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Sedimentology and Facies Distribution in the Lower Triassic Vardebukta Formation on Oscar II Land, Svalbard

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Abstract

This thesis concerns the Lower Triassic Vardebukta Formation at Oscar II Land. The field data collected from the Triassic exposure on Selmanset, Bertilryggen and Ramfjelldalen, north of Isfjorden, during fieldwork in 2017 has been used for sedimentological facies analysis and identification of facies associations, in order to improve the understanding of the Lower Triassic Vardebukta, in the heavily tectonized area of Oscar II Land.

Oscar II Land has been considered as an important region when it comes to demonstrating the contractional Tertiary tectonic, since an almost 50 km wide intensely deformed zone of Late Paleozoic and Mesozoic strata is exposed. As a consequence of the early Cenozoic folding, the stratigraphy seen at Selmaneset and Ramfjellet are steeply dipping to 90 degrees, and the general quality of the outcrop on these locations are variable.

11 facies and 7 facies associations are interpreted based on the sedimentary analysis from the outcrops and the logs. This is followed by a description of the logs from the different locations, based on the facies and facies associations. Based on presented results, an upwards coarsening trend has been seen at Selmaneset, grading from offshore deposits to upper shoreface and barrier bar deposits. This is similar to the coarsening up trend seen at Festningen. However, a significantly difference in the thickness has been seen between Selmaneset and Festningen. The complex tectonics may have resulted in several repetitions at Selmaneset, resulting in a thick succession, compared to neighbouring areas.

A deepening trend has been seen from Selmaneset to Bertilryggen, which has been interpreted to be distal offshore transition deposits, followed by a deepening to offshore deposits. This interpretation is supported by the the eastward deepening trend seen in the findings across Spitsbergen. However, in order to get a better understanding of the depositional environment, further studies of the structural geology of Oscar II Land will be important.

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Sammendrag

Denne oppgaven undersøker avsetningene fra nedre trias blotningene på Oscar II Land, Svalbard. Innsamlede data fra Selmaneset, Bertilryggen og Ramfjelldalen, gjennom feltarbeidet i august 2017, er anvendt til detaljert sedimentologisk facies analyse og identifikasjon av facies assosiasjoner. Målet er en bedre forståelse av det kompliserte og utpreget tektoniserte Oscar II Land.

Oscar II Land har blitt ansett som et svært viktig område når det kommer til å demonstrere den Tertiære tektonikken, ettersom et område på 50 km av intenst deformerte mesozoikum og sen-paleozoikum avsetninger er eksponert på Oscar II Land. En konsekvens av foldningen fra tidlig kenozoikum er at lagene observert på blant annet Selmaneset og Ramfjelldalen er vertikale til sub-vertikale, og den generelle kvaliteten på blotningene er varierende.

11 facies og 7 facies assosiasjoner er beskrevet og tolket. Basert på dette arbeidet har den sedimentologiske utviklingen i loggene fra hver lokasjon blitt beskrevet og tolket. En oppover grovende trend er observert pÃĕ Selmaneset, med en gradering fra offshore avsetninger, til øvre strandsone og barriere avsetninger. Liknende avsetninger har blitt sett på Festningen. Tykkelsen på suksesjonen på Selmaneset kan være et resultat av den kompliserte tektoniske alterneringen sett på Oscar II Land. En dypgående trend av avsetningene i østlig retning er observert fra Selmaneset til Bertilryggen, hvor distale offshore overgangs avsetninger har blitt tolket, etterfulgt av en transgression, til offshore avsetninger. Denne tolkningen er støttet opp av den proksimal-distale østlige trenden som har blitt sett gjennom Spitsbergen i eksisterende studier. For en ytterlige forståelse av avsetningsmiljøet på Oscar II Land, vil et fremtidig samarbeid mellom sedimentologer og strukturgeologer bli viktig.

Preface

This thesis is part of a master‘s degree in petroleum geology at the Department of Geoscience and Petroleum at the Norwegian University of Science and Technology (NTNU). The main supervisor for the project has been Professor II Atle Mørk at NTNU.

The data for the thesis was collected during three weeks of fieldwork to Oscar II Land, August 2017. The field crew contained three master students from NTNU; Ingrid N.Hoel, Chrissy McCabe, Ingvild Jonassen and Sofie Bernhardsen, including Ole-Marius Solvang from UiB, two sedimentologists, Erik P. Johannessen and Sondre Krogh Johansen, two geologists from Norwegian Petroleum Department; Kjetil Kaada and Andre Frantzen Jensen, structural geologists Tormod Henningsen and paleontolog Nina Bakke.

Chapter 1 (Introduction), 2 (Regional geology) and 3 (Statigraphy of The Early Triassic) are based on the work the 15 credit TPG4570 - Petroleum Geosciences, Specialization Project, fall 2017, with minor changes. The topic of the project work was coastal to shallow marine sedimentation in the Lower Triassic succession, with emphasis on Svalbard and Western Spitsbergen. In Chapter 4 (Methology), gives an outline of the study area, the description of the fieldwork and the workflow for the thesis. The results of the fieldwork are presented in Chapter 5 (Results), which includes the facies analysis and the facies associations based on the logs from the localities. Also included in this chapter is a description and interpretations of the localities in terms of the facies associations and depositional environment. In Chapter 6 (Discussion), the results and the interpretations are discussed, supported by the project work. This has been significantly modified. A summary of the of the main findings are presented in Chapter 7 (Summary and Conclusion), including recommendations for future studies. All photographs are taken during the fieldwork in August 2017 by members of the field party, otherwise this will be stated.

Acknowledgements

First and foremost, I would like to thank my supervisor Atle Mørk, Professor II at NTNU, for giving me the opportunity to be a part of this interesting project, and for the invaluable help and feedback through the weekly meetings. Your knowledge and your enthusiasm for the project has been inspiring, and it has motivated me during the entire writing process.

I would also like to thank Chrissy and Ingvild for being excellent field partners. A big thanks also goes to the rest of the field party; Ole Marius, Sondre, Andre, Kjetil, Tormod and Erik P, for fantastic days in the field.

Next, I would like to thank Erik P. Johannessen for excellent guidance on the last week of the field work, and support and feedback in the work after the fieldwork.

I would like to thank Dale Oen Experience, and our captains at # Youexplore, Martin and Gisle, for keeping us safe and dry on Isfjorden, and for memorable evenings on the boat.

Finally, I would like to thank my fiance, Anders, and my family, for always believing in me, and for their unlimited support thoughout my five years at NTNU.

Contents

Chapter 1

Introduction

1.1 Aim of this thesis

Prior to this thesis, a literature study was performed as a part of the Specialisation Project 2017 for the Petroleum students. In this specialisation project , the literature concerning the Lower Triassic succession on Svalbard was reviewed. Based on the sedimentological logs presented from different section of Svalbard, and the overall interpretations and paleogeographical models from previous work, the purpose of the project was to get an overview of the observations and interpretations from the Lower Triassic succession on Svalbard, and the general interpretation of the depositional environment during the Early Triassic.

The sedimentological data from the Lower Triassic at Oscar II Land, located in the central parts of Spitsbergen, forms the basis of the study for this thesis. A further understanding of the sedimentology and the depositional environment of the highly tectonized area of Oscar II Land is the motivation behind this study. The aim is to investigate the sedimentological processes, and to create a detailed facies model of the Lower Triassic Vardebukta Formation on Oscar II Land. This will be done by using outcrop data from three different locations: Selmaneset, Bertilryggen and Ramfjelldalen. Based on the facies analysis, facies associations will be identified, and a detailed description of the logged sections will be provided.

Thus, the main goals for this thesis will be: Based on facies analysis and identification of facies associations, provide a reliable depositional model for the Lower Triassic Vardebukta Formation of the heavily tectonized Oscar II Land.

1.2 An Overview of the study area

The Svalbard Archipelago covers a land area of only 63 000 km^2 and represents an uplifted part of the Barents shelf, situated in the northwest corner of the Barents Shelf (Nøttvedt et al., 1993). This gives the archipelago the ideal position for recognition and understanding of the controlling factors involved in the development of the western Barents Shelf (Worsley, 2008).

The spectacular geology on Svalbard early drew the attention of geologists, due to its easy access of outcrops and the lack of vegetation. The first geological expedition was initiated by the Norwegian geologist Baltazar M.Keilhau in 1827, who first went to Bjørnøya, Prins Karls Forland and Edgeøya (Sysselmannen, 2012; Dallmann et al., 2015).

The interest for the archipelago has increased the past three decades, mainly because of the petroleum potential in the Barents Sea, especially in the Triassic and Middle Jurassic successions (Lundschien et al., 2014).The well exposed strata exposed on Svalbard allows for a detailed study of the stratigraphy and sedimentology, which can be combined with seismic data and drilling information from the Barents Sea. Based on this information can the petroleum potential be interpreted (Lundschien et al., 2014). The Triassic outcrops can be found all around the Svalbard archipelago, and the offshore exploration the last 30 years has proved that it is also widespread on the Barents Shelf. This makes Svalbard a key area for studying the Triassic succession (Vigran et al., 2014).

1.3 Previous studies

The Triassic stratigraphy has been targeted since the 19th century by Norwegian, Swedish, Russian, Polish and English scientists, attracted by the abundant fossil faunas observed throughout the archipelago. An increased interest for for the archipelago has been seen the last three decades, due to the petroleum potential in the Barents Sea, especially in the Triassic and Middle Jurassic succession (Lundschien et al., 2014).

Earlier studies of the basal Vardebukta Formation includes Buchan et al. (1965), who defined the Vardebukta Formation from the Lower Triassic succession at Festningen, the study of the palynoflora by Vigran et al. (2014), a study of the geochemistry by Wignall et al. (1998) and Wignall et al. (2016), who also did a facies analysis of the Vardebukta Formation at Festningen. However, as this was not the main topic of Wignall et al. (2016), the only detailed sedimentological study published from the Festningen succession was performed by Mørk et al. (1982). Solvang (2017) newly presented a sedimentological and petrographical investigation of the Early Triassic Vardebukta Formation on the western Spitsbergen in his thesis, and his findings will also be considered in the later discussion. And also, Bergh et al. (1997) has given a detailed documentation of tectonic events in this area.

Chapter 2

Regional Geologic setting

2.1 The geological development of Svalbard

The tectonic history of the Late Palaeozoic and Mesozoic of the Barents Sea was dominated by extensional tectonic movements. At first these movements were represented by the collapse of the newly formed Caledonian and Uralian orogenic belts, later followed by the Pangaen supercontinent break-up. The tectonic events are recorded in the Early-Middle Devonian, Carboniferous, Permian, Triassic and Late Jurassic-Early Cretaceous, and the significance of each event varies from location to location. The result of these tectonic events where the development of the major rift basins, and the platforms and structural highs across the Barents Shelf (Doré, 1995).

Two major provinces make up the offshore Barents Shelf, separating eastern region from western region by a north-south trending, ”generally monoclinal structure” (Worsley, 2008). According to Dallmann et al. (2015) these provinces were probably juxtapositioned during the final phase of the Caledonian Period. The eastern region is characterised by its South and North Barents basins, while the western province, with its complex tectonic, is reflected by ”the mosaic of basins, platforms and structural heights ”(Doré, 1995). These were a result of a long lasting interplay between ”tectonic processes along western and north western margins of the Eurasian plate ” (Doré, 1995; Worsley, 2008).

The 20 kilometere thick Precambriam - Lower Palezoic basement rock of Svalbard, contains 20 different lithostratigraphical groups and has collectively been named ”Hecla Hoek” (Worsley, 2008). According to Bergh et al. (1997), low- to high-grade igneous and meta-supracrustal rocks of arhean-silurian age makes up the strata of the basement, showing variable influence by the Caledonian orogeny.

Five distinct units makes up the covering strata overlaying the pre-Devonian basement (Bergh et al., 1997; Worsley, 2008). David Worsley's brief review of the post-caledonian development of Svalbard sums up the five main depositional phases from the Late Devonian to the Neogene. Each of these phases representing a part of Svalbard's continuous movement northwards from the equator to the arctic position Svalbard has today (Doré, 1995; Worsley, 2008).

The five depositional phases presented by Worsley (2008) are as follows:
1) Late Devonian to Mid-Permian
2) Late Permian to Middle Triassic
3) Late Triassic to Late Cretaceous
4) Paleogene
5) Neogene

2.1.1 Late Devonian to Mid-Permian

The Devonian age marks the end of the Caledonian orogeny, which lasted from the Ordovisian to the early Devonian time. The early stages of the super–continent "Pangea" was seen in the Devonian time (Dallmann et al., 2015). Widespread intratectonic rifting, late "Caledonian Svalbardian compressive movements" of late Devonian time and the development of a massive post-rift carbonate platform, stretching westward, all the way to the present-day Alaska. These are some of the characterising events of this period mentioned by Worsley (2008). The Old Red sandstone, a commonly used term for the terrestrial bedrock from the Devonian time, was accumulated in rift troughs developed by subsiding crustal block. (Dallmann et al., 2015) . A change in tectonic regime was seen in the Carbonifours period, from compressive-transpressive to extensional (Mørk et al., 1999a). From the end of Carboniferois to the Early Permian, this period saw the change from "deposition of the predominantly non-marine tropical humid clastics of the Billefjorden" to extensive areas of the shelf being dominated by shallow-marine carbonates, sabkha evaporates and local siliciclastics, and isolated deep basins containing halite in Gipsdalen Group. This period was dominated by frequent sea-level fluctuation, and the deposition of the sediments occurred in a warm and arid climate. An abrupt climatic shift from humid to warm, but arid regimes, and major regional uplift, characterises the unconformable contact between the Billefjorden and Gipsdalen groups (Worsley, 2008).

2.1.2 Late Permian to Middle Triassic

Figure 2.1 shows the position of Svalbard during the Late Triassic, illustrated by Dallmann et al. (2015). By that time, Svalbard was located at the northeastern margin of Pangaea, about 55°N. As the Laurentia continent fusioned with Siberia during the Permian, the Urial Mountain chain formed, as the contact between the southern areas, was sealed off (Lundschien et al., 2014). The end of the Permian age marked the end of the formation of the Uralides (Riis et al., 2008), and the Barents Sea was filled with sediments from the eroded Uralian Mountain chain and basement rock from Norway from the south-east during the Triassic (Lundschien et al., 2014).

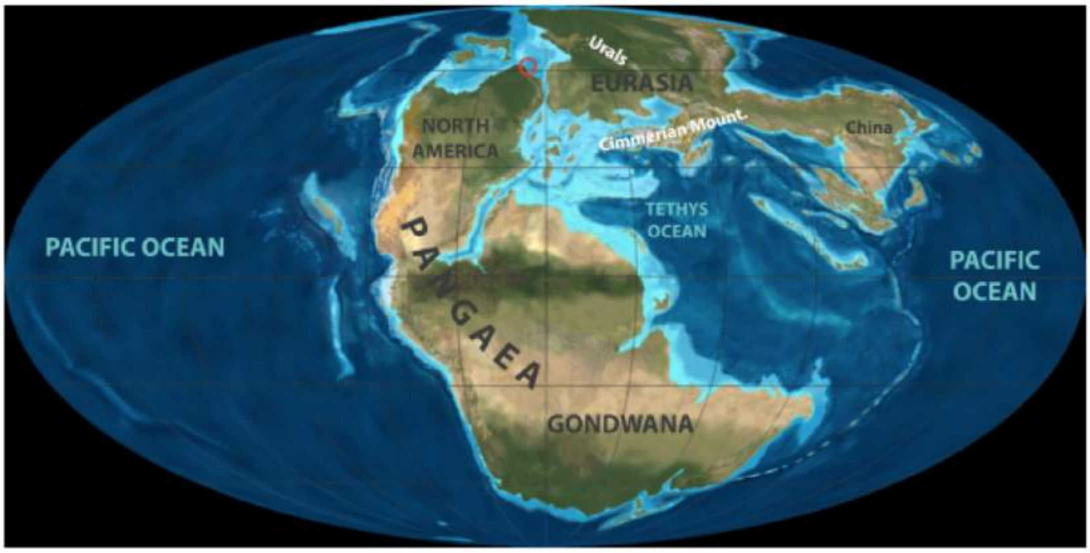


Figure 2.1: Svalbard's location during the Late Triassic, around 55°N (red circle), forming a part of the northeastern margin of Pangaea (Dallmann et al., 2015).

The transition between Permian and Triassic is marked by the mass extinction seen in the Late Permian, which can be observed in the pronounced change in the lithology and fauna in the Early Triassic (Dallmann et al., 2015). Although the Permian Kapp Starostin and the Lower Triassic Sassendalen Group show great differences in fauna and lithology, both successions contain shales and are relatively organic rich (Worsley, 2008). The Permian-Triassic boundary will be discussed in more details later in the report.

According to Mørk et al. (1999a), a significant change from carbonate deposits seen in the Late Carboniferous to the Early Permian, and the Late Permian spiculitic and cherty mudstone deposits was marked by the presence clastic deposition during the Triassic on Svalbard and on the Barents Sea Shelf.

In the early stage of Triassic, the south-western parts of the Barents Sea and the central European basins were isolated from each other. This was a result of the closure of the late Permian Zechstein seaway due to extensive "uplift of the mid-Norwegian and eastern Greenland shelves"(Worsley, 2008). Looking at the tectonic activity in the western Barents Sea and the Svalbard region during the Triassic, this has been considered a quiet period. No significant tectonic event or faulting has been recorded from this age. However, this period produced important depocenters, as the northern and southern

Barents sea were strongly effected by subsiding and high sedimentation rate. This further led to great variations in thickness of the Triassic succession across Svalbard and the western Barents Sea (Riis et al., 2008; Worsley, 2008).

The Early Triassic is characterised by a generally transgressive trend throughout this time period. This has been occasionally disturbed by the repeated coastal progradations, leading to the development of the "positive features", including the Sørkapp-Hornsund and Stappen highs by the Olenekian age (Worsley, 2008).

Figure 2.2 shows the interpreted palaeogeographic development of the Barents Shelf during the Early Triassic to Late Triassic. As mentioned in Worsley (2008), the thick sandstone intervals seen on Spitsbergen has been suggested to be related to the repeated coastal progradation from Greenland to the west. "Through much of the early to mid-Triassic, most of the south-western shelf was distal to an oscillating, but generally north-westerly prograding, coastline, with sand provenance being first from the Baltic Shield and then increasingly from the Urals" (Worsley (2008), page 306).

2.1.3 Late Triassic to Late Cretaceous

The Late Triassic to Late Cretaceous is characterised by deposition of many good reservoir sandstone units. Especially the lower part of this depositional phase has a good quality, then the unit fines up toward the top of the unit. The Late Triassic Kapp Toscana Group is a sandstone rich unit from this period (Worsley, 2008). During the Early to Mid Triassic, the sediment source was mainly from the west, but this changed drastically in the Late Triassic (Figure 2.2). The sediment source shifted direction towards the east and the newly established Ural Mountain. Kapp Toscana Group, the erosional products from this, filled the entire embayments (Dallmann et al., 2015).

A stabilisation of the area in the Late Triassic to Mid–Jurassic was seen, after the waning subsidence rate thoughout Triassic, followed by a major deltaic progradation. Rapidly decreasing sedimentation was seen as result of extensional tectonism in the Mid-Late Jurassic, leading to establishment of major platform and basin patterns, which can be seen today (Worsley, 2008).

The Jurassic–Cretacoeus regional development was dominated by deposition of fine clastic material, and reflects the polar Euramerican Basin development seen on the northern margins of the shelf. During the Mesozoic, the area moved northwards from the temperate latitudes to 60°N in the early Cretaceous Worsley (2008). During the Upper Jurassic and Lower Cretaceous, the opening of the Atlantic ocean possibly lead to the intrusion of the dolerite sill, intruding rock all over Svalbard, called Diabasodden Suits (Mørk et al., 1999a).

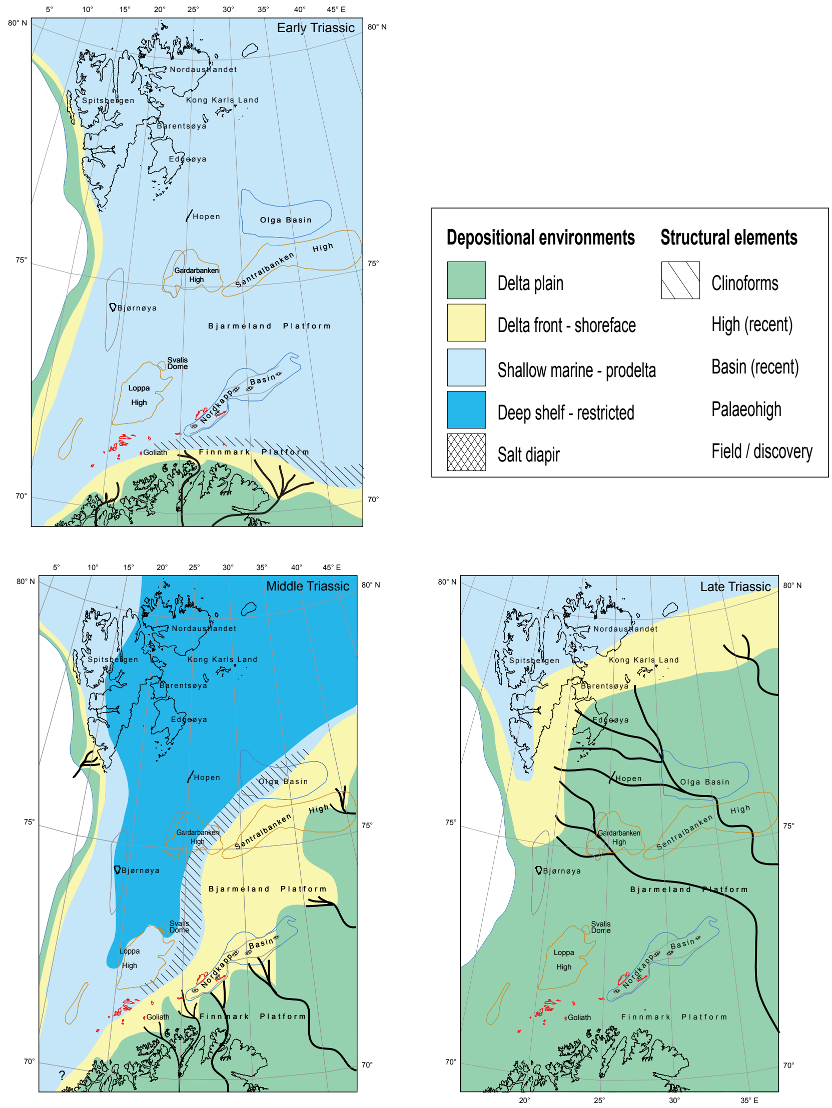


Figure 2.2: Paleogeographical reconstruction of the Triassic. From Lundschien et al. (2014)

2.1.4 Paleogene

Both the latest Cretaceous and Paleogene were, according to Worsley (2008), affected by transpressive and transtensional regimes that were changing along the western plate suture. The Central Tertiary Basin developed as a major depression due to rifting during the first epoch of the Palaeogene, and was filled with sediments from early Paleocene to Oligocene. The continuous plate motion resulted in the development of the so-called West Spitsbergen Fold Belt seen on Svalbard, otherwise referred to as the Eurekan Fold Belt (Dallmann et al., 2015). This was followed by "the Eocene/Oligocene break-up and the opening of the Norwegian-Greenland Sea" (Worsley, 2008).

2.1.5 Neogene

The clastic sediments of this period are only recognised on the continental shelf, and west and north of Svalbard, from the rifted continental margin offshore and there has not been recorded any stratigraphical terminology of the Neogene clastic sediments (Dallmann et al., 2015). Deposition of thick clastic wedges was shed from the newly developed western shelf margins in the Neogene. This has been related to the hinterland which was subjected to large scale depressions and uplift as a result of the shelf being repeatably glaciated and deglaciated (Worsley, 2008). As the spreading of the sea-floor in the North Atlantic and Arctic Oceans continued throughout Neogene and Quaternary, the position of Svalbard and Barents Shelf was moved farther away from Greenland (Dallmann et al., 2015).

2.2 Tectonic setting of Oscar II Land

As mentioned in previous section, the contionous plate motions during the Paleogene resulted in the development of the West Spitsbergen Fold Belt. Pointed out by Bergh et al. (1997), Oscar II land is an important region when it comes to demonstrating the character of the contractional Tertiary tectonic.

An east-northeast directed folding and thrusting was seen in the early Eocene, affecting the western part of Spitsbergen, all the way from Kongsfjorden to Sørkapp, as seen in (Bergh et al., 1997; Dallmann et al., 2015). Transpressinal stresses caused by the movement of Svalbard and the Barents Shelf from the north-eastern edge of Greenland to east of Greenland, at its present position, resulted in the formation of the Western Spitsbergen orogenic belt (Braathen et al., 1999; Manby and Lyberis, 1996). The West Spitsbergen orogenic belt has been described as a narrow (less than 40 Kilometre), transpressive orogene, developed between the shelves of Norwegian and Greenland, at a dextral transform plate margin. This happened during the North Atlantic opening in Paleogene (Bergh et al., 1997). The fold belt has been explained in broad terms to consist of a ”thick-skinned” thrust zone in the west, where the Caledonian basement rock of ”Hecla Hoek” is thrusted, and a ”thin-skinned” thrust zone in the eastern areas (”or foreland-thrust-belt-lie zone”) where only the post-Caledonian sediments are affected (Dallmann et al., 2015). The fold bends to a NNW-SSE trend, on Oscar II Land, and widens immediately to 50 kilometre southeast of Brøggerhalvøya (Dallmann et al., 2015).

According to Bergh et al. (1997),there are three major zones in the tertiary fold-thrust belt in Oscar II Land, confirmed by offshore seismic data collected by Statoil in Isfjorden. Presented in Bergh et al. (1997)(fig. 2, p.641) is a compiled geological-structural

map, presenting the three zones which shows distinctly different structural styles, and a cross-section of Oscar II land running approximately southwest-northeast, in other words, parallel to the direction of maximum Tertiary contraction. These three zones are of distinct structural character, as summed up in Bergh et al. (1997):
1) A western zone: This zone contains the basement involved fold-thrust complex (Hecla Hoek) and the Paleozic covering strata.
2) The central zone: Involves a thin-skinned fold-thrust unit, including the deformed sedimentary cover sequence of Late Paleozoic-Tertiary. The dominant structural feature of the central zone is, according to Bergh et al. (1997), the Triassic-Cretaceous shale-silt units involved in macrofolds.
3) The eastern zone: This zone is characterised by "the frontal duplex system in the fold-thrust belt". This is bounded easterward by basement rooted, steep reverse faults, as the Billefjorden and Lomfjorden fault zones (Bergh et al., 1997).

A shortening of 20 kilometre or 45% on Oscar II Land has been noted in Bergh et al. (1997). The two restored cross sections can be seen Bergh et al. (1997) (fig.3, p.643). An almost 50 km wide intensely deformed zone of Late Paleozoic and Mezosoic strata is exposed at Oscar II Land (Dallman et al., 1993). Associated with the development of the Central Tertiary Basin east of the prominent mountain belt, the folding and thrusting resulted in heavily deformed Triassic rocks in the west (Mørk et al., 1982; Buchan et al., 1965). This has caused problems for the stratigraphical correlation and paleogeographical reconstruction of the Triassic succession in this area.

Chapter 3

The lithostratigraphy of the Early Triassic

3.1 An Overview

Illustrated in Figure 3.1 is the correlation chart showing the lithostratigraphy across the Sassendalen Group and Kapp Toscana Group.

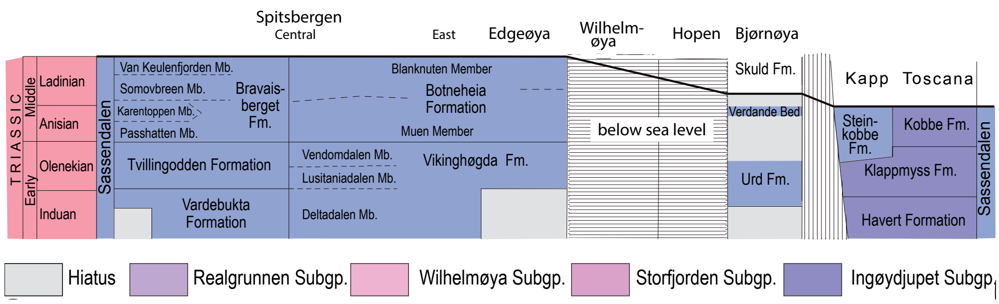


Figure 3.1: Lithostratigraphical the Sassendalen Group and Kapp Toascana Group, from Vigran et al. (2014), modified from Mørk et al. (1999b).

3.1.1 The Permian-Triassic Boundary

The Permian-Triassic Boundary (PTB) is characterised by the dramatic change from the Permian Tempelfjorden Group, dominated by chert, siliceous (spiculitic) shale, sandstone and limestone. This is covered by the Triassic Sassendalen Group, dominated by non-siliceous shales. The basal Vardebukta Formation is containing soft, poorly fossiliferous shales (Vigran et al., 2014). The lack of bioturbation in the lower parts of the overlying Vardebukta Formation has been associated with the late Permian major marine extinction. This mass extinction has been considered to be among the five greatest crises of the earth, and together with mass extinction at the Cretaceous-Palaeogene boundary (KPB), it is by far the most famous incident. It removed 96% of all known species, and was nearly as destructive on land as in the ocean (Dallmann et al., 2015). As the so-called ”Permian Chert Event” ended, the temperature of the waters increased significantly. This warming has been suggested to be a contributing factor to the major marine mass extinction (Worsley, 2008). The widely known intensification and development of the marine anoxia seen in the Permian-Triassic period is regarded as a direct cause for this major mass extinction (Wignall et al., 2016).

The PTB has traditionally been associated with the contact between the Permian Kapp Starostin Formation and Triassic Vardebukta Formation (Wignall and Twitchett, 1996). According to Vigran et al. (2014), the newly redefined boundary in the Spitsbergen exposures has been placed in the lower Vardebukta Formation and the Vikinghøgda Formation. As the ammonoid *Otoceras boreale* are found in the lower sections of these formations and in the latest Permian, and that there has not been observed any age diagnostic conodonts at Svalbard, Vigran et al. (2014) regards the boundary to be located in the lower parts of these formations.

The boundary is very distinct, both in outcrop and in the seismic. A sharp seismic reflector can be seen in the northern Barents Sea, whilst in the sounthern Barents Sea, this strong reflector represents the near top Permian Boundary (Mørk et al., 1999a; Worsley, 2008; Vigran et al., 2014; Lundschien et al., 2014). The PTB is marked by a major transgressive event in most areas where it has been correlated, indicating the onset of the overlying Triassic succession (Mørk et al., 1989; Vigran et al., 2014).

3.1.2 The Sassendalen Group

The Sassendalen Group was described by Buchan et al. (1965) as dominated by non-siliceous shales and mudstones, contrasting strongly with the underlying siliceous upper Permian unit. The upper Permian and the Lower to Middle Triassic show great differences when it comes to lithology and faunas, but both contains shales and have a locally high organic content (Dallmann et al., 2015; Vigran et al., 2014). The Lower Triassic succession is made up by ”two or locally three major” transgressive-regressive cycles, according to Mørk et al. (1989), defined as Vardebukta and Tvillingodden formations in southern and western Spitsbergen (originally defined by Buchan et al. (1965)), and by Vikinghøgda Formation in the central and eastern Svalbard.

With Sørkapp as an exception, Buchan et al. (1965) defined tree formations throughout ”Vestspitsbergen”, based on the available evidence: Vardebukta formation, Sticky Keep formation and Botnheia formation (Middle Triassic age). ”Sticky Keep Formation”, defined by Buchan et al. (1965) was changed to ”Sticky Keep Member” by Mørk et al. (1982) in the eastern areas, while the Tvillingodden Formation and Bravaisberget Formation was established in the west. The two upper members of Vikinghøgda Formation later replaced the ”Sticky Keep Member” (Mørk et al., 1999a).

The Vardebukta Formation was defined with a type section at Festningen by Buchan et al. (1965). The formation is composed of two members: Selmaneset Member and Siksaken Member, both defined by Buchan et al. (1965), and with type sections from Oscar II Land (Mørk et al., 1999a). The Vardebukta Formation is exposed along the Tertiary fold-thrust belt. It is equivalent in time with Deltadalen Member of Vikinghøgda Formation, representing a more distal part of the Early Triassic basin. Only a thin succession of the formation is found on the Sørkapp-Hornsund High, where it is represented by the Kistefjellet Member. The member is considered age-correlative with the uppermost part of the unit elsewhere on Svalbard, and unconformably covers the folded basement (Mørk et al., 1999a). The Formation has been defined as ”a shallow marine, coastal environment with prograding deltaic lobes”, with the presence of offshore bars (Mørk et al., 1999a).

Defined in the central and eastern Svalbard is the **The Vikinghøgda Formation**, described by Mørk et al. (1999b), with a new type section in Deltadalen. The three members of Vikinghøgda Formation are Deltadalen Member, Lusitaniadalen Member and Vendomdalen Member (Mørk et al., 1999b).

Tvillingodden Formation has its type section at Festningen in the outer Isfjorden area (Mørk et al., 1999a), and was first defined by Mørk et al. (1982). It is developed in the western area of Spitsbergen and can be observed along the Tertiary fold-thrust belt. The Lusianiadalen and Vendomdalen members in the central/eastern Spitsbergen are time equivalents to the Tvillingodden Formation. The formations contains two members defined by Buchan et al. (1965), Iskletten Member and Kaosfjellet Member, both with type sections in Oscar II Land.

Thickness variations across Sassendalen Group

The Triassic sediments, found on most of Svalbard, has a thickness variation from 250 meters 1200+ meters. Mørk et al. (1989). The thickness of the Sassendalen Group varies from more than 700 meters in the western Spitsbergen, in the outer Isfjorden area to Edgeøya, where less than 200 meter of succession has been detected, and continuous offshore in the direction of the southern-eastern Barents Shelf, where a development of more than 1500 meter has been recorded (Mørk et al., 1982; Mørk and Worsley, 2006; Vigran et al., 2014).

The thickness variations across Svalbard has been illustrated Figure 3.2. A thinning of the Sassendalen Group in the eastern direction, to more distal parts of the shelf (Mørk et al., 1989) can be seen, from the area around the mouth of Isfjorden, interpreted as the depocenter (e.g Mørk et al. (1982)).

