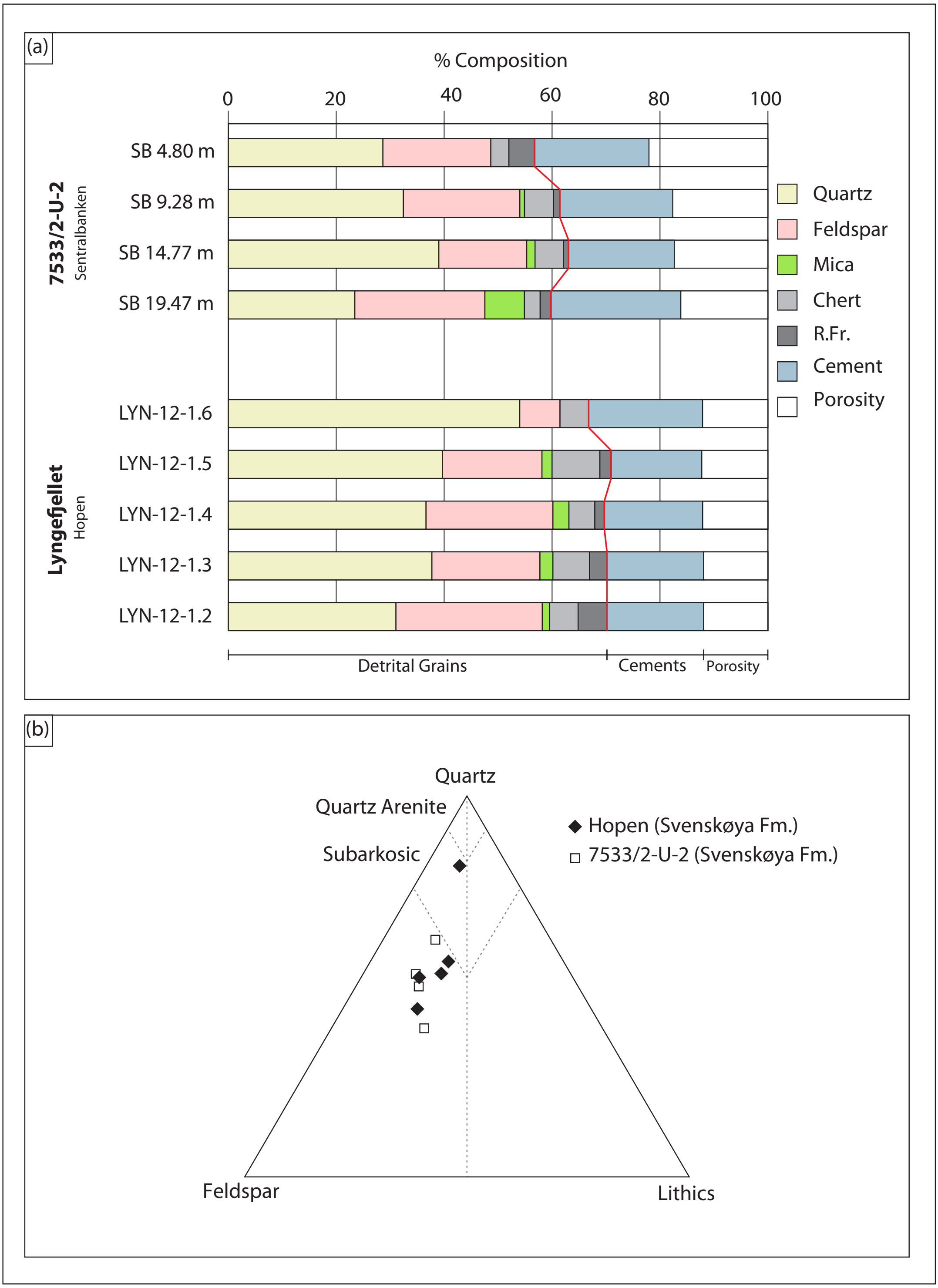


Fig. 9 *(a) Sandstone compositions, by percentage, for samples recovered from the Svenskøya Formation at Lyngefjellet and in well 7533/2-U-2 in Sentralbanken. R.Fr. = Rock Fragments. Diagenetic cements are typically quartz, clay minerals ± carbonate and pyrite (see text). Note higher inter granular volume (cements + porosity) in samples from Sentralbanken compared to Hopen,*

suggesting less compaction has occurred in the Sentralbanken area. (b) Sandstone classification by petrographic modal analysis for samples from Hopen (Lyngefjellet-12-1, Fig. 4) and Sentralbanken.

The detrital grains consist of quartz, feldspar (microcline and plagioclase), minor mica, and rock fragments of chert, and locally also chloritised (e.g. volcanic) rock fragments. Accessory heavy minerals observed are zircon, tourmaline, Cr-spinel, rutile, monazite, and garnet.

Diagenesis resulted in variable degrees of compaction, quartz cementation, precipitation of clay minerals (including abundant pore-filling kaolinite) and dissolution of labile grains. Petrographic data also show evidence of diagenetic replacement of kaolinite by chlorite, and that chlorite is more abundant in the mineralogically immature sandstones. The content of diagenetic quartz cement has been estimated to be ca. 5–14 % by petrographic modal analysis, with highest content in the upper sandstone (Unit 4, Lyngefjellet-12-1.6).

Secondary dissolution porosity occurs as micro-pores within chert and feldspar grains and as occasional oversized dissolution pores (Fig. 10a, d). The point-counted porosity value is ca. 12 % in all samples. These relatively low values are explained by the combination of diagenetic compaction and formation of abundant pore-filling clay-minerals (Fig. 10b). Networks with dissolution pores appear pale blue as shown in Fig. 10a, e, f). Pore filling kaolinite and secondary dissolution porosity in chert grains and feldspar is shown by SEM backscattered electron images of sandstones from Hopen (Fig. 10 b, d). However, when considering also the micro-porosity associated with clay mineral aggregates and altered labile grains, the *total* porosity values would be considerably higher, probably approaching 20 %.

Sandstone compositions and impacts of diagenesis - Sentralbanken

Sandstones of the Svenskøya Formation from Sentralbanken are slightly finer-grained and moderately sorted compared to those from Lyngefjellet on Hopen (Fig. 10e, f). The detrital grain composition consists of quartz, feldspar, mica, and rock fragments of chert and volcanic fragments. The sandstones classify as arkosic, overlapping the compositions from Hopen (Fig. 9a, b). Greenish grains interpreted as partly chloritised glauconite may represent intra-basin grains, supporting the marine depositional environment inferred from palynomorphs (Vigran et al. 2014; Paterson & Mangerud 2015; Paterson et al. 2016). Accessory heavy minerals present include tourmaline, zircon, rutile, Cr-spinel, monazite and garnet which were also detected in the sediments from Hopen.

Diagenesis involved compaction and alteration of ductile grains (e.g. mica), and precipitation of quartz cement and clay minerals. The amount of quartz cement is similar to the arkosic sandstones at Hopen (ca. 5–7 % quartz cement). The authigenic clay minerals appear as pore-filling and grain-replacing kaolinite, illite and chlorite. Carbonate cements include micritic siderite in mud clasts and biotite, and dispersed aggregates of sparitic calcite. The modal porosity values are 17–22 %, suggesting better reservoir quality in the Svenskøya Formation on Sentralbanken than on Hopen (Fig. 9a).

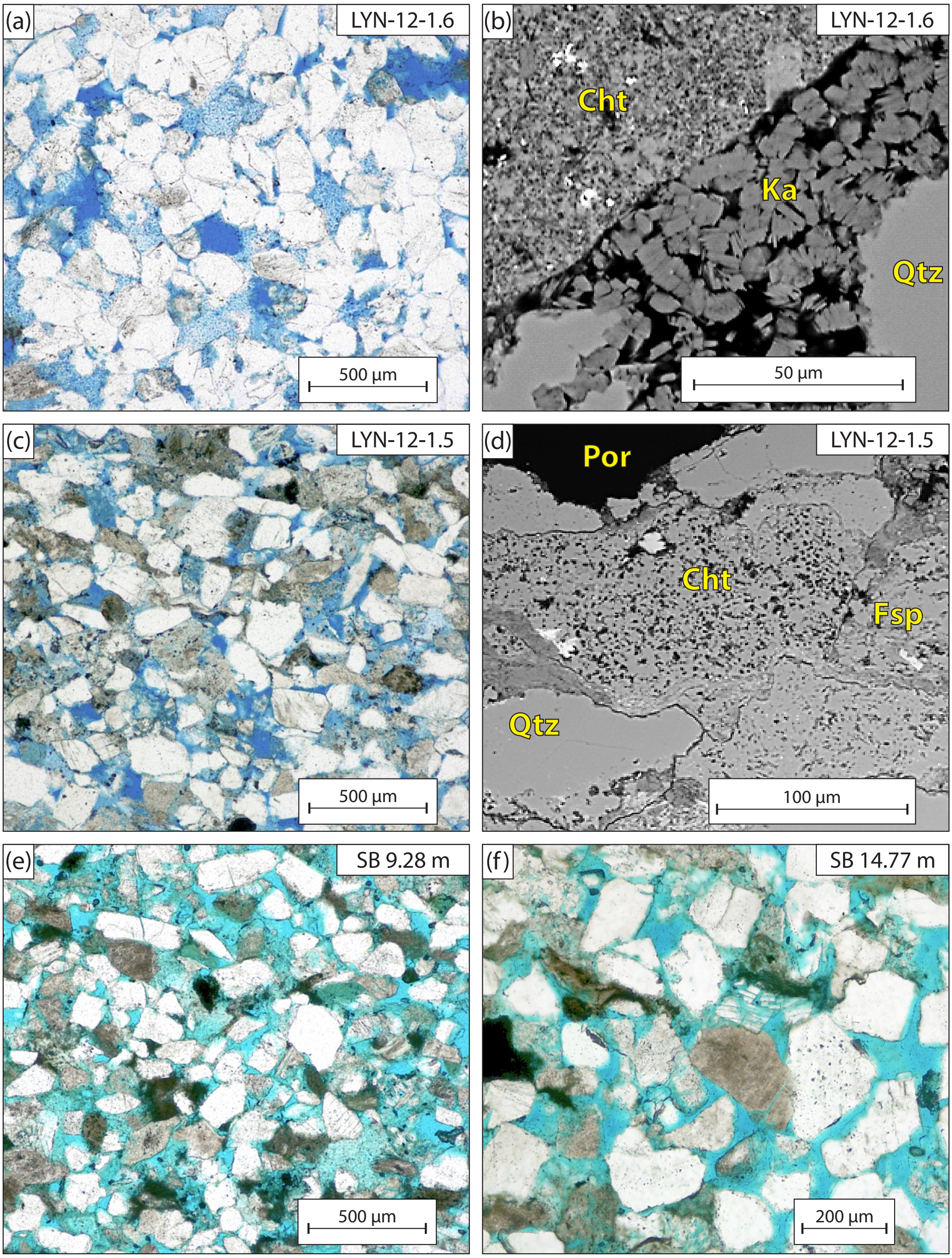


Fig. 10 *(a) Optical plain light micrographs from Lyn-12-1.6 recovered from Hopen, porosity in blue. Showing relatively mature, subarkosic sandstone composition. (b) Backscattered electron micrograph of Lyn-12-1.6, showing pore filling kaolinite and secondary dissolution porosity in chert grains. Porosity in black. (c) Optical plain light micrograph of sample Lyn-12-1.5 recovered from Hopen. Showing immature arkosic sandstone composition, porosity in blue. (d) Backscattered electron*

micrograph of Lyn-12-1.5, showing pore filling Kaolinite and secondary dissolution porosity in chert grains. Porosity in black. (e) Optical plain light micrograph of sample SB 9.28 m from Sentralbanken, porosity in blue. (f) Optical plain light micrograph of sample SB 9.28 m from Sentralbanken, porosity in blue. Porosity =blue, quartz =white, feldspar & lithics = dusty. Abbreviations: Por = Porosity, Qtz = Quartz, Fsp = Feldspar, Cht = Chert, Ka = Kaolinite.