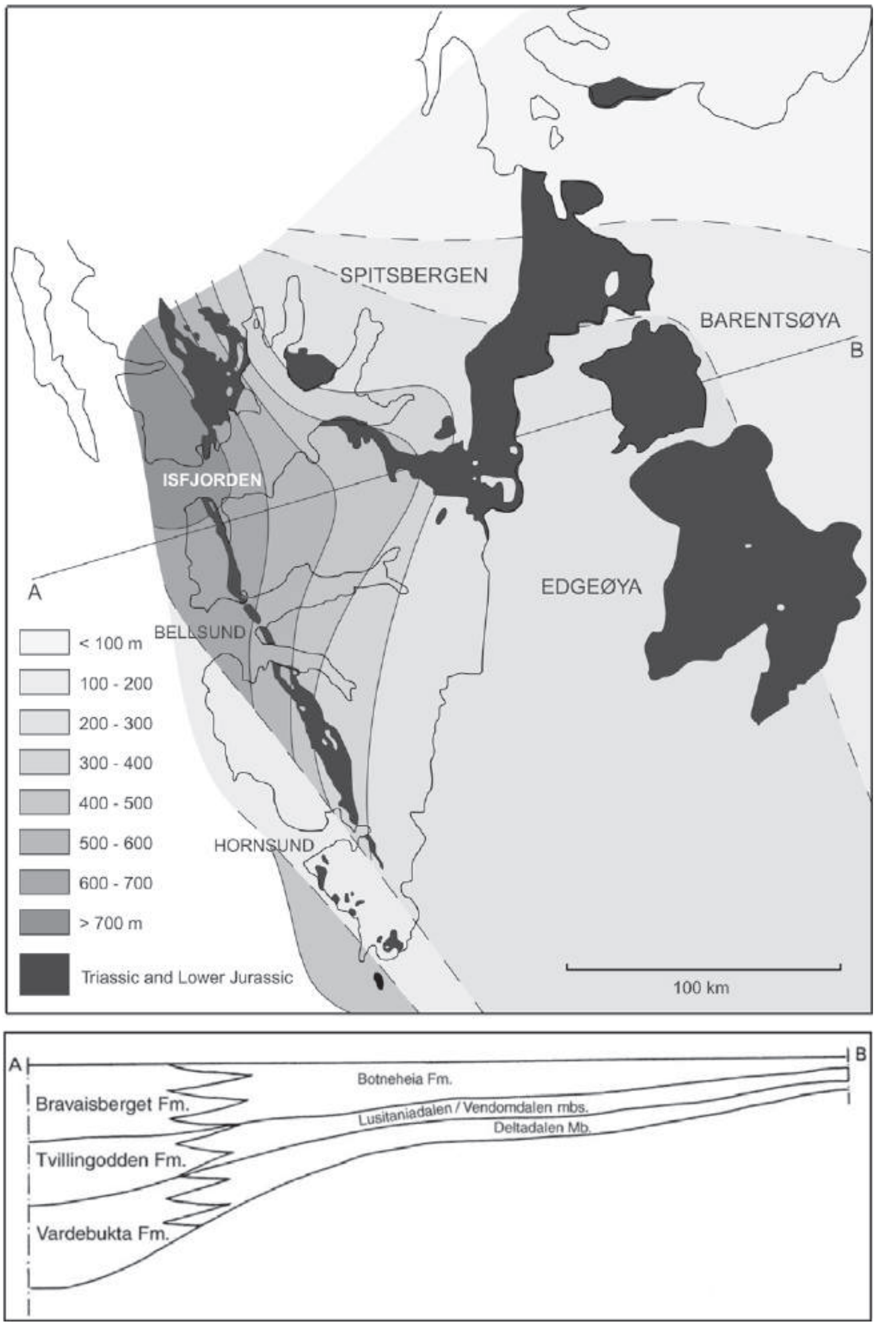


Figure 3.2: Presented here are the the thickness variations across the Lower and Middle Triassic Sassendalen Group from Mørk and Worsley (2006). Note the eastward thinning trend, the depocentre interpreted to be around the mouth of Isfjorden, near Festningen. The most dense section is seen in the Sørkapp-Hornsund High.

The most dense successions has been recorded in the Sørkapp-Hornsund High area, on the southern Spitsbergen, where the division between the two lower formations of the Sassendalen Group has not been recognised (Mørk et al., 1982; Vigran et al., 2014). According to Mørk et al. (1982), a thinner development of the Lower and Middle Triassic has been recorded on Bjørnøya, showing the Lower Triassic as a is thin, but complete succession. A slow subsidence on the Sørkapp-Hornsund High has been interpreted to cause a delayed transgression, which lead to a thinner succession compared to outcrops north and east for the High (Mørk et al., 1989). As noted by Mørk et al. (1982), the transgression of the High did not happened until the Dienerian. The thickness variations observed in the Sassendalen Group has been considered to be a consequence of ”the differential movements” along a series of north-south trending lineaments (Mørk et al., 1982).

Observations and interpretations from the Lower Triassic Vardebukta Formation

A selection of stratigraphical sections from the Early Triassic succession from all around Svalbard from Vigran et al. (2014) and Buchan et al. (1965) was presented in the project, including he observations and interpretations. Presented in Figure 3.3 is the a simplistic overview of the facies distribution and chronostratigraphy of the Early Triassic stratigraphy. In this sections, the observations and interpretations from Festningen and Bertilryggen are presented, as these will be discussed later in the thesis.

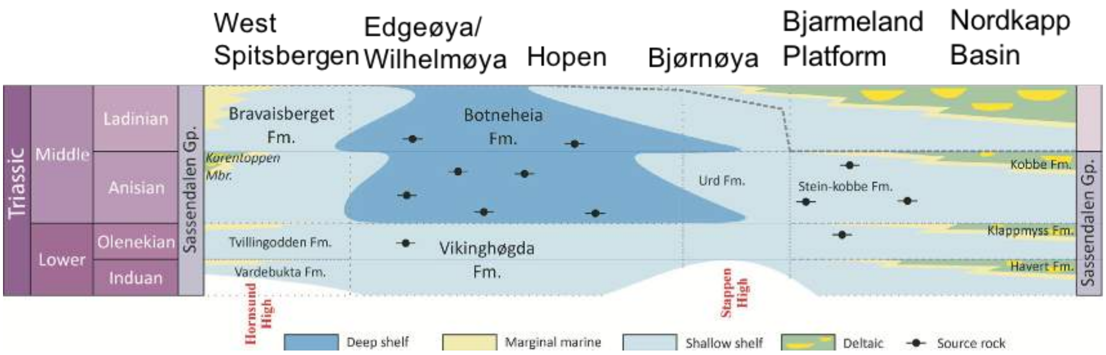


Figure 3.3: Presented in this figure is a chronostratigraphy and summary of the facies of the Early Triassic stratigraphy across Svalbard and the weatern Barents Sea. Modified after Fleming et al. (2016).

According to Mørk et al. (1989), the coarsening upward succession seen along the western Spitsbergen is a result of a coastal progradation. Two major (or locally three)(Mørk et al., 1989) transgressive-regressive (TR) cycles form the Lower Triassic Successions on Svalbard, both containing major coarsening up cycles, often with several subcycles within a cycle (Mørk et al., 1989; Wignall et al., 2016).

The lower cycle (Induan, Griesbachian-Dienerian) is represented by the Vardebukta Formation in the western Spitsbergen and the lower Vikinghøgda Formation member, Deltadalen Member, in the central and eastern areas of Svalbard (Mørk et al., 1989). Shale facies were developed through the whole region following this major transgression at the start of the Griesbachian Substage, and there after followed by a shallowing up trend. This lead to foreshore/shoreface sandstones developing during the Dienerian time in the west Spitsbergen outcrops(Wignall et al., 2016).

The next, major T-R cycle (Olenekian) is represented by the Tvillingodden Formation in the western Spitsbergen (Mørk et al., 1989), and the two upper members of Vikinghøgda Formation in the eastern and central areas (Vigran et al., 2014). No apparent transgressive-regressive trend in the lowermost unit has been observed in the eastern localities (Mørk et al., 1989).

Observations and Interpretations from Festningen: The Festningen section, located in the outermost Isfjorden area along the southern shore, has been considered a standard reference when it comes to the geology on Svalbard since early in the 1900, when the Norwegians started their expeditions. (Mørk and Worsley, 2006). This location shows, according to the Vigran et al. (2014), the thickest and most complete succession of the Triassic succession, where all units can be followed along the exposures on the shore west of Festningen. This is a result of ”the early Cenozoic folding”, leading to steeply dipping to vertical stratigraphy (Mørk and Worsley, 2006; Vigran et al., 2014). Due to the extensive faulting in this area, thickness estimations are, according to Vigran et al. (2014), difficult.

The stratigraphical section from Festningen, presented in Vigran et al. (2014) can be viewed in Figure 3.4. The lower 100 meters of the Vardebukta Formation shows almost no bioturbation, and both fossils and trace fossils are quite sparse in this part of the unit (Mørk and Worsley, 2006; Vigran et al., 2014). Only ”ammonoid Otoceras boreale” has been noted by Vigran et al. (2014) to exist in these beds. The base of the Vardebukta Formation has been interpreted to represent deep shelf deposits, grading into shallow shelf deposits, and the thin siltstone beds observed in the Vardebukta Formation on Festningen are interpreted to be storm deposits (Mørk et al., 1982). The logs shows coarsening upwards succession in the lower 150 meters, which is grading into a 70 cm thick bivalve rich layer, defined as the Myalina sp. A *Skolithos* rich bed is also observed, overlain by a plant fragment rich unit (Mørk and Worsley, 2006; Vigran et al., 2014). Gradually finer sediments in the top of the section has been interpreted as a slow transgression towards the top of the formation (Vigran et al., 2014). The transition between the Vardebukta Formation and the Tvillingodden Formation is marked by dark, fine, laminated unbioturbated mudstone at base, on top of silty shales of the underlying Vardebukta Formation (Mørk et al., 1982; Vigran et al., 2014). The entire section of Vardebukta Formation described from Festningen has been interpreted in Mørk et al. (1982) to "represent a major barrier bar progradation with the development of barrier sands with tidal inlets and lagoonal back barrier system"

Observations and Interpretations from Bertilryggen:

This section gives on overview of the previous findings from Bertilryggen, based on Buchan et al. (1965) and the log provided by "Institutt for kontinentalsokkelundersøkelser (IKU), report nr.04.6341.00/01/85 - unit Sassendalen Group", were a logged section by Forsberg in 1982 from Bertilryggen is presented.

Bertilryggen and Lundebohmfjellet, west of Ekmanfjorden displays an almost complete and undeformed Triassic succession. Here, (Buchan et al., 1965) divided the Sassendalen Group into Vardebukta, "Sticky Keep" and Botneheia Formations (Buchan et al. (1965), figure 11, page 36). Buchan et al. (1965) defined the first 86 meters to be the Vardebukta Formation, starting with dark grey shaly siltstone, with light green-grey weathering colour, and with local concretions. This is followed by fine grained sandstone, with greenish-grey weathering, lamination and ripples.

An almost 400 meter log is presented by Forsberg 82 in IKU. Looking at the log, the lowermost 100 meters displays a dominantly silty interval with occasionally beds of coarser grains, most likely very fine to fine sand. Structures like ripples are and lenticular bedding is noted, and ammonoids, bivalves and vertical burrows are marked in the log. Two coarsening up section may be seen in the lower 80 meters above the base, followed by finer grains, a possible transgression.

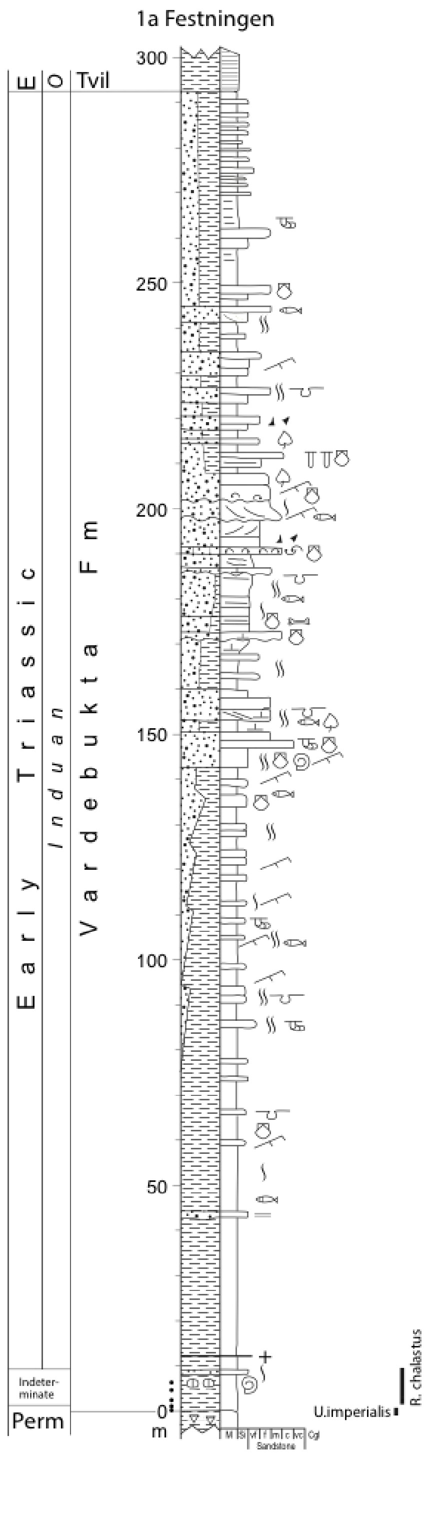


Figure 3.4: Stratigraphical section from Festningen (Vigran et al., 2014).

Chapter 4

Methodology

4.1 Fieldwork on Oscar II Land - logging and sampling

The study area of this master thesis is viewed in Figure 4.1. During three weeks of summer 2017, the fieldwork was conducted by a team of 7-9 researches at Oscar II Land. The sections presented in this thesis is based on observations from three locations: Selmaneset, Bertilryggen and Ramfjelldalen. The first day after arrival was spent at Festningen, looking at the Kapp Starostin Formation, and the Triassic succession here.

A total of 7 days were spent at Selmaneset, in which 4 days were spent on logging, were the succession between Selmaneset and Sylodden was studied. The last week of the field trip, the party sailed to Nordfjorden, to the area south of Flintholmen. Here, the beach profile found on Bertilryggen was studied. Two days were spent at Bertilryggen, only one day on logging and 1,5 days at Ramfjelldalen, were 1 day were spent on logging.

4.2 Methods

Sedimentary study of the outcrop

Lithostratigraphical logging of vertical sections was performed in the field. Features like sedimentary structure, grain size, layer boundaries and layer thickness were carefully examined, and the degree of bioturbation, body fossils, trace fossils and organic material was recorded. The cementation was tested with hydrochloric acid on fresh surfaces. The field equipment used was millimetre paper, meter stick, hand lens, geological hammer, grain size card , compass, GPS and camera. The GPS was important for measuring precise coordinates for the locations of the measured logs. The grain size was decided visually during logging, using hand-lens and a grain-size scale after J.A Udden and C.K Wentworth from Wentworth (1922). This was also used for deciding the grain-size in the thin-sections.

A bed-by-bed measurement of the sedimentary logs were conducted at a centimetre scale (1:25, 1:50 and 1:100), and the measured logs were drawn on millimetre paper. Included in the logs were also the description of grain size, sedimentary structures, body and trace fossils, observed tectonic features like fault gauge and slickenside, colour of the outcrop and degree of bioturbation. The degree of bioturbation was recorded based on a three levels of bioturbation: low (1), moderate (2) and intensive (3) bioturbation (See legend for the logs in Appendix A). A number of samples were also collected during the fieldwork for calibration of grain size. The samples were cut into thin sections and studied in the microscopy lab.

In order to recognise the depositional processes based on the collected data, a facies analysis was performed, based on the sedimentary field logs, supplied with the observations from samples collected during the fieldwork. 11 facies has been described based on parameters such as grain size, sedimentary structures, bioturbation, organic content, unit thickness, sedimentation. In some cases, the colour of the outcrop is included in the description. Based on facies analysis, 7 facies associations (FA) are recognised. These FA represents sub-environment and are described from offshore to upper shoreface environment. The measured section are described in terms of the facies and FA defined from Oscar II Land.

The work flow that has been applied in this thesis is presented below:
1) Definition of facies and facies associations based on the observations from the field
2) Interpretation of the facies.
3) Interpretation of facies associations and depositional environments for each association
4) Interpretation of the depositional environment from Selmaneset and Bertilryggen based on the facies and facies associations. In addition, compare the results with the observations from Ramfjelldalen.

Thin sections

During the field work, over 100 samples from the different localities were collected. A sample was collected every 10 meter of the measured log. 17 thin-sections were made and used to calibrate the grain size in the logs. In order to decide the average grain size for each of the thin-sections, the longest axis of ca 10 grains were measured, converted to millimetres, summarised and then divided on the number of grains.

Software

Adobe Illustrator 2017

For the digitising of the logs and editing figures, Adobe Illustrator 2017 has been used. This is a vector based graphic software.

4.3 Source of error

Calibration of the grain sizes:

As mentioned earlier, the samples that were brought back from the field were used to calibrate the logs, using thin sections. As it turns out, many of the thin section often showed a finer grained sample than noted in the field. It should therefore be noted that some of the strongly cemented sections might be finer than presented in the log.

Problems in the field

The second week was mostly spent in Longyearbyen, due to problems with the boat. One week out of three was then lost, which limited the days of logging and the amount of data collected.

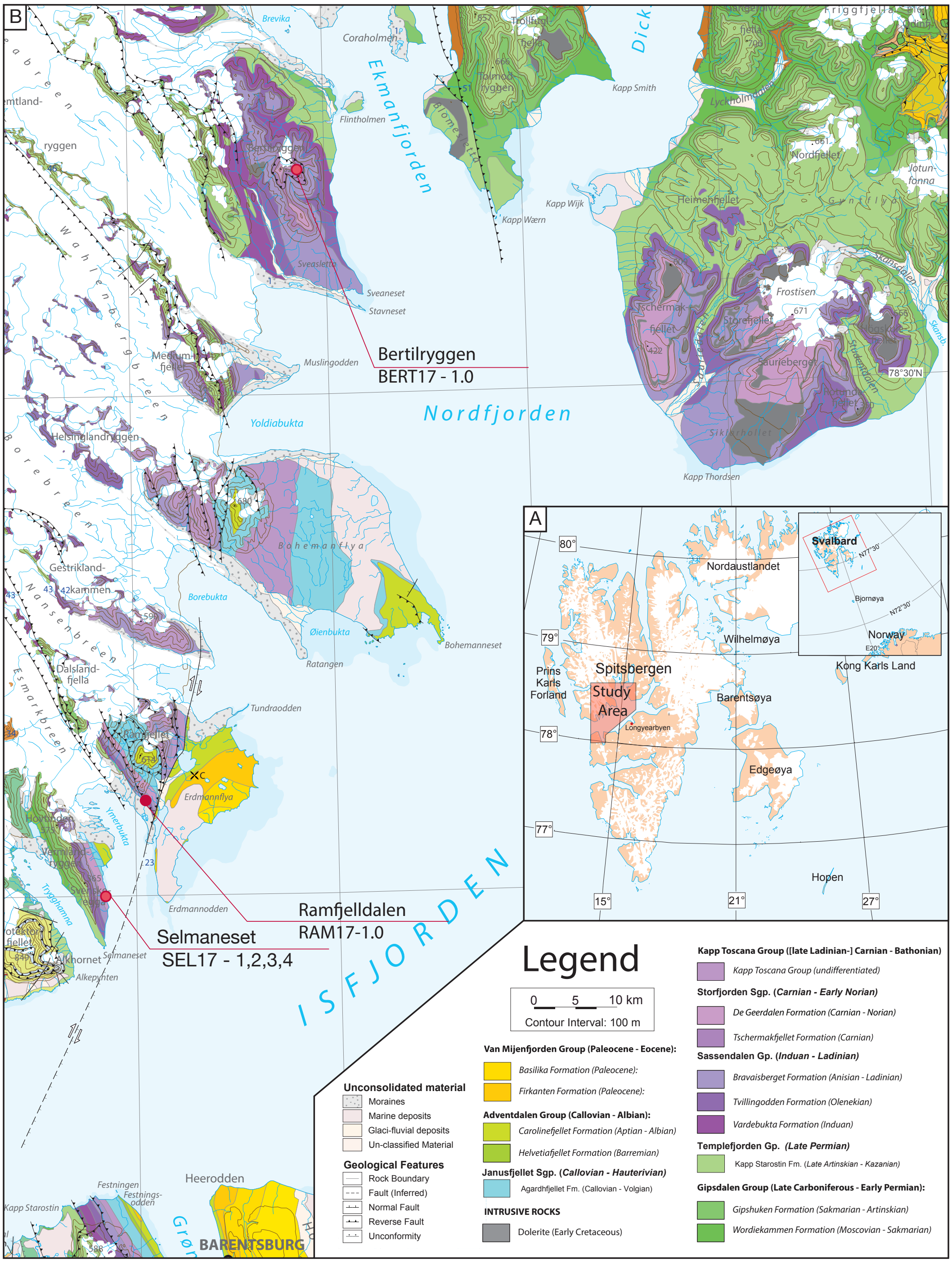


Figure 4.1: **a)** An overvie of Svalbards position in relation to Norway and the Barents Sea. Highlighted in red is the study area. **b)** The study area presented in a geological map, featuring the measured sections and the major stratigraphic units. Modified after Dallmann and Elvevold (2015)

Chapter 5

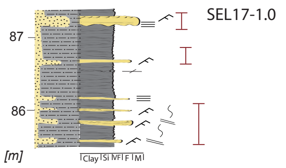
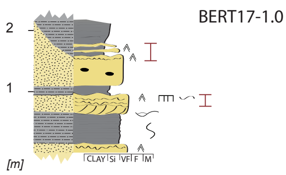
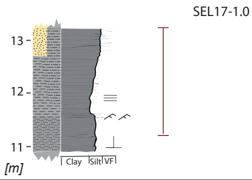
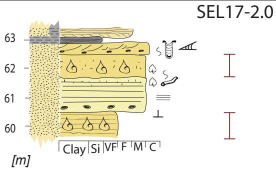
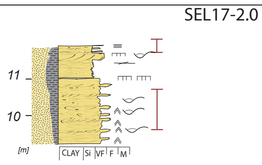
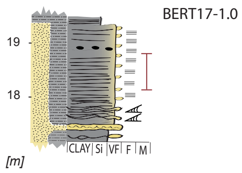
Results

In this chapter, the result of the facies analysis, and the facies associations will be presented. The measured sections will then be described in terms of the FA defined from Oscar II Land, with log examples and figures.

5.1 Facies in the Vardebukta Formation on Oscar II Land

5.1.1 Facies analysis

Based on the logs from Selmaneset and Bertilryggen, 11 facies has been analysed and interpreted. An overview is given in Figure 5.2. The description of the facies is mainly based on the observations from Selmaneset and Bertilryggen, as these localities showed more continuous succession compared to Ramfjelldalen. As mentioned in Chapter 4, the facies are described based on parameters such as grain size, sedimentary structures, bioturbation, organic content, unit thickness and sedimentation. In some cases, the colour of the outcrop has been included in the description.

Facies	Log Example	Description	Interpretation
F1		**Siltstone and Sandstone with small-scale asymmetrical ripple cross-stratification (5-20 cm)** This facies contains small-scale asymmetrical ripple laminated siltstone and sandstone, including very fine to fine cross-laminated sandstone, sandstone with sinous to linguoid ripples at the top surface of the beds and non-parallel lamination to cross-laminated siltstone to very fine sandstone. Bed thickness varies from 5 to 20 cm, and the thickness of the cross-laminated sets are less than 2 cm. Bioturbation: no bioturbation, to low - moderate.	*Asymmetrical ripples can be associated with current ripple cross-laminations typically found in a wide range of environments like fluvial-, deltaic- , shoreline and offshore shelf environments, and are produced by moderate velocity flow by unidirectional currents from the lower flow regime (Tucker, 2015; Nicols, 2009). The asymmetrical ripples showed planar to linguoid cross-laminations, indicating a varying flow regime across the facies. The adjacent facies found with F4 may suggest a shoreline environment, possibly varying from offshore transition zone to lower shoreface.*
F2		**Sandstone with symmetrical ripples (5-40 cm)** Very fine to fine sandstone, with symmetrical ripples. Typically seen in upwards grading beds, and heavily cemented, lenticular shaped silt and sandstone. The appearance of the facies varies between the different localities, both due to cementation and varying sand/mud ratio. Bed thickness varies from 5-40 cm, the colour is often reddish to light grey, and appears to be moderatly to strongly cemented, calcite cement is detected. Ammonoid and shell fragments was found within this facies. Bioturbation: low to moderate, typically at the bed surfaces. Trace fossils*: Planolites, Diplocraterion, Skolithos*, and less common, *Schaubcylindricus*.	*Symmtrical ripples could be associated with wave ripple cross-lamination, pruced by oscillatory motions by relatively low orbital velcity (Nicols, 2009; Komar and Miller, 1979). The chevron upbuild often seen in the symmetrical ripples are a typical characteristic of wave ripples. Commonly found in shallow marine environments affected by oscillatory waves (Nicols, 2009; Johnsom and Baldwin, 1996). Based on the observations of the adjacent facies, this may represent a offshore-transition zone to shoreface deposit.*
F3		**Massive to Laminated silty shale** This facies comprises of massive to laminated silty shale, with sections of local thin lamianes of silt, and streaks of very fine sand, typically with some kind of ripples within. The colours varies from grey to ligh yellowish, probably due to the calcite cementation of some of the beds. No bioturbation has been documented here, but this may be due to the mass exctinction, assciated with the Permian-Triassic boundary, see Chapter 2. This will be discussed later.	*This type of facies may be associated with plumes of suspended material, for instance hyperpycnal flows (Nicols, 2009) in low-energy enviroments. The ripples seen in the streaks of sand may originate from current activity in a quiecent background, for instance turbidity currents (Boggs, 1987). Based on the overall observations, this facies may originate from below storm-wave base, indicating a offshore to offshore transition zone.*
F4		**Bioclastic sandstone - Shell rich beds (10-40 cm)** Very fine to medium sandstone,with shell material and organic fragments. 10-40 cm thick beds with abundant shell material, seen as local accumulations of shell debris within thick sandstone bodies, or laterally, contionous and separate layers. Calcite cemented. Reddish and yellowish weathering colour, and features like large-scale cross stratified sandstone (F10) and planar bedded sandstone (F6) were found directly above and below F4. Coal fragments and organic material were also observed within this facies. Bioturbation: Low to moderate, and trace fossils: *Arenicolites, Planolites, Thalassinoides* and *Skolithos*.	*Accumulations of shell debris, as found at Selmaneset, are commonly observed in shallow marine, foreshore environment. The formation of this facies typially occur within high energy settings. Beaches, subjected to active wave reworking, (Nicols, 2009) would be a common place to find F4. Compared to the other facies defined, this facies is relatively rare.*
F5		**Large-scale hummocky cross-stratified to small-scale hummocky cross-stratified sandstone sandstone (10-70 cm)** The large-scale HCS sandstone varies from very fine to medium in grain size. Plant fragments, mud clasts. Parting lineation on top surfaces. Bioturbation: low to moderate, commonly on surfaces. Trace fossils: *Planolites* and *Diplocraterion*. The small-scale HCS has the has the same appearance as the first sub-facies. Strongly cemented. Found with lense shaped, undulating layers of symmetrical rippled fine sandstone. Bed thickness 10-20 cm, may be even thinner in some cases. Laterally change in thickness. No documented bioturbation.	*HCS are typically associated with strong oscillatory flows, and the lower shoreface and shelf enviroment (Quin, 2011). HCS has also been recognised as a characteristic of storm events and tempestite beds (Morsilli and Pomar, 2012)*
F6		**Planar parallel stratified sandstone(10-80cm)** Very fine to fine planar parallel stratified sandstone. Light grey, to heavily cemented, reddish and white sandstone. Often observed a relatively high mud content in this facies, up to 40:60 mud/sand. This facies can in some cases be interpreted to be large-scale HCS. Ammonoid imprints, shell imprints and some plant fragments observed. Bioturbation: low to moderate. Trace fossils: *Planolites, Diplocraterion, Skolithos*, including some unidentified horisontal burrows	*May be associated with the upper flow regime, deposited by strong currents or lower flow regime, by low flow velocity in coarser sand, or by deposition of suspended material of fine sediments (i.e slow settling of mud in a lake or plumes in marine environments) (Boggs, 2011). The trace fossils, the symmetrical ripples and the shell debris found in this facies may suggest a marine enviroment. As it occurs in a wide range of environments, it is not a unique enviroment indicator (Boggs, 2011).*

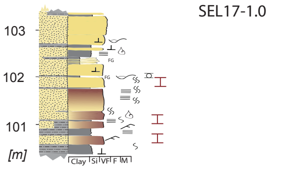
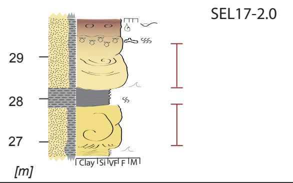
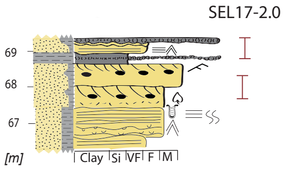
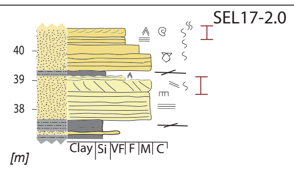
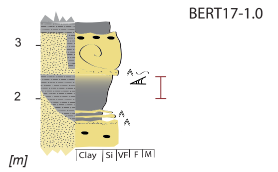
F7		**Massive, strongly cemented sandstone and structureless, heavily biorturbated silt and sandstone (2-20cm)** Massive, strongly cemented very fine to fine sandstone, reddish in colour, calcite cemented. No structures are seen, possibly due to the cementation. Heavily bioturbated siltstone and very fine to fine sandstone is also a part of this facies. No structures are visible, due to extensive bioturbation. Some beds at Selmaneset appears to be massive, but have extensive bioturbation at the bed surfaces. Parting lineation has been observed at the bed surfaces. Ammonoid imprints in the sandstone. Trace fossils: *Planolites, Thalassinoides, Skolithos,* and less common, *Schaubcylindrichnus.*	*The massive apparence might be due to surface weathering or uniform grain-size or rapid deposition or dumping, where no structures are developed due to limited time (Tucker, 2015). It may also be difficult to see the strucutres due to the strongly cementation of the beds. High degree of bioturbation, possibly in a relatively low energy setting .The trace fossils suggest a marine origin, and the intesity of the activity could indicate a lower energy setting excluding for instance high energy environments like beach-shelf transition zone(Boggs, 1987).*
F8		**Soft-sediment deformed sandstone (20-100 cm)** Fine to medium, well cemented, deformed sandstone. Bed thickness: 20-100 cm, with varying degree and scale of deformation. Two localities, both at Selmaneset and Bertilryggen had relativily thick and continous beds, with trough-shaped deformation, often appearing massive. The deformed sandstone also occured at the base of beds. Features like flame structures and water escape structures were observed in these beds. Moderate to heavily bioturbated bed surfaces, typcally with branching trace fossils. *Thalassinoides* were also found here. Imprints of ammonoid were found at bed surfaces, together with bivalves.	*Associated with post-depositional sedimentaty processes, and might occure in several setting (Tucker, 2015). Generated by gravitational induced processes, including mass movements (slumping and sliding), or internal disruptions caused by dewatering and loading (Tucker 2015; Loon, 2009). Not many trace fossils were observed here, which could be caused by the rapid depostion of the sediments, giving the organisms limited time to disrupt the sediments (Boggs, 1987). The trace fossils found, however, suggest a marine setting.*
F9		**Mud flake conglomerate (10-25 cm)** Fine to medium sandstone with mud clasts and coal fragments. The bed thickness varies from 10-25 cm. The mud clasts varies in diameter, from 1-3 cm. Often found within cross-stratified sandstone, with mud clasts in the foresets. Ripples tip surface. Relatively rare facies, typically found in the most shallow part of the successtion. No documented bioturbation. Trace fossils: *Thalassinoides* (found close to the facies)	*May be produced in a variety of settings: fluvial setting, as for instance channel deposits (Dalrymple and Choi, 2007), as storm deposits (Morsilli and Pomar, 2012) or by mass transport, like turbidity currents (Posamentier and Walker, 2006). The dominace of the fine to medium sand, the features like coal fragments and the adjacent facies of large-scale cross-stratification (F5) and symmetrical ripples (F2) may suggest a relatively shallow marine environment.*
F10		**Large-scale cross-stratified sandstone** The angle of the cross-stratification are in some cases very low, almost planar, and could be interpreted to be large-scale HCS. The colour varies from white and light grey, to reddish. Tabular and trough cross-stratified. The bed thickness 10-70 cm.The colour varies from white and light grey, to reddish. Plant fragments, mud clasts. Parting lineation on top surfaces. Bioturbation: low to moderate, commonly on surfaces. Trace fossils: *Planolites* and *Diplocraterion.*Tabular and trough cross-stratified. The bed thickness 10-70 cm.	*Trough and tabular cross-bedding are often produced by migration of large-scale, straight-crested dunes and ripples Boggs (2011), and are associated with the lower flow regime conditions. These kind of structures may be found in both marine and fluvial regimes, but the trace fossils found may suggest a marine environment. The low angled cross-stratified sandstone could also indicate large-scale HCS.*
F11		**Lenticular bedded siltstone and sandstone** The facies consist of cross-laminated sandstone with lenses encased in shale, and were only seen at Bertilryggen. Both sharp and gradual contacts between the beds are seen. A great number of concretions found. The scale of the lenses varies from mm scale, typically found in the more silty part of the facies, planar laminated silty shale., to cm scale, with symmetrical ripples with mud drapes in the more sandy part of the facies. No bioturbation has been documented.	*Typically associated with alternating energy-regimes in for instance tidal-flats and delta-fronts (Tucker, 2015; Nicols, 2009). Features like these may also be produced by weak storms in offshore settings and on alluvial plains during episodes of flooding (Daidu et al., 2013). The adjacent facies of silty shale (F3), large-scale cross-stratification and possibly HCS (F5), and loaded sandstone (F8), might suggest offshore-transition zone to lower shoreface.*

Table 5.1: Overview of the 11 facies defined from Oscar II Land, including example from logs, a short description and interpretation of each of the facies.

Facies 1: Siltstone to Sandstone with small-scale asymmetrical ripple cross-stratification

F1 contains small-scale asymmetrical ripple laminated siltstone and sandstone, as seen in Figure 5.1. Due to varying degree of cementation, the appearance of this facies seems to be slightly different between the different localities, especially at Selmaneset. The cross-lamination usually showed set thickness less than 6 cm. Presented below is three sub-facies:

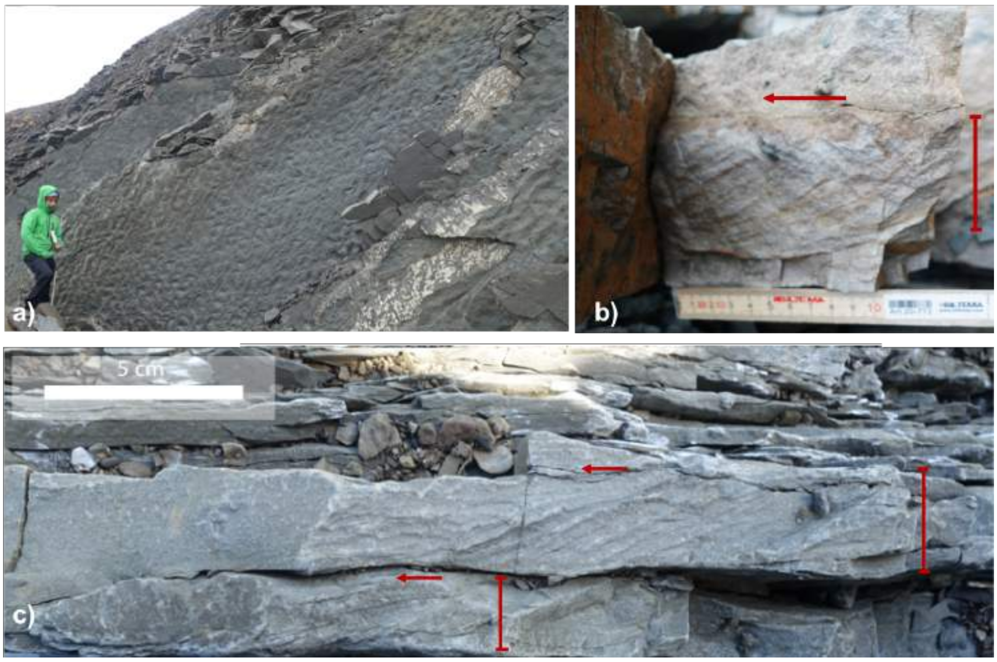


Figure 5.1: *F1: Siltstone to sandstone with small-scale asymmetrical ripple cross-lamination:* **a)** A top surface of a sandstone bed of very fine to fine sandstone with linguoid ripples from the Selmaneset locality. Geologist for scale. **b)**The picture shows one set of cross-stratified very fine sandstone from the Selmaneset locality. The cross-stratification are scoop-shaped, with a tangential base, and can be defined as trough cross-stratification. The direction of the current is from left to right, and is illustrated with an red arrow.The set is also marked with a red line. **c)** Presented in this photo is two sets of tabular cross-stratified sandstone, showing a planar structure with angular basal contact. The direction of the current is from left to right, and are illustrated with an red arrow. The sets are marked by a two red lines.

Very fine to fine cross-laminated sandstone: This sub-facies contain layers of 4-10 cm thick beds of very fine to fine cross-laminated sandstone, and can be viewed in Figure 5.1a,b. The thickness of the sets are measured to be approximatly 2 cm in one location. This facies is generally moderately to heavily cemented, with reddish to grey colour. It appears to be upwards coarsening in some locations, but this may also be due to variations in cementation. The biotubation degree here is low to moderate. The exception is in the lower parts of the measured section at Selmaneset, were no bioturbation was found in the first 60 meters. Siderite concretions and mud clasts were also found in this sub-facies, however, only at the Bertilryggen locality. This facies can be found interbedded with silty shale and laminated mudstone (F3).

Very fine to fine sandstone with linguoid ripples at top surface: This sub-facies contains very fine to fine sandstone, were sinous to lingouid ripples were found at the top surface. This can be seen in Figure 5.1a. It appears to be more planar parallel laminated at the base of the bed, and grades up to rippled top surface. The bed thickness where measured to be around 50-70 cm, and no bioturbation was observed here.

Non-parallel lamination to cross-laminated siltstone to very fine sandstone: 5-20 cm thick beds were observed, with non-parallel lamination to asymmetrical rippled cross laminated siltstone to very fine sandstone. Some slight planar lamination can also be seen in combination with the ripples. The amount of mud varied from 15-25%. The degree of bioturbation was relatively low throughout the sub-facies, and fragments of organic material was observed.

The two last sub-facies described can be found overlaying planar laminated facies (F6) or with symmetrical ripple cross-laminated facies (F2). Colours that appears in this facies are grey and reddish.

Interpretation:

The formation of asymmetrical ripples requires moderate velocity flow by unidirectional currents, from the lower flow regime (Nicols, 2009; Tucker, 2015). The ripples seen in Figure 5.1c, appears to be tabular cross-stratified, which is produced by straight-crested ripples (Tucker, 2015). The contact with the basal surface appears to be relatively angular, although this is very hard to see here due to the weathered surface (Tucker, 2015). The ripples viewed in Figure 5.1a could only be seen in plan view. They have been interpreted to be sinous to linguoid ripples, which can, according to Tucker (2015) indicate an increasing flow velocity, compared to more straight crested ripples as seen in Figure 5.1c.

The asymmetrical ripples found in F1 can be interpreted to be current ripple cross-lamination, which can be found in environments like rivers, deltas, shoreline environments, offshore shelf and deep sea (Tucker, 2015). In shallow marine environment, they may be produced by unidirectional currents, typically found in the shoaling wave zone, were a stronger landward current causes more sediments to be carried in this direction,than seaward (weak seaward current) (Reading and Collinson, 1996). Wave-induced currents like rip-currents and longshore currents (operating in the surf and breaker zone), and also tidal currents (Reading and Collinson, 1996). It can alternatively be interpreted to be asymmetrical wave-formed ripples, which can occur, according to Tucker (2015), when one of the directions of the wave motion is more powerful than the other one. These are often challenging to distinguish from straight-crested current ripples. If the motion is purely oscillatory, however, the ripples will be symmetrical, but as Nicols (2009) states, a superimposed current can result in asymmetrical wave ripples. The asymmetrical cross-stratified silt to sandstone varied between planar to tabular structure, as presented in Figure 5.1, indicating a variation in energy-level. This can also be indicated by the varying amount of mud and sand found in the outcrops, as it is also often found interbedded with shale. The bioturbation may indicate that this is a marine environment. Based on the overall observations of this facies from Selmanset an Bertilryggen, F1 may be interpreted to origin from a shallow marine environment.

Facies 2: Sandstone with symmetrical (wave-formed) ripples

This facies is assigned to symmetrical rippled, very fine to fine sandstone. The sandstone beds are grey to reddish coloured, and often very hard. This is especially the case for the facies found on Selmaneset, where calcite cement is found in most of the beds. Figure 5.2 show a typical example found in Selmaneset (Figure 5.2a) and at Bertilryggen (Figure 5.2b). Parting lineation has been found on the top surface in the presence of this facies, and the general degree of bioturbation varies from low to moderate. Some beds are also completely bioturbated, mostly at top/base surfaces.

Figure 5.2: *F2:Sandstone with symmetrical (wave-formed) ripples.* **a)** Heavily cemented, lenticular shaped sandstone, typically found at Selmaneset. **b)** Wave ripples, typically found at Bertilryggen.Notice the draping forset laminae seen in this structure and mud draps.

The bed thickness varies from 5-40 cm thick beds, the thickest beds may be up to 30-40 cm thick, and appears to be more cemented, often reddish in colour, and are more protruding.

Ammonoids and shell fragments have also been found in this facies in some locations. F2 was found interbedded with silty shale and laminated mudstone (F3), in relatively thin beds, but also in combination with planar parallel sandstone (F6), large-scale cross-stratified sandstone (F10), and at the top of HCS beds (F5). It has further been seen in the top layer of apparently massive or structurless sandstone beds (F7), especially in Ramfjelldalen. Trace fossils that were typically found in this facies were *Planolites*, *Diplocraterion*. Less common trace fossils found were *Schaubcylindrichus* and *Skolithos*, including some unidentified horizontal burrows.

Presented below is two sub-facies:

Graded sandstone with rippled top surface

This sub-facies (Figure 5.2b) contains upward coarsening (UC) sections, from silt to very fine sandstone, and very fine to fine sandstone (in some cases medium sand), with rippled top surfaces. The thickness of the UC sections can be up to 60 cm thick and trace fossils like *planolites* was observed.

Heavily cemented, lenticular shaped silt/sandstone

This sub-facies has a different appearance than the symmetrical ripples seen earlier. They appear to be strongly cemented, pretruding, lens-shaped layers. The amount of sand/mud varies from 70:30 to 50:50 in this sub-facies, and thin layers of shale has also been found the same localities at Selmaneset, but this has been interpreted as fault gauges. Some beds show planar lamination at base, and grades up to symmetrical rippled top surface It is characterised by sharp boundaries and undulating boundaries due to rippled surface, with 3D structures in some cases.

Interpretation:

Symmetrical ripples are thought to be formed by oscillatory motions, by relatively low orbital velocity and in absent of strong currents (Nicols, 2009; Komar and Miller, 1975). The wave-length of the symmetrical ripples are controlled by the grain-size and depth of the water, and larger ripples are more likely to occur in coarser sentiments and deeper water (Nicols, 2009).

The symmetrical ripples seen in this facies could be associated with wave ripples and wave ripple cross-lamination, based on several features that were observed in the field, for instance the chevron upbuild, illustrated in (Tucker, 2015)(fig.5.19), especially seen on Bertilryggen, were the internal structures were more visible.

According to Johnson and Baldwin (1996), the features that distinguishes wave-generated cross-lamination from the asymmetrical and unidirectional flow, for instance as in F1: The irregular and undulating boundary surface, the shape of the cross-strata, that is less trough-like, the upbuilding of foreset laminae showing a more bundle-wise structure, short and swollen lenticular sets, showing ”curved upper and lower set boundaries, with great variations in dip direction” and ”offshooting and draping foresets.” (Tucker, 2015; Johnson and Baldwin, 1996; van de Meene et al., 1996).

Wave ripples occur in a wide range of environments, and are common in many different shallow marine environments that are affected by the oscillatory waves (Nicols, 2009; Johnson and Baldwin, 1996). This also includes large lakes and lagoons, especially in shelf seas, where they are particularly well developed (Johnson and Baldwin, 1996). According to Johnson and Baldwin (1996), flows are highly variable in nature, and a certain degree of asymmetry can be seen in these structures, often directed onshore. Based on the observations, this may indicate a shallow marine environment, probably in the oscillatory zone, which stretches from the offshore-transition zone to the shoreface (Reading and Collinson, 1996).

Facies 3: Massive to Laminated silty shale

This facies has been assigned to units of massive to laminated silty shale, and are presented in Figure 5.3. This facies appears in combination with sandstone beds and lenses of very fine sand (2-3 cm thick), containing planar lamination (F6), symmetrical (F2) and asymmetrical ripples (F1). Beds with HCS (F5) occur interbedded with this facies. Two sub-facies has been recognised, and are described below:

Figure 5.3: *F3: Massive to laminated silty shale:* **a)** Shale with streaks of very fine sandstone, showing asymmetrical ripples and planar lamination, marked by an red arrow.**b)** Shale with local thin laminaes of silt, found close to the boundary between the Vardebukta Formation and the Periman Kapp Starostin at Selmaneset. **c)** Massive shale with yellow-greyish cemented layers, marked by red arrows.

Shale with local thin laminaes of silt

In this sub-facies, seen in Figure 5.3, the shale appears to be laminated with occasionally local lamination of siltstone of mm thickness to about 1 cm thickness. Thick continuous calcite cemented beds appears occasionally, from 2-20 cm in thickness. There is no evidence of organic material or any bioturbation in this facies. The colour of the facies varies from dark grey to more yellowish-greyish colour, which can be seen in Figure 5.3d.

Shale with streaks of very fine sandstone

This sub-facies, presented in Figure 5.3a, appears to have thin streaks of planar laminated sand varying from mm thickness up to cm thickness. Asymmetrical ripples (F1) are visible in the sand, and it also appears to be planar parallel laminated. Some concretions observed. The percentage of sand compared to shale vary from 20:80 to 50:50. 2-5 cm thick heavily calcite cemented layers were found here, tested by using hydrochloric acid. Some of these heavily cemented layers shows the same colour, interpreted to be dolomite cemented. There is no bioturbation observed in this facies, and no other evidence of organic material.

This facies also occurs close to a dolerite intrusion seen on Selmaneset, but it is darker here and the structures are harder to distinguish. As it approaches the dolerite, it get gradually darker. The facies appears to be ”baked” in this area.

Interpretation

Similar facies has been described by Solvang (2017) from the Lower Triassic succession found on Festningen and Studentdalen. Here, the facies has been assumed to originate from plumes of suspended material (Nicols, 2009) in a low-energy environment, for instance by hyperpycnal flows. According to Posamentier and Walker (2006) and Reading and Collinson (1996), hyperpycnal flows, as a result of the density contrast between waters from the rivers and the basin, will cause the sediments to be deposited offshore by bypassing the shoreline as density underflows. This may result in deposits of fluid mud or graded beds of silty or sandy deposits, for instance turbidites.

The graded appearance often seen in turbidites has not been observed, but the second sub-facies contained up to 20-50 % sand in the shale were observed, which may indicate events of higher energy. The dominant structures observed here are asymmetrical ripple cross-lamination, and parallel to non-parallel lamination. These ripples, seen in Figure 5.3a, may indicate current activity in a quiescent background.

If one look carefully at these structures, smaller scale ripples of silt, possibly seen as laminated mudstone, can be observed. This may be an indication of variations in current activity, and as these ripples were only seen in the lower part, this may indicate decreasing activity upwards in the section. The lack of bioturbation, also observed by Solvang (2017), will be discussed later in this thesis. Based on the observations, this facies may have been deposited below storm-wave base, and indicate an offshore to offshore transition zone.

Facies 4: Bioclastic sandstone - shell rich beds

This facies contains very fine to medium grey to reddish bioclastic sandstone with shell material. These occur either as local accumulations of shell debris within thicker sandstone, or in laterally continuous,separate sandstone layer. It contains 10-40 cm thick beds with abundant shell debris (Figure 5.4c), fragmented bivalves (Figure 5.4a) and bed surfaces, tightly packed with bivalve imprints (Figure 5.4b).

The thickest bed found measured around 80 cm. Small scale loading were found with some of the shell beds. The beds were strongly cemented, typically by calcite cement. Planar stratified to large-scale cross-stratified, white sandstone (F10) could be observed directly above and below this facies, typically with erosive base, and sometimes with symmetrical rippled top surface (F2). Plant fragments or organic material were also observed in this facies. Laminated shale (F3) with ammonides and possibly fragments of bivalves were also observed close to F4. A bed of deformed sandstone (F8) contained bivalves at the top surface at one location, and ammonoid imprints were found in a 40 cm thick, reddish sandstone bed, with organic material and coal shale in another. The general degree of bioturbation in these beds were from low to moderate, and trace fossils typically observed within this facies were *Arenicolites*, *Planolites*, *Thalassinoides* and *Skolithos*. This facies are restricted to the middle of section at Selmaneset, found in repeated section upwards in the succession.

Figure 5.4: *F4: Bioclastic sandstone - shell-rich sandstone* **a)** Fragmented bivalves, typically found at Selmaneset, similar to Coquina beds described in the Upper Triassic Isfjorden Member by Lord et al. (2017a). **b)** Bivalve imprints, common on top surfaces found at Selmaneset. **c)** 15 cm of bioclastic sandstone, above a 10 cm thick fine material, possibly fault gauge. The layers have tightly packed shell debris, and is a laterally continuous bed. Geological hammer for scale.

Interpretation:

Accumulations of shell debris, fragments and imprints, as found at Selmaneset, are commonly observed in shallow marine, and, the formation of this facies typically occur within high energy settings. Beaches, subjected to active wave reworking, would be a common place to find F4. According to Reineck and Singh (1980), the concentration of shell fragments, as seen at Selmaneset, may be a result of massive tranportation and erosion of shells, and deposition in a low hydrodynamic energy setting. Remains of invertebrates, like the bivalves seen at Selmaneset, may also be preserved in lacustrine environments (Boggs, 2011). Similar facies has been described in the Upper Triassic Isfjorden Member, defined as Coquina beds (Lord et al., 2017a). F4 was interpreted to be of a shallow marine origin, representing a wave influenced shell bank deposit, accumulated by current or wave activities. F4 has therefore been interpreted to be from a relatively proximal shallow marine setting, based on the adjacent facies.

Facies 5: Large-scale hummocky cross- stratified to small-scale hummocky cross-stratified sandstone

This facies contains large-scale hummocky cross-stratified sandstone (HCS) and small-scale hummocky cross-stratification (HCS) sandstone. The bed thickness varies from 10 cm to 70 cm. Two sub-facies are described below:

Large-scale hummocky cross-stratified sandstone

This sub-facies is assigned to the large-scale HCS sandstone. The grain size varies from very fine sandstone to medium grained sandstone. The colours varies from white sandstone, to less cemented, gray sandstone. The white sandstone beds on Selmaneset (see Figure 5.5b), is a typical example of the large-scale HCS sandstone. The structures appears to be planar parallel, but are interpreted to be large-scale HCS. Bioturbation was generally low to moderate, and was often observed on the top surface of the beds. Parting lineation has also been found on the top surface, including other features like plant fragments and mud clasts. Trace fossils in this facies are *Diplocraterion* and *Planolites*.

This facies has been observed in thin beds of very fine sandstone, interbedded with laminated shale (F3). It has also been observed covering planar parallel white sandstone (F6), and with rippled top surface (F1,F2).

Small-scale hummocky cross-stratified sandstone

This sub-facies (Figure 5.5a,c) has the same appearance as the first sub-facies, but the scale is smaller, and it is generally more cemented. It only appears in one location at Selmaneset, and can be found with lens-shaped, and undulating layers of symmetrical rippled fine sandstone (F2), some with planar lamination as internal structure. No bioturbation has been observed here. The bed thickness varies from 10 cm to 20 cm, and appears to change laterally. Swaley cross-stratification has possibly been observed in the top of this section.

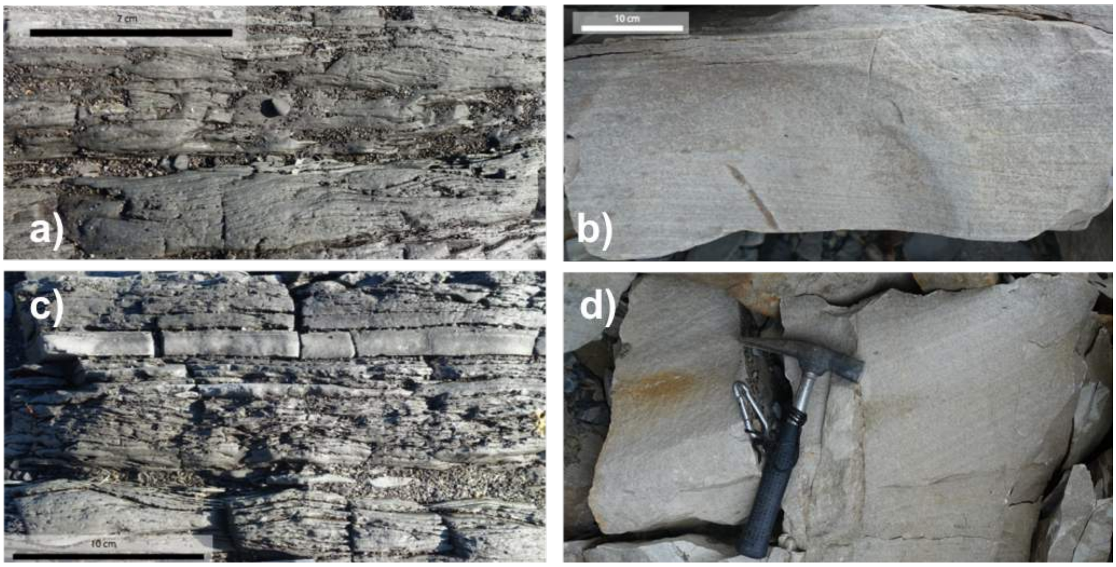


Figure 5.5: *F5: Large-scale hummocky cross-stratified sandstone and small-scale hummocky cross-stratified sandstone.* **a)** Small-scale cross-stratified sandstone. **b)** Low-angle cross-stratified sandstone, found at Selmaneset. Appears to be planar parallel bedded in some cases, and could be interpreted to be Large-scale HCS. **c)** Small-scale hummocky cross-stratified sandstone. **d)** An example of steep angle, tabular cross-stratified sandstone, found on Selmaneset. Geological hammer for scale.

Interpretation:

Figure 5.5a) and c) presents examples of the small-scale HCS seen at Selmaneset. Every layer drapes over the next, thickening over the crest and thinning down in the trough, as seen from the example in Figure 5.6. Based on the scale, (ca 10 cm wave-length, and 1-2 cm wave-height) these are there defined as small-scale HCS.

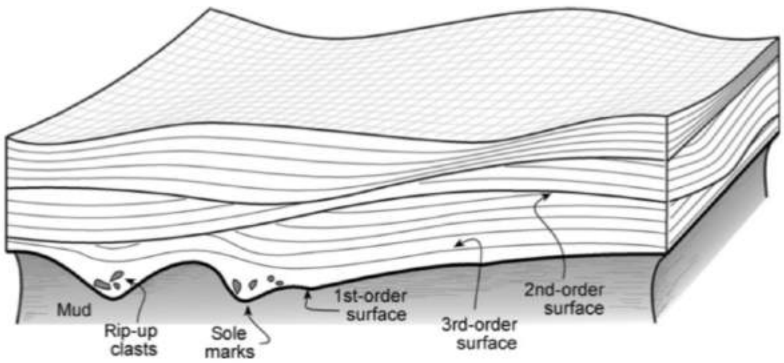


Figure 5.6: Illustration of the hummocky cross-stratification, modified by Morsilli and Pomar (2012).

Both the small-scale and the large-scale structures that were seen in the field were often found with symmetrical rippled and undulating surfaces, which could be associated with waning storm deposition, like wave ripples with straight-crested (Quin, 2011).

According to (Quin, 2011; Johnson and Baldwin, 1996), HCS are defined as medium to large-scale cross-stratified structures, were the 3D bed form is preserved by undulating and gently dipping laminae. The cross-stratification usually show no preferred orientation, and the lower bounding surface of the sets are often erosive, with dip angle lower than 10 ° and up to 15° (Quin, 2011; Morsilli and Pomar, 2012).

HCS has typically been interpreted to be the deposit of large-scale ripples, and often tied to strong oscillatory flows, partly due to its commonness in lower shoreface and shelf facies Quin (2011); Johnson and Baldwin (1996). But as Quin (2011) also mentions, HCS-like structures has been found in both deep water settings, in turbidite sandstone beds, and in fluvial deposits, and several hypotheses has been investigated to explain this. HCS-like structures has also been found in lacustrine environment, estuarine environments, on intertidal flats and in pelagic settings (Morsilli and Pomar, 2012), but since HCS were first defined, it has been considered to represent a diagnostic structure of the offshore transition zone to shoreface environment, and has commonly been used as a criterion for recognition of storm events, as it is characteristic for tempestite beds (Morsilli and Pomar, 2012).

Moving landward, the diameter of the wave orbital close to the seabed will increase, were it reaches a maximum in the breaking zone in the shallow waters. The diameter will then decrease further landward as the bottom friction and breaking reduces the energy of the waves (Yang et al., 2006; Reading and Collinson, 1996). According to the findings of Yang et al. (2006), the wave length of HCS should change in the same manner. Figure 5.7, from Yang et al. (2006), illustrates a probable change in the diameter of the bottom orbital and the wavelength of HCS from shelf to the coast.

Based on the observation presented above, this facies has been interpreted to origin from storm dominated offshore transition zone to shoreface environment. The second sub-facies may be more proximal compared to the firts, based Figure 5.7.

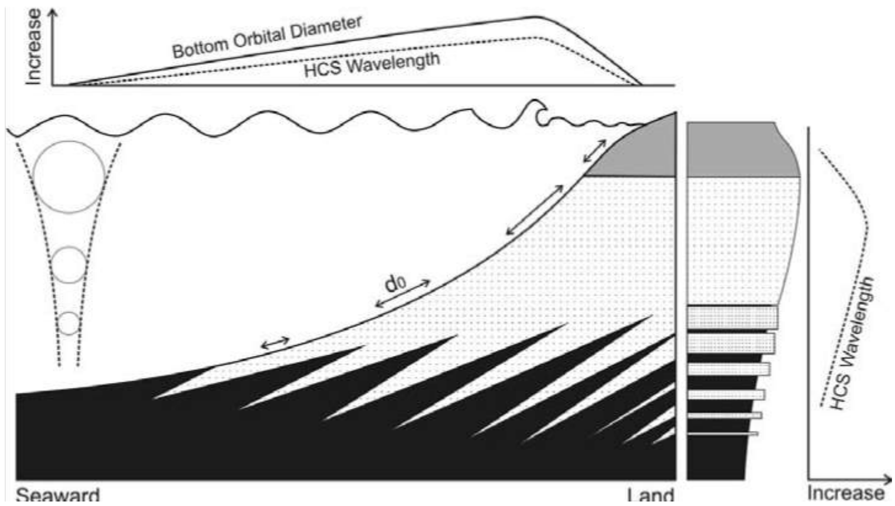


Figure 5.7: Schematic diagram modified from Yang et al. (2006), presenting a probable change in the diameter of the bottom orbital and the wavelength of HCS from shelf to the coast.

Facies 6: Planar parallel stratified sandstone

This facies contains very fine to medium sandstone with planar parallel stratified sandstone (Figure 5.8). Some ripples, both symmetrical (F2) and asymmetrical (F1) may also be found in this facies in some localities. The bed thickness of this facies varies from 10 to 40 cm. In one location, the beds were 50-80 cm thick. The thickest section found was around 1.3 m.

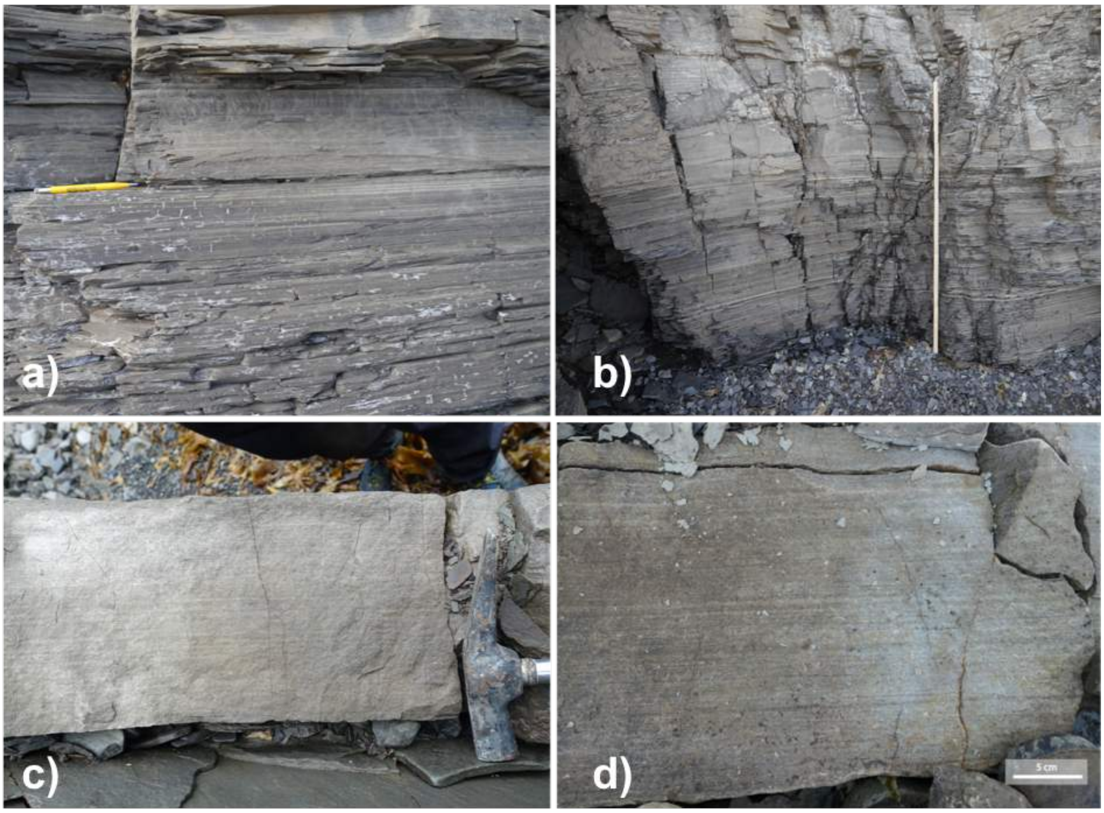


Figure 5.8: *F6: Planar parallel stratified sandstone* **a)** Planar laminated very fine to fine sandstone from Bertilryggen. Pencil for scale. A log example has been included in the table above (Figure 5.2). **b)** Example from Bertilryggen: Planar laminated very fine sandstone. Measuring stick for scale. **c)** Planar laminated fine sandstone. Example from Selmaneset. Geological hammer for scale. **d)**Example from Selmaneset: Planar parallel stratified sandstone

The colour of the facies varies from light grey to heavily cemented, reddish and white sandstone. The mud/sand ratio of the facies in one location 40:60. This facies is sometimes accompanied by symmetrical ripples (F2), large-scale cross-stratification white sandstone (F10) and HCS (F5), and are occationally very cemented. At Bertilryggen, this facies is often observed with lenses of coarser sand, possibly caused by ripples. Trace fossils like *Planolites, Diplocraterion, Skolithos* and unidentified horizontal burrows have typically been seen within this facies, together with ammonoid imprints and shell imprints, and some plant fragments. Minor loadcast could also be seen in one bed with abundant *Skolithos*. The bioturbation degree varies from low to moderate, and concretions of yellow colour were found at one location.

Interpretation:

Based on the the trace fossils, the symmetrical ripples and the shell debris found within this facies, it may suggest a marine environment. These structures are often found with symmetrical ripples (F2) and low angled large-scale cross-stratification (F10).

Plane bedding and planar lamination are associated with the upper flow regime, deposited by strong currents (Tucker, 2015), illustrated in Figure 5.9. They may also form at relatively low flow velocity in coarser sands, but as the velocity increases, dune beds are generated. As the flow velocity increases, ripples and dunes bedforms becomes washed out, producing plane beds with well defined planar lamination (Tucker, 2015; Nicols, 2009). Planar lamination are also produced as result of deposition of suspended fine material or low density turbidity currents, and are typically found in mudrock, fine-grained sandstones and limestones (Tucker, 2015; Boggs, 2011).

As this type of structure occur in a variety of environments, it can not be used as an indicator on a depositional environment on its own (Tucker, 2015). Based on the trace fossils, however, this facies can be associated with a marine environment.

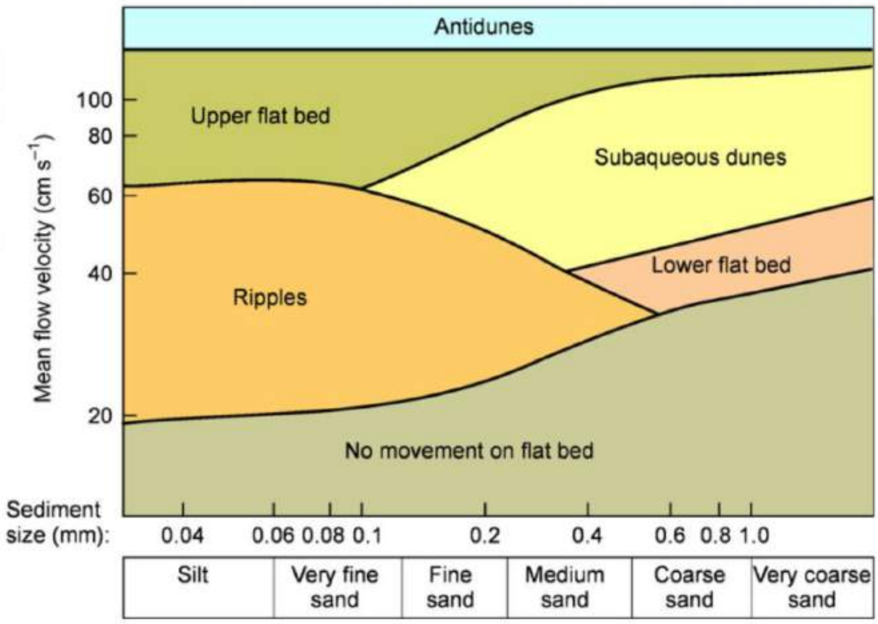


Figure 5.9: A bedform stability diagram, presented in Nicols (2009)

Facies 7: Massive to structureless, heavily bioturbated silt and sandstone

This facies is typically found at Selmaneset and Ramfjelldalen. F7 is divided into two sub-facies: Heavily cemented, massive sandstone, and heavily bioturbated, apparently structurless sandstone. The bed thickness varies from 2 cm to 10 cm, and the colour varies from grey to red.

Heavily cemented sandstone

This sub-facies is restricted to Selmaneset, were it typically found in the middle of the measured section. Several beds of very fine to fine sandstone appears to be structureless.

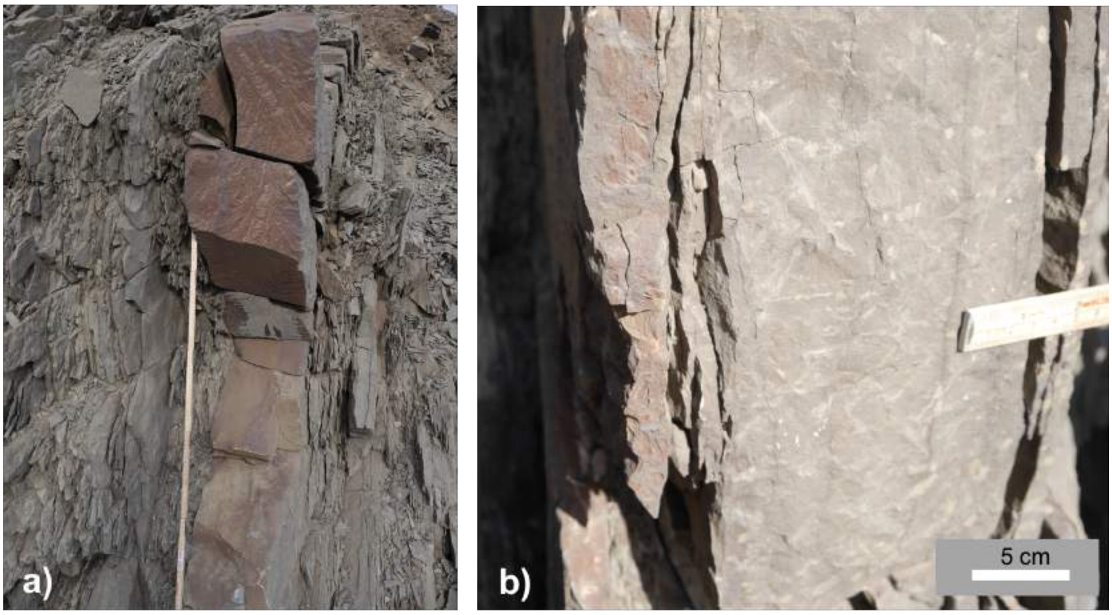


Figure 5.10: *F7: Massive to structureless, heavily bioturbated silt and sandstone.* **a)** An example of a strongly cemented, reddish coloured bed of apparently massive sandstone. It is only bbserved at Selmaneset and in Ramfjelldalen. Measuring stick for scale. **b)** A heavily bioturbated bed, found on Selmaneset. No visible structures.

The colour is often reddish, and it appears to be strongly cemented by calcite cement. Some parting lineation is found on the top surface of some of these beds, and top and base may be low to moderately bioturbated. Trace fossils observed within F7 are *Planolites, Thalassinoides, Skolithos.*

Ammonoids has been identified on the top surfaces of the sandstone beds. This facies appears in thin beds, interbedded with laminated shale (F3), sometimes showing rippled top surface (F1), (F2), and in some cases being found with planar laminated sandstone beds (F6), with parting lineation at its top surface.

Heavily bioturbated sandstone

As a part of this facies, heavily bioturbated sandstone has been included. These sandstones beds are bioturbated throughout, and no structrues are visible. The grain size varies from very fine to fine sandstone. Some of the beds found at Selmaneset appears to be massive, but show extensive bioturbation on top/bottom surface.

The bed thickness varies from 7-9 cm thick beds in the upper part of the succession at Selmaneset. Colour of this sub-facies is light grey to reddish.

Interpretation:

There may be several reasons why the sandstone beds in this facies (Figure 5.10) appear massive or structureless. Firstly, it may appear massive simply due to surface-weathering or uniform grain size. Figure 5.10a may be affected by the first option mentioned, as this bed is clearly heavily cemented. According to Tucker (2015), there are several methods to bring the structures to light in the lab, but these methods has not been performed in this thesis. The beds may also appear massive or structureless due to a very high degree of bioturbation, which are the case for Figure 5.10b. In some cases it may also be difficult to decide whether the bed is actually bioturbated or massive, as individual traces may be difficult to recognise (Nicols, 2009). Massive beds may also be produced as a result of rapid deposition or dumping, where no structures are developed due to limited time (Tucker, 2015). The latter are typically the feature of debris-flow deposits, turbidity currents and grain-flow sandstones, and also in some fluvial sandstones (Tucker, 2015; Posamentier and Walker, 2006; Reading, 2001).

The massive, heavily cemented, reddish layers appear along the whole section at Selmaneset. But as these origin of the massive apparance of the reddish sand bed may be a result of post-depositional process, like cementation, this may not be a good paleoenvironment indicator. The heavily bioturbated sandstone, however, could give an idea of what kind of environment this is. For instance, as Boggs (1987) mentions, only a few species can survive in the near-shore beach and shelf zone, dominated by the high-energy setting, and bioturbation rate in the sandy deposits from the beach-shelf transition zone are therefore generally low. The sandy deposits found in deeper environments on the shelf may be bioturbated in the upper parts. This could indicate that the origin of this sub-facies is in low -energy environment. In order to make an detailed interpretation of the depostional environment, it will be important to use adjacent facies. However, based on the trace fossils found within this facies, it appears to be a marine environment.

Facies 8: Soft-sediment deformed sandstone

This facies can be described as fine to medium, well cemented, deformed sandstone, and a given example of the facies is given in Figure 5.11.

Figure 5.11: *F8: Soft-sediment deformed sandstone.* Three examples of soft-sediment deformed sandstone, found at Bertilryggen (**a)** and **b)**, and at Selmaneset (**c)**).

The grain size appears to be fine to medium grain sized, and the bed thickness varies from 20 cm to 100 cm, and the degree of deformation also varies. Two localites showed relatively large-scale, trough-shaped deformation, were the entire bed was disrupted, while in most cases, small scale deformations occurred at the base of the beds.

The sedimentary structures that were observed in the beds were often planar lamination at the top of the bed, and with features like flame structures and water escape structures at the bottom of the deformed bed. The sandstone beds could also appear to be massive in the thickest sandbeds. This facies often appears with HCS and SCS (F5), overlying laminated mud facies (F3) interbedded with thin layers of symmetrical rippled sandstone (F2), and heavily bioturbated sandstone (F7).

The deformed beds typically show moderately bioturbation to heavily bioturbated surfaces on top surface, and trace fossils like *Thalassinoides* and branching trace fossils has been observed. Bivalves and ammonides has been observed on the top surface of one of the deformed beds at one of the localities.