Discussion

Development of the Svenskøya Formation

Overall, the Svenskøya Formation on Hopen represents the deposition of clastic sediment in a regressive shoreline environment. The onset (Unit 1) is marked by an erosive base dominated by small fluvial distributary channels, deposited in a coastal environment that are subsequently overlain by two units (Units 2 and 3), dominated by shoreface deposits. The upper part (Unit 4) suggests a clear change in depositional style from fine-grained clastic sediment to clay and silt, likely in an estuarine environment, with small fluvial channels. The uppermost silt bed most likely represents a change to high-stand system and shallow marine conditions.

The lower part of the Svenskøya Formation on Hopen may represent a sheet-like sandstone braid-plain, formed by small braided channels (Skelly et al. 2003), during rapid deltaic advance and may account for the amalgamated channel architecture seen in the lower part of the Formation. The basal part of the Svenskøya Formation also appears to share some characteristics with the Cretaceous Festningen Sandstone Member in central Spitsbergen (Mørk et al. 1999; Midtkandal et al. 2007). The presence of thin clay beds at the top of Unit 1 could be interpreted as the development of overbank deposits or palaeosols with subaerial exposure occurring (cf. Kraus 1999).

The onset of shoreface facies in Units 2 and 3 likely suggest back-stepping of the shoreline and the onset of an overall transgressive regime during a period of relative sea level rise. This may also however, be a result of avulsion of the fluvial system and autogenic controls occurring on the delta plain (Olariu 2014). The south-eastwards palaeo-current measurements are in contrast to those seen on Wilhelmøya that suggest a northwards or north-westwards direction. On Kong Karls Land, palaeo-current measurements for the lower part of the Svenskøya Formation show a trend to the north-east, whilst overlying beds give palaeo-current directions to the south-east. This suggests that on Hopen the seawards dipping foresets in the shoreface sandstones indicate a migration of the shoreline to the south-east.

The upper part of the Svenskøya formation on Hopen (Unit 4) is still somewhat enigmatic in terms of its origin. We have interpreted the uppermost sandstone beds to have been formed as part of an estuarine complex, with mudstones likely representing tidal influence or variations in fluvial discharge. However, it cannot be ignored that diagnostic tidal signatures have not been observed in this unit, neither has bioturbation. These sandstone beds could alternatively represent submarine channels or slumps based on their discontinuous lenticular geometries. However, no convolute or soft-sediment deformation is observed in the bedding. The internal scours with mud-flake lag also points to a fluvial origin for these sandstone, thus an estuarine setting is preferred.

The very uppermost exposures of Unit 4 on Hopen represent mud and siltstones with thin sandstone and siderite concretions. This part is interpreted to represent a marine unit, suggesting drowning of the deltaic system observed in underlying units.

Regional comparison of sedimentary, petrographic & stratigraphic properties

A simplified correlation of stratigraphic and depositional environments from Wilhelmøya and Kong Karls Land in northern Svalbard, to Hopen and Sentralbanken is presented in Fig. 8. The Svenskøya Formation shows widespread regional correlation in terms of the basal contact. At Hopen, Wilhelmøya and Sentralbanken, fluvial and shoreface deposits dominate the succession. It is impossible to determine the thickness of the formation on Hopen as this is eroded. In Sentralbanken approximately 100 m of the unit is present with only base (7533/2-U-2) and upper part (7533/2-U-3) being cored. On Wilhelmøya the full thickness of the formation is present (ca. 25 m) and is also interpreted as being composed predominantly of shoreface deposits.

A thicker succession is seen on Kong Karls Land (Mørk et al. 1999) to the east of Svalbard and deposits of the formation here are determined to represent tidal flat, tidal channel and coastal plain deposits (Mørk et al. 1999; Larssen et al. unpubl. ms.). The thinning of the unit is also within regional trends for the Upper Triassic succession in Svalbard, where underlying units are seen to reduce in thickness considerably from east to west (Lord et al. in press).

The Wilhelmøya Subgroup becomes condensed in eastern and central Spitsbergen where it is defined as the Knorringfjellet Formation. The lateral change from the Flatsalen, Svenskøya and Kongsøya formations to the Knorringfjellet Formation is not yet well understood, but is thought to be related to variations in basin subsidence and accommodation space (Ryseth 2014; Olaussen et al. 2015).

The palaeogeography for the Svenskøya Formation give the evidence for an east and south-eastwards trend of palaeo-current measurements, with seawards dipping foresets seen in shoreface deposits. The Rhaetian Fruholmen Formation has been regarded to have been sourced from the Novaya Zemlya region (Fleming et al. 2016; Klausen et al. 2016). In wells from the southern Barents Sea, Klausen et al. (2016) relate the influx of mature sandstones in the Fruholmen and Tubåen formations to increased denudation in the southerly source area of Fennoscandia, during the Late Triassic and Early Jurassic (Hendriks & Andriessen 2002).

While this may certainly be the case for southern areas of the Barents Sea, for Svalbard considerations must be made, given the clear thickening of the Rhaetian and early Jurassic units from west to east. The Knorringfjellet Formation in Spitsbergen is a condensed unit of mudstones and sandstones (Nagy & Berge 2008). Thus it may be likely that in the northern areas of the Barents Shelf and Svalbard, a western source area may be dominating at this time (Bue & Andresen 2013).

The Flatsalen Formation represents a major transgression occurring during the mid-Norian, with the Slottet Bed representing a transgressive basal lag deposit (Mørk et al. 1999; Klausen & Mørk 2014). This subaerial unconformity is also widespread throughout Svalbard and can also be found in the Barents Sea (Klausen et al. 2016). The erosive unconformity at the base of the Svenskøya Formation may represent a significant time gap (Rismyhr et al. unpubl. ms.) and marks the onset of a regressive system during the Rhaetian or later in the Jurassic.

The sandstones of the Svenskøya Formation, with a widespread erosive lower boundary throughout the Barents Sea basin may suggests the presence of a relatively high order sequence, likely second or third order as similarly described by Mørk and Smelror (2001) and may be correlative throughout the Arctic (Mørk et a. 1989). It is likely that a period of subaerial exposure occurred prior to the deposition of fluvial channels that form the lower part (Unit 1) of the Svenskøya Formation. Thus an unknown amount of the Flatsalen Formation may have been eroded and it is also highly likely that mud-flakes that form the conglomeratic beds are derived from the Flatsalen Formation. This in turn may also obscure dating by palynology (Niall W. Paterson pers. comm. 2016) giving older ages as accurate palynological dating is biased to finer-grained material with younger spores having poor preservation potential in sandstone.

The similar nature of the boundary between the Flatsalen and Svenskøya formations on Wilhelmøya and in the Sentralbanken area, suggests that the boundary is regionally extensive. In the latest part of the Norian and possibly Rhaetian a regressive system filled what was likely a shallow basin, in the region that is now Svalbard and the northern part of the Barents Sea.

The three lower units of the Svenskøya Formation represent low-stand fill of the basin, with a destructive fluvial and wave dominated delta (based on the presence of extensive fluvial and shoreface deposits), prograding rapidly and incising the underlying formation, forming the major sequence boundary at the base. The upper unit probably represents a tidal ravinement surface with estuarine deposits overlain by a transgressive mudstone. The upper mudstone however is only seen as a few metres at the very top of the Lyngefjellet locality and the extent, or significance of the unit cannot be determined from such limited exposure. It may correlate to a similar interval seen on Wilhelmøya however this should also be regarded as tentative.

The provenance area of these sandstones is not addressed directly here. However, the contrasting palaeo-current measurements and petrography of the Svenskøya Formation on Hopen must be considered as these are very different to the sandstones of the Carnian De Geerdalen Formation. The east and south-eastwards palaeo-current directions measured in the Svenskøya Formation on Hopen are also in contrast to the well documented north-westwards prograding system earlier in the Triassic (Bergan & Knarud 1993; Riis et al. 2008; Glørstad-Clark 2010; Klausen et al. 2014; Anell et al. 2014a b; Lundschien et al. 2014).

Implications for Northern Hydrocarbon Resources

The good reservoir properties of the Fruholmen, Tubåen and Stø formations of the southern Barents Sea suggest that the Rhaetian to Middle Jurassic Realgrunnen Subgroup may potentially be a prolific reservoir rock in the northern areas as well. Previous petroleum systems have been active in the current uplifted Spitsbergen (Abay et al. 2017) and potential Mesozoic source rocks are easily viewed at outcrop level in Svalbard (Mørk & Bjørøy 1984; Lundschien et al. 2014).

The underlying succession from the Ladinian – Norian feature highly organic marine shales at various stratigraphic intervals. The Anisian and Ladinian aged Botneheia Formation has ca. 1–10 % TOC in Svalbard and 3.2–10.3 % TOC offshore Kong Karls Land (Mørk & Bjørøy 1984; Leith et al. 1993; Mørk et al. 1999; Lundschien et al. 2014). The marine shales of the Flatsalen Formation (Mørk et al. 1999; Mørk et al. 2013; Klausen & Mørk 2014; Lord et al. 2014a, b) also contain a moderate organic content. Furthermore, the organic rich shale succession of the Agardhfjellet Formation (Leith et al. 1993) is also present in northern areas. Three viable source rocks are found in the northern Barents Sea area, in close stratigraphic proximity to the sandstones of the De Geerdalen, Svenskøya and Kongsøya formations.

Lundschien et al. (2014) state that the Realgrunnen Subgroup is absent throughout large parts of the northern Barents Sea, mostly due to erosion and where it is present is either thin, or has an incomplete stratigraphy. Onshore in Spitsbergen the Wilhelmøya Subgroup is condensed, forming the Knorringfjellet Formation with a vastly different geological development in comparison to its eastern counterpart (Rismyhr et al. unpubl. ms.). In Svalbard, the Svenskøya Formation is 25 m thick on Wilhelmøya, minimum 35 m thick on Hopen, is 190 m thick on Kong Karls Land and ca. 100 m in the Sentralbanken area of the Barents Sea. The average thickness for the Svenskøya Formation is somewhat comparable to the thickness measurements of equivalent units in the southern areas of the Barents Sea, where the Tubåen Formation is typically 40–50 m (Klausen et al. 2016).

Conclusions

The Svenskøya Formation on Hopen can be regarded as a viable analogue to sandstone reservoirs in the northern Barents Sea area. A compelling stratigraphic correlation, sequence stratigraphic similarity and comparable reservoir properties, provide a good basis for a unit worthy of further and more detailed observations.

The sedimentology of the Svenskøya Formation on Hopen shows a clear succession of fluvial and shoreface dominated deltaic sandstones, prograding in what is deemed to be a south-easterly direction. On Wilhelmøya shoreface deposits are also prevalent in the Svenskøya Formation, with palaeo-currents suggesting a north-easterly direction of migration. The overlying Kongsøya Formation on Wilhelmøya shows a change to shoreface sandstones with marine properties and heavy bioturbation.

On Kong Karls Land, the lower part of the Svenskøya Formation is interpreted as being fluvial and estuarine, with extensive tidal deposits. The lower part of the formation in Kong Karls Land is similar in facies as that seen on Hopen and is thus considered correlative.

In the Sentralbanken area, the Svenskøya Formation is similar in facies that on Hopen, where fluvial and delta front facies dominate. The Stø Formation is similar in facies to the Kongsøya Formation on Wilhelmøya where shoreface facies are also evident. The unit here is expected to be ca. 100 m in thickness, thinner than the unit on Kong Karls Land.

Sandstones from Hopen and Sentralbanken show an overlapping arkosic composition, and also include similar types of lithic grains and accessory heavy minerals and mica. The upper sandstone unit on Hopen (Unit 4) differ by a marked increase in mineralogical maturity, which could reflect changes in depositional environments, re-working of older sediments or rejuvenation of a western source area. The mineral proportions have also been somewhat influenced by diagenetic dissolution of feldspar and labile grains.

Lower reservoir quality in Hopen than Sentralbanken is largely due to differences in diagenesis which caused lower effective porosity at Hopen which evidence more compaction and mineral dissolution combined with extensive precipitation of pore-filling clay minerals.

The potential for hydrocarbons in the Norwegian sector of the northern Barents Self is still promising and whilst resources may be less abundant due to the geological development of the area, suitable petroleum systems are present.

Acknowledgements

We thank the NPD and SINTEF Petroleum AS for organising the many expeditions to the island that have enabled data collection in this remote area of Svalbard. NPD is further thanked for their generosity with access to confidential data that has significantly strengthened this study. Geologists Even Nikolaisen, Turid Haugen (NTNU) and Frode Karlsen (Aker BP) are greatly thanked for their expert help and companionship in the field.

References

Abay T.B., Karlsen D.A., Lerch B., Olaussen S., Pedersen J.H. & Backer-Owe K. 2017. Novel proof of Migrated Petroleum in the Mesozoic strata in Svalbard and detailed Organic Geochemical Characterization-Implications for Regional Exploration. *Journal of Petroleum Geology 40 (1)*, 5–36.

Anell I., Braathen A., Olaussen S. & Osmundsen P.T. 2013. Evidence of faulting contradicts quiescent northern Barents Shelf during the Triassic. *First Break 31*, 67–76. doi: 10.3997/1365-2397.2013017

Anell I.M., Braathen A. & Olaussen S. 2014a. The Triassic – Early Jurassic of the northern Barents Shelf: a regional understanding of the Longyearbyen CO2 reservoir. *Norwegian Journal of Geology*, 94, 83–98.

Anell I.M., Faleide J.I. & Braathen A. 2016. Regional tectono-sedimentary development of the highs and basins of the northwestern Barents Shelf. *Norsk Geologisk Tidsskrift 96 (1)*, 27–41. doi: 10.17850/njg96-1-04

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*, 167–179. doi:10.1016/j.marpetgeo.2014.03.005

Bergan, M. & Knarud, R. 1993. Apparent changes in clastic mineralogy of the Triassic-Jurassic succession, Norwegian Barents Sea: possible implications for palaeodrainage and subsidence. In Vorren T.O., Bergsager E., Dahl-Stamnes Ø.A., Holter E., Johansen B., Lie E. & Lund T.B. (eds.) *Artic Geology and Petroleum Potential*. NPF Special Publication 2. Pp. 481–493.

Bue E.P. & Andresen A. 2013. Constraining depositional models in the Barents Sea region using detrital zircon U-Pb data from Mesozoic sediments in Svalbard. *Geological Society, London, Special Publication 386*, 261–279.

Cant D.J. & Walker R.G. 1978. Fluvial processes in the sandy braided South Saskatchewan River, Canada. *Sedimentology 25*, 625–648.

Dallmann W.K. & Elvevold S. 2015. Chapter 7 – Bedrock Geology. In Dallmann W.K. (ed.): *Geoscience Atlas of Svalbard*. Report Series 148, Norsk Polarinstitutt, Tromsø. Pp. 133–174.

Dallmann W.K., Elvevold S., Majka J. & Piepjohn K. 2015. Chapter 8 – Tectonics and tectonothermal events. In Dallmann W.K. (ed.): *Geoscience Atlas of Svalbard*. Report Series 148, Norsk Polarinstitutt, Tromsø. Pp. 175–224.

Dalrymple R.W. & Choi K. 2007. Morphologic and facies trends through the fluvial-marine transition in tide-dominated depositional systems: A schematic framework for environmental and sequence stratigraphic interpretation. *Earth Science reviews 81*, 135–174.

Dimakis P., Braathen B.I., Faleide J.I., Elverhøi A., & Gudlaugsson S.T. 1998. Cenozoic erosion and the preglacial uplift of the Svalbard-Barents Sea region. *Tectonophysics 300*, 311–327.

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

Embry A.F. 2009. *Practical sequence stratigraphy*. Canadian Society of Petroleum Geologists, 79 pp.

Fichter L.S. & Poche D.J. 2001. *Ancient Environments and the Interpretation of Geologic History, 3rd Edition*. Prentice Hall: Upper Saddle River, NJ. 310p.

Fielding C.R. 2006. Upper flow regime sheets, lenses and scour fills: Extending the range of architectural elements for fluvial sediment bodies. *Sedimentary Geology 190*, 227–240.

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

Flood B., Nagy J. & Winsnes T.S. 1971. The Triassic succession of Barentsøya, Edgeøya and Hopen (Svalbard). *Norsk Polarinstitutt Meddelelser Nr. 100.* 28p.

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*. Graham & Trotman, London. Pp. 1105–1129.

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.

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 Fleet A.J. & Boldy S.A.R., (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Pp. 247–259.

Hampson G.J., Rodriguez A.B., Storms J.E.A., Johnson H.D. & Meyer C.T. 2008. Geomorphology and high-resolution stratigraphy of progradational wave-dominated shoreline deposits: Impact on reservoir scale facies architecture. *SEPM Special Publication 90*, 117–142.

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

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 Publication 196. Pp. 117–137.

Henriksen E., Bjørnseth H. M., Hals K. T., Heide T., Kiryukhina T., Kløvjan O. S., Larssen G. B., Ryseth A. E., Rønning K., Sollid K. & Stoupakova A. 2011. Uplift and erosion of the greater Barents Sea: impact on prospectivity and petroleum systems. *Geological Society, London, Memoirs 2011, 35*, 271–281. doi: 10.1144/M35.17

Høy T. & Lundschien B.A. 2011. Triassic deltaic sequences in the northern Barents Sea. *Geological Society London, Memoirs 2011,* 35, 249–260.

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

Klausen T.G., Müller R., Slama J. & Helland-Hansen W. 2016. Evidence for Late Triassic tectonism in enigmatic provenance areas and Early Jurassic sediment supply turnover in northern Pangea. *Geological Society of America 8 (6)*. doi: 10.1130/L556.1

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

Korĉinskaja M.V. 1980. Rannenoriskaja fauna Arhipelaga Svalbard. (Early Norian fauna of the Svalbard Archipelago.) In D.V. Semevskij (ed.): *Geologija osadnocnogo cehla Arhipelaga Svalbard. (Geology of the platform cover of the Svalbard Archipelago.)* Pp. 30–43. Leningrad: Scientific Research Institute of Arctic Geology (Nauèno-issledovatelskij Institut Geologii Arktiki).

Kraus M.J. 1999. Paleosols in clastic sedimentary rocks: their geologic applications. *Earth-Science Reviews 47*, 41–70.

Kraus M.J. & Aslan A. 1999. Palaeosol sequences in floodplain environments: a hierarchical approach. *Special Publication, International Association of Sedimentologists 27,* 303–321.

Larssen G. B., Olaussen S., Helland-Hansen W, Johannessen E. P., Nøttvedt A., Riis F. Rismyhr B. Smelror M. & Worsley D. unpubl. Ms: Geological evolution of the Kong Karls Land archipelago, High Arctic Norway: a key to the Jurassic and Lower Cretaceous basin development of northern Barents Sea.

Launis A., Pott C.P. & Mørk A. 2014. A glimpse into the Carnian: Late Triassic plant fossils from Hopen, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 129–136.

Leith T.L., Weiss H.M., Mørk A., Århus N., Elvebakk G., Embry A.F. Brooks P.W., Stewart K.R., Pčelina T.M., Bro E.G., Verba M.L., Danyushevskaya A. & Borisov A.V. 1993. Mesozoic hydrocarbon source-rocks of the Arctic region. In Vorren T.O., Bergsager E., Dahl-Stamnes Ø.A., Holter E., Johansen B., Lie E. & Lund T.B. (eds.) *Artic Geology and Petroleum Potential*. NPF Special Publication 2. Pp. 1–25.

Lord G.S., Johansen S.K., Støen S.J. & Mørk A. in press: Facies Development of the Late Triassic De Geerdalen Formation on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard. *Norwegian Journal of Geology*.

Lord G.S., Solvi K.H., Ask M., Mørk A., Hounslow M.W. & Paterson N.W. 2014a. The Hopen Member: A new member of the Triassic De Geerdalen Formation, Svalbard. *Norwegian Petroleum Directorate Bulletin 11*, 81–96.

Lord G.S., Solvi K.H., Klausen T.G. & Mørk A. 2014b. Triassic channel bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution. *Norwegian Petroleum Directorate Bulletin 11*, 41–49.

Lundschien B.A., Høy T. & Mørk A. 2014. Triassic hydrocarbon potential in the Northern Barents Sea: Integrating Svalbard and stratigraphic core data. *Norwegian Petroleum Directorate Bulletin 11*, 3–20.

Midtkandal I., Nystuen J.P. & Nagy J., 2007. Paralic sedimentation on an epicontinental ramp shelf during a full cycle of relative sea-level fluctuation; the Helvetiafjellet Formation in Nordenskiöld land, Spitsbergen. *Norwegian Journal of Geology 87*, 343–359.

Mørk A. & Bjorøy M. 1984. Mesozoic source rocks on Svalbard, In: Spencer A.M. (ed.): *Petroleum Geology of the North European Margin*, Norwegian Petroleum Society, Graham & Trotman, London. Pp. 371–382.

Mørk A., Dallmann W.k., Dypvi, H., Johannessen E.P., Larssen G.B., Nagy J., Nøttvedt A., Olaussen S., Pčelina T.M. & Worsley D. 1999. Mesozoic Lithostratigraphy. In Dallmann W.K., (ed.): *Lithostratigraphic Lexicon of Svalbard, Upper Paleozoic to Quaternary Bedrock – Review and recommendations for nomenclature use*. Norwegian Polar Institute, Tromsø. Pp. 127–214.

Mørk A., Embry A.F. & Weitschat W. 1989. Triassic transgressive-regressive cycles in the Sverdrup Basin, Svalbard and the Barents Sea. In Collinson J.D. (ed.): *Correlation in Hydrocarbon Exploration*. Norwegian Petroleum Society, Graham & Trotman, London, 1989. Pp. 113–130.

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., Lord G.S., Solvi K.H. & Dallmann W.K. 2013. Geological Map of Svalbard 1:100 000, Sheet G14G Hopen. *Norsk Polarinstitutt Temakart* No. 50.

Mørk A. & Smelror M. 2001. Correlation and Non-Correlation of High Order Circum-Arctic Mesozoic Sequences. *Polarforschung 69*, 65–72.

Nasuti A., Ottemöller L., Dallmann W.K., Storheim B.M., Atakan K. & Olesen O. 2015. Chapter 9 – Geophysics. In Dallmann W.K. (ed.): *Geoscience Atlas of Svalbard*. Report Series 148, Norsk Polarinstitutt, Tromsø. Pp. 225–240.

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.

Olariu C. 2014. Autogenic process change in modern deltas. *In* Martinius, A. W., Ravnås, R., Howell, J. A., Steel, R. J. and Wonham, J. P. (eds.): *From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin.* International Association of Sedimentologists Special Publication, 46, pp. 149–166.