Interpretation: Soft-sediment deformed sandstone beds may occur in several settings, but are mostly associated with post-depositional sedimentary processes (Tucker, 2015; Nicols, 2009). Many different structures may form after deposition, often generated by gravitational induced processes, including mass movement, like slumping and sliding, or more internal disruption caused by dewatering and loading (Tucker, 2015; Loon, 2009).

Slumps contain a large variety of deformed sediments, according to Posamentier and Walker (2006). The slump units may vary in thickness from meters to tens of meters, and the lithology may consist of only mudstone, to pulled-apart or rolled-up sandstone beds, in a mudstone matrix. The depostion of slumps usually happens very fast, and may often be initiated along weak layers of high pore pressure. The transport distance of slumps may vary greatly. From meter sized slumps from channel collapsed walls to ”hundres of kilometre across the basin floor” (Posamentier and Walker, 2006).

Other gravity-induced soft-sediment deformation structures may form due to ”differential vertical movement in unstable sediment”s, as a result of ”reversed density gradients.” This may lead to material sinking into the underlying material, forming load casts, both small scale to meter sized (Loon, 2009). The structures related to loading are produced when sand of high density are deposited on lower density mud deposits. Flame structures, observed at one location in Bertilryggen, may occure when mud is pushed up into the overlying sand bed (Nicols, 2009). Dewatering structures are defined as soft-sediment deformation formed by fluidisation processes, as a result of expolsion of pore fluid (Nicols, 2009).

A genetic interpretation of the soft-sediments deformation structures may often be difficult, as stated by Loon (2009). Further studies of these beds would therefore be required in order to make a more detailed interpretation of their origin.

Facies 9: Mud flake conglomerate

This facies is assigned to fine to medium sandstone with mud clasts and coal fragments, and are only found at Selmaneset. Some beds have large-scale cross-stratification (F10) near the top surface, gradually getting more laminated near the base. The bed thickness vary from 10 - 25 cm, and are commonly mud supported. The mud clasts varies from 1-3 cm in diameter, in some cases smaller. This facies is more rare compared to the others, and can be seen overlying planar laminated (F6) to symmetrical rippled sandstone (F2), and bioclastic sandstone (F4).

Figure 5.12: *F9: Mud flake conglomerate.* Typical examples of F9 observed at Selmaneset, the size varying from less that 1 cm, to almost 3 cm in diameter.

Interpretation:

Similar facies were described by Wignall et al. (1998): a conglomerat, consisting of intraclasts and extraclasts of a few centimetres siltstone clasts, often with a ”flat pepple” shape. These were found in the Lower Triassic Siksaken Member at Festningen, and similar pebbles were presumably observed all over the sandstones of this member. The facies succession that were described from Siksaken Member in Wignall et al. (1998) were interpreted to be from an upper offshore storm setting, transitioning into shoreface deposits.

Rød et al. (2014) also described a similar facies. Mud flake conglomerate were presented as one of the described facies from Upper Triassic De Geerdalen Formation from Edgeøya to Central Spitsbergen, and states that this feature is one of the characteristic on distributary channel facies, together with erosive base. This has been described by Dalrymple and Choi (2007), were the term mud pebbles been used. Dalrymple and Choi (2007) describes mud pepples as typical features of channel bottom deposits in tide-dominated and tide-influenced conditions, and ties this type of facies to the middle reach of estuaries and delta-plain environment.

Mud clasts or mud flakes like this may be formed in a variety of settings, like for instance storm deposits (Morsilli and Pomar, 2012), fluvial deposits and mass transport deposits (Posamentier and Walker, 2006). However, as this facies is relatively rare (only observed in two-three locations), it is difficult to use this alone as an indicator. Based on the adjecent facies, however, this appears to be marine deposits.

Facies 10: Large-scale cross-stratified sandstone

This facies is typically seen at Selmaneset. The grain size varies from fine sandstone to medium grained sandstone (in some cases coarser), showing tabular and trough-scale cross stratification. The colours varies from heavily cemented red to white sandstone. The angle varies from low, typically found in the white sandstone beds on Selmaneset (see Figure 5.5b), to steep (Figure 5.5d). More examples can be see in the Facies association section, later in this chapter (Figure 5.17b,c). Bioturbation is generally low to moderate, often observed on the top surface of the beds. Some parting lineation has also been found on the top surface in some localities, including other features like coal fragments and mud clasts. Trace fossils observed in this facies are *Diplocraterion* and *Planolites*.

The facies is found overlying planar parallel white sandstone (F6), and with rippled top surface (F1,F2). In some cases it is covered by planar parallel stratified sandstone (F6) or heavily cemented, structureless sandstone (F7).

Figure 5.13: *F10:Large-scale cross-stratified sandstone* a) Tabular cross-stratified sandstone, typically seen in thick, reddish sandstone beds at Selmaneset. **b)** Large-scale cross-stratified sandstone, tabular cross-stratification.

Interpretation:

The structures seen in Figure 5.5b,d, appears to be large-scale cross-stratification. As mention, both tabular- and trough cross-bedding have been observed. The tabular cross-bedding may be produced by straight-crested dunes or wind ripples, while the trough cross-bedding are usually formed by lunate and sinuous dunes, produced in the lower flow-regime (Tucker, 2015; Boggs, 2011), (see Figure 5.9), which could be found in both marine and fluvial environments. Based on the trace fossils observed within this facies, and the coal fragments and the mud clasts, this has been interpreted to be shallow marine deposits.

Facies 11 : Lenticular bedded siltstone and sandstone

This facies features cross-laminated sandstone in lenses encased in mud, and could only be seen at Bertilryggen. The contacts changes between being sharp to gradual and the scale of the sand lenses seems to vary. The lenses varies from mm scale to cm scale. Figure 5.14a,b and c show examples of lenticular bedding observed at Bertilryggen. This can be found in between silty shale (F3), and it has also been observed covering large scale cross-stratified structures (F10), and HCS (F5) and below loaded sandstone (F8). Figure 5.14d shows lenses of sand in mm scale, found in the uppermost section of Bertilryggen (See Appendix F). A great number of concretions are also observed in the uppermost part of this section, together with planar laminated silty shale, and thin layers of cemented, symmetrical rippled sandstone (F2).

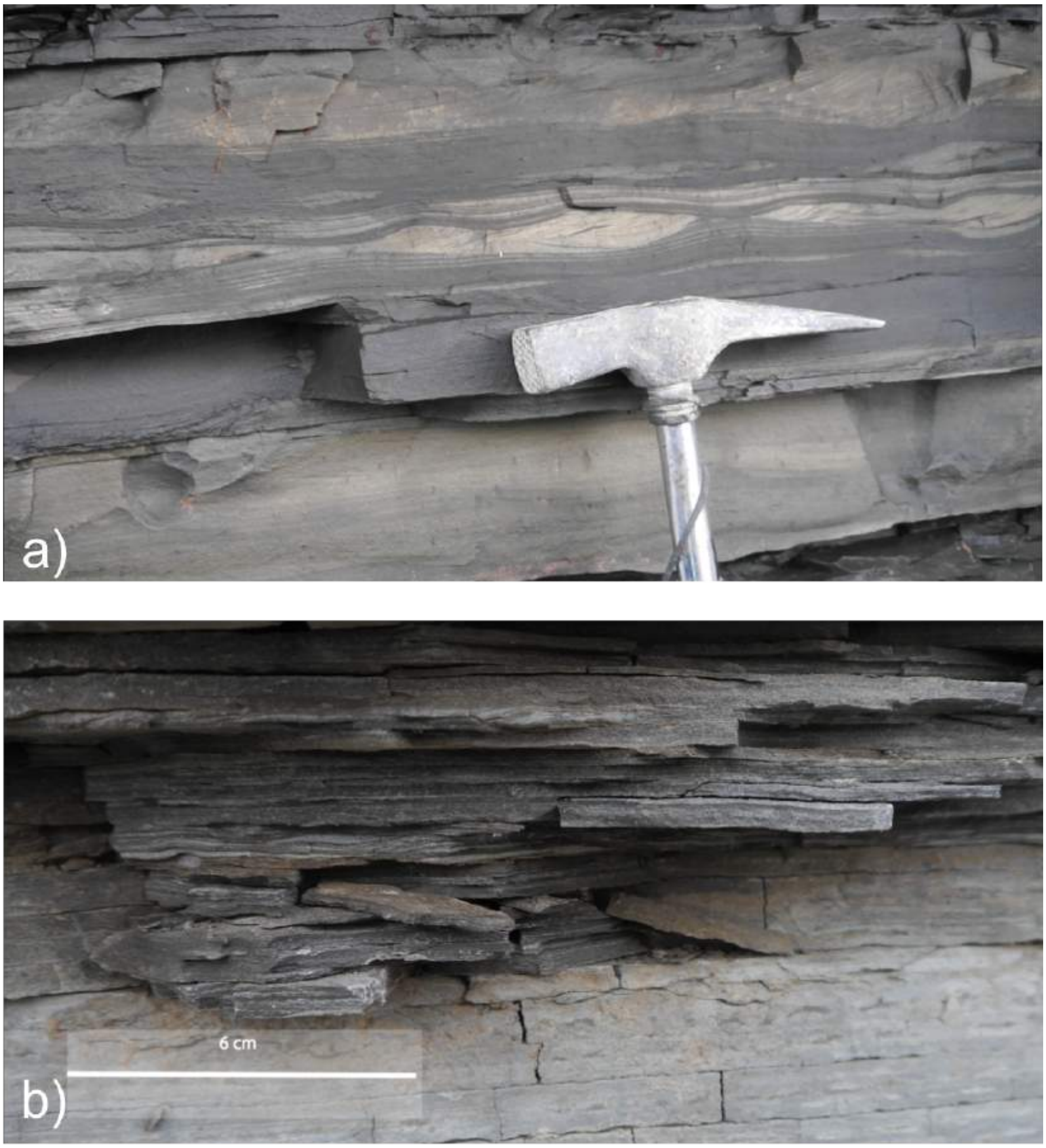


Figure 5.14: **a)** Presented in this photo is symmetrical rippled lenses of sandstone, incased in shale. This lenticular bedding was typically found at Bertilryggen. **b)** Small-scale lenses of very fine sand, incased in shale. Typically found in the upper 12 meters of the Bertilryggen section.

Interpretation:

The terms lenticular, wavy and flaser bedding are used to describe the alternation between of cross-laminated sand and mud beds and laminae, and are typically associated with alternating energy-regimes in settings like tidal-flats and delta-fronts (Tucker, 2015; Nicols, 2009). According to Daidu et al. (2013), these features can also be produced by weak storms in offshore settings, and on alluvial plains during episodes of flooding. The primary occurence, however, is in tidal settings.

Compared to the cross-laminated sandstone described in F1 and F2, this facies shows a periodically movement between sand and mud. As Tucker (2015) states, the mud is result of suspension and deposition during times of slack water, and the sand reflects times of current activity.

Ichnofacies observed in the Vardebukta Formation at Oscar II Land

Trace fossils are produced by a wide range of organisms, and may be classified based on the morphology (tracks, trails, burrows, boring etc.), the organisms presumed behaviour (resting traces, crawling traces, grazing traces, feeding and dwelling structures), and based on preservation process (Boggs, 1987).

According to Boggs (1987), particular interest is put into the marine ichnofacies, where seven groups has been recognised, each named by a representative trace fossil: *Skolithos*, *Cruziana*, *Terodolites*, *Trypanites*, *Glossifungites*, *Zoophycos* and *Nereites* (Boggs, 1987). Only the first two ichnofacies, *Skolithos* and *Cruziana*, were observed at Oscar II Land, and these will be explained further. Figure 5.15 presents four typical examples from Selmaneset and Bertilryggen.

Trace fossils can be a powerful tool when it comes to interpreting paleoenvironments, and the observed changes in trace fossil assemblages, ichnofacies can be used as evidence for changes in the environment (Nicols, 2009). However, as the trace fossils occur in a wide range of depositional environments, they do not give an accurate estimate of the paleo-bathmetry (Boggs, 2011).

The trace fossils were typically found on the bed surfaces. It should be noted that the trace fossils observed in the field occurred independently to the facies defined, and will therefore only be used as a supplementary observations when interpreting and discussing paleoenvironments. This section will give a brief presentation of the ichnofacies observed in the Vardebukta Formation at Oscar II land.

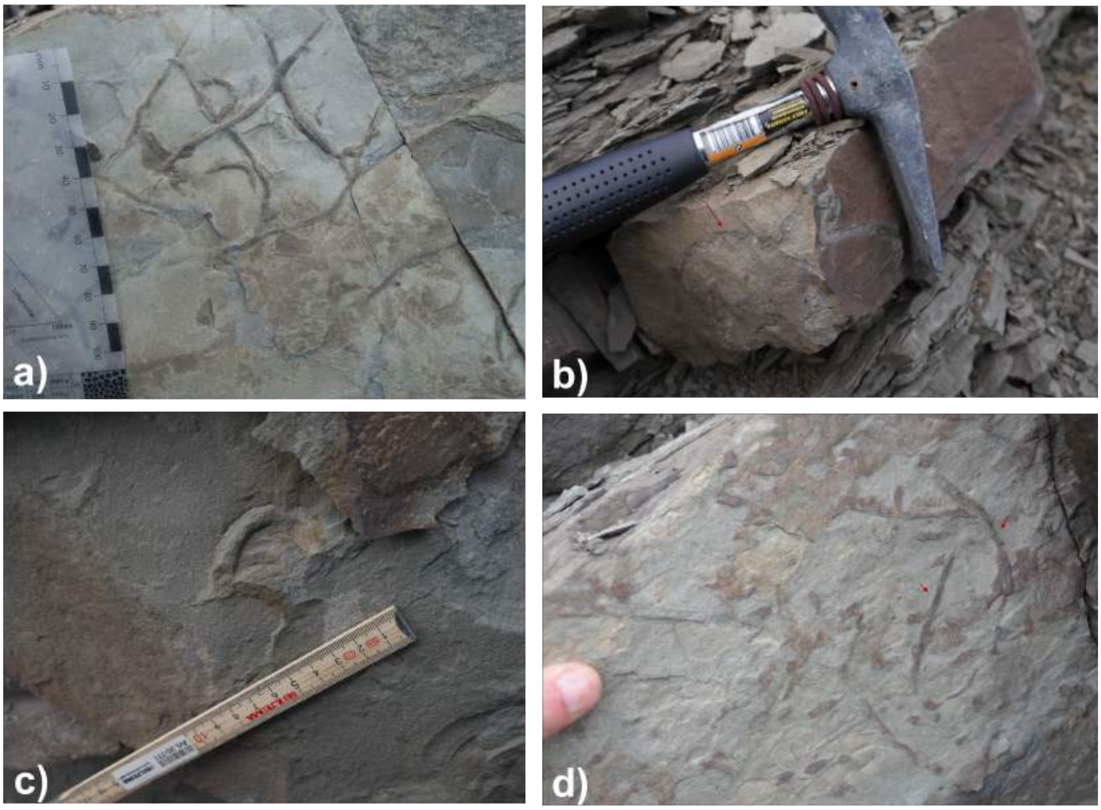


Figure 5.15: **a)** Branching trace fossils found on the surface of deformed medium sandstone, at Selmaneset. This has been interpreted to be *Thalassonoides*. **b)** A U-shaped burrow. As no spreite is observed within, this has been interpreted to be *Arenicolites* **c)** *Dipocraterion* **d)** horizontal and vertical burrows

Skolithos ichnofacies

According to (Nicols, 2009), the *Skolithos* ichnofacies includes *Skolithos*, *Diplocraterion*, *Arenicolites* and *Ophiomorpha*, where all except the latter were observed in the field. This assemblage is named after simple vertical tubes produced by from the high-energy foreshore region, and are associated with the harsh conditions found on the intertidal zone of sandy coast, and the high-energy processes such as waves, currents, desiccation and saility flucturation, where the organisms adapt to these conditions by burrowing in to the sand (Boggs, 1987), creating the characteristic U-shaped and the vertical burrows of *Skolithos*, *Diplocraterion*, *Arenicolites* and *Ophiomorpha*.

Skolithos are, as stated by Hasiotis (2014), defined as ”straight vertical to slightly inclined cylindrical tube burrows”, with parallel burrows, not branching, with structureless infill, and can be slightly J-shaped. *Skolithos* are described as dwelling burrows produced by a variety of marine organsisms and insect larvea (Hasiotis, 2014), and the assemblage is often associated with sandy shorelines (Nicols, 2009). *Skolithos* were found in the most sandy parts of Selmaneset, and relatively rare at Bertilryggen, only observed in one bed.

Diplocraterion are described as an U-shaped burrow with spreite. These were seen at several localities at Selmaneset. It is typically associated with middle shoreface, but also sandy tidal flats and channels (Hasiotis, 2014). An example from the field is presented in Figure 5.15c and Figure 5.17d. Abundant *Diplocraterion* were found in medium sandstone, with planar lamination (F6) to large scale cross-stratification (F10) and symmetrical ripples (F2). The 2 meter reddish sandstone bed seen in the log and the picture in Figure 5.19 represents the location at Selmaneset with most abundant *Diplocraterion*.

Arenicolites are described as vertical to slightly inclined U-shaped burrows. No spreite is seen, and the tubes are cylindrical with smooth walls (Hasiotis, 2014). *Arenicolites* were only found at one location at Selmaneset, in strongly cemented, very fine sandstone, with shell debris. The example from the field are presented in Figure 5.15.

Cruziana ichnofacies

Moving seaward, the elements of the *Cruziana* ichnofacies should be recognized (Dalrymple and Choi, 2007), as the environment gets less demanding, but still affected by erosive currents (Boggs, 1987). Burrow tend to be shorter, and feeding burrows can be found due to the abudant organic matter in this zone. The *Cruziana* ichnofacies includes *Cruziana, Rhizocorallium, Chondrites, Planolites* and *Thalassanoides* (Nicols, 2009). Among these were *Rhizocorallium, Planolites* and *Thalassanoides* observed in the Vardebukta Formation at Oscar II land.

Planolites are relatively simple unlined and unbranched burrows, cylindrical to subcylindrical. They appear to be straight to gently curved, and are usually horizontal to oblique to the bedding planes, and are associated with shallow marine to deep marine deposits. They may also be found in continental deposits, like alluvial, lacustrine and eolian (Hasiotis, 2014). *Planolites* could be found at the surfaces of sandstone beds across the whole succession at Selmaneset and Ramfjelldalen.

Thalassanoides can be described as branched cylindrical burrows, interconnected by vertical shafts, which forms a three dimensional boxwork. They are typical found in shallow marine and deep marine environments, for instance in turbidites Hasiotis (2014). These were found in three locations at Selmaneset, usually in cemented, very fine to fine sandstone. At one point it was found in a deformed sandstone bed (F8), with adundant bivalves at the top surface. *Rhizocorallium* consist long and U-shaped tubes, were the spreite has sinuous, bifurcating or planispiral internal structure (Hasiotis, 2014).

However, *Rhizocorallium* and *Thalassanoides* were less common in the Lower Triassic succession at Oscar II land, compared to the trace fossils presented above.

According to A.Buatoisa et al. (2018), the *Skolithos* ichnofacies prevails in the offshore transition zone to the lower shoreface during storm dominated settings. As the storm diminishes, the *Cruziana* ichnofacies becomes more distinct. However, as also stated by A.Buatoisa et al. (2018), storm dominated settings typically shows a wide ichnological range, and elements from both ichnofacies may therefore be seen.

Based on this, the trace fossils seen in the Vardebukta Formation at Oscar II Land may be associated with a shallow marine environment, from the high-energy sandy shore, to less energetic shelf settings.

5.2 Facies Associations

Presented below is the 7 facies associations (FA) identified on Oscar II Land in the Lower Triassic Vardebukta Formation. A summary is given in Figure 5.3. The terminology used to interpret the facies associations are mainly based on Reading and Collinson (1996) (fig 6.6).

In this figure, Reading and Collinson (1996) illustrates a generalised shoreline profile, including the subenvironments, processes and facies. A modified version has been presented in Clifton (2006), and can be viewed in Figure 5.16. A vertical succession are included in this figure, illustrating the vertical and the horizontal relationship between the associations.

As the terminology may vary between the different studies, whether the emphasis has been put on the process or the morphology, the position of the subenvironments may be differentiated based on the storm and fairweather wave base, mean high- and low-tide levels. The nature of the wave transformation may also be considered (Reading and Collinson, 1996). The definitions of the subenvironments will be used in discussion (Chapter 6).

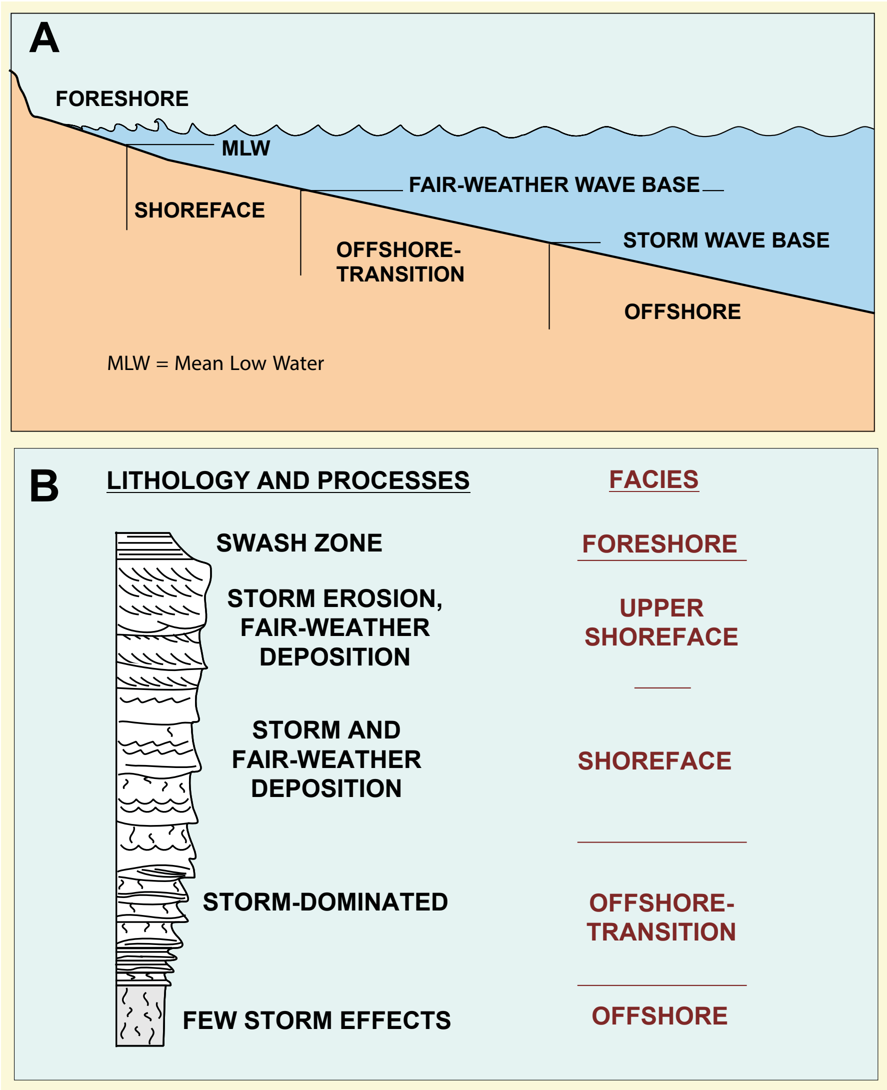


Figure 5.16: "Beach to offshore-profile" from Reading and Collinson (1996), modified by Clifton (2006).

Depisitional Enviroment	Facies Associations (FA)	Facies	Description	Geometry/thick-ness
Shoreface	FA 7: Barrier bar deposits	F2, F3, F4, F5, F6, F7, F9	Upward coarseing sections from siltstone with planar laminated very fine sandstone, to low angle to trough cross-bedded white and reddish sandstone, with wave rippled top surfaces. Bivalve rich beds and beds with conspicuous *Diplocraterion*. Mud flake conglomerate and coal fragments observed within the sand-stone in thin siltstone layers. This FA is similar to the barrier bar deposits described at Festningen (Mørk et al. 1982), but no evidence of tidal influence or lagoonal deposits are observed.	*A 53 meter thick interval found on Selmaneset, with several 3-8 meter thick small-scale coarse-ing up sequences. FA 7 grades into the lower shoreface deposits FA 5, possibly due to a trans-gressive event.*
	FA 6: Upper Shoreface	F1, F2, F5, F6	Dominated by small-scale HCS and wave reworked sediments. The dominant grain size is fine to medium sandstone. Lense-shaped sandstone beds, possibly swaley cross-stratified, and local deformed sandstone has been found. Based on the lack of bioturbation and the wave reworked/small-scale HCS sandstone, this has been interpreted to be upper shoreface deposits.	*A 9 meter interval occurs at Selmane-set. Can be found between two inter-vals of FA 5.*
	FA 5 : Lower to Upper shoreface	F1, F2, F3, F4, F5,	Very fine sandstone, reworked by asymmetrical currents to symmetrical oscillatory movements. Beds of abundant bivalves and shell debris is common, typical-ly in the wave rippled sandstone .The shell debris may indicate a high energy setting (Clifton et al. 2006). Low to moderate bioturbation, and trace fossils observed are *Planolites* and *Skolithos*, *Thalassonoides*, and *Arenicolites*. This FA has been interpreted to be lower shoreface to uppershore face deposits.	*The thickest associ-ation found, possibly repeated. Comprises of slightly shallowing up units, 2 - 8 meters thick.*
	FA 4 : Lower Shoreface	F1, F2, F3, F6, F7, F10	This association is dominated by silt to very fine sandstone, with ripple cross-laminations (F1, F2), and low to moderatly bioturbated surfaces. The sand-stone units have decreased in thickness and abun-dance, the cementation rate is much higher and the mud content has increased compared to the underly-ing unit.	*Makes up the last 68 meters of Selmane-set. Comprises of coarsening up units (2-7 meter thick.) Covereing the FA 5, which could indicate an transgression.*
Offshore transition Zone	FA 3: Offshore transition zone to lower shoreface	F1, F2, F3, F5, F6,	This facies association contains 1 to 2 meter thick units of very fine sandstone with laminated silt in between. With low to moderate bioturbation, shell hash, fish fragments, plant fragments and trace fossils like *Planolites*. It has been interpreted to origin from offshore transition zone to lower shoreface.	*Coarsening upwards units of 1-2 meters. Makes up an interval of 17 meters at Selmaneset. May also be found at Bertilryggen, but possibly more distal .*
	FA 2: Lower offshore transition zone	F1, F2, F3, F5, F6,	This facies association is still considered to be of an outer shelf settings, but abundance of siltstone and sandstone beds has increased. Laminated shale with calcite cemented siltstone and sandstone beds with planar lamination to current ripples dominated this FA, and are interpreted to be of storm deposits. Ammonoid imprints has been seen in the lower section of this FA, including some shell fragments and slight bioturbation.	*Can be found within a 36 meter thick interval at Selmaneset. Cover-ing the deeper shelf depostis of FA 1 and are overlain by the more proximal FA 3. Also found at Bertil-ryggen.*
Offshore	FA 1: Offshore deposits	F1, F3, F6	This association is characterised by silty shale with laminaes of silt and very fine sandstone with current ripples. No bioturbation has been observed in this FA , and calcite cementation is common. Occasional thin siltstone and very fine sandstone streaks with current ripples has been interpreted to be of a storm generat-ed origin. This FA has been interpreted to be offshore deposits.	*Makes up the lower 53 meters of the Selmaneset section and the upper 12 meters at Bertilryggen.*

Table 5.3: Summary of the facies associations recognised in the Vardebukta Formation. The terminology used for the different depositional environments are based on Reading and Collinson (1996) (fig.6.6)

5.2.1 Facies association 7 - Barrier Bar Deposits

This FA is seen in an interval of 53 meters, and comprises of upwards coarsening sections from 30 cm to 150 cm of laminated shale (In some cases this has been interpreted to be fault gauge) with thin layers of very fine sandstone, covered by 20-200 cm thick fine to medium sandstone. The weathering colour varies from reddish colour to more white coloured, and are heavily cemented by calcite cement. Presented in Figure 5.17 is a section of the measured log containing FA 7, and several typical structure observed within this FA.

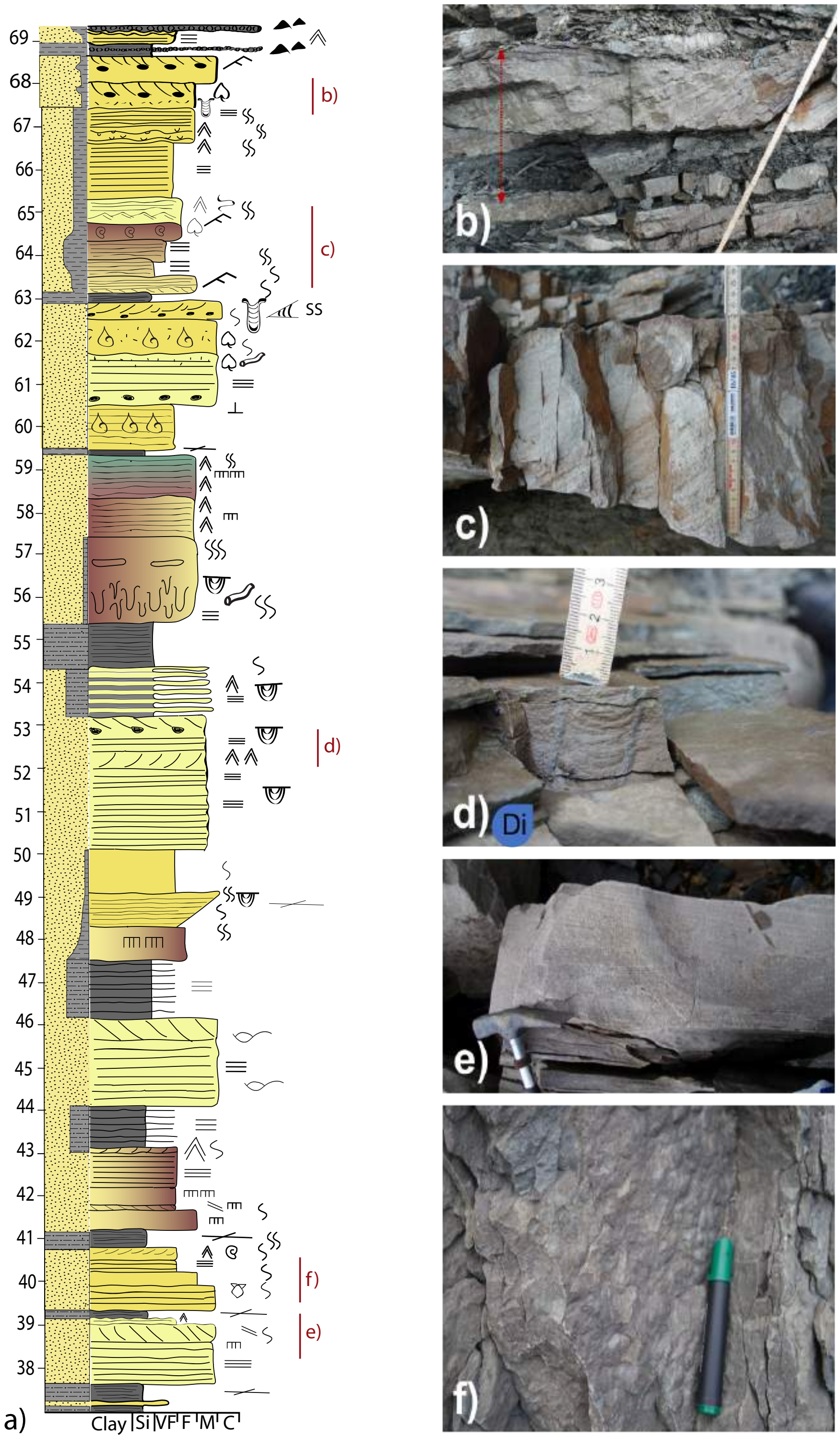


Figure 5.17: *FA 7 - Barrier Bar Deposits:* Included in this picture are the representative log with the main features from FA. **b)** Cross-stratified fine sandstone with mud clasts on the foresets, and coal fragments. Below the thick cross-stratified set, 10 cm thick mud flake conglomerate is observed. The mud flake conglomerate facies seen here are discussed in F9 earlier in this chapter.**c)** Large-scale cross-stratified fine sandstone **d)** Trace fossils often observed in this FA; *Diplocraterion* **e)** Large-scale cross-stratified, white sandstone, of fine to medium grain size. It appears to be parallel to low angled cross-stratified near the base of the bed. **f)** Overview of the thick, large-cross stratified white sandstone typically observed in this FA. Geologist for scale. **g)** An overview of a typically logged section from this FA: beds of large-scale cross stratified, reddish fine sandstone, interbedded with laminated sandstone and siltstone, possibly fractured. **f)** Bivalve rich top surfaces typically found in this FA.

Figure 5.18: Overview of the thick, large-cross stratified white sandstone typically observed in this FA. Geologist for scale.

The white sandstone beds, seen in Figure 5.17, are characteristic for this facies associations. The structures are typically planar stratification (F6, Figure 5.8c), overlain by large-scale cross-stratified beds (F10, Figure 5.18b,c), and hummocky cross-stratified sandstone (F5, Figure 5.18e), and appears to be symmetrical rippled at top (F2).

Another less common feature observed is parting lineations on the top surface, typically seen on the thickest sandstone beds. Moving upwards in the succession, the FA becomes more bioturbated, and mud clasts, coal fragments, and imprints of ammonoids and bivalves are features that becomes more frequent. Mud clasts of approximately 2-10 cm thickness (F9,Figure 5.12), have been observed below the thick, large-scale cross-stratified sandstone beds, Figure 5.18b (for a more detailed photo, see), and also interbedded with 30 cm thick planar laminated very fine sandstone layers and shale. Abundant bivalves (Figure 5.18f), and possibly some plant fragments are typically found in this FA. The bioturbation varies greatly in this FA, but are generally more pronounced near the bivalve rich sandstone. The bioturbation generally varies from minor bioturbation through the sandstone beds, to moderately and heavily bioturbated surfaces higher up in the stratigraphy.

Also observed in this FA was an almost 2 meter thick sandstone bed, dominated by sub-vertical to vertical burrows dominated. Figure 5.19. Overlaying the conspicuous *Diplocraterion* bed, are shell rich beds, interpreted to have abundant bivalves. Ammonoid imprint has also been found, but are less common. Trace fossils found within this FA includes *Diplocraterion*, *Skolithos* and *Planolites*. Less frequent trace fossils; *Rhizocorallium*.

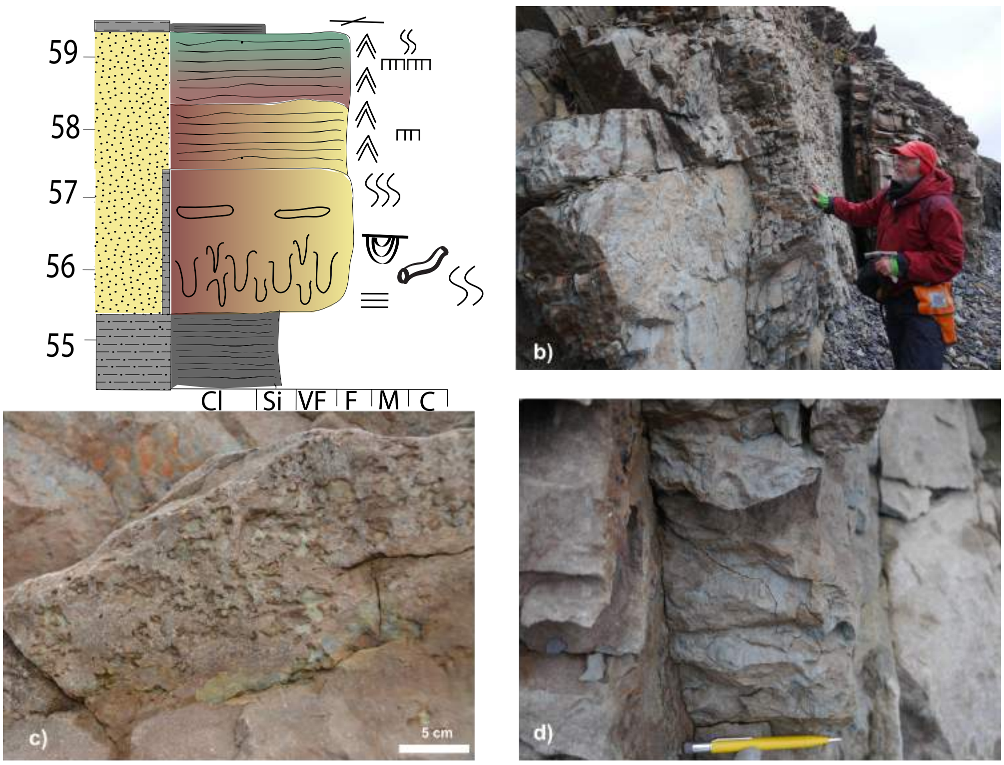


Figure 5.19: **a)** A section from the example log showing the 2 meter layers of reddish sandstone with the vertical burrows, interpreted to be *Diplocraterion*. **b)** An overview of the *Diplocraterion* rich bed. Geologist for scale. **c)** Typically seen on the surfaces: horizontal burrows. Interpreted to be *Planolites*.