Olariu C. & Bhattacharya J.P. 2006. Terminal distributary channels and delta front architecture of river-dominated delta systems. *Journal of Sedimentary research 76 (2)*, 212–233.

Olaussen S., Gloppen T.G., Johannessen E. & Dalland A. 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 Northwest European Margin. Norwegian Petroleum Society, Graham & Trotman, London, 61–80.

Olaussen S., Husteli B., Lord G.S., Rismyhr B., Johannessen E.P. & Mørk A. 2015. The Early Norian transition in Svalbard and the Barents Sea: A record of slowing down of basin subsidence, alteration of facies associations and shift of provenance and climate change. 2nd Boreal Triassic Conference 2015, Svalbard, *Abstract and proceedings Geol. Soc. Norw*. 39–42.

Osmundsen P.T., Braathen A., Rød R.S. & Hynne, I. 2014. Styles of normal faulting and fault controlled deposition in the Triassic of Hopen and Edgeøya, Svalbard. *Norwegian Petroleum Directorate Bulletin 11,* 61–80.

Paterson N.W. & Mangerud G. 2015. Late Triassic (Carnian – Rhaetian) palynology of Hopen, Svalbard. *Review of Paleobotany and Palynology 220*, 98–119.

Paterson N.W., Mangerud G., Cetean C.G., Mørk A., Lord G.S., Klausen T.G. & Mørkved P.T. 2016. A multidisciplinary biofacies characterization of the Late Triassic (late Carnian-Rhaetian) Kapp Toscana Group on Hopen, Arctic Norway. *Paleogeography Paleoclimatology Paleoecology 464*, 16–42.

Pčelina T.M. 1972. K voprosu o vozraste osadočnoj tolšči ostrova Nadeždy (Sval'bard). (On the age of the sedimentary succession of the island of Hopen (Svalbard)). In Sokolov V.N. & Vasilevskaja N.D. (eds.): *Mezozoiskie otloženija Sval'barda (Mesozoic deposits of Svalbard).* NIIGA, Leningrad, 75–8 (in Russian).

Reading H.G. & Collinson J.D. 1996. Chapter 6 - Clastic coasts. In Reading, H. G. (ed.): *Sedimentary environments: processes, facies and stratigraphy, Third edition*. Blackwell Science Oxford, pp. 154–231.

Reineck H.E. & Singh I.B. 1980. *Depositional Sedimentary Environments, Second Edition*, Springer-Verlag, Berlin Heidelberg, 549 pp.

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

Rismyhr B., Bjærke T. & Olaussen S. unpubl. ms: Depositional environments, sequence variability and palynostratigraphy of the uppermost Triassic–Middle Jurassic succession in the northwestern Barents Shelf.

Ryseth A. 2014. Sedimentation at the Jurassic–Triassic boundary, south-west Barents Sea: indication of climate change. 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 46*, 187–214.

Senger K. 2017. Integrated thermo-baric modelling of the hydrate stability zone onshore Svalbard, Arctic Norway, 9th International Conference on Gas Hydrates, 25-30/6/2017, Denver, USA.

Skelly R.L., Bristow C.S. & Ethridge F.G. 2003. Architecture of channel-belt deposits in an aggrading shallow sandbed braided river: the lower Niobrara River, northeast Nebraska. *Sedimentary Geology 158*, 249–270.

Smelror M., Larssen G.B., Olaussen S., Rømuld A. & Williams R. unpubl. ms: Late Triassic to Early Cretaceous palynostratigraphy of Kong Karls Land, Svalbard, Arctic Norway.

Smith D.G. 1974. Late Triassic pollen and spores from the Kapp Toscana Formation, Hopen, Svalbard—a preliminary account. *Review of Palaeobotany and Palynology 17*, 175–178.

Smith D.G., Harland W.B. & Hughes N.F. 1975. Geology of Hopen, Svalbard. *Geological Magazine 112*, 1–23.

Smith D.G., Harland W.B., Hughes N.F. & Pickton C.A.G. 1976. The geology of Kong Karls Land, Svalbard. *Geological Magazine 113 (3),* 193–304.

Solvi K.H. 2013. *Visualize and interpret the geometry, heterogeneity and lateral continuation of channel bodies in the De Geerdalen Formation at Hopen*. Master Thesis, Norwegian University of Science and Technology, 122pp.

Throndsen, T. 1982. Vitrinite reflectance of coals and dispersed organic matter in tertiary deposits in the Advendalen area, Svalbard. *Polar Research*, 77–91.

Tozer E.T. & Parker J.R. 1968. Notes on the Triassic Biostratigraphy of Svalbard. *Geological Magazine 105*, 526–542.

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*. 269p.

Worsley D. 1973. The Wilhelmøya Formation – a new lithostratigraphic unit from the Mesozoic of Eastern Svalbard. *Norsk Polarinstitutt Årbok 1971*, 7–16.

Worsley D. 2008. The post-Caledonian development of Svalbard and the Western Barents Sea. *Polar Research 27*, 318–338.

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*, 42–65.

Paper 6

Sequence patterns in the Triassic Succession of Svalbard and the northern Barents Sea.

Gareth S. Lord, Atle Mørk & Tore Høy

Manuscript in prep.

This paper is not yet published and is therefore not included.

Part IV

Conference abstracts and other contributions related to this study

Conference Contributions

The Svenskøya Formation on Hopen, An accessible analogue to sandstone reservoirs in the Realgrunnen Subgroup

Gareth S. Lord, Mai Britt E. Mørk, Atle Mørk & Snorre Olaussen

Presentation and poster, at the NGF Onshore-Offshore Conference in Trondheim, October 2016 and the NGF Winter-meeting in Oslo in January 2017.

Abstract

The island of Hopen is situated in the far south-eastern corner of the Svalbard archipelago, at approximately N76° 35" E25° 20, Wilhelmøya is situated some 300 km further north. The geology of these islands is, or should at least be considered, as highly relevant for geologists conducting hydrocarbon exploration in the Barents Sea.

The islands are composed entirely of Mesozoic strata spanning the Triassic late Carnian to Rhaetian on Hopen and Carnian – Middle Jurassic on Wilhelmøya. In this study, the sedimentology and reservoir characteristics of the Rhaetian Svenskøya Formation is addressed in detail, as this unit can be considered correlative to the Tubåen Formation of the Barents Sea Realgrunnen Subgroup. The Kongsøya Formation is presented however good exposures of the formation are only present on Wilhelmøya and the currently inaccessible Kong Karls Land.

The stratigraphy of Hopen and Wilhelmøya is dominated entirely by Late Triassic rocks of the De Geerdalen, Flatsalen and Svenskøya Formations. The Svenskøya Formation is a prominent cliff-forming white and grey sandstone and is determined to be Rhaetian in age. The Svenskøya Formation represents a fluvial dominated delta front succession. Medium grained sandstones with large scale trough and planar cross stratification dominate the section. The upper part shows a clear change to sediments with a more marine origin, where siltstone and mud flake conglomerates dominate. The uppermost part may also represent a formation boundary, however this requires some debate.

The correlation to the Barents Sea is uncanny; the Svenskøya Formation represents the onshore equivalent of the Tubåen Formation whilst the Kongsøya Formation of Svalbard is likely the equivalent to the Stø Formation. The Nordmela Formation is thought to not present in Svalbard or in the Sentralbanken area. The potential discrepancies in age and the east to south-east oriented palaeo-current directions may have notable implications for the palaeogeography for the Late Triassic – Mid Jurassic in the northern areas.

Hopen can be well regarded as an onshore analogue to the Late Triassic in the Barents Sea. The Svenskøya Formation sandstones from Hopen have received little detailed attention in recent publications documenting the islands geology. However, given the recent discoveries of viable hydrocarbon resources in the Realgrunnen Subgroup sandstones in the Hoop area, the relatively accessible outcrops should be regarded by those conducting exploration activities in the northern license blocks of the Barents Sea.

Facies development of the Late Triassic De Geerdalen Formation on Barentsøya, Wilhelmøya and NE Spitsbergen, Svalbard

Gareth Steven Lord, Sondre Krogh Johansen, Simen Jenvin Støen & Atle Mørk

Presentation and poster presented by Sondre K. Johansen, at the NGU Onshore-Offshore Conference in Trondheim, October 2016.

Abstract

We present field data collected during the summer field season of 2015 from the north-easternmost Triassic exposures of Spitsbergen, Wilhelmøya and Barentsøya. Sedimentological analysis has been conducted in order to understand the development of Late Triassic sediments deposited in a deltaic environment. We build upon previously completed studies from the eastern areas of the Svalbard archipelago and seek to extend this understanding northward.

Deltaic sediments are recognised throughout the field area, facies analysis and the application of a depositional environment model show that the Late Triassic De Geerdalen Formation is essentially composed of three discrete intervals. The lower interval (early Carnian) is dominated by shallow marine and delta front/ shoreface facies, the middle (middle Carnian) is dominated by delta front to delta top deposits, with the upper section (late Carnian – early Norian) of the De Geerdalen Formation and Isfjorden Member being predominantly delta top sediments, consisting of a lagoon, lacustrine and palaeosol deposits.

These observations show that the De Geerdalen Formation represents a distal depositional setting in comparison to the depositional environments observed on the islands of Edgeøya and Hopen by previous studies. Correlation becomes complex to these areas due to erosion and a thinner De Geerdalen Formation being present in the visited areas, in comparison to other eastern islands.

The paralic Triassic of Edgeøya.

Jonas Enga, Trond Harstad, Gareth S. Lord & Atle Mørk

Poster presented at the NGF Winter Meeting 2015 in Stavanger during October 2015.

Abstract

The Late-Triassic De Geerdalen Formation of Svalbard has been extensively studied on Spitsbergen and Hopen. The formation represents large scale deltaic sedimentation of clastic material derived from the Uralian mountain chain, into a shallow epi-continental shelf environment throughout the latter part of the Triassic. The proximal paralic nature of the Formation is well-defined on the island of Hopen in the SE of the Svalbard Archipelago. Its distal nature is well documented in central Spitsbergen, representing a more tidally dominated environment.

We argue for the extension of the definition of the De Geerdalen Formation as a paralic environment to Edgeøya. Contemporary and lateral sedimentological studies have suggested that the nature of the De Geerdalen Formation in these areas is still representative of a paralic environment. Terrestrial depositional processes are observed in addition to numerous palaeosol horizons and coal beds. Minor packages of marine influenced sedimentation are also seen to be present and are interpreted as representing marine incursions onto the delta front, representative of tidal and storm influenced environmental processes.

Late Triassic depositional systems of eastern Svalbard

Gareth Steven Lord, Sondre Krogh Johansen, Simen Jenvin Støen & Atle Mørk

Presentation at the AAPG 3P Arctic Conference, in Stavanger, October 2015 and at the Boreal Triassic II Conference in Longyearbyen, September 2015.

Abstract

Recent studies have provided an insight into the depositional systems within the Triassic succession of Svalbard and the Northern Barents Sea. We focus on the interpretation of recent offshore data from the eastern Svalbard region in the unopened area of the Barents Sea. Comparing this dataset with extensive onshore studies in Eastern Svalbard allows for a better understanding of the semi-regional development of the pro-deltaic to deltaic depositional environment.

The depositional styles of Hopen, Edgeøya and Eastern Spitsbergen are characterised by paralic deposits, with a diminishing fluvial influence to the north-west, in concordance with the accepted direction of deltaic progradation. Offshore, this is confirmed by a series of well pronounced clinoforms seen in seismic, from Induan to Carnian age, prograding to the north-west in the Northern Barents Sea. Clinoforms are not visible onshore as they extend over long distances on a shallow slope. Facies studies and biostratigraphic dating have allowed for the observation of sequences within the Triassic succession onshore, which can be related to clinoform geometries in the local offshore zone where such geometries can be observed.

Facies distributions in the eastern islands of Svalbard reveal that on Hopen the Upper Triassic is dominated by paralic deposits, with intervals of distinct channel sandstones. On Edgeøya the lower part of the Upper Triassic is present and similarly paralic in nature, with a greater presence of floodplain and delta top deposits that are situated conformably above a series of well-developed pro-deltaic growth faults. Contrary to this, a thinner succession of the Upper Triassic is present in Spitsbergen which is dominated by delta front and tidal deposits. In the Kong Karl Platform to the south-east of Svalbard, the Lower and Middle Triassic are seen to be much thicker and thin towards Svalbard. The onshore stratigraphic relationships show that Edgeøya and Spitsbergen represent the same part of the system, whilst Hopen represents the youngest deposits and are eroded from Edgeøya.

Although clinoforms cannot be seen in the field in Svalbard, the variations in facies and thinning of the stratigraphy, suggest a depositional style that can be considered comparable in scale and analogous to the system seen in the northernmost Barents Sea.

The Geology of Hopen, Svalbard: Sheet G14G

Gareth S. Lord, Atle Mørk, Winfried K. Dallmann & Kristoffer H. Solvi,

Presentation at the AAPG 3P Arctic Conference in Stavanger, October 2015.

Abstract

The island of Hopen is a unique bastion of Triassic strata situated in the south-eastern corner of the Svalbard archipelago. Whilst its existence has long been known by whalers, the island has only seen significant scientific expeditions during the last half century. Initially, by the Cambridge Arctic Shelf Programme and Norwegian reconnaissance studies, throughout the 70's and 80 are followed by more decisive expeditions by Norwegian institutions and companies since 1996. Whilst preliminary versions existed, no official geological map of the island had been produced.

Following intensive investigation and lateral correlation of stratigraphical units the importance of the islands geology has only recently become apparent, moreover due to the advancement of hydrocarbon exploration into the Northern Barents Sea. In 2013 a 3D geological model of the island was produced and this allowed for a far greater understanding of the geology. The result was a new 1:100,000 scale geological map 'Sheet G14G Hopen,' published in 2013 as part of the Norwegian Polar Institutes Temakart map series of Svalbard.

The island exposes a paralic succession of the Upper-Triassic De Geerdalen Formation, the equivalent unit to the Barents Sea Snadd Formation. Within these strata lie a series of extensive channel sandstones, sequestered within a highly heterolithic package, just alike those of the Snadd Formation.

The steep cliffs of Hopen allow geologists a unique and inexpensive opportunity to look into the Triassic strata of the Barents Sea. Cliff sections allow for a good understanding of the development and reservoir properties of the numerous sandstone channel bodies seen on the island, which are analogous to those seen in the Barents Sea Snadd Formation.

In addition to the new map, a new member unit, the Hopen Member in the uppermost part of the De Geerdalen Formation has been identified. With the application of its stratigraphic position, sedimentological nature and through the implementation of palynology and magnetostratigraphy, it is determined to be an equivalent unit to that of the Isfjorden Member of Central and Eastern Spitsbergen, representing the same flooding event.

The Norian transition in Svalbard and the Barents Sea: A record of slowing down of basin subsidence, shift of provenance and climate change

Snorre Olaussen, Berit Husteli, Gareth S. Lord, Bjarte Rismyhr, Erik P. Johannessen & Atle Mørk

Presentation by Snorre Olaussen, at the AAPG 3P Arctic Conference in Stavanger, October 2015.

Extended Abstract

One of the major purposes of the joint RCN (Petromaks2), industry and academia supported Triassic North Project is to integrate onshore and offshore datasets to improve the understanding of basin fill in relation to tectonic activity. Specifically one of the aims is to improve the facies trends within a tectonostratigraphic and sequence stratigraphic framework.

The Upper Triassic Basin Fill

The Latest Permian to Carnian succession in the Greater Barents Sea consists mainly of repeated packages of north-westward prograding clinoforms, separated by thin, transgressive successions (Glørstad-Clark et al., 2010, 2011; Høy and Lundschien, 2011). This foreland and broad sag/epicontinental basin fill is mainly sourced by the Uralide mountain chain in the east and southeast (Riis et al., 2008). Similar to the North Sea and Norwegian Sea basins, the Greater Barents Sea and Svalbard region experienced high overall sedimentation rates in the Early Triassic to Carnian. In the southeast Barents Sea the succession is 8000 m thick which gradually thins to less than 1000 m in east Svalbard (Anell et al., 2014).

East and west of the Barents Sea platform the Norian to Bathonian succession may reach up to 1000 m in deep basins, e.g. well 7219/9-1, but thins or are absent on platforms and highs and is for example only 25-40 m thick in Spitsbergen (Mørk et al., 1999). The subsidence rates decreased across the Triassic to Jurassic boundary in the south-west Barents Sea (Ryseth, 2014). This slowing down in subsidence which caused an upward decrease in accommodation space is probably initiated in the latest Carnian/Early Norian. Gradual lack of accommodation space may explain the highly variable facies belts with distinct changes within the upper part of the De Geerdalen Formation, represented by the Early Norian Isfjorden Member on Spitsbergen and the Hopen Member on Hopen.

The complex and variable facies associations cannot be easily interpreted as a retro-gradational top-set capping a clinothem, but rather as a precursor to the highly condensed and eroded overlying Norian to Bathonian succession in Spitsbergen; the Wilhelmøya Subgroup.

The Early Norian shift

The variable facies association within the Isfjorden Member is well documented by Pčelina (1972, 1983). This study is consistent with her conclusions in Deltaneset and Agardhbukta, Spitsbergen (Figs. 1, 2 and 3). Here we have recorded; 1) multiple thin red beds with calcrete soil profiles, 2) very thin coal beds 3) 2-3 m thick fluvial meandering channels , 4) minor mouth bars or crevasses, 5) open marine offshore mudstone to lower shoreface to foreshore deposits, 6) tidal channels, flats and bars,7) bay or lagoonal deposits, 8) algal mats (i.e. flat laminated limestones; stromatolites) and sandy and glauconitic grainstones/wackestones and coquinas with crinoids, mussels, gastropods, ammonoids.

Similar facies are also recorded from the Upper Carnian/Lower Norian cored strata in the basin margins in the South Barents Sea.

The correlative Hopen Member (Mørk et al., 2013; Lord et al., 2014a, 2014b) is a similarly thick succession consisting of fine grained heterolithic packages, showing a gentle upwards coarsening trend from siltstones to thin hummocky cross stratified fine sands. Bioturbation is abundant but within finer grained facies. Slightly thicker sandstone beds are common with planar cross stratification and hummocks. The Hopen Member does not display the continental facies observed in the Isfjorden Member on Spitsbergen. No calcrete beds, red/green beds are observed and all channel features are constrained to the remainder of the De Geerdalen Formation underlying the Hopen Member (Lord et al., 2014a). The primary constraint for the base of the member is the notable transition from paralic deltaic facies to marine facies and tempestite storm sands with the absence of fossilized plant roots and coal beds. The member is interpreted as representing either an inter delta lobe bay or large inter-distributary bay. Hopen Member is absent from Edgeøya and Barentsøya, being eroded. However, may occur on the island of Wilhelmøya and in northern areas of Storfjorden.

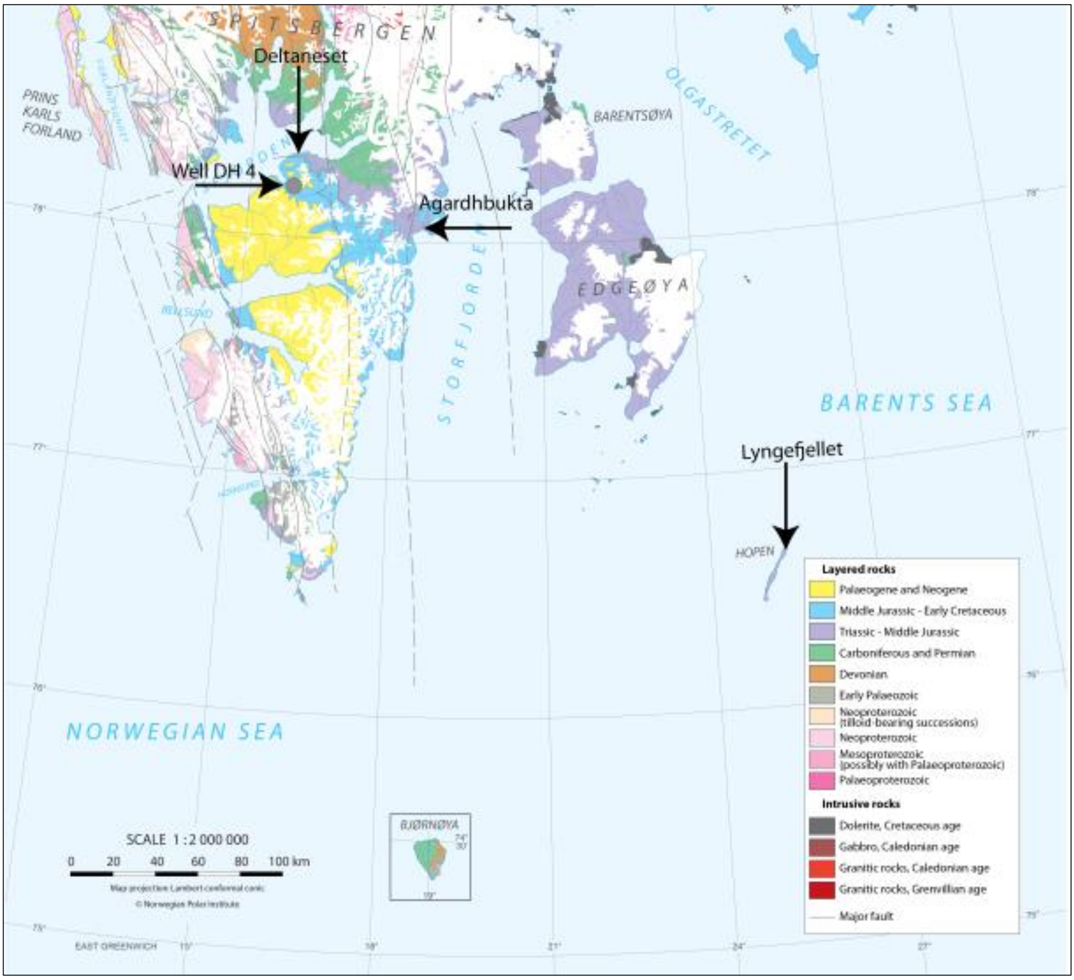


Figure 1: *Location map of the three outcrops and the well location discussed in the text. Geological map from Norsk Polarinstitutt.*

Correlation of the Hopen Member to the Isfjorden Member by Lord et al. (2014a) was conducted by implementing palynology, magnetostratigraphy and ammonoid biostratigraphy. Palynology shows the Isfjorden Member is spore dominated whilst the Hopen Member is more pollen rich. Two zones have been identified in the De Geerdalen Formation on Hopen, a lower *Leschikisporis* Acme Zone and an upper *Protodiploxypinus spp*. Acme Zone. Marine palynomorphs (e.g. acritarchs) are also more abundant in the Hopen Member. The transition between the two Acme Zones correlates closely with the Base of the Hopen Member. Magnetostratigraphic studies was conducted on Hopen and correlated to the Isfjorden Member seen at Dalsnuten in central Spitsbergen. Close matches in correlative, reverse and normal polarities are seen in the lower parts of both member units. Ammonoid biostratigraphic correlation based on the presence of sirenitid ammonoids in the overlying Flatsalen Formation determined the Hopen Member to be earliest Norian in age and most likely older (Carnian).