Interpretation:

FA 7 exhibits an upwards shallowing succession, from thick benches of white medium sandstone, with low-angled cross-stratification, interpreted to represent HCS, overlain by beds containing mud flake conglomerates, coal fragments and abundant bivalves.

The low angled cross-stratified sandstone could also be interpreted to be large-scale HCS, were the symmetrical rippled top surfaces often could be due to the waning flow. As mentioned in F5, HCS are often associated with the process-response features of storm beds, together with other features like planar parallel laminated (horizontal to sub-horizontal). Layers with parting lineation found directly on the erosive base has also been tied to the characteristics of storm-beds, and assumed to be deposition under continuous conditions of combined flow (Johnson and Baldwin, 1996).

A similar FA is described from Festningen by Mørk et al. (1982), were the bivalve rich beds, which can also be found in the FA 5, and the conspicuous *Diplocraterion* found directly below, are observed. The bivalve rich beds are similar to the Promyalina beds described from Festningen, in the middle of the Vardebukta Formation (Vigran et al., 2014; Mørk et al., 1982). This has been interpreted to be barrier bar and lagoonal deposits. According to Boyd et al. (1992), a barrier bar system reveals a highly transgressive nature, and may be found in proximity of landward facies like estuarian deposits, lagoons and marches. Similar features has been described at Festningen by Mørk et al. (1982), as lagoonal deposits were found in close proximity to the barrier bar deposits. However, this was not observed within this FA Selmaneset. No exposure have been seen at Selmaneset or Bertilryggen, but fragments of coal and organic material are observed. Based on the unidentified shell debris, interpreted to be bivalves, coal fragments and the mud clasts, this is suggested to be the shallowest part of the section. The presence of the thick sandstone beds, with planar parallel stratification to large-scale cross stratification, with extensive bioturbation, overlying laminated shale with thin sandstone layers, including the marine trace fossils, this FA suggests found a barrier bar complex, indicating an open clastic shoreline (e.g (Posamentier and Walker, 2006)).

5.2.2 Facies Association 6 - Upper Shoreface Deposits

This facies association is dominated by very fine to medium sandstone, reworked by oscillatory movements, generating structures like small-scale HCS and swaley cross-stratification (SCS) (F5, Figure 5.5a,c) and wave ripples (F2, Figure 5.2a). Lens-shaped sandstone beds with laterally change in thickness and local beds of deformed sandstone are also common within FA 6. Small-scale coarsening up sequences with wave rippled top (F2) are also observed within this FA. No bioturbation has been observed.

This facies association can be seen in Figure 5.20. There is a distinct difference in appearance compared to FA 5, which included wave rippled, very fine sandstone, grading into bivalve rich banks, generally moderately bioturbated through out.

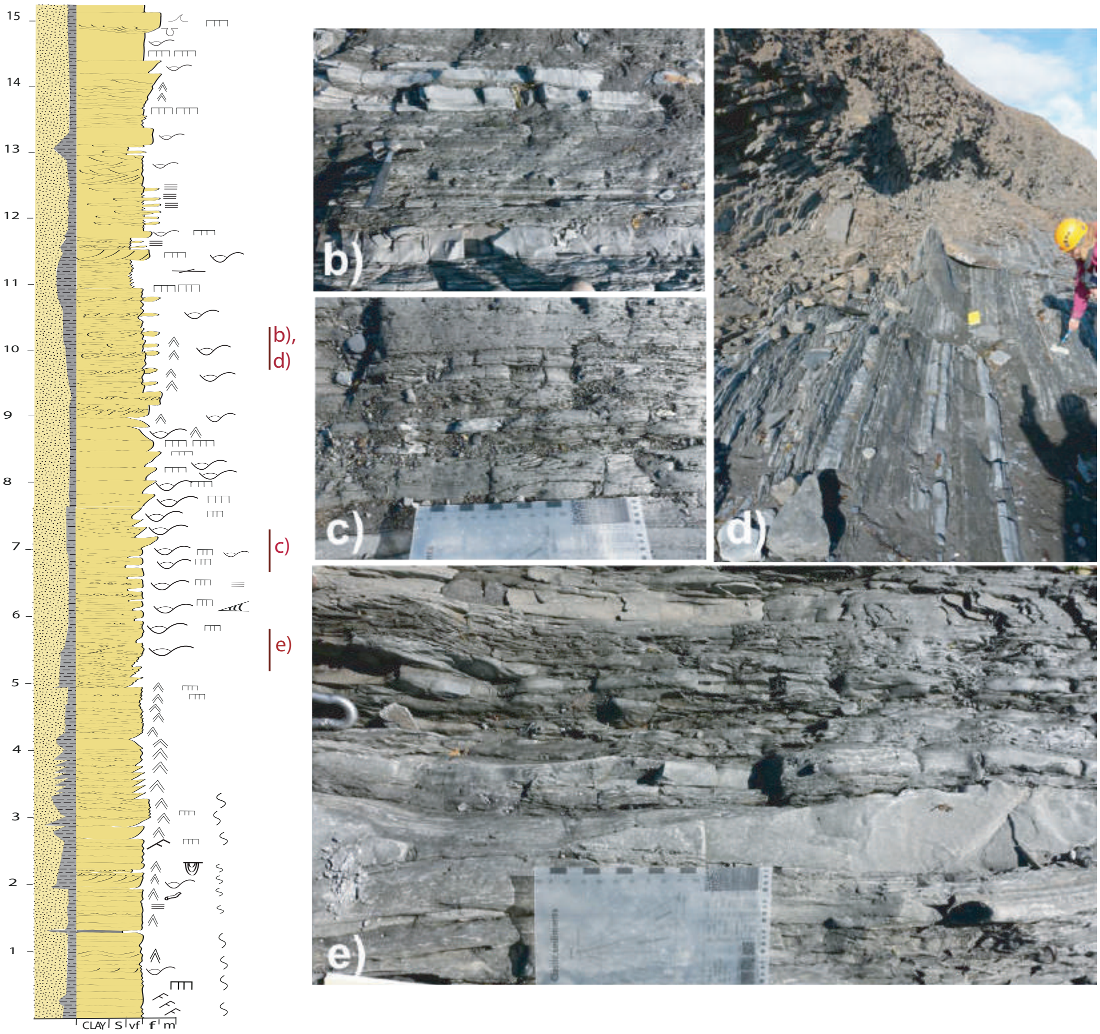


Figure 5.20: *FA 6: Upper Shoreface deposits:* **a)** Logged section of this FA. **b)** Picture from the field, showing the upper parts of the log in a) (marked with the red, dotted, line). It contains lens-shaped, very fine to fine sandstone, and it appears to be rippled throughout, with possibly HCS in the lenses. Geological hammer for scale. **c)** Small-scale symmetrical rippled very fine sandstone, possibly small-scale HCS. **d)** Overview of the upper part of the log seen in a).

Firstly, this interval is more dominated by small-scale HCS (F5), including the symmetrical rippled (F2) very fine to medium sandstone, and are generally strongly cemented throughout. Typical small-scale HCS, characteristic for this FA, are presented in Figure 5.5. Secondly, the colour is also slightly different, no longer as red as further down in the succession, but heavily cemented, grey weathering colour. This FA is also less bioturbation compared to further down in the succession. Lenses of sand can be seen through the whole unit, possibly containing HCS. The thickness of the sandstone beds are generally thinner than further down, and varies from 7 to 10 cm, typically changing laterally in thickness.

Heavily cemented and apparently structureless sections (F7), and planar lamination (F6) grading into symmetrical rippled (F2) top surface can be seen, covered by intervals showing current ripples (F1), grading into wave ripples in the top of the interval. Tabular cross-stratification, of sets smaller then 2 cm could be observed, Figure 5.1c. One part of the section had an interval of several beds of coarsening upwards sections, typical of 10 cm thickness (F2). The finer grains seems to be less cemented. The structures changes from more planar lamination and symmetrical rippled into small-scale HCS upwards in the succession.

Local beds of deformed sandstone (F8) were also found here, with flame structures (Figure 5.21). Below this, large-scale lens-shaped sandstone beds have been outlined, and interpreted to represent HCS and SCS. Similar HCS and SCS structure can also be seen in Figure 5.20e. Typically for these layers are that they change thickness laterally. Typical trace fossils include *Planolites* and *Diplocraterion*

After this 9 meters interval, the FA seems to be similar to FA 5 seen below this interval. The FA appears to be more bioturbated compared to the lower most parts, massive beds are relatively abundant, and asymmetrical (ripple laminated throughout) and symmetrical ripples becomes more common again. Approaching the deformed bed, the degree of bioturbation is increasing from no observed bioturbation to strongly bioturbated. Bioclastic sandstone with abudant shell inprint were observed.

Figure 5.21: *FA 6: Upper Shoreface deposits:* Marked in red is typical lens-shaped sandstone beds found in this FA, possibly SCS. Marked in yellow is a local deformed sandstone bed.

Interpretation:

As mentioned earlier in the sub-chapter concerning the facies analysis, a possible reason for the small-scale HCS and the short wavelength of the HCS could be a decrease in energy due to bottom friction as the waves moves towards land (Yang et al., 2006). The small-scale HCS found at Selmaneset could therefore be interpreted to be of a relatively shallow marine origin, based on Figure 5.7. The lack of bioturbation may also suggest a relatively shallow environment, as the degree of bioturbation has a tendency to decreases landward (Reading and Collinson, 1996).

Moving up in the succession, the structures becomes increasingly more asymmetrical, which could indicating a shallowing up (Reading and Collinson, 1996). This FA has therefore been interpreted to originate from an upper shoreface environment.

5.2.3 Facies Association 5 - Lower to upper shoreface deposits

This association is considered to be the thickest compared to the other defined at Oscar II Land, and has been seen repeatedly at Selmaneset. Figure 5.22 shows a section of this FA and the corresponing log with the main features. In Figure 5.23, a typical interval of FA 5 is presented.

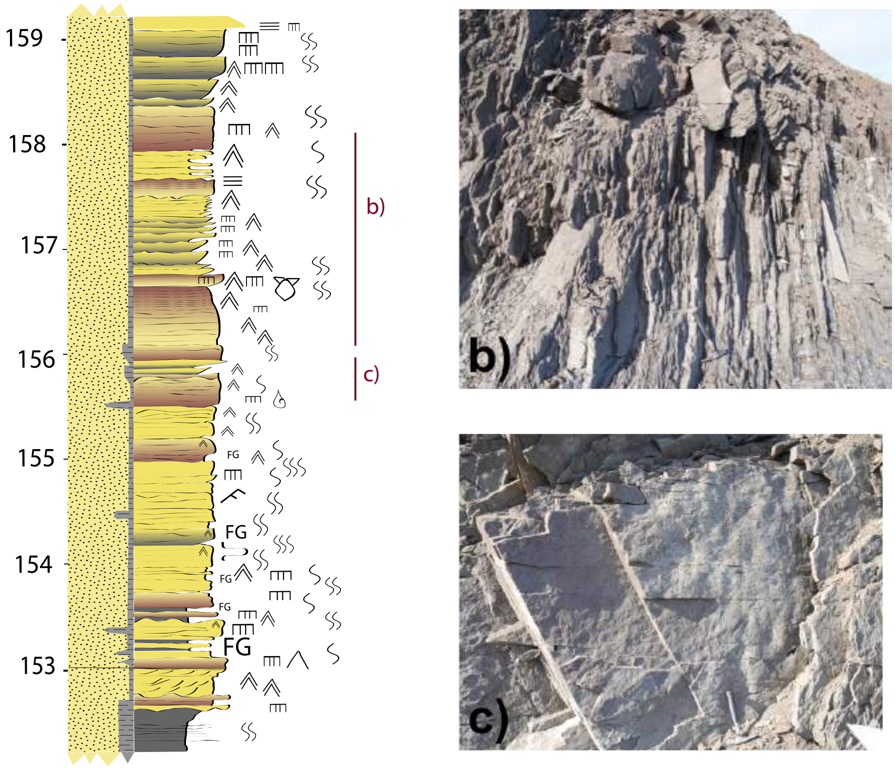


Figure 5.22: *Facies Association 5 - Lower to upper shoreface deposits:* This figure shows an example of a log of FA4. Typically seen in this FA: Reddish very fine sandstone, interbedded with less cemented sandstone, with symmetrical ripples. **b)** The logged section, marked with a red line in the log. Geological hammer for scale. **c)** Heavily bioturbated surfaces commonly found in this FA. Geological hammer for scale.

Figure 5.23: This picture presents a typical interval of FA 5. Geologists for scale.

fa 5 is dominated by wave rippled cross-stratified very fine to fine sandstone (F2), generally low to moderately bioturbated throughout, and the degree of bioturbation increases towards the top of the section. Calcite cemented sandstone beds are common, and often appears massive (F7). Fragmented shells and bivalves (coquina beds) may also be found in thin, reddish to yellowish, bioclastic sandstone beds (F4, Figure 5.4). The lower parts of FA 5 may be dominated by current rippled sandstone (F1, Figure 5.1). Less common structures HCS sandstone (F5).

FA 5 changes further up in the succession, were it becomes more cemented, and dominated by normal graded sandstone, of about 1-5 cm thick beds, from very fine to fine sand. The ripples becomes less symmetrical upwards in the succession, increasingly more dominated by asymmetrical cross-stratification (F1) and planar parallel lamination (F6). The surfaces of the beds may still be symmetrical rippled. Sharp contacts between tthe cross stratified beds has been observed. FA 5 seen directly below FA 6 is more cemented and have the similar lens-shaped rippled very fine to fine sandstone, this is also seen further up in the succession. Trace fossils found within this FA are *Planolites* and *Skolithos*, and, less common, *Thalasssinoides* and *Arenicolites*. These are more abundant lower in the succession.

Interpretation:

On the basis of the presence of wave dominated sandstone, the marine trace fossils observed (Posamentier and Walker, 2006), and the bioclastic sandstone, this association has been interpreted to be lower to upper shallow marine deposits. The fragmented bivalves seen in this FA are similar to the shell banks described in FA 7.

The bivalve rich beds described in this FA has certain similarities to the coquina beds described in Lord et al. (2017b) and Johansen (2016) from the Upper Triassic succession. The coquina beds described in Johansen (2016), from the Upper Triassic De Geerdalen Formation, contains fragmented bivalves in reddish, heavily cemented sandstone beds, with no visible sedimentary structures. They have been interpreted to be shell banks accumulated by currents or waves in a shallow marine environment. This explanation supports the interpretation of the lower to upper shallow shoreface of this FA. The assamblage found at Selmaneset (Figure 5.4a) were well-preserved, partly fragmented bivalves, and gives an indication of a higher energy setting (Reineck and Singh, 1980). As the bioturbation degree is still relatively high, this has been interpreted to be lower to upper shoreface, as the bioturbation decreases landwards (Reading and Collinson, 1996).

Fragmented shells may indicate a high-energy environment (Lord et al., 2017b), often found on beaches, subjected to active wave processes. Coquina beds has been observed in this FA, representing shell banks deposited under high-energy settings at the shoreface Tucker (2015).

5.2.4 Facies Association 4 - Lower Shoreface

This association is restricted the upper 68 meters of Selmaneset. This association is dominated by silt to very fine sandstone, with ripple cross-lamination (F1, F2), and low to moderately bioturbated surfaces. The sandstone units have decreased in thickness and abundance compared to FA 6 and FA 7, and the cementation rate is relatively high and the mud content has increased.

FA 4 consists mainly of cross-stratified well cemented very fine to fine sandstone, with 4 cm to 40 cm thick beds. Sharp lower boundaries have been observed, and layers of siltstone (4-10 cm thick) (F3) have been observed inbetween the sandstone.

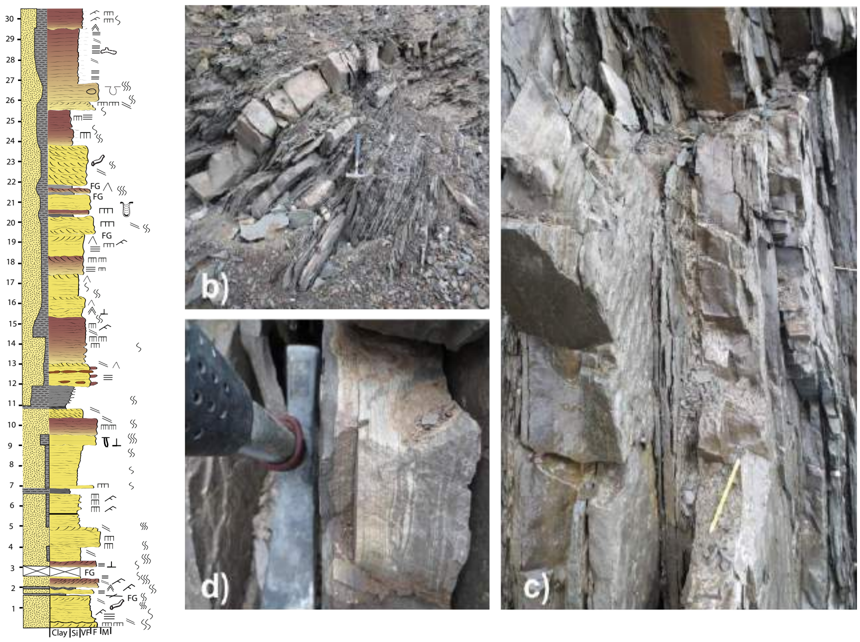


Figure 5.24: *FA 4 - Lower Shoreface:* The main features of this FA with an associated log.**a)** Example log showing a typical section of FA 4. **b)** Interbedded planar parallel laminated, very fine sandstone to cross-stratified very fine to fine sandstone. Geological hammer for scale. **c)** Well cemented, interbedded siltstone and very fine cross-stratified sandstone. Yellow pencil for scale. **d)** Very fine sand, with mud laminae, increasing amount of mud. Lenses of very fine sand in the mud. Geological hammer for scale.

The amount of siltstone increases towards the top of the FA, from about 40 % to 60 % higher up in the succession. Thin non-parallel lamination, possibly ripple lamination (F1) of shale, are often observed in the very fine sandstone. The weathering colour is typically grey, to light yellowish to reddish, as illustrated in the log. The FA 4 is generally highly bioturbated, varying from low to heavily bioturbated bed surfaces throughout the FA. Trace fossils observed in FA 4 are *Planolites*, *Rhizocorallium*, *Thalassinoides* and *Skolithos*.

It should be noted, however, that great parts of this FA was strongly influenced by faulting, and the last section was partly scree covered.

Interpretation:

Based on the sandy characteristic of FA 4, including the dominating appearance of the symmetrical ripples and the thin layers of mud interbedded with the sandstone layers, and the relatively high degree of bioturbation, compared to FA 6 and FA 7, this FA has been interpreted to be lower shoreface environment (Posamentier and Walker, 2006).

As the degree of bioturbation has increased compared to the upper shoreface associations, it has therefore been assumed that this environment may have been more distal in comparison, as the bioturbation tends to decrease landwards (Reading and Collinson, 1996). This FA may have been deposited just below fairweather base (Reading and Collinson, 1996), based on the relatively high amount of mud still present. But as Lord et al. (2017b) also describes in the lower shoreface deposits from the Upper Triassic succession, the lower shoreface have a higher sand content compared to the transition zone deposits, as this environment is under constant reworking of the fine sediments by oscillatory movements Posamentier and Walker (2006). A unit similar to FA 4 is briefly explained in Mørk et al. (1982), in the description of the depositional environment of the Vardebukta Formation. The sandstone units decrease in thickness and quantity in the upper section of the Vardebukta Formation at Festningen. Although this is the case for FA 4, as a fining upwards is observed from FA 6 to FA 4 in the upper part of Selmaneset, the unit at Festningen show a more storm influenced character, which is not seen in the same manner in FA 4 at Selmaneset.

5.2.5 Facies Association 3 - Offshore transition zone to lower shoreface deposits

Examples of this FA is seen in Figure 5.25 and Figure 5.26, showing two typical sections from Selmaneset and Bertilryggen. This facies association comprises of coarsening up sections from laminated shale to very fine to fine sandstone beds. The thickness of the sandstone beds varies between 5-45 cm thick beds, and a general thickening-upward trend of the sandstone beds have been seen in this FA. Some of the thickest layers have a reddish weathering colour, probably heavily cemented (F7, Figure 5.10a). The most prominent sand layers with HCS shows symmetrical rippled top surface. The occurrence of reddish coloured, strongly cemented beds increases upwards as well as the thickness, including the overall bioturbation, which varies between moderate, except for a few heavily bioturbated surfaces.

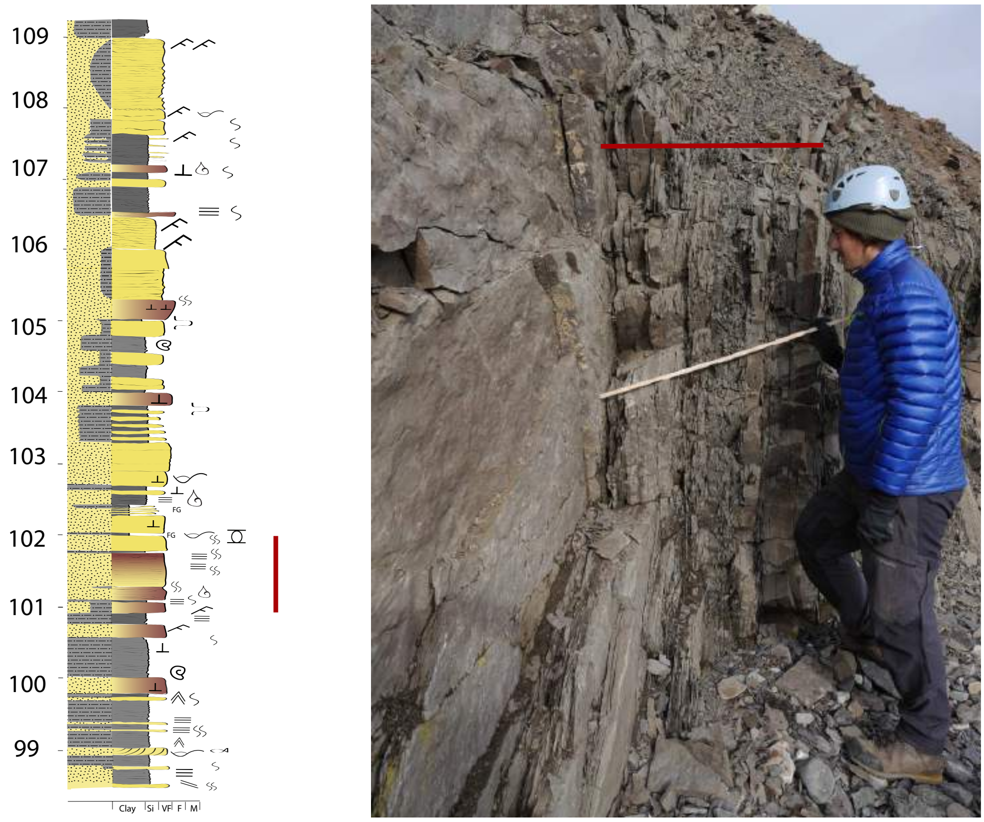


Figure 5.25: *FA3: Lower Shoreface to Offshore transition Zone*: Example of measured log, with a picture from the field. The measured section is marked by a red line. The red coloured beds in the log illustrates the strongly cemented sandstone beds seen in the photo to the right, interbedded with less cemented sandstone and shale. The sandstone beds had slight lamination at the base of the beds. Geologist for scale.

Typical structures seen in the sandstone beds, are planar parallel laminated sandstone (F6) with rippled surface (F1, F2 and F5) (Figure 5.27c), and structureless to massive reddish beds (F7). The sandstone beds generally have low to moderately bioturbated surfaces, sometimes rippled, with a sinusoidal appearance (F1, Figure 5.1a). Parting lineation were also observed on top surfaces. Typical features of FA 3 is presented in Figure 5.27.

Plant fragments, possibly some fish fragments, and shell fragments have been observed in this FA, but only at Selmaneset. Ammonides are seen in the shale on both localities. Abundance of concretions were also observed, especially at Bertilryggen. Typical trace fossils found in the FA at Selmaneset, is *Planolites* (Figure 5.27b), and less common, *Diplocraterion* and *Arenicolites* (Figure 5.27a). At Bertilryggen, horizontal burrows are quite common, although *Skolithos* also occurs.

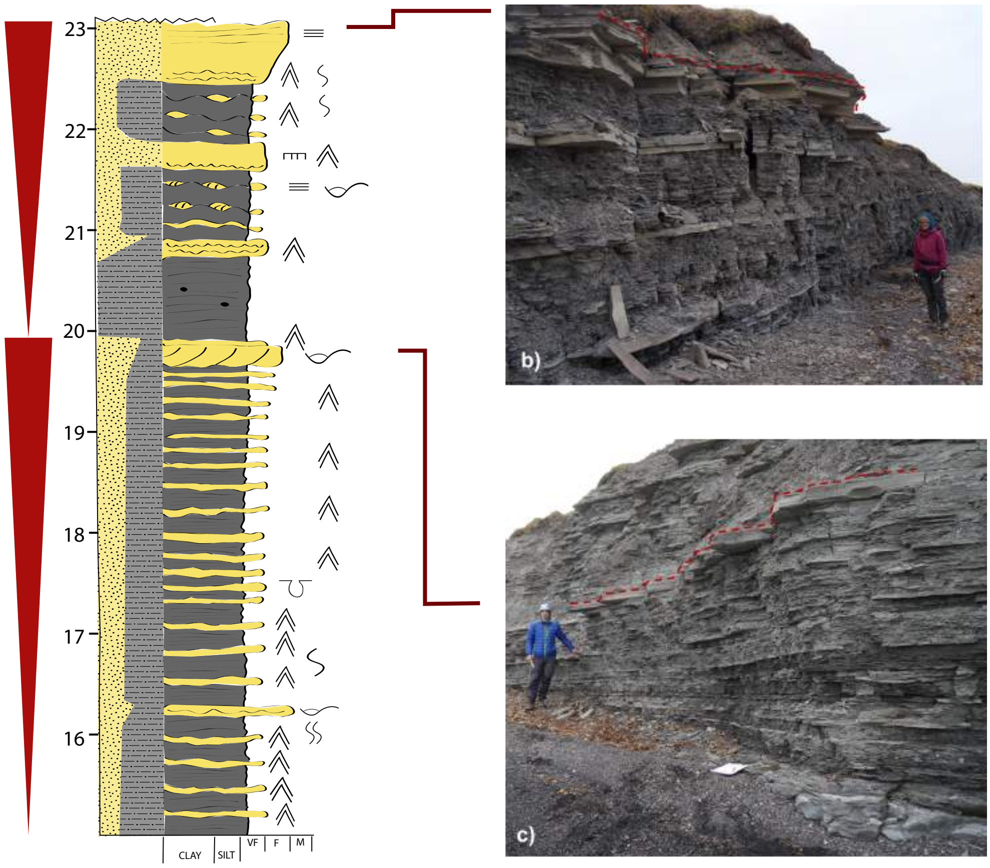


Figure 5.26: *Coarsening up-sequences in FA 3 at Bertilryggen:* **a)** The logs shows a typical example of coarsening up sequences seen at Bertilryggen. The lower sequence consists of interbedded silt and very fine sandstone with wave ripples in the sand. One bed of cemented fine sandstone bed had HCS, with moderately bioturbated base. The thin sandstone layers are relatively continuous in thickness. The first sequence is capped by a 20 cm thick fine sandstone bed, with HCS. Bioturbated at observed at the base of sandstone beds. Some bioturbation was also observed in the silt. **b)** The upper sequence of the log. The top of the coarsening up sequence is marked by a red line. Geologist for scale. **c)** The lower sequence of the log. The top of the coarsening up sequence is marked by a red line. Geologist for scale.

Figure 5.27: *FA3: Lower Shoreface to offshore-transition zone deposits:* Typical seen in FA3 is thick cemented beds of very fine sandstone of reddish colour, with moderately bioturbated surfaces. **a)** Marked in this picture is *Arenicolites* trace fossils, observed in several beds in FA3. **b)** horizontal burrows observe on a strongly cemented surface, possibly *Planolites* trace fossils. The reddish sandstone is interbedded with siltstone and less cemented very fine sandstone. **c)** Laminated to cross-laminated, reddish sandstone.

Interpretation:

This association is very similar to FA 2, but the thickness of the sandstone beds and amount of shale has decreased. As the lower shoreface is more affected by the reworking of finer material by waves and oscillatory compared to the transition zone (Posamentier and Walker, 2006). Based on the occurrence of HCS and wave ripples, including the heterolitic character seen at Bertilryggen, this has been interpreted to be offshore transition to a distal lower shoreface deposits.

A similar associations was described by Grundvåg and Olaussen (2017), identified in the Rurikfjellet Formation of Early Cretaceous age, and Lord et al. (2017b) from the Upper Triassic succession on Barentsøya, Wilhelmøya and north-east Spitsbergen. Their interpretation has been based on the heterolitic character and the HCS sandstone described in the association, including the marine trace fossils observed. Based in their description, this looks more similar to Bertilryggen than Selmaneset, which has a higher amount of sandstone, and no heterolitic sedimentary structures.

The dominance of coarsening-up sequences (especially seen in Figure 5.26) and the general upwards thickening trend may reflect a progradation and shoaling system (Posamentier and Walker, 2006). The increase in wave activity is also seen in this FA, including several beds of HCS sandstone, which may indicate a increased storm influence of the sediments. This supports the interpretation of an offshore transition zone to lower shoreface setting.

The deposition of this FA may have occurred between fairweather and storm wave base, indicated by the occurence of HCS, and can be interpreted to have resulted from aggradation of sediments under combined influence of oscillatory and unidirectional flow (Morsilli and Pomar, 2012). The finer sediments is attributed to settling during fairweather conditions, or at the end of waning storms (Posamentier and Walker, 2006). Shell fragments were only seen at Selmaneset. According to Reineck and Singh (1980). shell beds seen in the transition zone are usually allochthonous shells.

The FA 3 observed at Bertilryggen seems to be more wave dominated, and heterolitic structures such as lenticular bedding (F11) has been observed here. In contrast, the FA 3 seen on Selmaneset, with the occurrence of plant fragments and shell debris, may indicate a higher energy setting compared to Bertilryggen, and possibly closer to the lower shoreface. The actual depth of the offshore transition zone may depend on several factors, most importantatly the energy of the coast (Reineck and Singh, 1980).

5.2.6 Facies Association 2: Lower offshore transition zone deposits

This Facies association mainly comprises of silty shale (F3) with cm thick very fine sandstone beds and makes up a 52 meter thick succession on Selmamenset (see Figure 5.28).

The shale appears to be laminated for the most parts and the sand layers varies from being planar laminated (F6) to asymmetrical ripple cross lamination (F1), with possibly some starved ripples. Symmetrical ripple cross lamination (F2) has also been found in the sandstone . Some layers possibly contains small-scale HCS (F5), although this is higher up in the stratigraphy. Some of the sand/silt layers show planar lamination at base and ripples at top. The most heavily cemented layers appears to be structureless very fine sandstone. These showed undulating base. Some of the sandstone beds appeared more or less structureless (F7).

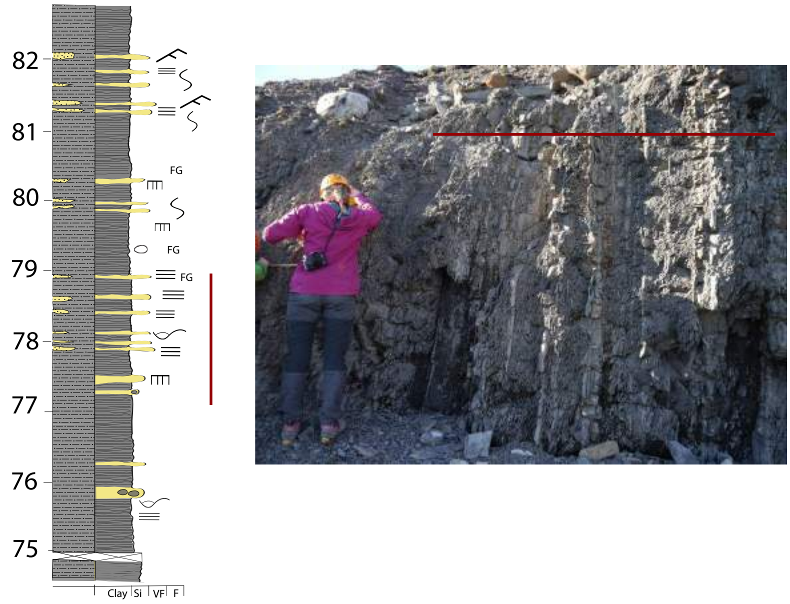


Figure 5.28: *FA 2 - Lower offshore-transition deposits at Selmaneset.* The log presented to the left is an typical example of FA2. Laminated shale with beds of silt to very fine sandstone with sharp bases. The structures seen in the sandstone beds are planar lamination to current ripple cross-lamination, usually in the top of the bed. Some of the beds could also contain small-scale HCS. Concretions has also been observed. The picture to the right is the logged section marked in grey. Geologist for scale.

Most of the sandstone beds were moderately calcite cemented, which included some parts of the shale too. This increased upwards in the succession, together with the thickness of the sandstone. The degree of bioturbation increases upwards in the succession, from low to moderate. Ammonoids and shell fragments were also observed, and there may also been detected bivalves here. The trace fossils such as *Thalassinoides*, *Planolites*, and unidentified horizontal burrows, were the most frequent trace fossils observed, and could be seen on the surfaces of the cemented sandstone beds. Plant fragments and fish fragments were also noted at Selmaneset, but these occurred less frequent. This FA grades up to a thick, moderately to heavily bioturbated very fine sandstone interval (F7), with asymmetrical ripples at top (F1).

Interpretation:

As mentioned in the interpretation of F3, the laminated mud may be associated with plumes of suspended material, with minor inputs of very fine sandstone. The dominance of very fine sandstone layers with planar lamination, current and wave ripples, and some HCS, between the finer grained, laminated deposits may indicate that the main deposition of this FA happened during fairweather conditions.

The offshore-transition zone defined by Solvang (2017) at Festningen show several similar features to FA 2. As Solvang (2017) mentioned, the slight coarsening up sequences observed may indicate a proximity to a prograding system. As this has been suggested to be lower offshore transition deposits, this fits well. The offshore-transition zone is defined as the transition between the fair-weather base and the storm wave base (Reading and Collinson, 1996), and comprises of a variety of unique structures. Typically seen in such an environment is storm reworked sediments, with hummocky and swaley cross-stratification (Posamentier and Walker, 2006; Tucker, 2015). During storms, extensive erosion of the upper shoreface may have lead to redeposition of sediments, forming storm generated beds in the lower shoreface and offshore area (Elliot, 1989). As the HCS and SCS seems to be relatively rare in this FA, this may indicate that the stronger storm events were less common in this area during the Early Triassic, as mentioned by Wignall et al. (2016). The dominance of sandstone beds grading from planar lamination to current ripples may therefore be a result of minor storm, in which the structures may be associated with waning flow. Shoreface attached turbidites (Wignall et al., 2016) was not considered, due to the absence of the organised layers found in turbidites (Boggs, 1987).