The overlying Wilhelmøya Subgroup in Svalbard shows a much more (although eroded and condensed) homogenous facies trend within a broad tidal influenced shallow marine, tidal to paralic siliciclastic depositional environment (Fig. 2). Fluvial, deltaic, estuarine, tidal flat and coastal plain with coals bed, and shoreline to inner shelf environment are recognized in the onshore Wilhelmøya Subgroup and the offshore counterpart; the Realgrunnen Subgroup (Fig. 2).

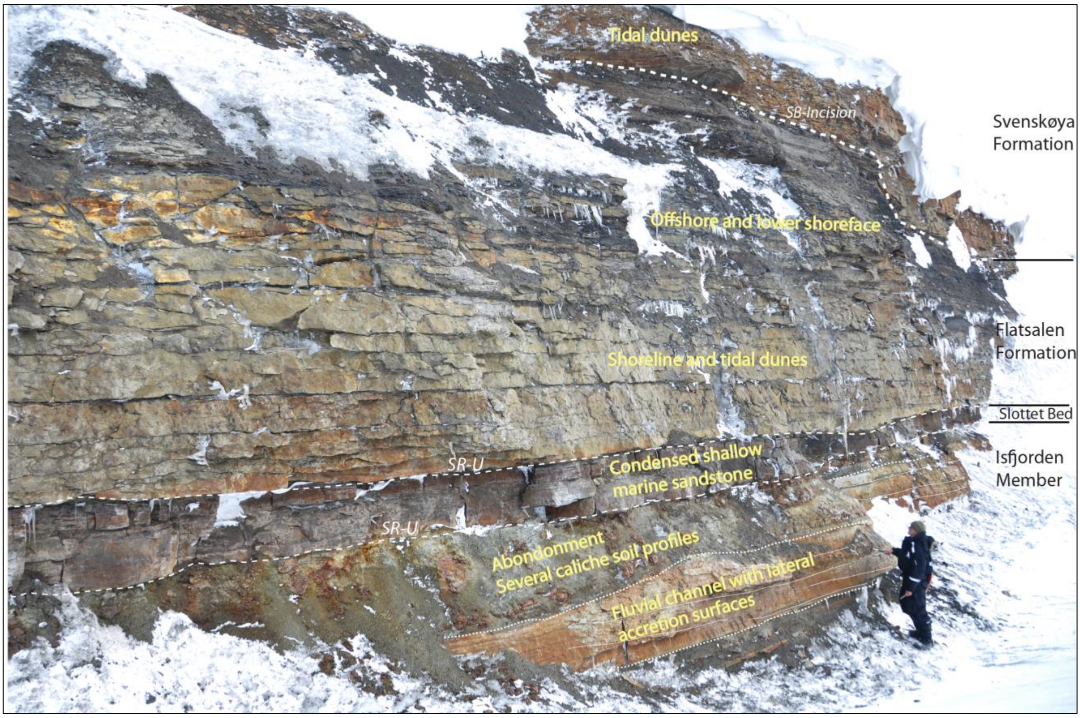


Figure 2: *The boundary between the Isfjorden Member and the overlying Flatsalen Formation. East coast of Spitsbergen.*

The transition from red beds with calcrete soil profiles to the coastal plain with coals bed in the overlying Realgrunnen Subgroup suggests that the Barents Sea as in the UK, North Sea, Norwegian Sea and East Greenland experienced a change in climate from more arid/semi-arid to more humid near the Triassic Jurassic boundary (c.f. Hallam, 1985; Nereo et al., 2010). However small-scale differences do exist, probably due to some local area conditions which still experienced a dryer climate in the Rhaetian to Early Jurassic. The change to a more widespread humid climate may be caused by major transgressive events in the Early Jurassic (e.g. Frostick et al., 1992; Ahlberg et al., 2002).

Mineralogy and grain size of the sandstones change from very fine to fine grained and mineralogically immature and (i.e. micaceous arkosic arenites) in the Isfjorden Member, to very fine to coarse grained mature (i.e. quartz arenites) of the overlying Wilhelmøya Subgroup in Svalbard. This petrographic transition is very sharp in Svalbard (Mørk, 2013) but also, with a few exceptions detected in wide areas of the Barents Sea (Mørk, 1999). This shift in sandstone composition cannot only be explained by change in climate from semi-arid to humid climate. The overall change in grain size which also includes gravels and quartz conglomerates points to a prominent change in provenance. Recent zircon studies are consistent with a change in provenance (Bue & Andresen, 2013). We speculate that the Norian to Bathonian basin fill in Svalbard and North Barents Sea has it drainage area in north, while the southern Barents Sea might also be sourced from Fennoscandia.

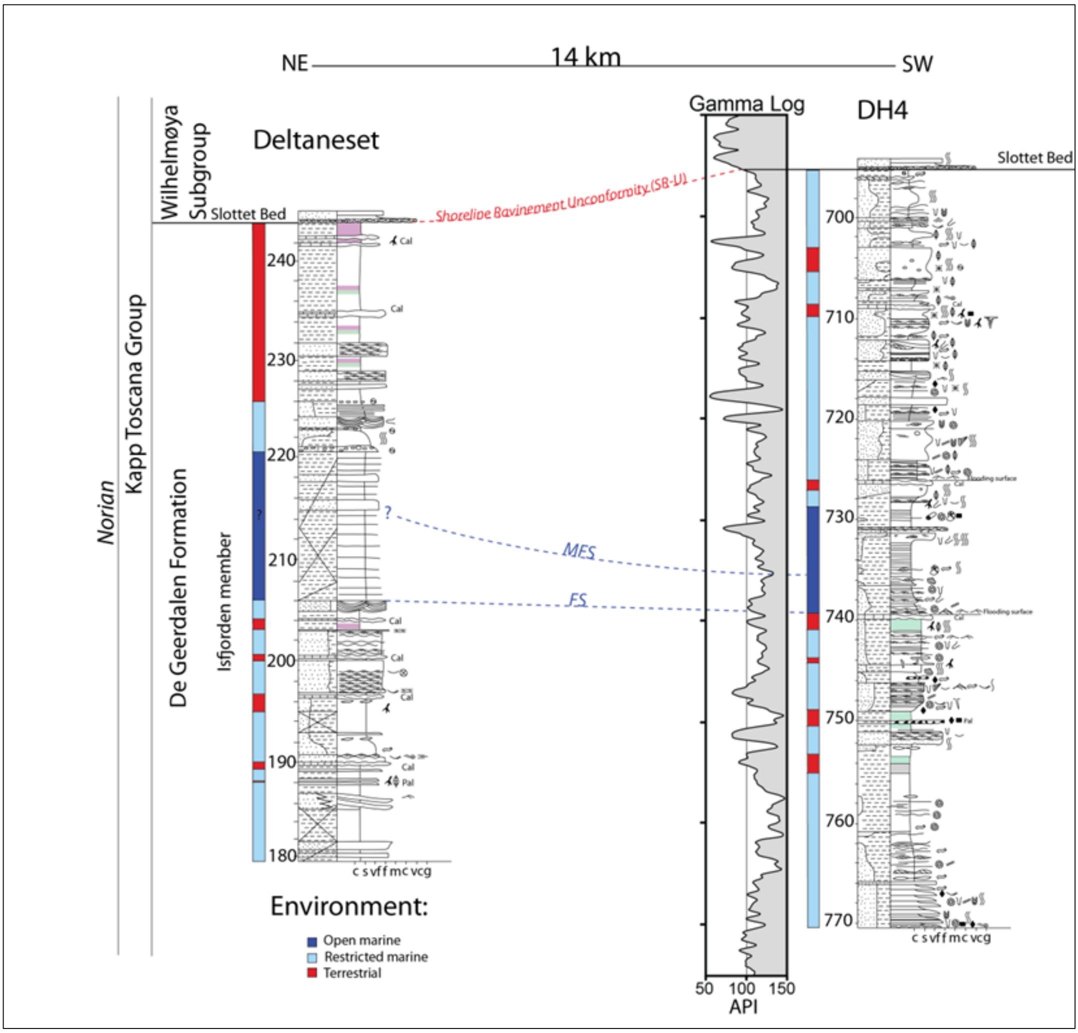


Figure 3: Sedimentological and stratigraphic log of the penetrated and outcropping Isfjorden Member in Adventdalen and Deltaneset, respectively. Reddish and green colours mark soil profiles. See map for location. From Husteli et al in prep.

Conclusions

The Latest Carnian to Early Norian gradual diminishing in available accommodation space, shift in provenance and climate change have important effect of facies development and the prediction of potential prolific reservoir sandstones in the Northern Barents Sea, probably a valid interpretation throughout the Greater Barents Sea area.

References

Ahlberg, A., Arndorrf, L. & Guy-Ohlson, D. 2002: Onshore climatic change during the Late Triassic marine inundation of the Central European Basin. *Terra Nova, 14*, 241–248.

Anell, I. M., Braathen, A., & Olaussen, S. 2014: The Triassic – Early Jurassic of the northern Barents Shelf: a regional understanding of the Longyearbyen CO2 reservoir. *Norsk Geologisk Tidsskrift, 94*, 83–98.

Bue, E. P., & Andresen, A. 2013: Constraining depositional models in the Barents Sea region using detrital zircon U-Pb data from Mesozoic sediments in Svalbard. Geological Society, London, Special Publications. In Scott, R. A., Smyth, H. R., Morton, A. C. & Richardson, N. (eds) *Sediment Provenance Studies in Hydrocarbon Exploration and Production. Geological Society*, London, Special Publications, 386.

Frostick, L., Linsey, T.K. & Read, I. 1992: Tectonic and climatic control of Triassic sedimentation in the Beryl Basin, northern North Sea. *Journal Geological Society London,* 149, 13–26.

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.

Hallam, A. 1985: A review of Mesozoic climates. *Journal Geological Society London*, 142, 433–44.

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.

Lord, G.S. Solvi, K.H., Ask, M., Mørk, A., Hounslow, M.W. & Paterson, N.W. 2014a: The Hopen Member: A new lithostratigraphic unit on Hopen and equivalent to the Isfjorden Member of Spitsbergen. *Norwegian Petroleum Directorate Bulletin,* 11, 81–96.

Lord, G.S., Solvi, K.H., Klausen, T.G. & Mørk, A. 2014b: Triassic channel bodies on Hopen, Svalbard: Their facies, stratigraphical significance and spatial distribution. *Norwegian Petroleum Directorate Bulletin,* 11, 41–59.

Mørk A., Dallmann W.K., Dypvik H., Johannessen P., Larssen G.B., Nagy J., Nøttvedt A., Olaussen S., Pcˇelina T.M. & Worsley D. 1999: Mesozoic lithostratigraphy. In W.K. Dallmann (ed.): *Lithostratigraphic lexicon of Svalbard. Upper Palaeozoic to Quaternary bedrock. Review and recommendations for nomenclature use. Norwegian Polar Institute*. 127–214.

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-permeability Upper Triassic–Middle Jurassic reservoir sandstones, Longyearbyen CO2 lab well site in Svalbard, Norway. *AAPG Bulletin*, v. 97, 577–596.

Pčelina, T.M. 1972: K voprosu o vozraste osadočnoj tolšči ostrova Nadeždy (Sval'bard). (On the age of the sedimentary succession of the island of Hopen (Svalbard)). In V.N. Sokolov & N.D. Vasilevskaja (eds.): Mezozoiskie otloženija Sval'barda (Mesozoic deposits of Svalbard), NIIGA, Leningrad, 75-81. (In Russian).

Pčelina, T.M. 1983: Novye dannye po stratigrafii mezozoja arhipelaga Špicbergen (New data on the Mesozoic stratigraphy of the Spitsbergen Archipelago). In Krasil'ščikov, A.A. & Basov, V.A. (eds.): Geologija Špicbergena (The Geology of Spitsbergen). PGO Sevmorgeologija", Leningrad, 121–141. (In Russian).

Nereo P, Kustatscher, E. & Wignall, P.E. 2010: Triassic climates — State of the art and perspectives. *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 290, 1–10.

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.

Ryseth, A. 2014: Sedimentation at the Jurassic-Triassic boundary, south-west Barents Sea: indication of climate change. *Int. Assoc. Sedimentol. Spec. Publ*. (2014) 46, 187–214.

Triassic channel bodies on Hopen

Gareth S. Lord, Kristoffer H. Solvi, Tore G. Klausen & Atle Mørk

Presentation at the Triassic and Jurassic reservoir development in the Barents Sea Seminar in Stavanger, June 2015 and at the AAPG 3P Conference in Stavanger, October 2014.

Abstract

Channelized deposits are observed in the steep cliff sections on the island of Hopen in SE Svalbard. This presents a unique opportunity to study the geometry and spatial distribution of these channel bodies within the paralic depositional environment of the Carnian aged De Geerdalen Formation. In this study we have combined field observations with a 3D geological model of the island.

Utilising PhotoModeler™ software, with an extensive photo database of the study area, it has been possible to identify the presence of 25 channel bodies on the island. 12 have been observed directly in the field, with the remainder being identified with photo mosaics and by implementing the 3D geological model. Analysis has shown that the channels were deposited in three different depositional environments; fluvial, tidal and estuarine. Channel deposits that have not been observed in the field are interpreted based on their geometries and visible internal architectures seen within high resolution outcrop photographs.

Channel bodies are seen to be confined to discrete stratigraphical intervals within the De Geerdalen Formation, defined as channel zones. Three zones are described, based upon the concentration of channels within each interval. These intervals are categorised as a lower fluvial zone, a middle tidal zone and an upper fluvial zone.

These zones are subsequently overlain by a marine flooding event represented by the Hopen Member. An overall paralic depositional environment for the De Geerdalen Formation on Hopen is maintained, however the nature of channels clearly shows a greater influence of fluvial deposition for the formation in this region of Svalbard. This indicates deposition in a more proximal position relative to the source area, than elsewhere on Svalbard.

The geology of Hopen

Gareth S. Lord

Presentation at the AAPG 3P Conference in Stavanger, October 2014 and as a poster and presentation at the NGU Ungeo Conference in Trondheim, February 2013.

Abstract

The island of Hopen is a unique bastion of Triassic strata situated in the south-easternmost corner of the Svalbard archipelago. Whilst its existence has been long known by whalers, the island has only in the last 50 years seen significant scientific expeditions. Initially by the Cambridge Arctic Shelf Programme, throughout the 70's and 80's followed by more decisive expeditions by Norwegian institutions and companies since 1996. No official geological map of the island has been presented until now and following intensive investigation the importance of the islands geology has only recently become apparent, moreover due to the advancement of hydrocarbon exploration into the Northern Barents Sea.

The island exposes the most proximal deltaic strata of the Upper-Triassic De Geerdalen Formation, the equivalent unit to the Barents Sea Snadd Formation. Within these strata lie a series of extensive channel sandstones, sequestered within a highly heterolithic package, just alike those of the Snadd Formation. This allows geologists a unique and inexpensive opportunity to look into the Triassic strata of the Barents Sea; gain an insight into the reservoir properties of these channel bodies and understand the reality of their nature and extent. In addition to the new map, a new member unit, the Hopen Member in the uppermost of the De Geerdalen Formation has been identified. With the application of its stratigraphic position, sedimentological nature and through the implementation of palynology and magnetostratigraphy, it is determined to be an equivalent unit to that of the Isfjorden Member of Central and Eastern Spitsbergen, representing the same flooding event.

Industrial Reports

Late Triassic: Geology and facies development of northern Storfjorden and Wilhelmøya, Svalbard: Fieldwork results from 2015

Gareth S. Lord & Atle Mørk

With contributions from: Simen J. Støen, Sondre K. Johansen & Turid Haugen

Internal Report No.7020809/01/16 SINTEF Petroleum AS, 2016.

Abstract

In this study we present field data recorded during a four week period throughout the summer field season of 2015. The study area includes the easternmost Triassic exposures of Spitsbergen, Wilhelmøya and Barentsøya. Sedimentological analysis has been conducted in order to understand the development of Late Triassic sediments deposited in a deltaic environment. We build upon previously completed studies from the eastern areas of the Svalbard archipelago and seek to extend this understanding northward.

Deltaic sediments are recognised in this study throughout the field area, facies analysis and the application of a depositional environment model shows that the Late Triassic De Geerdalen Formation is essentially composed of three discrete stratigraphic intervals that are defined by the facies within. The lowest interval is dominated by shallow marine and delta front/ shoreface facies, the middle is dominated by delta front to delta top deposits, with the upper section (the Isfjorden Member) being predominantly delta top sediments consisting of a lagoon, lacustrine and palaeosol deposits.

These observations are in line with those from the island of Edgeøya, whilst discrepancies in the thickness of the De Geerdalen Formation and quaternary erosion make correlation to the island of Hopen more complex.

New geological map of Hopen

Atle Mørk, Gareth S. Lord, Krostoffer H. Solvi & Winfried K. Dallmann

Internal Report No.7020155/01/13 SINTEF Petroleum AS, 2013.

Abstract

The present report is a preprint of a new thematic map that will be printed by the Norwegian Polar Institute and distributed in 2014. Most of the fieldwork was done under the Hopen Geology project financed by the petroleum licenses listed above as well as the Norwegian Petroleum Directorate.

During the Hopen project we have had the opportunity to improve the geological map of Hopen. Winfried K. Dallmann of the Norwegian Polar Institute (NPI) participated in the 2009 Hopen expedition, by the Norwegian Petroleum Directorate (NPD) and conducted the basic studies for the creation of a new map. Throughout the "Hopen Geology Project" we have mapped faults and measured many new sections. We have also redrawn some sections from the 1995 Norsk Letesamarbeid, Hopen expedition (NPD, Statoil, Norsk Hydro, Saga Petroleum and the first author from SINTEF Petroleum Research). The recognition of the Hopen Member permitted us to also localise the contact between the De Geerdalen Formation and the Flatsalen Formation in wider areas.

The Hopen Member: A new lithostratigraphic unit on Hopen and equivalent to the Isfjorden Member of Spitsbergen

Gareth S. Lord, Kristoffer H. Solvi, Marianne Ask, Atle Mørk, Mark W. Hounslow & Niall W. Paterson

Internal Report No. 7020155/02/13 SINTEF Petroleum AS, 2013.

Abstract

A new stratigraphic unit, the Hopen Member, is recognized and defined on the island of Hopen in the south-easternmost corner of the Svalbard archipelago. The dark coloured Hopen Member is easily recognized in the mountain sides of Hopen where it forms the upper ~70 m of the De Geerdalen Formation.

The unit represents an extensive, ~70 m thick succession of marine influenced sandstone and shales resting atop paralic and non-marine packages of the De Geerdalen Formation. Magnetostratigraphy and palynology indicate an age of at latest Carnian earliest Norian for the member.

The Hopen Member correlates well to the Isfjorden Member of central Spitsbergen and may correlate well with the uppermost clinoforms of the De Geerdalen / Snadd formations in the Barents Sea and Svalbard.

Part V

Appendices

Appendix 1

See inclusion on back page.

Geological Map of Svalbard 1:100 000 Sheet G14G Hopen

Atle Mørk, Gareth S. Lord, Kristoffer H. Solvi & Winfried K. Dallmann

Geological Map published by the Norwegian Polar Institute

Appendix 2

På jakt etter reservoaranalog

Halfdan Carstens (Editor)

Published in the GEO and online at Geo365.no

På jakt etter reservoaranalog

På den lille øya Hopen har dedikerte geologer kartlagt en serie med ca. 230 millioner år gamle elvekanaler. På den måten bygger de kunnskap som kan brukes for å finne og utvinne olje og gass i Barentshavet.

Geologisk feltarbeid kan være krevende på Hopen. Av og til er det nødvendig å bryne seg på bratte skrenter i håp om å få en god beskrivelse og tatt prøver av hele lagrekken.

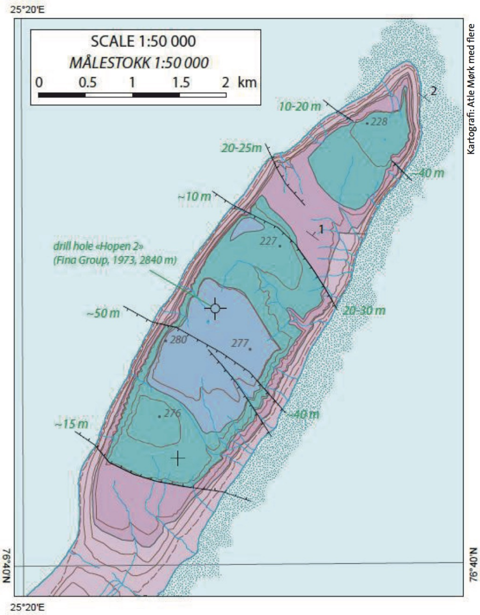
Foto: Turid Haugen, NTNU/UNIS

TEKST: Halfdan Carstens

– Vi har besøkt Hopen hvert eneste år siden 2007, forteller Atle Mørk i SINTEF Petroleumsforskning.

Unntaket var i fjor da sommerværet ikke tillot forskerne å gå i land. For på denne forblåste utposten finnes ingen naturlige havner, og slett ingen kunstige, for de eneste «fastboende» er den lille staben på den meteorologiske stasjonen.

Atle Mørk er en gammel traver på Svalbard. Hans første besøk var som student i 1970, og etter at han ble hyret inn som vitenskapelig assistent i 1977, har han dratt nordover omtrent hvert eneste år, omtrent som trekkfuglene. De siste årene har han også blitt godt kjent med Hopen, den lange, smale øya som ligger ganske så alene ute i havet, 30 timers reise med båt fra Longyearbyen.



Det nylig utgitte geologiske kartet i skala 1: 50.000 viser at Hopen kun består av trias bergarter, og at den er gjennomskåret av små forkastninger. Det er boret to letebrønner på Hopen. Fina-gruppen stod bak begge i årene 1971 og 1973 (Hopen 1 og Hopen 2, boret til hhv. 908 og 2840 meter), men det ble ikke påvist verken gass eller olje. Dataene fra disse brønnene er fortsatt tilgjengelige.

EN GAMMEL TRAVER

Hensikten med disse gjentatte besøkene har vært å utvikle forståelse for den geologiske utviklingen gjennom trias, men ikke minst å øke kunnskapen om sandsteinslagene – Snaddformasjonen – som mot sørvest, der oljeselskapene driver sin virksomhet, kan være gode reservoarbergarter.

For i Barentshavet blir mer og mer olje funnet i sandsteiner fra denne tidsperioden. Og da er det viktig å skaffe seg førstehånds kunnskap fra blotninger på land. Nålestikkene som borehullene representerer er ikke tilstrekkelige.

Og ekte geologer klager ikke over tett tåke, vått regn, kald sludd, sur vind og kraftige brenninger. Såpass må man tåle når man skal drive geologisk kartlegging i Arktis. Men utstyret må være i orden, alt fra overlevelsesdrakter, gevær og hjelm til hammer, lupe og notatbok.