5.2.7 Facies Association 1: Offshore deposits

This facies association forms a 53 m thick succession in the lower parts of the Vardebukta Formation at Selmaneset (Figure 5.29), and the upper 12 meters measured at Bertilryggen (Figure 5.30). It is dominated by dark grey, laminated to massive silty shale, with streaks of silt and sand showing laminated to rippled structure. Lenticular bedding (F11, Figure 5.14b) has been observed in FA 1 at Bertilryggen, including abundant fine grained concretions. Thick layers of calcite cemented, yellow layers can be found. Some calcite concretions were also found here (F3, Figure 5.3). One section at Selmaneset contains a 3 meter thick planar laminated very fine sandstone interval with some ripples (F6). FA 1 is also recognised by the lack of bioturbation.

Figure 5.29: Presented here are a typical section of FA 1 in the log, including the measured section from the field. Geologist for scale.

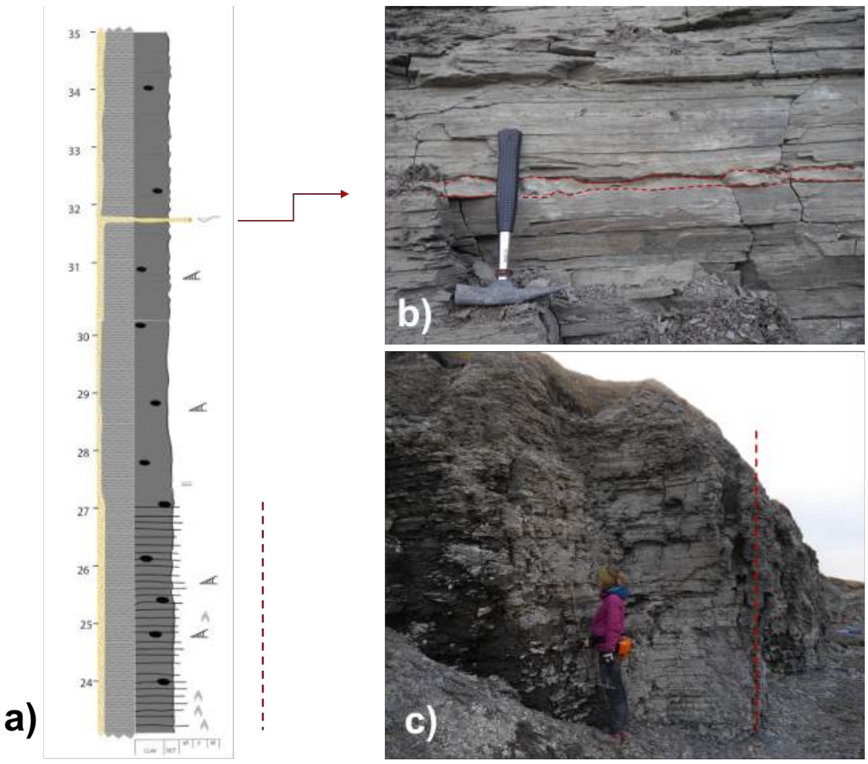


Figure 5.30: *FA 1 - Offshore deposits at Bertilryggen* **a)** FA 1 in the measured section from Bertilryggen. Note the abundant concretions. **b)** Fine laminated siltstone. Marked in red is a distinct sandstone layer, slightly lens-shaped, but continuous. HCS may be seen in this layer. **c)** The lower part of the log, marked with a red line. This section contains siltstone with thin layers of cemented, very fine sandstone with wave ripples, with a lot of concretions of fine material. This FA consists almost entirely of siltstone and mud. Some planar lamination is also seen further up in the section. Geologist for scale.

Interpretation:

This is the most distal association observed from the different locations, based on the fine-grained character and the position below the more shallow deposits of FA 2 and FA 3, interpreted to be offshore transition deposits to lower shoreface deposits. Apart from the laminated to massive silty shale, only streaks of silt and very fine sand were found, with current ripples. The ripples may indicate episodic current activity in a quiescent background. A low energy, basinal setting may be suggested based on the laminated shale, with varying amount of siltstone. The presence of silt and sand laminae, however, may indicate some variations in sediment input and events of higher energy, for instance distal storm generated sediments, as described by (Mørk et al., 1982) in the basal Vardebukta Formation from Festningen.

A similar sediment package was observed at Festningen by Solvang (2017). The interval was in this case interpreted to be prodelta deposits, and the input of sediments were associated with deltaic hyperpycnal plumes,(i.e low-density turbidites). But Solvang (2017) points out, the laminaes may not be exclusively a result of hyperpycnal plumes. Considering the overlying FA for Selmaneset, a prodelta setting does not fit well with the observations and interpretations in this area. The term used to define this FA is therefore offshore deposits, but the amount of reworked sand in these deposits may indicate deposition closer to the transition zone. As mentioned in Chapter 3, the Lower Triassic succession on Spitsbergen is highly affected by the marine anoxia (Wignall et al., 2016), which may explain the lack of bioturbation in this FA. This may especially be true for the basal Vardebukta Formation at Selmaneset.

5.3 The measured sections from Oscar II Land

This section describes the sedimentology of the measured logs from Selmaneset, Bertilryggen and Ramfjelldalen (Figure 5.31) in terms of the facies analysis and the FA described above. The coordinates of the logs and further details can be found in Appendix-B,C,D,E,F,G.

Four logs were measured from Selmaneset. These follow each other directly. One log were measured at Bertilryggen, from the boundary between Kapp Starostin and the Vardebukta formations, while the section from Ramfjelldalen was measured between scree covered intervals, and the exact position in the stratigraphy is uncertain. An overview of the logs will be provided for each location, the legend can be found in Appendix A. It should also be noted that some parts of this section have uncertainty in the lithology column. As mentioned earlier, the colour of the outcrop is included in the log.

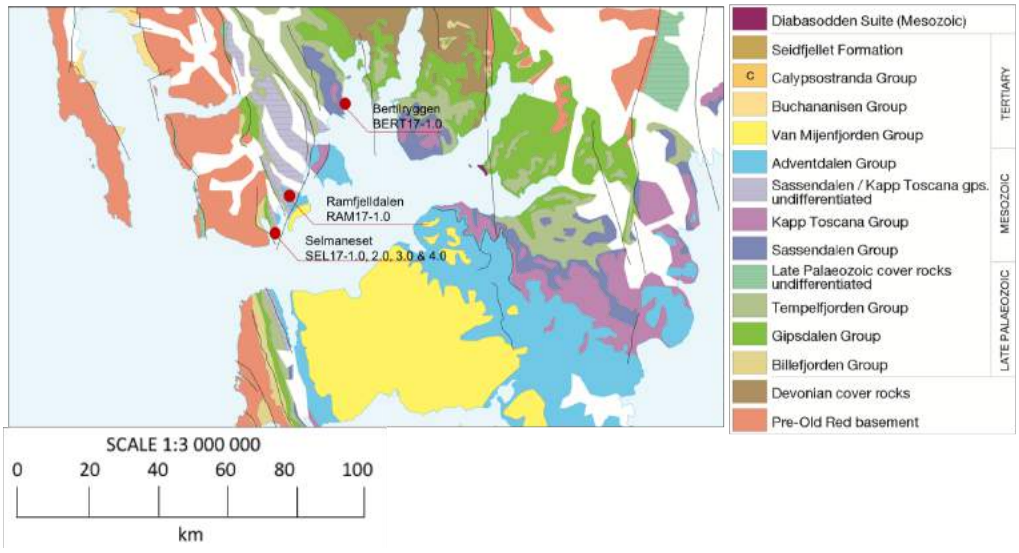


Figure 5.31: Study area including a legend showing the different groups, modiefied from Dallmann (1999)

5.3.1 Selmaneset

Presented below in Figure 5.34, Figure 5.35 Figure 5.36, Figure 5.37, Figure 5.38 and Figure 5.39 are the four measured sections from Selmaneset.

Selmaneset is located on the cape of the northern shore of Isfjorden, on the opposite side of Festningen (See Figure 5.31). This area contains the thickest succession compared to the two other locations that were studied, and it is assumed that the whole Vardebukta

Formation is exposed along the beach at Selmaneset, between Selmaneset and Sylodden. Based on the description of the Selmaneset Member from Mørk et al. (1999a), the member has been defined as the first 96 meters of the formation, made up by FA 1 and FA 2, defined earlier in this chapter. The following Siksaken Member has therefore been assigned to the last 304 meters.

This region is highly tectonized as a result of the intense deformation by the Tertiary fold-thrust belt. This is further explained in the subsection about the tectonic setting on Oscar II Land and these tectonic events has been well documented by (Bergh et al., 1997). As a result of the Cenozoic folding, the stratigraphy on this location was overturned to steeply dipping to about 90 degrees, (Vigran et al., 2014), and the general quality of the outcrop on this location was variable, and highly affected by the tectonic events Figure 5.33 . Due to this complexity, the thickness estimations of the formation is uncertain, as repetitions may occur. The sections are logged continuously, but may as well be several repeated sections. It should also be mentioned that the outcrop on Selmaneset is strongly cemented in some locations.

As mentioned in Chapter 3, the Triassic succession at Selmaneset is highly affected by the Cenozoic folding, which led to a steeply dipping to a vertical stacking of the exposure. Fault gauge was found all along the section, and in general, all over Selmaneset Figure 5.32. These have been marked in the log as FG and sometimes slikensides has been marked as SS. The fault gauges (FG) were observed between the beds of siltstone and sandstone, and can be described as foliated, fine grained material, with the appearance of mudstone. However, as these layers were often found along fault planes, these were interpreted to be a product of fault slip events. The thickness of the FG varied, from only a few centimetres to almost a meter in some locations.

Figure 5.32: Two examples of the observed fault gauge, typically found at Selmaneset. The pictures are taken from the shaly lower part of Selmaneset. The fault gauge is marked by the red lines and the red arrow. Note the thickness variations.

Figure 5.33: Illustrated here are the varying conditions at Selmaneset.

SEL17-1.0
Selmaneset
33X 475364mE
8684118mN

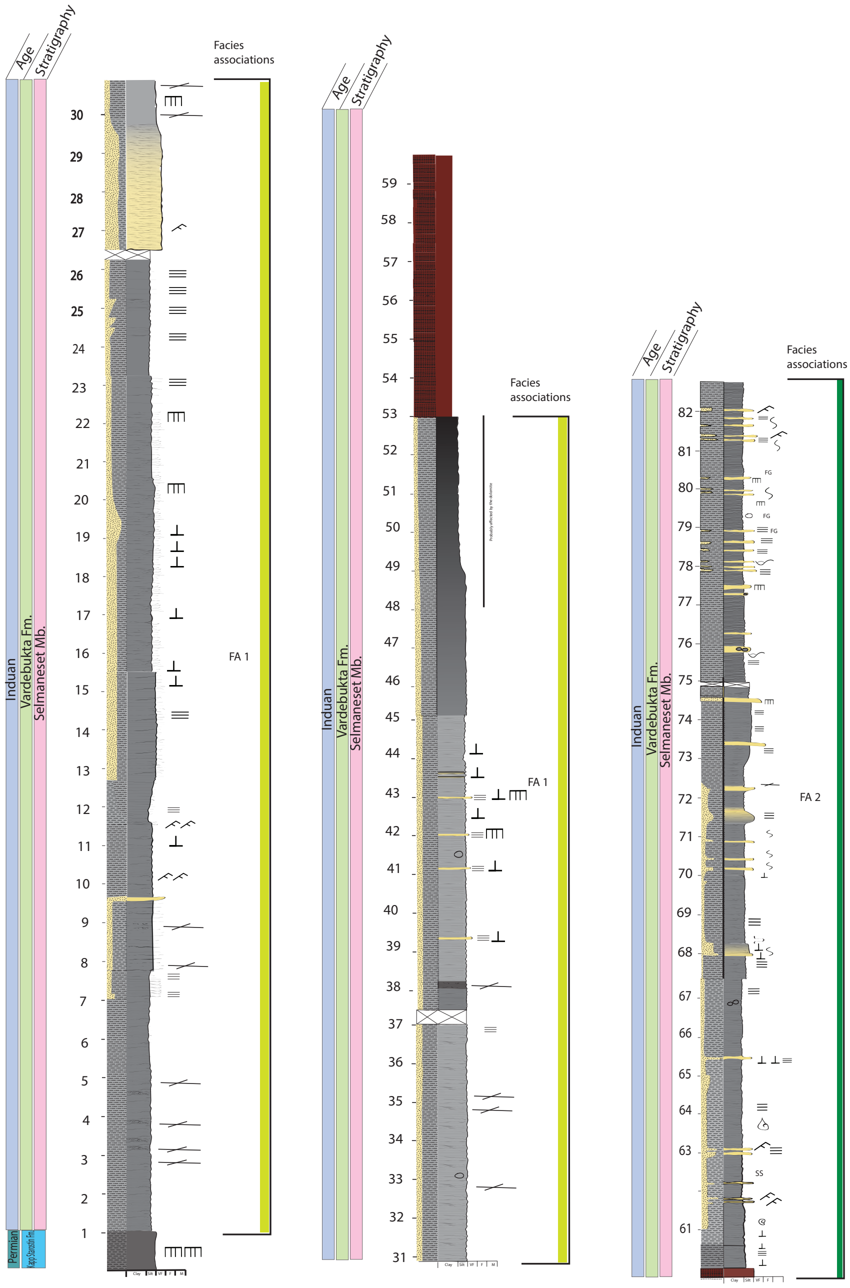


Figure 5.34: SEL17-1.0

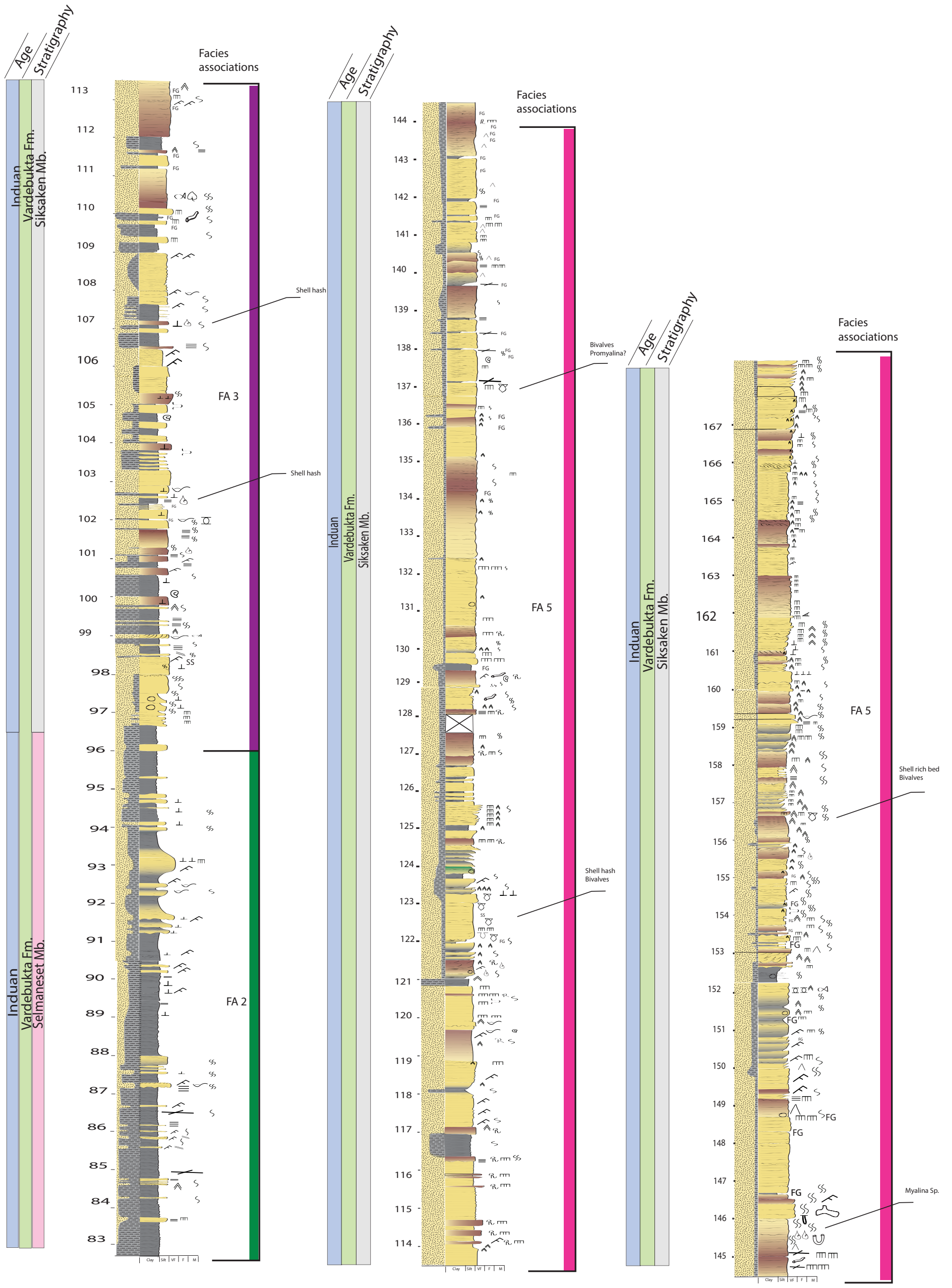


Figure 5.35: *SEL17-1.0*: Presented here are the first measured section from Selmaneset, which contains the lower 168 meters of the succession. Measured by Ingrid N.Hoel, Chrissy McCabe and Ole-Marius Solvang. The lithostraigraphical change from the Kapp Starostin Formation to the Vardebukta Formation is marked by a sharp transition from black, heavily cemented shale to soft, grey, laminated silty shale. The lower 53 meters of the Vardebukta Formation are characterised by silty shale, with streaks of silt and very fine sandstone (FA 1) and are completely devoid of any trace fossils, except for ammoinds imprints found in these beds. This grades into shale with thin beds of very fine, laminated to current rippled sandstone, with an upwards increasing thickness and abundance of sandstone (FA 2 and FA 3). The uppermost 54 meters of SEL17-1.0 are dominated by wave rippled sandstone, with occasional beds of shell debris and bivalve rich beds, with relatively high degree of bioturbation. Hummocky cross-stratified sandstone beds are found within this section. This section has been interpreted to be offshore deposits grading into offshore-transition to lower shoreface deposits.

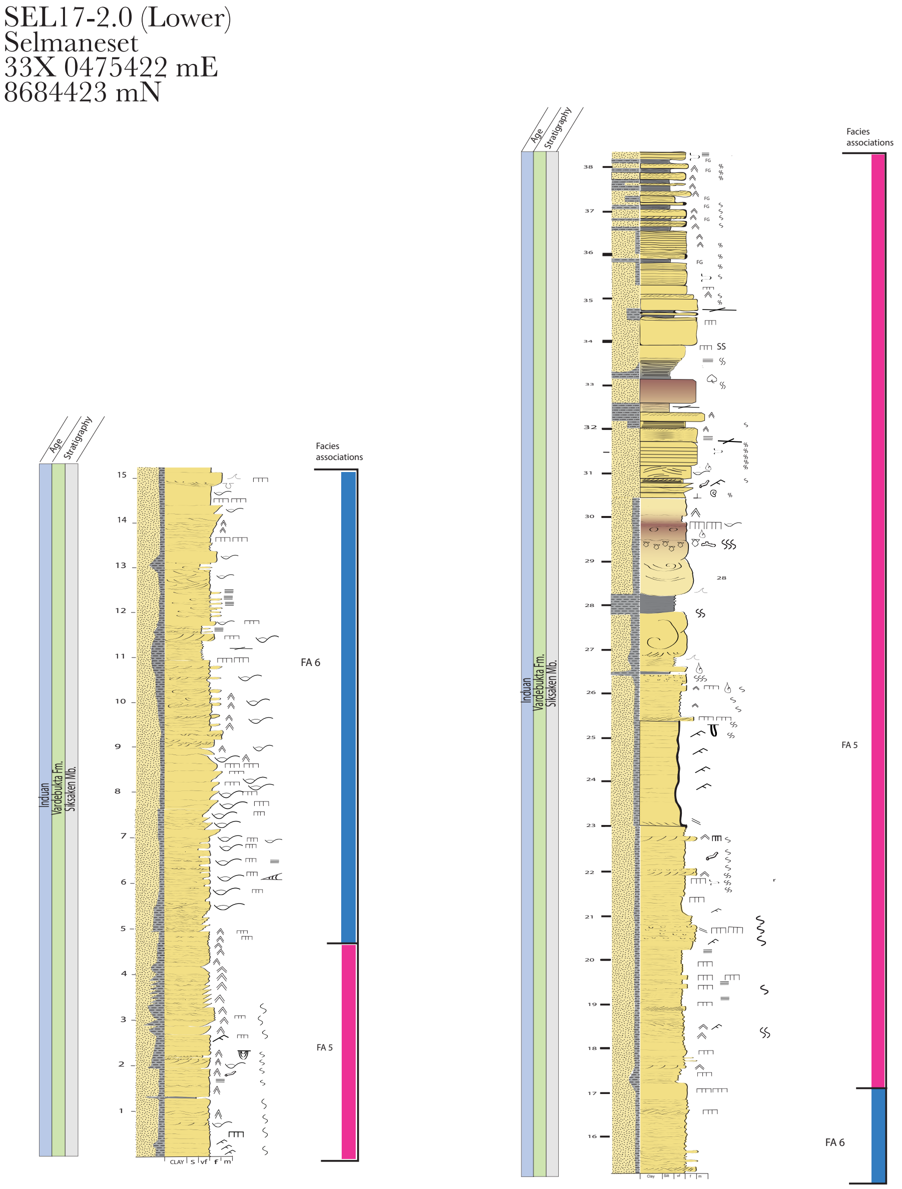


Figure 5.36: *SEL17-2.0 - Lower part*: Presented here are the lower part of SEL17-2.0, containing 38 meters of logged section from Selmaneset. Measured by Sondre K. Johansen and Ole-Marius Solvang. A transition from wave rippled very fine to fine sandstone with some low bioturbation degree, and trace fossils like *Diplocraterion* and *Planolites* (FA 5), to a section dominated by upwards coarsening layers with small-scale HCS, and lens-shaped very fine to fine sandstone, with no observed bioturbation (FA 6). This has been interpreted to be lower shoreface grading in to upper shoreface deposits, dominated by small-scale HCS. A transition back to wave rippled and current rippled sandstone, with beds of shell debris and bivalve rich layers, abundant trace fossils and bioturbation, has been interpreted to be a slight deepening from upper shoreface to lower shoreface deposits.

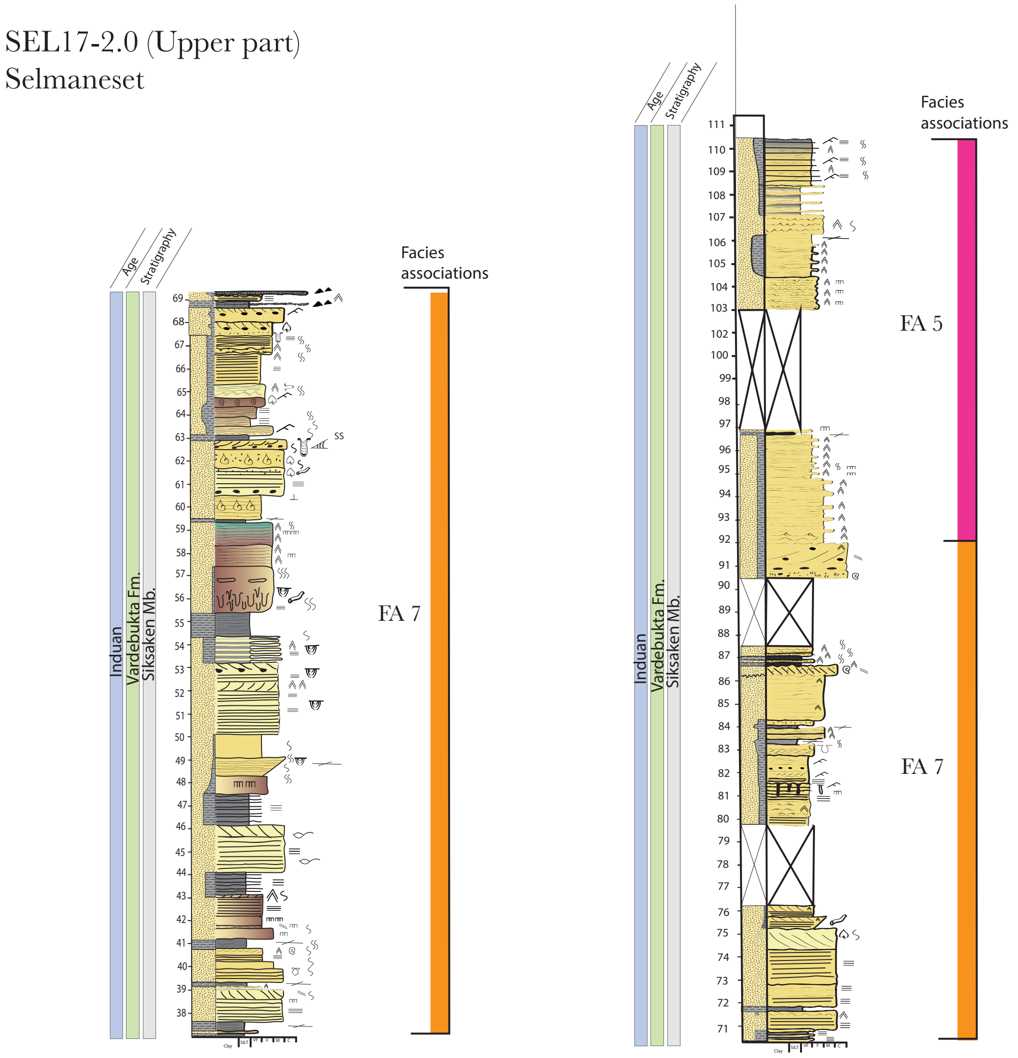


Figure 5.37: *SEL17-2.0 - Upper Part*: Presented here are the upper part of SEL17-2.0, containing 70 meters of logged section from Selmaneset. Measured by Sondre K. Johansen and Ole-Marius Solvang. A prominent shallowing up from lower shoreface (FA 5) deposits to barrier bar deposits (FA 7) can be seen, containing small-scale coarsening up sequences laminated silt and very fine sandstone to pronounced benches of fine to medium sandstone, with planar to low-angled cross-stratification to HCS. Increasing abundance of bioturbation, mud flakes and coal fragments upwards in the succession, and beds of bivalves has been found increasingly upwards. A conspicuous layer completely bioturbated by vertical burrows, interpreted to be *Diplocraterion* has been found. A slow transgression has been interpreted in the uppermost part of the section, as barrier bar deposits (FA 7) grades into lower to upper shoreface deposits (FA 5), dominated by wave rippled sandstone.

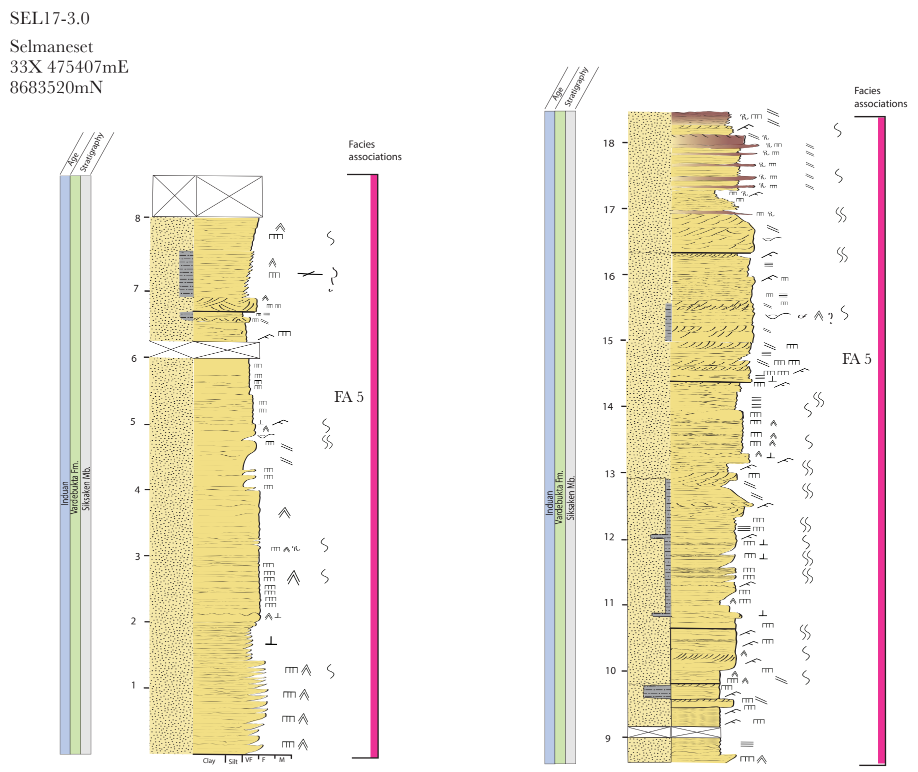


Figure 5.38: *SEL17-3.0*: Presented here are the third measured section, containing 18 meters from Selmaneset. Measured by Ingrid N.Hoel and Chrissy McCabe. This section contionous with the same wave rippled, very fine sandstone defined in the uppermost part of SEL17-2.0. A slight increase in bioturbation can be seen across this section, and a change from dominantly wave ripples to asymmetrical rippled sandstone upwards. This section has been interpreted to be lower shoreface to upper shoreface deposits.

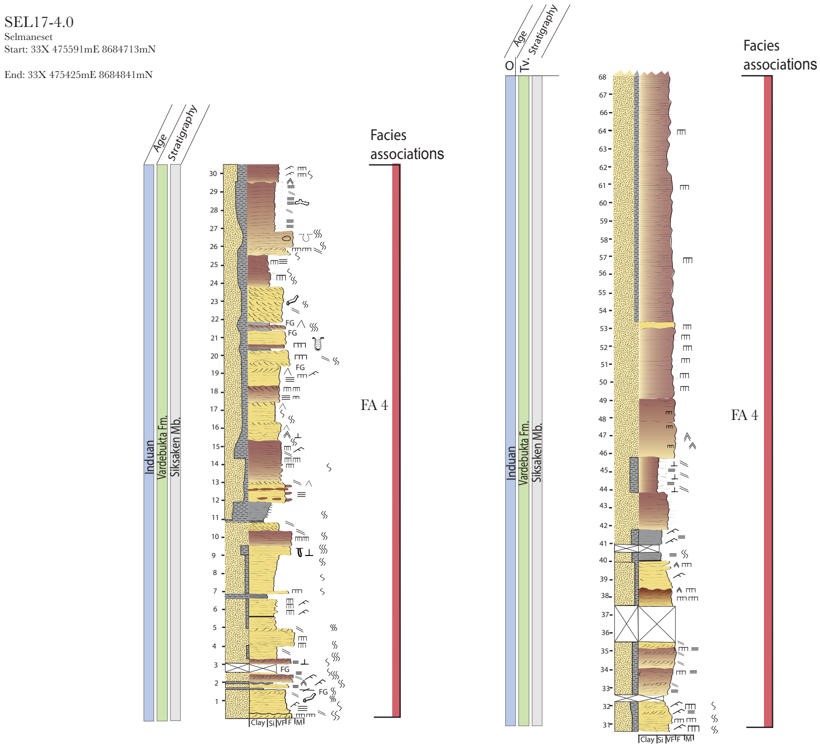


Figure 5.39: *SEL17-4.0*: This section represent the last measured section from Selmaneset, containing the upper 68 meters of the Vardebukta Formation. Measured by Ingrid N.Hoel and Chrissy McCabe. This section is dominated by small-scale upward coarsening sequences from silt and very fine sandstone, to fine sandstone. The lower 10 meters is moderately to heavily bioturbated. It should be noted that this section was partly scree covered and highly cemented, which gives the observations some uncertainty. The sandstone beds are dominated by unidentified ripples, most likely current generated. Beds of laminated to wave rippled sandstone has also been noted in this section. The thickness of the sandstone beds and the bioturbation decreases towards the top of the section. This section has been interpreted to be lower shoreface deposits. A transgressional trend is seen in the last 68 meters of the Selmaneset section. The boundary between the Vardebukta Formation and Tvillingodden Formation is marked by a transition from very fine, calcite cemented, partly scree covered sandstone to dark, laminated shale.

SEL17-1.0:

The first section makes up a 168 meter log, measured by Ingrid N.Hoel, Chrissy McCabe and Ole-Marius Solvang. The lithostratigraphical change from the Kapp Starostin Formation to the Vardebukta Formation is marked by a sharp transition from black, heavily cemented shale to soft, grey, laminated silty shale, and can be viewed in Figure 5.40.

Figure 5.40: The boundary between the Permian Kapp Starostin Formation (KSFm.) and the Triassic Vardebukta Formation (VaFm.), marked by a sharp contact between heavily cemented black shale, and soft, grey silty shale. The boundary is marked by a red line. Geologist for scale.

The lower 53 meters of the Vardebukta Formation are characterised by silty shale, with streaks of silt and very fine sandstone with current ripples (F3, Figure 5.3), defined as FA 1 (Figure 5.29). This section is completely devoid of any life, except for ammonoids imprints found in these beds. This is followed by a 7 meter thick dolerite sill, presented in Figure 5.41. No structures were seen in the shaly facies found below the sill (Figure 5.3b). It was therefore assumed that the shale could have been affected by the dolerite. Similar thick dolerite sills has been described as Diabas odden Suite (Mørk et al., 1999a), according whom, dikes and sills of dolerite cut through strata of all ages up to early Cretaceous in most areas on Svalbard. The age of the dolerite sills and dykes has been considered to be of Cretaceous age, and the age of the host rock of the sills decreases in east ward direction.

Figure 5.41: A 7 meter thick dolerite sill were observed in the lower parts of the Vardebukta Formation.

The sand content increases, and for the next 36 meters, the succession is characterised by laminated shale interbedded with very fine sandstone (FA 2, Figure 5.28). The sandstone beds, typically calcite cemented, contains laminated to current rippled very fine sandstone. Bivalve imprints may have been observed above the sill, but this is otherwise rare. Ammonoid imprints are seen in the shaly facies above the dolerite sill.

FA 2 grades into an offshore-transition zone to lower shoreface deposits of FA 3, with increased beds of sandstone and bioturbation, horizontal burrows and bivalve rich beds (Promyalina), including some plant fragments and organic material. This interval contains smaller coarsening up sequences, grading from shale (ammonoids observed) to very fine sandstone, with some bivalve rich beds.

The thickness of the sandstone beds increases upwards in the succession, including the degree of bioturbation (FA 3, Figure 5.25). This section comprises of coarsening up sequences from laminated shale to beds of very fine to fine sandstone, with low to moderately bioturbated surfaces (Figure 5.27b), and a general thickening upwards. Typically seen here are a reddish weathering colour, commonly calcite cemented. Structures like planar parallel lamination (F6) Figure 5.27c, wave ripples (F2) and HCS has been found in the sandstone layers, and abundant massive to structureless reddish beds are typically seen here . Plant fragments and fish fragments has also been observed within this interval, and typical trace fossils are *Planolites*, *Diplocraterion* and *Arenicolites* (Figure 5.27a,b).

FA 3 grades into sandstone-rich uppermost 54 meters of SEL17-1.0 (FA 5, Figure 5.22), largely containing very fine to fine, cemented sandstone, with low to moderately bioturbated surfaces. Figure 5.23 shows a typically interval of this section, with beds of reddish, calcite cemented very fine sandstone. From FA 3 to FA 5, the very fine sandstone grades into very fin sandstone with current rippled cross-lamination, containing several accumulations of bivalves (Figure 5.42). Several beds with abundant bivalves are observed along the succession on Selmaneset. Examples of bivalve rich beds in the uppermost FA are also presented. This section has been interpreted to be coarsening-up from the offshore to offshore transition zone deposits of FA 1 to more proximal deposits of FA 2, still in the offshore transition zone, is seen in the lower 97 meters of the the Vardebukta Formation at Selmaneset.

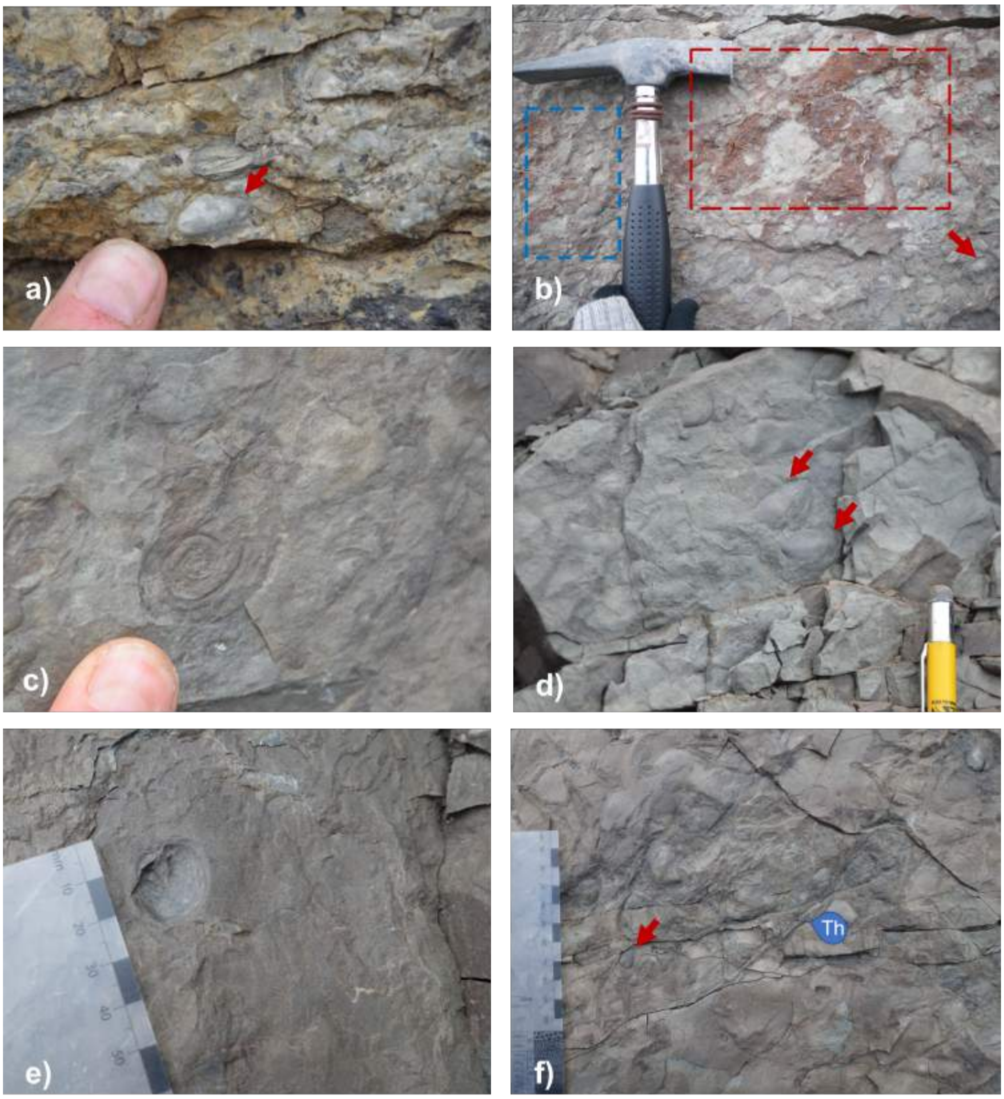


Figure 5.42: Seen in the pictures are examples of accumulations of Bivalves and other features that are found near the banks. These beds are found in several locations at Selmaneset in FA 5. The bivalve rich beds has been connected to the Myalina Sp. (Promyalina), a term used for the Bivalve rich beds found in the middle of Vardebukta Formation, which can also be observed in the Lower Triassic Vardebukta Formation at Festningen (Mørk et al., 1982). **a)** Bivalve rich bed. **b)**Blue square: Mud clast conglomerate, red square: shell debris. Red arrow: bivalves. **c)** Ammonoid imprint in very fine sandstone. **d)**Bivalves, marked by red arrows. **e)** Shell imprint. **f)** Bivalves, marked by red arrow. Branched trace fossils, possibly *Thalassonoides* (Th).

SEL17-2.0:

Presented here are the lower and upper part of SEL17-2.0, containing 38 meters of the lower SEL17-2.0, and 70 meters of upper part of the logged section. This section is measured by Sondre K. Johansen and Ole-Marius Solvang. This section follows SEL17-1.0 directly, but was logged in two different scales. For further details, see Appendix C.

A transition from wave rippled very fine to fine sandstone with some low bioturbation degree can be seen FA 5. The lower part consists of almost 5 meters of FA 5, grading into 12 meters of sandstone dominated by upwards coarsening layers with small-scale HCS, and lens-shaped very fine to fine sandstone, with no observed bioturbation (FA 6, Figure 5.20). This has been interpreted to be upper offshore deposits, supported by the low bioturbation observed here, which is typically low in the upper shoreface Dashtgard et al. (2012).

This is again covered by 21 meters of FA 5 again. The percentage of sandstone has now increased, but layers of mud is still present. Beds of deformed sandstone (F8), with abundant bivalves and shell fragments. The bioturbation increases towards the top of the section, which is highly tectonized. Trace fossils like *Diplocraterion* and *Planolites* are typically seen in this section.

This has been interpreted to be lower shoreface grading in to upper shoreface deposits, dominated by small-scale HCS. A transition back to wave rippled and current rippled sandstone, with beds of shell debris and bivalve rich layers, abundant trace fossils and bioturbation, has been interpreted to be a slight deepening from upper shoreface to lower shoreface deposits.

A great change in the facies from the lower to the upper sections of SEL17-2.0 can be seen. Important features to be noted here are the distinct white, cemented beds, showing large scale cross stratification (F10), and the beds of shell debris and imprints of bivalves (F4), coal fragments and mud clasts (F9). Beds of bivalves imprints has been found increasingly upwards. A 2 meter conspicuous layer completely bioturbated by vertical burrows, interpreted to be *Diplocraterion* can be viewed in Figure 5.19. A slow transgression has been interpreted in the uppermost part of the section, as barrier bar deposits (FA 7), grade into lower to upper shoreface deposits (FA 5), dominated by wave rippled sandstone.

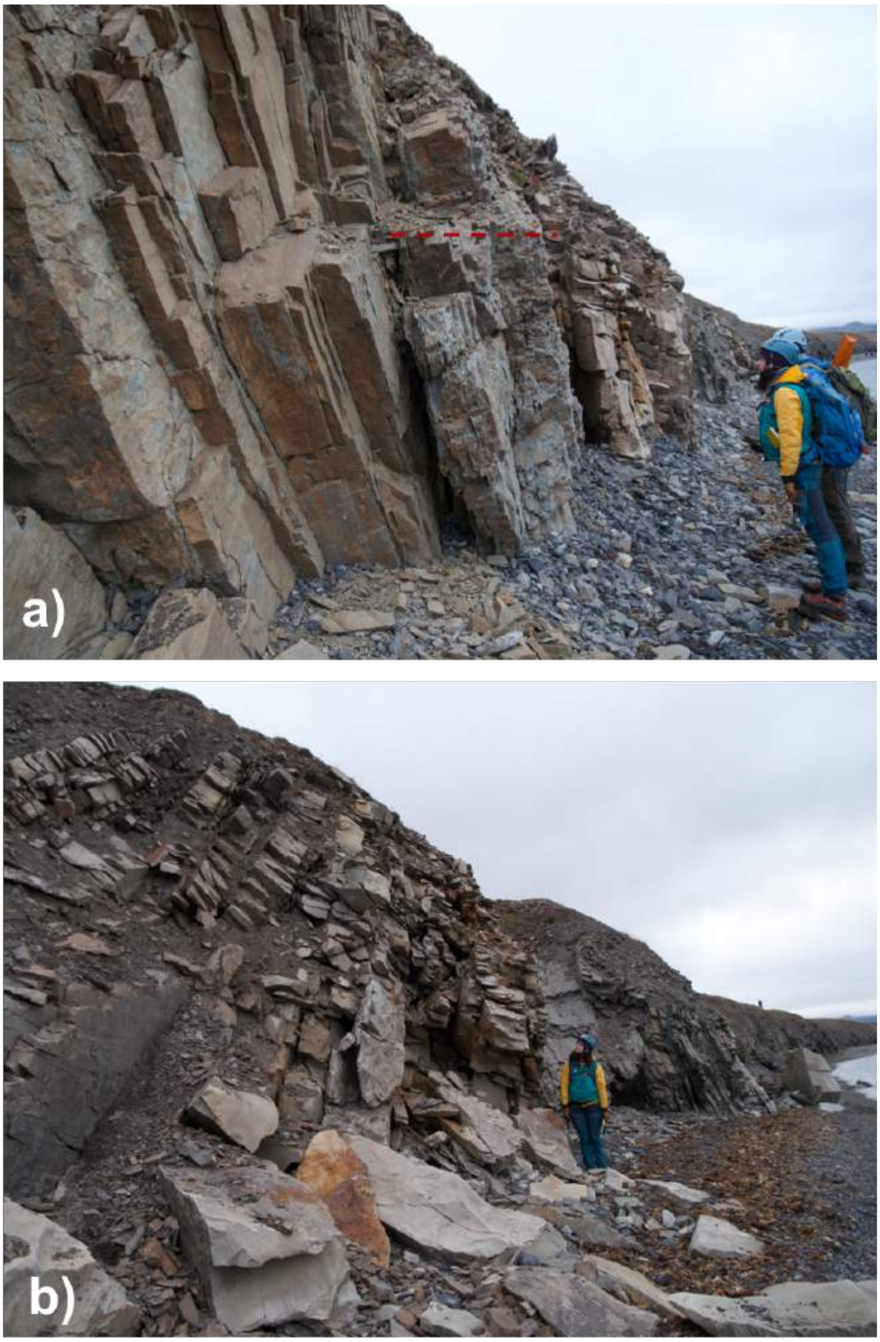


Figure 5.43: **a)** Marked with a red line is the prominent *Diplocraterion* dominated bed found in this section. **b)** The thick sandstone benches dominating this interval. Geologist for scale.

Figure 5.44: Presented here are the uppermost interval of SEL17-2.0.

SEL17-3.0:

Presented here are the third measured section from Selmaneset, containing 18 meters from Selmaneset (Figure 5.38). Measured by Ingrid N.Hoel and Chrissy McCabe.

This section continuous with the same wave rippled, very fine sandstone defined in the uppermost part of SEL17-2.0. The lower most part of the section contains calcite cemented, upwards coarsening layers (8-12 cm thick) from very fine to fine sandstone, with wave rippled top surfaces. A slight increase in bioturbation can be seen across this section, and a change from dominantly wave ripples (F2) to asymmetrical rippled (F1) sandstone upwards. Some larger scale ripples, most likely HCS (F5), were also observed, but these were less abundant.

This section has been interpreted to be lower shoreface to upper shoreface deposits (FA 5). A slight increase grain size may indicate an increase in the energy level. This is also seen by the large-scale ripples observed in the upper part of this section.

SEL17-4.0:

This section represent the last measured section from Selmaneset, Figure E.1, containing the upper 68 meters of the Vardebukta Formation. Measured by Ingrid N.Hoel and Chrissy McCabe. It is important to note that the quality of the outcrop gets worse towards the highly cemented top section. As the assumed boundary between the Vardebukta Formation and Tvillingodden Formation was approached, a majority of the outcrop was partly scree covered.

This section is dominated by small-scale upward coarsening sequences from silt and very fine sandstone, to fine sandstone. The lower 10 meters is moderately to heavily bioturbated. The sandstone beds are dominated by unidentified ripples, most likely current generated (F1). Beds of laminated (F6) to wave rippled sandstone (F2) has also been noted in this section. The thickness of the sandstone beds and the bioturbation decreases towards the top of the section.

A transgressional trend is seen in the last 68 meters of the Selmaneset section. The boundary between the Vardebukta Formation and Tvillingodden Formation is marked by a transition from very fine, calcite cemented, partly scree covered sandstone to dark, laminated shale. This section has been interpreted to be lower shoreface deposits (FA 4, Figure 5.24). The boundary between Vardebukta Formation and Tvillingodden Formation can be seen in Figure 5.45. A distinct transgression can be seen from the Vardebukta Formation to the Tvillingodden Formation, from the sandy, reddish, heavily cemented and wave rippled sandstone and siltstone, to fine laminated, black shale.

Figure 5.45: The boundary between sandy, heavily cemented Vardebukta Formation (VaFm.) and the dark, laminated shale of the Tvillingodden Formation (TvFm.) The transition is marked by a red line. Geologist for scale.

Interpretations:

The general trend seen at Selmaneset is an upwards coarsening from offshore deposits (FA 1), dominated by shale and thin sheets of sandstone, into the offshore transition zone (FA 2-3), with increasing thickness of the sandstone beds, and occurrence of wave ripples, bioturbation and large scale cross-stratification. The general degree of cementation increases as one moves up the succession. This is covered by the sandy, wave dominated lower to upper shoreface deposits (FA 5), with repeated bivalve rich beds, and low to moderate bioturbation. A further regression is seen when the FA 5 is covered by upper shoreface deposits (FA 6), dominated by small-scale HCS. As this is again covered by highly deformed FA 5, this could be a repetition, rather than a trangressional event. A prominent change from lower to upper shoreface (FA 5) to barrier bar deposits (FA 7), characterised by the large-scale cross-stratified sandstone, bivalve rich beds (Promyalina), coal fragments and mud clasts. A transgression is seen, as FA 7 is covered by lower to upper shoreface deposits (FA 5) again, and further by lower shoreface deposits (FA 4).

A typical feature observed in the Siksaken Member on Selmaneset is repeated sections of shell debris and bivalve rich beds. Earlier studies of Festningen (Wignall et al., 2016, 1998; Mørk et al., 1982) has documented accumulations of shell imprints, shell debris and shell rich beds. These bank deposits are found in other locations on western Spitsbergen Dallmann et al. (2015). In the stratigraphical section from Festningen, described in Vigran et al. (2014), the lower 150 meter were described as a coarsening upward succession, grading into a 70 m thick bivalve rich bank deposit (Myalina Sp.). At Selmaneset, the first observed accumulation of bivalves were found after about 100 meter in the lower parts of the Siksaken Member, in FA 3. Repeated accumulations of bivalves were found at several locations at Selmaneset. These accumulations of bivalves has been interpreted to be similar to the bivalve rich beds (Promyalina) found at Festningen (e.g Wignall et al. (2016); Mørk et al. (1982)) in the dominantly sandy section.

5.3.2 Bertilryggen

The mountain Bertilryggen is located in Ekmansfjorden (see Figure 4.1). The exposed Triassic succession was followed along the beach between Flintholmen and Sveaneset. The general quality of the outcrop was much better compared to Selmaneset and Ramfjelldalen. The beds were subhorizontal and much less cemented. However, the boundary between Vardebukta Formation and the overlying Tvillingodden Formation was not found, and due to limited time, the team did not have the opportunity to spend more than one day of logging. The measured log from Bertilryggen is presented in Figure 5.46. As seen from Figure 5.48, the layers are sub-vertical.

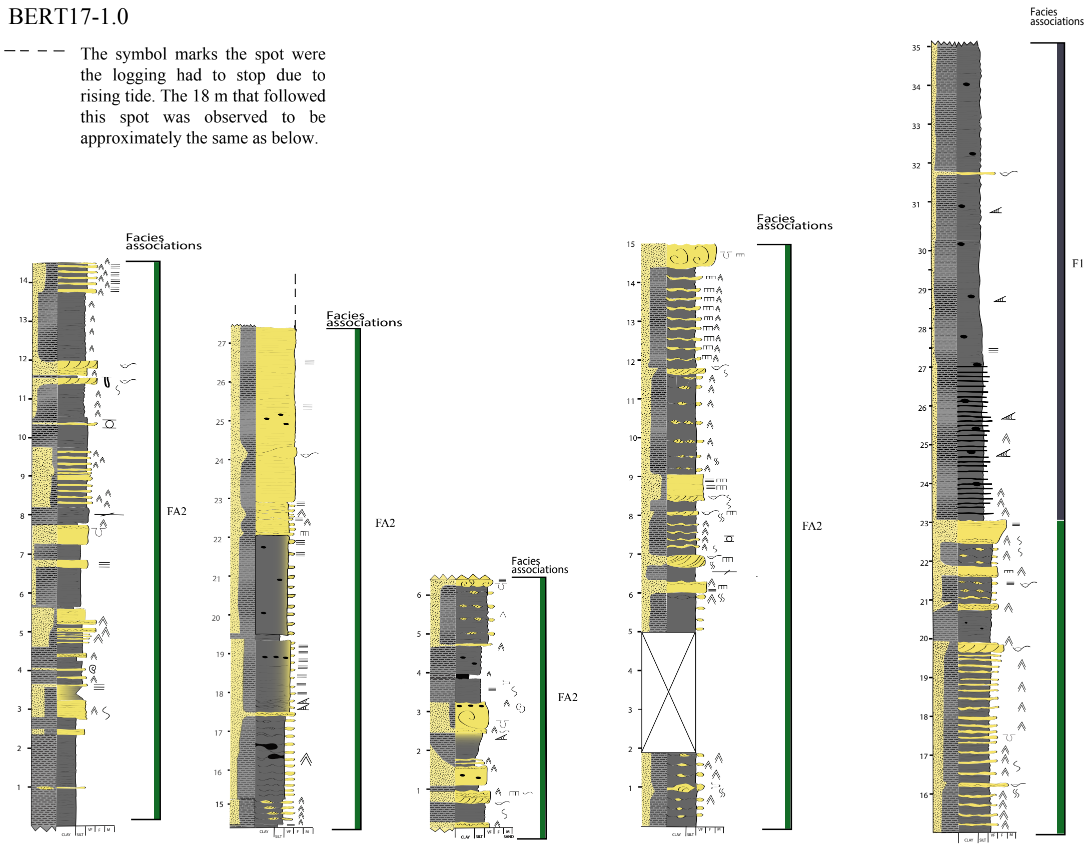


Figure 5.46: *BERT17-1.0*: Presented here are the measured section from Bertilryggen. 68 meters were logged in total. Marked in the log is 18 meters that could not be measured due to rising tide. A transgression is seen in the upper 12 meters, dominated by siltstone with thin lensese of very fine sandstone and anbundant concretions. The boundary between the Vardebukta Formation and Tvillingodden Formation was not discovered, due to limited time.

Observations:

Prior to the measured section, a relatively coarse, light sand (possibly silicified), with clear vertical burrows were observed. The sections was highly bioturbated, with coarsening up sections. A dolerite sill was also observed, but this appeared to be coarser than the dolerite observed on Selmaneset.

The boundary between Permian Kapp Starostin and Triassic Vardebukta Formation was scree covered, which made an exact position of the base difficult. A 10 meter interval of scree cover divides the assumed Permian deposits of white, bioturbated sandy outcrop from the shale rich outcrop of the Vardebukta Formation. The boundary has therefore been assumed to be underneath the scree (See Figure 5.47).

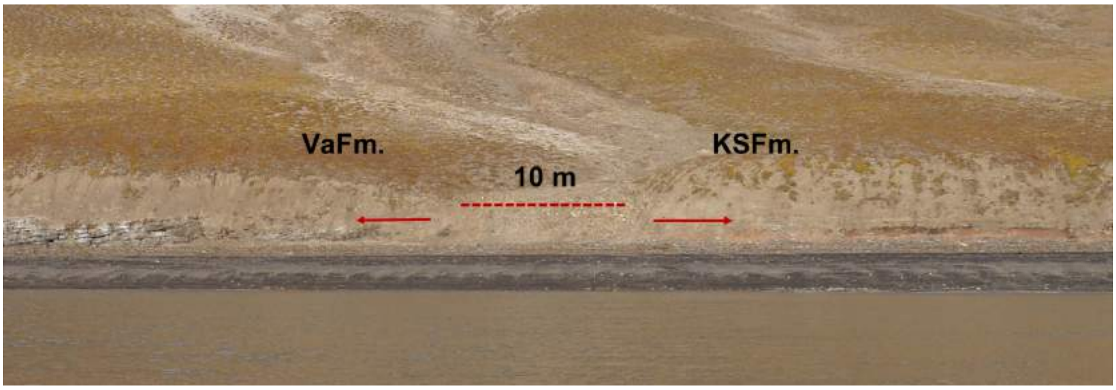


Figure 5.47: Overview of the beach where the measured section starts: marked in the photo is the 10 meter scree cover that divides the Permian Kapp Starostin Formation (KSFm.) and the Triassic Vardebukta Formation (VaFm.)

A coarsening up trend from shale into laminated silt/very fine sand with ripples (F2) can be seen in the lowermost 27 meters of the log. It is dominated by small-scale coarsening upward sections, with interbedded mudstone and very fine to fine sandstone, and shale/siltstone with lenses of very fine to fine sandstone. The shape of the lenses may indicate some form of ripples, and based on the observations, they are assumed to be symmetrical (F2). The sandstone beds usually contains some amount of mud, and are typically from 5 cm to 40 cm thick, with laminated siltstone in between. The sedimentary structures seen in the sandstone are mostly symmetrical ripples (F2), to hummocky cross-stratification (F5). Some planar lamination is also noted (F6, Figure 5.8a,b), including a deformed bed of sand, 50 cm thick, with symmetrical ripples at top was also observed (F8, Figure 5.11b). Concretions are also observed in within the first 27 meters. As it approaches the top of the first measured interval, the structures in the sand lenses appears to be more planar laminated (F6/F2). In the top of this interval, the laterally changing layers of sandstone (5-12 cm thickness), with lamination at base and symmetrical ripples at top. No bioturbation has been observed, except for in the lowermost part of the first interval.

The next 18 meters were not logged, due to rising tide. These 18 meters were noted as more or less the same as below, including some sandstone layers containing HCS and symmetrical ripples. The logging was continued were the water did not reach the outcrop. Figure 5.48 presents the interval that was not logged. Note the three coarsening up sequences marked in the picture.

Figure 5.48: The 18 meters that were not logged in this section due to tide has been presented in this picture. Three coarsening up sequences was observed.

The interval following the 18 meters (0-6.25 m), contains four small scale coarsening upward sections, from siltstone, with thin layers of wave rippled sandstone and lenticular bedding (F11, Figure 5.14a), to 15-70 cm thick very fine sandstone beds. These typically showed structures like HCS (F5), wave ripples (F2) and planar parallel stratification (F6). Some of the sandstone beds contains concretions, with symmetrical ripples at top, and a 70 cm thick layers of deformed sandstone (F8, Figure 5.11a), with shale, and ripples at top of the bed could be found here.

This is followed by 23 meter of lenses of very fine sandstone, of thickness 2-5 cm, with symmetrical ripples in the lenses of sand (F2). The next meters contains possibly 6 coarsening up sections (UC), with interbedded silt and cemented very fine to fine sandstone (2-10 cm thick sand layers), with 25 to 70 cm thick sandstone beds in the top of the UC sections. A typical example can be seen in Figure 5.49. Seen in this section is the siltstone with wave rippled sandstone lenses, grading up to benches of very fine to fine sandstone with planar parallel stratification at base, to HCS and wave rippled top surfaces. The thinner beds shows symmetrical ripples, with some bioturbation at base. A 60 cm thick deformed sandstone bed are also found here, possibly loadcast, with symmetrical ripples at top of the bed (F8). The sand layers becomes more lens-shaped in the upper part of this interval, and some concretions are found here. Another example of this interval can also be seen in Figure 5.26.

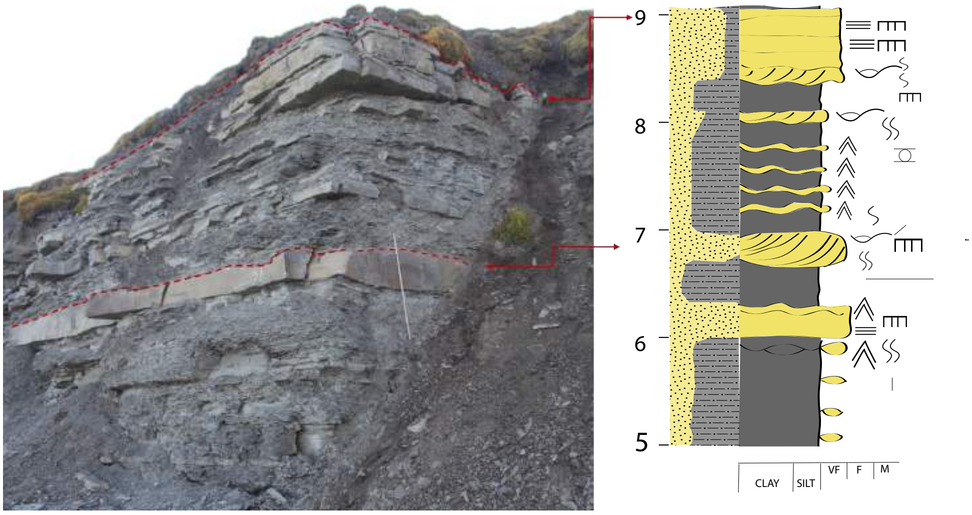


Figure 5.49: This figure presents two coarsening up sequences, at Bertilryggen. Lenses of very fine sand in the silt, displaying symmetrical ripples, grades up into approximately 25 to 50 cm thick fine sandstone beds. The lower layers grades from planar lamination to wave rippled cross-laminated top surface. The next bed is made up of large-scale cross-stratified sandstone, with moderately bioturbated base. The last coarsening-up sequence have a higher sand content, were thin wave rippled layers of very fine sandstone are interbedded in the siltstone, with HCS seen in the two upper sandstone beds, while the last 70 cm of the upper sandstone bed contain planar parallel lamination. This could also be interpreted to be large-scale HCS. The three sandstone beds all have low to moderately bioturbated lower surfaces.

The uppermost 12 meters of the section (see FA 1, Figure 5.30) contains mostly mud, but probably 90 % silt. It contains for the most part laminated siltstone (F3) with thin layers of cemented sandstone with symmetrical ripples and concretions, getting more planar parallel laminated towards the top of the section (F6). Moving up in the stratigraphy, the structures are more wavy to lenticular laminated (F11, Figure 5.14b). The upper most part of this section was mostly scree covered. The coordinates of the end of the log can be seen in the Appendix F.

Interpretations:

The section is dominated by several coarsening up sequences, with increasing sandstone thickness, often seen with a thick sandstone bed with HCS. The thin sandstone beds found at Bertilryggen are dominated by wave and storm structures (F2 and F5), and the general amount of fine grained material, with the wave reworked sandstone suggests offshore transition zone. A transgression has been seen in the uppermost 12 meters the section, were a transition from offshore transition zone to offshore deposits has been observed.

The abundant wave rippled sandstone, with occasionally storm deposits may suggest a relatively distal environment, based on descriptions from similar findings from Tschermakerfjellet (Wignall et al., 2016). As stated by Wignall et al. (2016), the thin wave reworked sandstone beds seen at Tschermakfjellet, may indicate that the water depth are shallow enough in order to be affected by waves.

Comparing the observations from Bertilryggen with the findings from Selmaneset, the amount of fine material may suggest a deeper setting than Selmaneset. A wave dominated to storm dominated offshore transition zone may be suggested, followed by a deepening to offshore deposits in the last 12 meters. This may also be supported by the heterolithic structures observed at Bertilryggen (F11, Figure 5.14). As the lenticular bedding is not considered a unique structure for tidal processes, (Daidu et al., 2013), a tidal dominated environment has not been considered. But as mentioned by Daidu et al. (2013), the focus on the recognition of the typical tidal structures may lead to a misidintification, and open coast tidal-flats may be interpreted to be wave-dominated environments. However, in order to make a more detailed interpretation, further studies of the succession at Bertilryggen should be done.

5.3.3 Ramfjelldalen

In addition to Selmanset and Bertilryggen, two days were spent in Ramfjelldalen. The valley, Ramfjelldalen is located northeast of Ramfjellet, which can be seen on Figure 5.31. It should be noted that due to limited time, this area was not studied in detail. However, a brief description of the outcrop, including a measured section from a 55 meter exposure, are presented in this section.

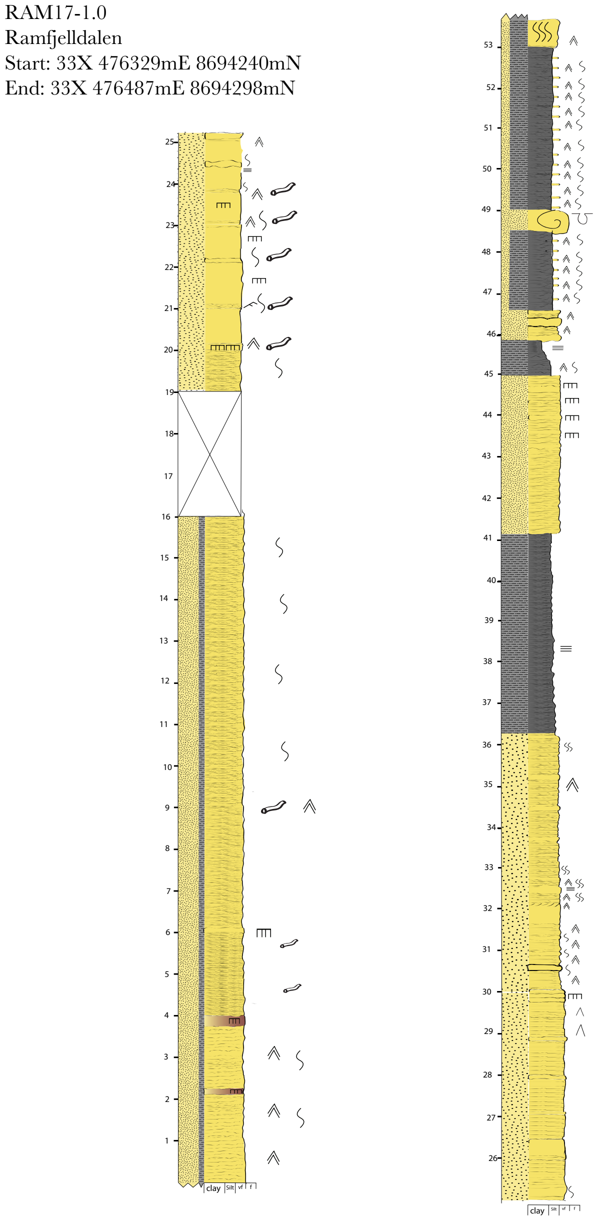


Figure 5.50: *RAM17-2.0*: Presented here are a measured section from Ramfjelldalen. Measured by Ingrid N.Hoel and Erik P.Johannessen.

Observations:

As most of the outcrops was scree covered and highly deformed, the boundary between Kapp Starostin Formation and Tvillingodden Formation was not found. An interval of black shale further in the valley was defined as The Middle Triassic Bravaisfjellet Formation. 2-3 exposures of very fine sand beds were found, interpret to be the Vardebukta Formation.

A 55 meters interval was measured in Ramfjelldalen. It contained separate sandstone layers, with some silt in between the sandstone layers. The colour of the outcrop was yellowish, with blue-grey fresh surface. The studied section from Ramfjelldalen was strongly bioturbated, typically on the surface, with a few exceptions were the whole bed were bioturbated thoughout. The first 16 meters are presented in Figure 5.51, are dominated by very fine to fine sandstone, wave rippled (F2) to massive beds (F7), with beds of 1-2 cm thickness. The thickness of the beds were increasing upwards in the section. 10 cm thick, heavily cemented beds were found in the middle of the section with reddish weathering colour. These were often massive at base, with wave rippled top surfaces. This is followed by scree cover. The next 17 meters, (Figure 5.51), contains same as below; beds of very fine to fine sandstone, with massive appearance (F7) and wave rippled top surfaces (F2), typically bioturbated with horizontal burrows, possibly *Planolites*. An increase in finer material is seen in the uppermost section. 5 meters of laminated fine grained material, described as paper shale, in 1 cm thick layers. This can be seen in Figure 5.51c. This is followed by 2 meters of very fine to fine sandstone, heavily cemented, dominated by massive beds, with low bioturbation rate. The last 9 meters logged before a new scree cover, was assumed to be the last of the Vardebukta Formation. This section contained 9 meters of alternating massive sandstone, wave rippled very fine sandstone and silty mudstone.

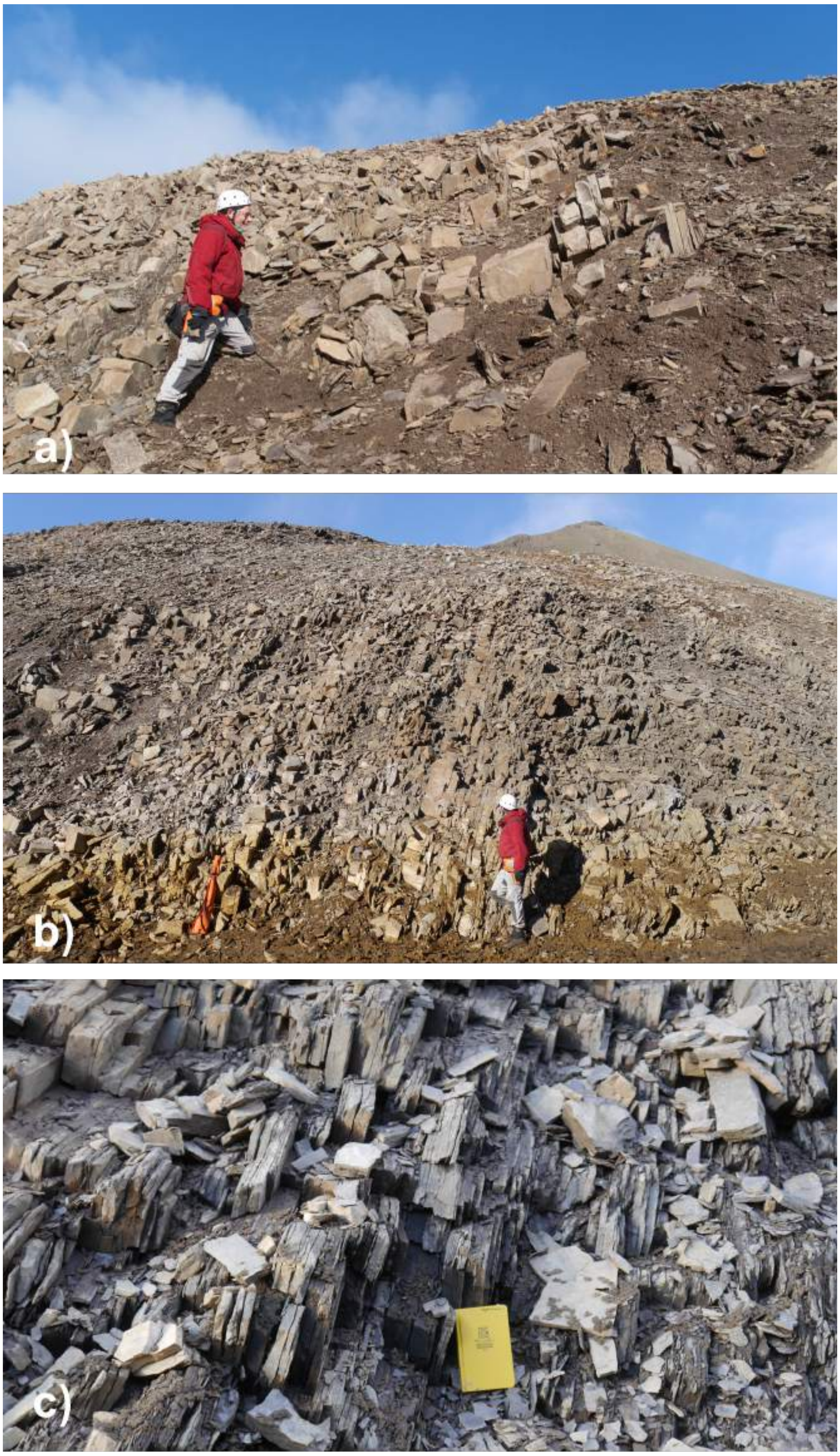


Figure 5.51: Presented here are three examples of the highly deformed and partly scree covered outcrop studied at Ramfjelldalen.