Mørk har gjennom disse sommerukene på Hopen vært kjentmann for en gruppe med studenter, forskere og geologer fra universiteter, oljeselskaper og Oljedirektoratet. I all hovedsak er det fem lisenser i Barentshavet som har finansierte «moroa», med Lundin, Eni og Wintershall (som alle har gjort funn i Snaddformasjonen) i spissen. Seg i mellom konkurrerer de om å finne de beste prospektene, men samtidig samarbeider de om å skaffe bedre kunnskap som grunnlag for å utvikle nye ideer og nye modeller.

Tilliten til Mørk skyldes at han gjennom 35 år har drevet feltarbeid, praktisert som ekskursjonsleder og vært veileder for studenter på Svalbard. Det er få som kjenner øygruppens geologi så godt som han. Det er heller ikke mange som vet like godt hva som er nødvendig når krevende feltsesonger skal planlegges.

Nå er han også blitt lommekjent på Hopen, og i vinter ble en liten milepæl nådd. Det nye geologiske kartet over øya var ferdig trykt.

FRA 2 TIL 26

Det er den nye forståelsen av avsetningssystemene på Hopen som inspirerer den rutinerte geologen med eksamen fra Blindern på 1970-tallet.

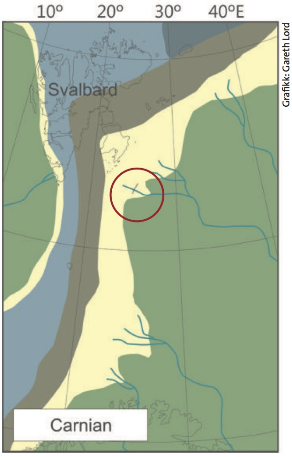
– Vi startet ut med å tro at det i lagrekken på Hopen lå 2-3 kanaler inne i tykke pakker med skifre, men før feltarbeidet var avsluttet endte vi opp med til sammen 26, forteller Gareth Lord, en av Mørks studenter på øya, som har en bachelor fra Plymouth.

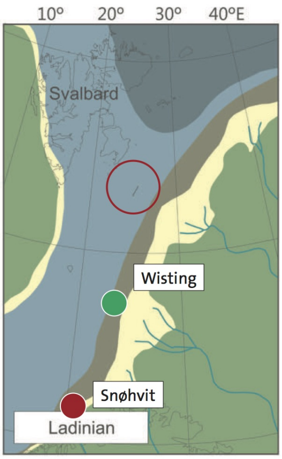
– Kanalene kjennetegnes av finkornet sand, silt og leire, og det interessante er at de opptrer like hyppig og har samme dimensjoner som tilsvarende reservoarbergarter fra trias som har blitt påvist ved boring lengre sør i Barentshavet.

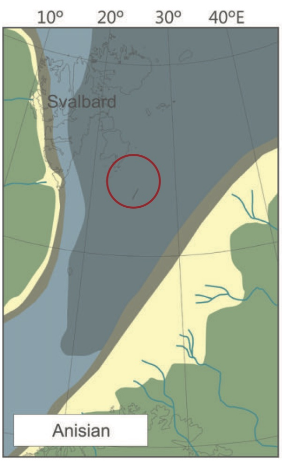
Engelskmannen har forelsket seg i Svalbards natur, og han simpelt hen elsker feltarbeid. Det var en sommer som assistent på Svalbard som åpnet øynene hans, og etter det tok han en mastergrad på triaslagrekken ved NTNU. Nå er han godt i gang med en doktorgrad på Hopen. Også denne gangen dreier det seg om store avsetningssystemer i trias.

Erkjennelsen om et stort antall kanaler med grovklastiske sedimenter inne i tykke pakker med skifre kom etter at en rekke geologer har gjort forskjellige typer feltarbeid de siste årene. Det inkluderer flybilder, fotografering fra båt, klippeklatring (nesten hele øya begrenses mot sjøen av en bratt skrent) og mer tradisjonell overflatekartlegging på toppflaten. Her er noe for enhver smak, og til sammen har de nye dataene skapt helt ny kunnskap som har stor interesse for oljeselskapene.

Mørk trekker spesielt frem Kristoffer Solvi og Tore Klausen som har tatt hhv. masteroppgave og doktorgradsoppgave på data fra denne øya langt mot nord. Solvi bearbeidet fotoer tatt fra båt (av Terje Hellem) og baserte en 3D-modell på dem, mens Klausen gjorde tradisjonelt feltarbeid. Som en del av oppgaven har han publisert en artikkel hvor sandsteinslag fra trias blir brukt som parallell til Snaddformasjonen.







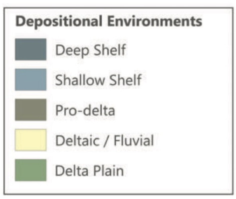
Strandhugg ved en av de mange deltakanalene som er kartlagt på Hopen.

– Til sammen har vi fått gjennom fire masteroppgaver og en doktorgradsoppgave, samt publisert et geologisk kart i skala 1:100.000. Fremfor alt har vi økt kunnskapen om kanalsandsteinene, og forhåpentligvis har oljeselskapene også fått med seg viten de kan bruke i letingen etter olje og gass.

ET MISSISSIPPIDELTA I TRIAS

– Sandsteinskanalene i skifrene ligner veldig på Snaddformasjonen, slik vi kjenner den fra brønnene i Barentshavet. De er også avsatt på samme tid, midt til sen trias, forklarer Mørk.

– Sedimentene er avsatt i grensesonen mellom land og hav, og kanalene kan knyttes til elvesystemer som ender opp i et kjempemessig delta. Hopen er i det hele tatt et fantastisk sted for å forstå Snaddformasjonen.



Paleogeografiske kart fra tre tidsintervaller i midtre trias (anis, ladin) og sen trias (carn). Legg merke til at deltaflaten bygger seg nordvestover i retning Svalbard, hvorpå de dype sokkelområdene etter hvert blir begravd. Kildebergart er derfor mest sannsynlig i nedre og midtre trias (Steinkobbeformasjonen), mens reservoarbergarter vil være mer utbredt lengre opp i lagrekken (Snaddformasjonen).

Kartet forteller oss at det er stor avstand fra Hopen til borehullene i Barentshavet. Det er også stor avstand til lignende avsetninger på Svalbard. Der er de kjent som De Geersdalsformasjonen. Over hele dette store området er det den samme type avsetninger som finnes i intervallet midt til øvre trias. Det er derfor naturlig å tro at ett, stort avsetningssystem har dominert store deler av Barentshavet i midtre til sen trias, gjennom endrøyt ti millioner år lang periode (ladin-carn).

– Vi må se for oss et gigantisk delta der kolossale mengder med sedimenter har blitt transportert med elver fra Uralidene i sørøst. Vi kan kanskje best sammenligne med Mississippideltaet i dag, mener Mørk.

– I det russiske Obdeltaet er det imidlertid mer sand, så det er mulig dette er en bedre analog, korrigerer han seg selv.

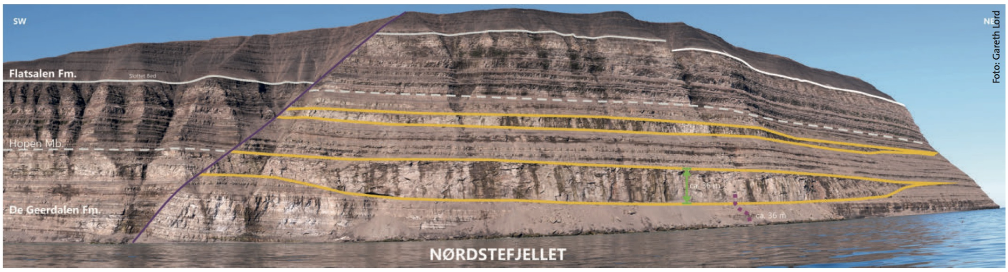
Det er altså slike systemer vi må ha i hodene når vi tenker på Snaddformasjonen, mulige reservoarer og eventuelle oljefunn.

– Dette var på en tid da Svalbard lå på kanten av Pangea og grenset mot et stort hav. Og mens permtiden var dominert av organiske bergarter (kalksteiner), begynte klastisk sedimentasjon å dominere som følge av nye fjellkjededannelser i øst.

– Klastiske sedimenter i Barentshavet fylte en kontinentalsokkel som stort sett var 400 meter dyp, men samtidig innsynking, spesielt i enkelte bassenger, har gitt mektigheter som lokalt blir over en kilometer tykke på norsk side, og flere kilometer på russisk side.

EN PERFEKT ANALOG

Øygruppen Svalbard består for det meste



To tydelige kanaler i brattskrenten langs Hopen (begrenset av gule striper). Mens kanalene består av silt- og sandstein, består de omkringliggende lagene av leirstein og skifer. Vi ser at begge kanalene brytes av en normalforkastning med et kast på omkring 50 meter.

Hopen en mai-dag. Legg merke til de bratte skrentene som gjør feltarbeid vanskelig.

av sedimentære bergarter som «tilhører» Barentshavet. Det er med andre ord de samme formasjonene vi finner under vann som over vann. Det er til god hjelp når geologene skal rekonstruere den geologiske historien i dette store området.

Men fremfor alt kan landgeologien gjøre nytte for seg til å forstå hvordan avsetningssystemene ser ut i tre dimensjoner. Vi har sett at et prosjekt på den lille øya Hopen sørøst for Spitsbergen illustrerer dette poenget svært godt.

– Hopen er en perfekt parallell for Snaddformasjonen. Kartleggingen hjelper oss å forstå både fasis og geometri, og dette kan være til stor hjelp når olje- og gassreservoarene må forstås i tre dimensjoner. Det er nødvendig for å gjøre nøyaktige estimater over hvor mye hydrokarboner som er til stede, samt planlegge hvordan reservoaret skal produseres, konkluderer Atle Mørk.

HOPEN

Hopen er en lang, smal øy som stikker opp av havet ca. ti mil sørøst for Edgeøya. Med store fuglefjell er Hopen på listen over viktige fugleområder i Europa, blant annet på grunn av store kolonier av polarlomvi og krykkje. I vintre med normale isforhold er Hopen et viktig hiområde for isbjørn. Den internasjonale isbjørnavtalen fra 1973 forplikter Norge til å bevare isbjørnens habitat, med spesiell vekt på hi-, jakt- og migrasjonsområder. De grunne havområdene rundt Hopen er antatt viktige leveområder for hvalross i vinterhalvåret. Øya ble fredet som naturreservat i 2003 pga. store naturfaglige verdier, men også pga. kulturminner fra gammel tid.

Øya huser Hopen meteorologiske stasjon med helårlig bosetning.

Geomorfologisk er øya særpreget med sin spesielle langstrakte og klippeaktige form. Landarealet er bare 46 km². Den er ca. 38 km lang, bare ca. 1,5 km bred i gjennomsnitt (2,5 km på det bredeste) og har utseende som en lang, smal rygg som stikker opp av havet. Bortsett fra noen mindre strandflater på enkelte steder, stiger landskapet bratt opp fra ei smal strandstripe rundt hele øya. Høyest oppe er det bratte klipper med horisontale hyller egnet for hekkende sjøfugl.

Berggrunnen på Hopen stammer fra perioden trias. Bergartene er stort sett avsetningsbergarter som sandstein, siltstein og skifer. Disse er dannet fra avsetninger i elvesletter, elvekanaler og i grunne sokkelområder. I Jordas middeltid var det et rikt plante- og dyreliv. Avsetningene inneholder derfor fossiler.

Kilde: Norsk Polarinstitutt

Hopen meteorologiske stasjon