Prior to the logged section presented in Figure 5.50, ca 14 meters of outcrop was studied. This interval was dominated by very fine to fine sandstone, with separate sandstone layers of 2-10 cm thickness. They were typically calcite cemented, moderately to heavily bioturbated at the surfaces, with wave ripples (F2), see Figure 5.52a,b. Seen from Figure 5.52b, 12 cm thick sandstone beds of fine sandstone. The thickness of the sandstone layers increase slightly upwards. Trace fossils commonly found were *Thalassonoides* and *Planolites*.

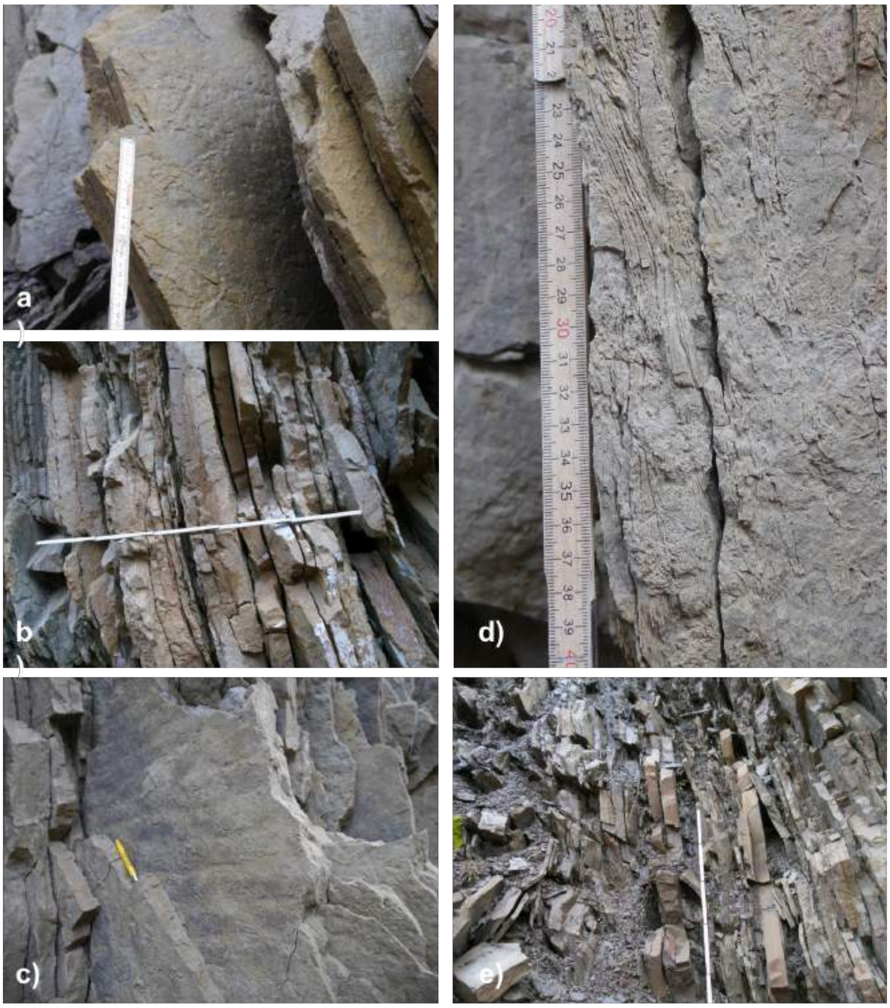


Figure 5.52: Presented here are typical examples of the structures seen in the Vardebukta Formation at Ramfjelldalen. **a)** Moderate to intense bioturbation of the sandstone surfaces. **b)** Heavily cemented, reddish, very fine sandstone beds. **c)** Wave ripples at top surface. Yellow pen for scale. **d)** Asymmetrical rippled very fine sandstone. **e)** Heavily cemented sandstone beds with thin layers of silt in between.

Interpretations:

Based on the dominant wave reworked sediments, the marine fossils found in the outcrop, and the rate of bioturbation seen in the short interval studied in Ramfjelldalen, this has been interpreted to be of lower shoreface deposits.Compared to the observations from

Selmaneset, this section could be correlated with the sandy, wave dominated section of the lower to upper shoreface deposits (FA 5). Although this was assumed to be the Vardebukta Formation based on the Kapp Starostin Formation and Bravaisfjellet Formation, there are some uncertiainties regarding this, no apparent upper boundary with Tvillingodden Formation was found. As this interval was highly deformed, some sections appeared to repeated, possibly due to folding.

Chapter 6

Discussion

Based on the 11 facies (Section 5.1) and the 7 facies associations (Section 5.2) described and interpreted in Chapter 5, a depositional environment for the different locations were presented in Section 5.3.

An upwards coarsening succession is recognised at Selmaneset, with a relatively thick sandstone rich section. Following the shoreline profile presented in Reading and Collinson (1996) (fig.6.6), the result is described as follows:
Approximately 100 meters of dominantly silty shale, grading up from offshore deposits (FA 1) to offshore transition deposits (FA 2 and 3) with thin storm generated sandstone layers. This continuous to grade up into lower to upper shallow marine deposits (FA 5, FA 6), still wave and storm generated. A further regression is seen as an interval containing several small-scale coarsening upward sections, dominated by large-scale cross-stratified sandstone in white sandstone beds (F5), with mud flake conglomerate (F9), bivalves rich beds and layers of bioclastic sandstone (F4), interpreted to be barrier bar deposits (FA 7). This interval is about 90 meters thick, followed by a 18 meter thick interval of lower to upper shallow marine deposits (FA 5). A transgression is seen in the uppermost 68 meters of the Vardebukta Formation, as the lower shoreface deposits (FA 4) dominated by shale is observed.

As mentioned earlier, similar observations has been found on Festningen. The Vardebukta Formation was studied at Festningen and classified by Mørk et al. (1982) as a prograding barrier bar system, with tidal inlets and back barrier-lagoonal facies. Mørk et al. (1982) described a 140 meter interval of siltstone with storm generated sandstone beds, followed by a 90 meter thick sandstone dominated interval, interpreted to represent a barrier bar system, followed by a transgression and a fining up the uppermost 50 meters. Additional studies, such as Wignall et al. (2016, 1998) suggests a shoreface depositional environment, with sediments grading from fine grained offshore deposits in the basal Vardebukta Formation, to proximal foreshore deposits. The white sandstone benches observed in the middle of the Vardebukta Formation at Selmaneset (FA 7) was also described by (Wignall et al., 1998) at Festningen, in association with a major change in sedimentary facies observed 117 meters above the base of the Siksaken Member.

Observed here are a shell rich limestone bed with erosive base, covered by a white-weathered sandstone bench, and followed by 10 cm of conglomerate with flat pebbled clasts of green siltstone. Similar features has been observed at Selmaneset within a 53 meter thick interval. This has been described as several coarsening up sections, from silt and very fine sandstone to benches of white sandstone with low-angle cross-stratified sandstone. These are further grading up to bivalve rich sandstone beds (Promyalina), a thick sandstone layer dominated by *Diplocraterion*, mud flake conglomerate and coal fragments.

Based on the findings from Bertilryggen, this sections appears to be of a more distal character compared to Selmaneset. A simplified correlation between the two logs are presented in Figure 6.1. Dominated by FA 3, containing offshore transition deposits of shale with thin wave rippled sandstone beds, shallowing up into 12 meters offshore deposits (FA 1), this interval has been interpreted to be distal offshore transition zone, dominated by wave ripples and storm deposits. This also fits with the observations from other studied Lower Traissic successions in the area, for instances Tschermakerfjellet,(Wignall et al., 2016), where similar distal sandstone deposits are found.

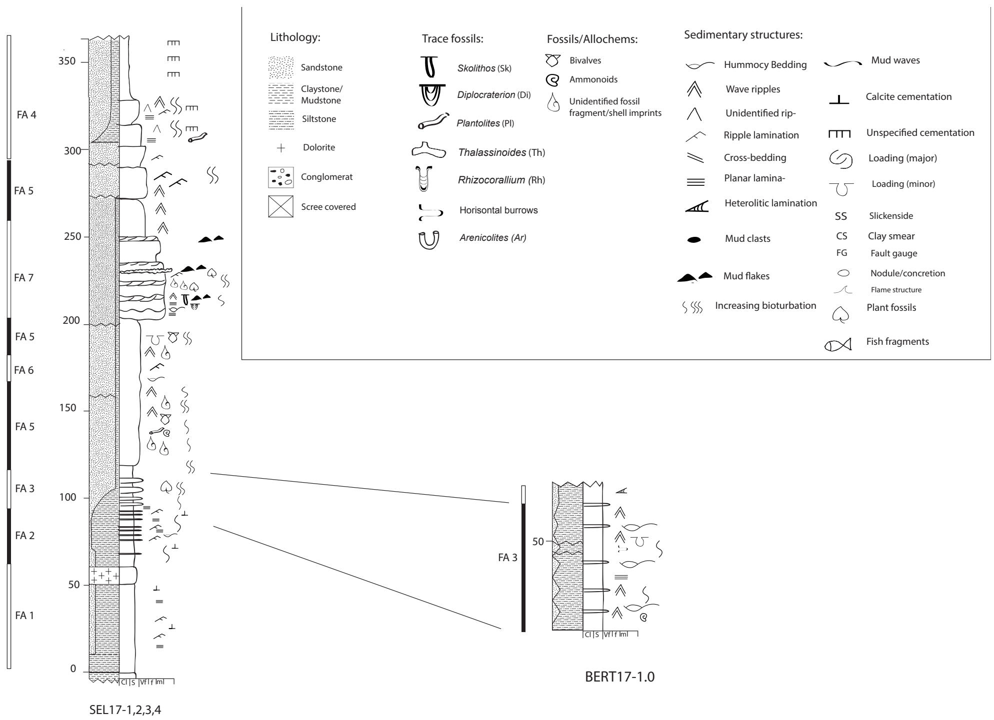


Figure 6.1: A simplified sketch of Bertilryggen and Selmaneset has been made in order to illustrated a potential correlation between the associations.

The results presented in Chapter 5 (Subsection 5.3.3) from Ramfjelldalen revealed a heavily deformed succession, comprising of beds of very fine to fine sandstone, with marine trace fossils like *Planolites* and *Thalassonoides*. Based on the sedimentological observation, this section could be correlated with the sandy lower to uppers shoreface deposits of Selmaneset. However, due to the complexity of the area, this section will require more time, including the knowledge of the structural deformations of the area, in order to correlate the Triassic succession with neighbouring areas.

According to Figure 6.2, the Sassendalen Group is thickening from Festningen to Selmaneset. As mentioned in Chapter 3, studies (e.g Wignall et al. (1998)) show that the thickest succession of Sassendalen Group is found near the inlet of Isfjorden, and successively thinning in eastward direction. This fits well with the results from Selmaneset (Chapter 5). 400 meter succession was measured at Selmaneset, and makes up the Vardebukta Formation. Both Selmaneset and Festningen (Mørk et al., 1982) show major sandbodies in the uppermost section of Vardebukta Formation. The Vardebukta Formation has been measured to be around 290 meters in the stratotype at Festningen, Figure 3.4. In comparison, the sand dominated section of Selmaneset is measured to be about 233 meters thick, dominated by very fine sandstone (FA 3 and FA 5) to fine to medium sandstone (FA 6 and FA 7). As described in Chapter 5, the succession on Selmaneset shows clear evidence of an complex tectonic influence, by Bergh et al. (1997) (Chapter 3). Fault gauges were found between layers of cemented sandstone and mudstone, fault planes and clear folded section outcrops. The most important evidence of the extensive tectonic activities seen in the outcrop at Selmaneset, may therefore be in the thickness measurements.

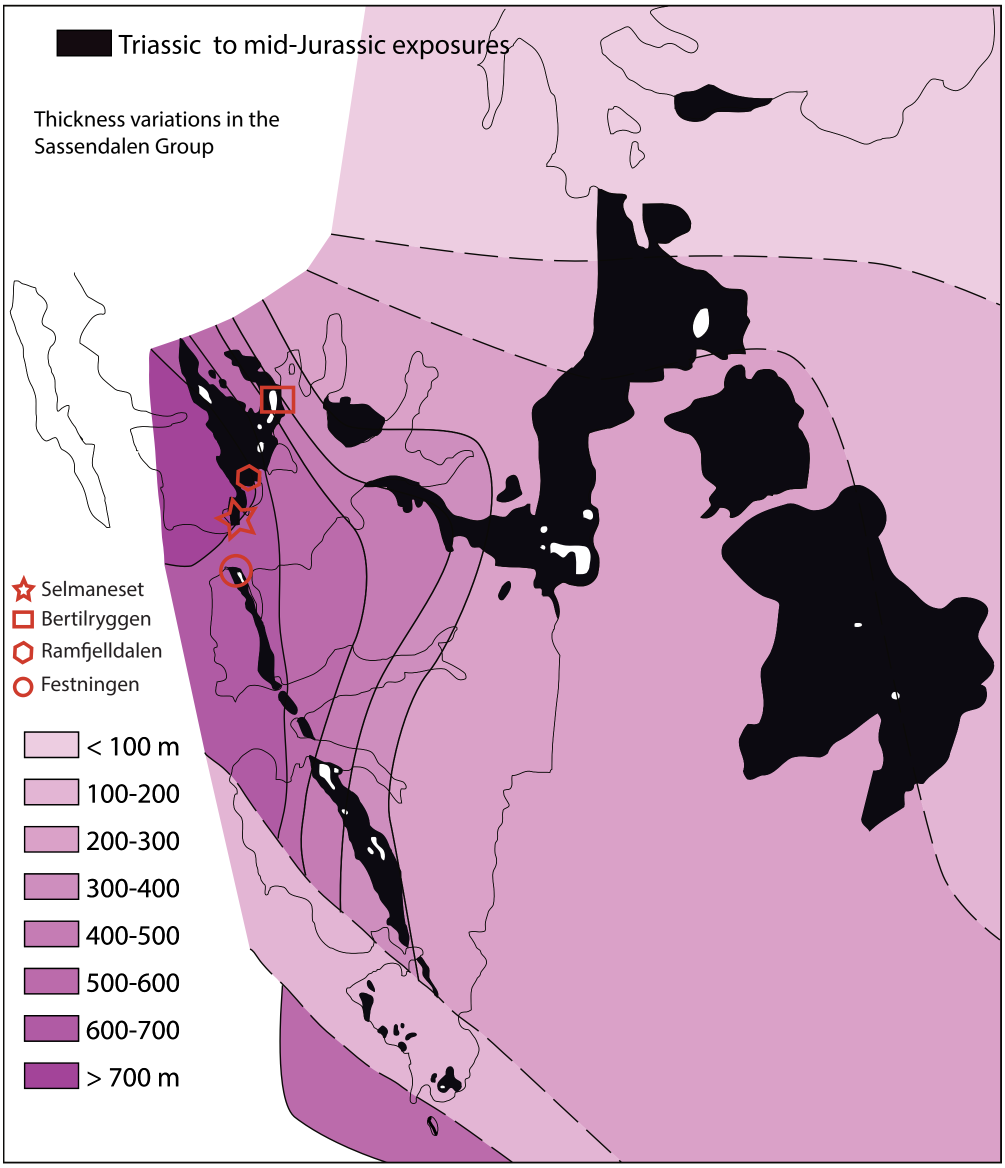


Figure 6.2: "The thickness variations of the Sassendalen Group on Svalbard", modified from Vigran et al. (2014). The red symbols marks the locations studied in this area, including Festningen.

A deepening trend from Selmaneset to Bertilryggen has thus been interpreted. This eastward thinning of the sandstone dominant intervals supports the proximal to distal transition from west to east presented by previous studies Wignall et al. (2016, 1998); Mørk et al. (1982). A palaeogeographical interpretation can be viewed in fig.10a in Mørk et al. (1982) (p.381), illustrating the coastal prograding system from the west.

A more recent study was performed by Solvang (2017), of the Vardebukta Formation at Festningen. Solvang (2017) argues that a classification of barrier bar at Festningen may not necessarily be the only reasonable interpretation. A grading up from mud-rich prodelta, to delta front, up to lower delta plain deposits was observed by Solvang (2017), who suggested that clear progradation signature could be seen at Festningen. This is symptomatic for prograding deltas (Bhattacharya, 2006). Based on the combination of sedimentary processes observed on Festningen (tidal, wave and fluvial influence) Solvang (2017) suggests a mixed type delta. Although a progradational trend was seen at Selmaneset, the lack of fluvial and tidal influenced deposits may indicate a non-deltaic succession. The sediment supply for non-deltaic coasts are primarily marine, and not fluvial, as for tidal-and wave dominated deltas (Reading and Collinson, 1996).

Chapter 7

Summary and Conclusion

The aim of this thesis was to perform detailed facies analysis and identify facies associations from Oscar II Land based on a sedimentological investigation from the outcrops from Selmaneset and Bertilryggen, in addition to Ramfjelldalen. In addition, the goal was to provide a reliable depositional model for the Lower Triassic Vardebukta Formation at Selmaneset and Bertilryggen, and compare them with neighboring areas.

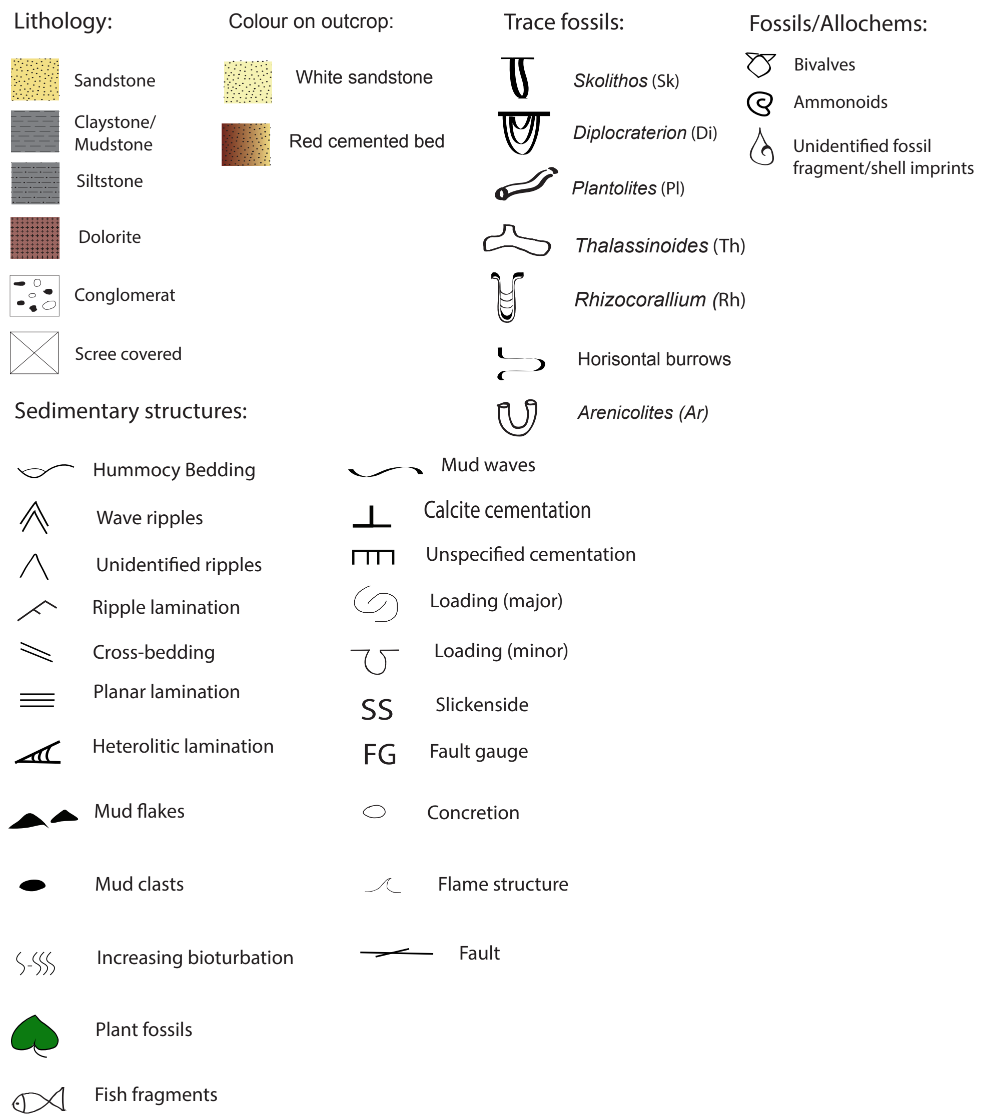
Based on the findings from Selmaneset, a coarseing up trend from offshore deposits to upper shoreface and barrier bar deposits, following the shoreface profile described by Reading and Collinson (1996) (figur 6.6), similar to the findings of Mørk et al. (1982) from Festningen. A deepening trend eastward seen in previous studies from Spitsbergen supports the interpretation of Bertilryggen as a distal storm and wave dominated offshore transition deposits. The complex tectonic nature of Oscar II may have caused several repetitions at Selmaneset, resulting in a thicker succession found here. The heavily deformed outcrop found at Ramfjelldalen was, based on the observations, interpreted to be marine deposits, possibly lower shoreface to upper shoreface. However, further study of the tectonic events at Oscar II Land, in cooparation with the sedimentologist will be important for further understanding of the area.

7.1 Recommendation for further research

Due to limited time, this study had its main focus on the facies and sedimentology of Oscar II Land. In order to gain a better understanding, additional studies with emphasis on tectonostratigraphic evolution should be carried out. A recommandation for further studies would be to a closer cooperation with structural geologist. This is study that would require time, due to the complexity of this area.

Appendix A

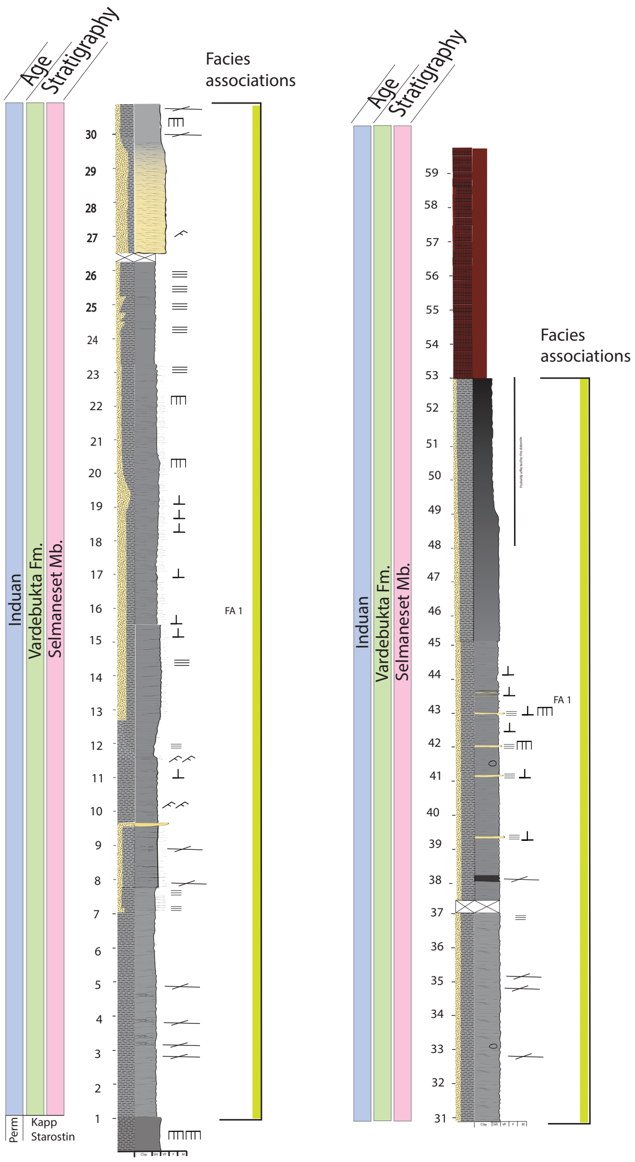
Legend

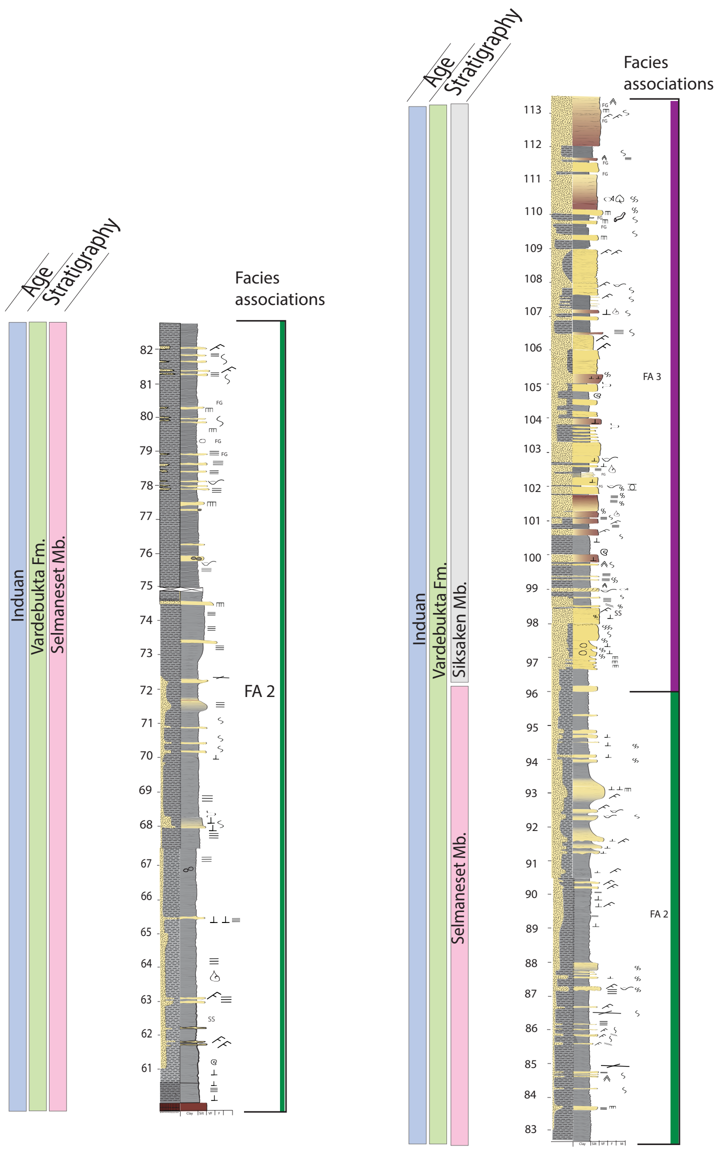


Appendix B

SEL17-1.0

Selmaneset
33X
475364mE
8684118mN




Age
Stratigraphy
Induan
Vardebukta Fm.
Selmaneset Mb.
Facies associations
FA 2
82
81
80
79
78
77
76
75
74
73
72
71
70
69
68
67
66
65
64
63
62
61
Age
Stratigraphy
Induan
Vardebukta Fm.
Siksaken Mb.
Selmaneset Mb.
Facies associations
FA 3
FA 2
113
112
111
110
109
108
107
106
105
104
103
102
101
100
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98
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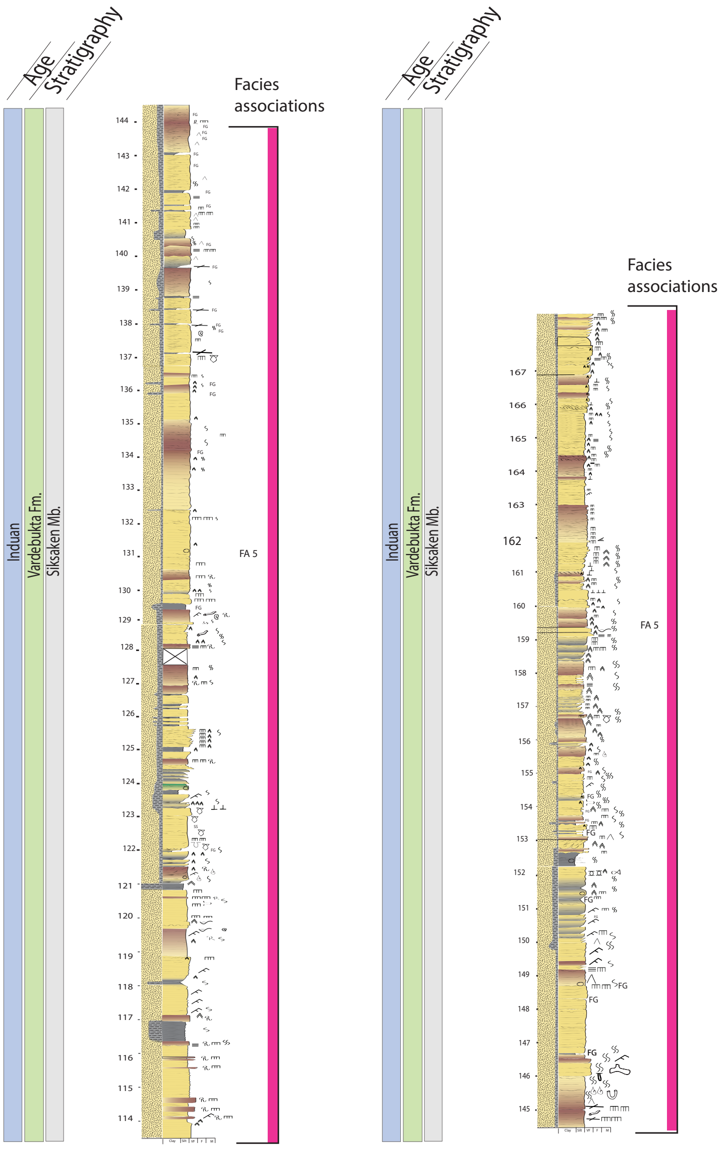
83


Age
Stratigraphy
Induan
Vardebukta Fm.
Siksaken Mb.
Facies associations
FA 5
Age
Stratigraphy
Induan
Vardebukta Fm.
Siksaken Mb.
Facies associations
FA 5

Appendix C

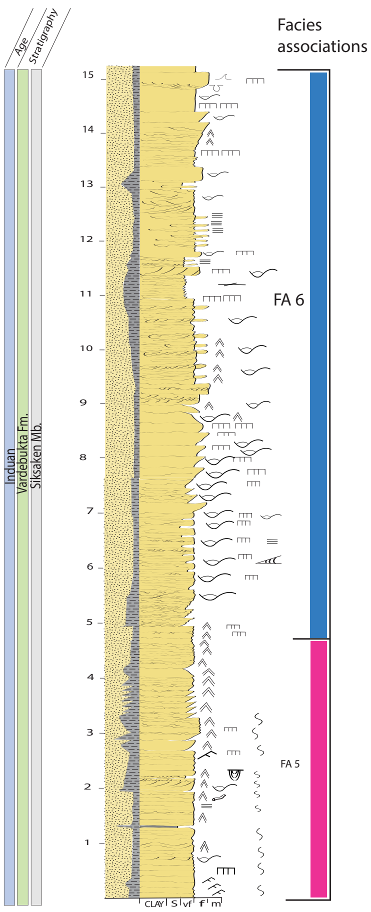
SEL17-2.0

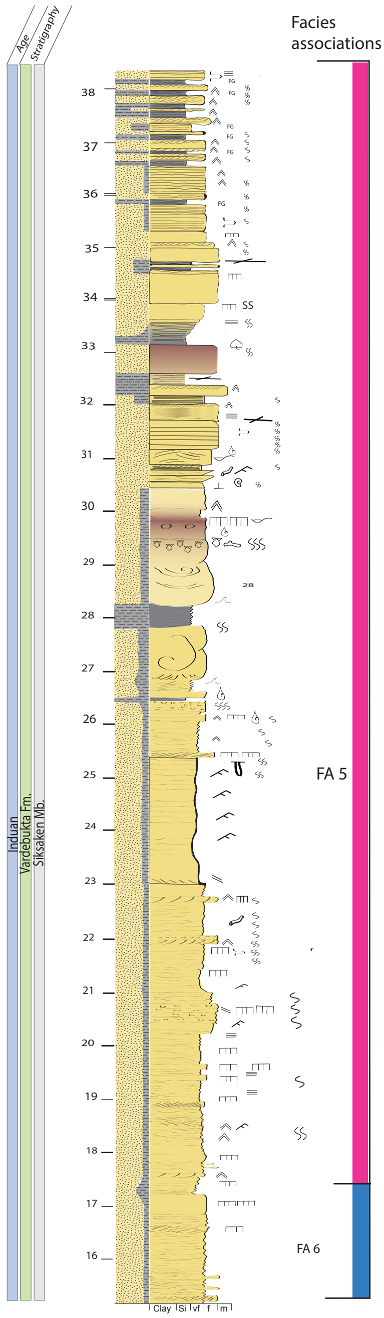
Selmaneset

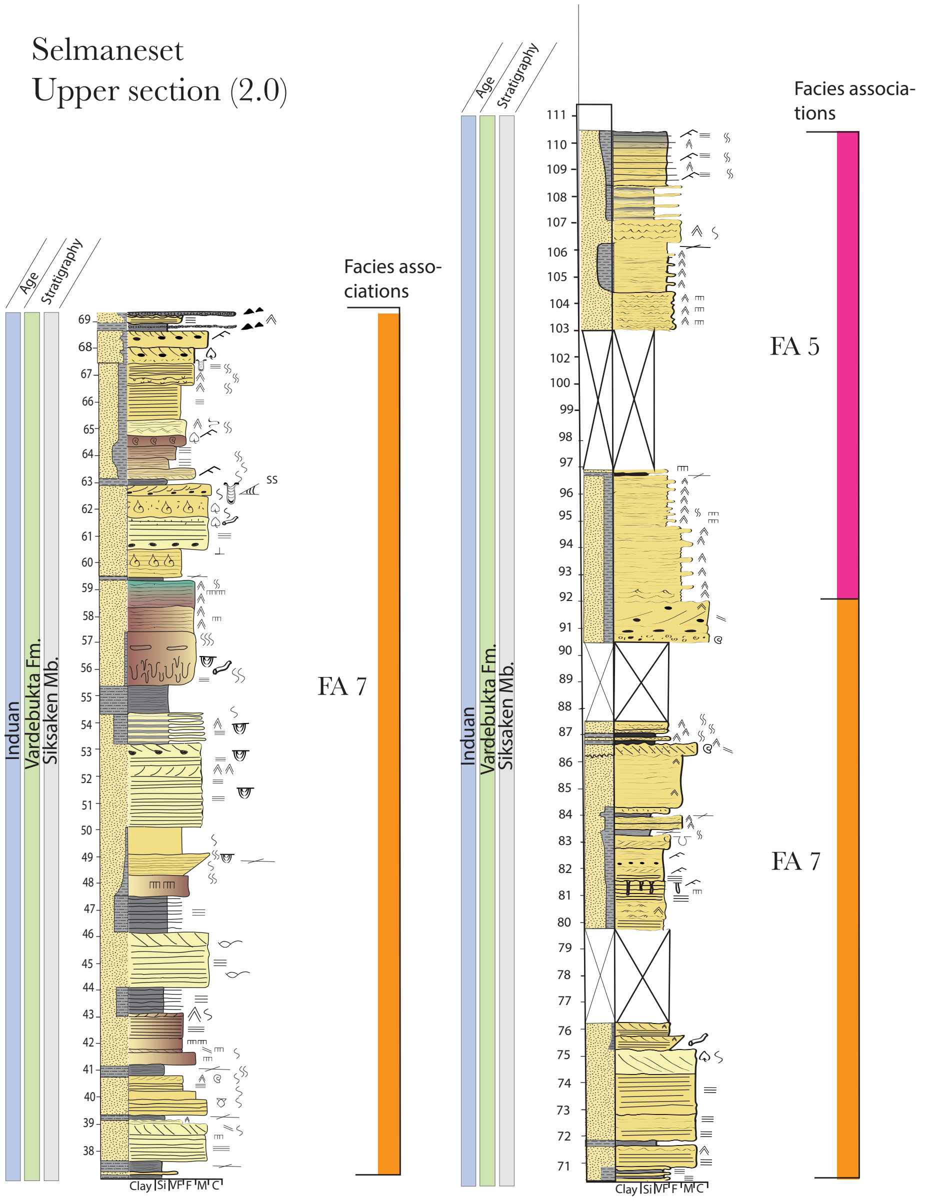
Lower section (2.0)

33X 0475422 mE

8684423 mN



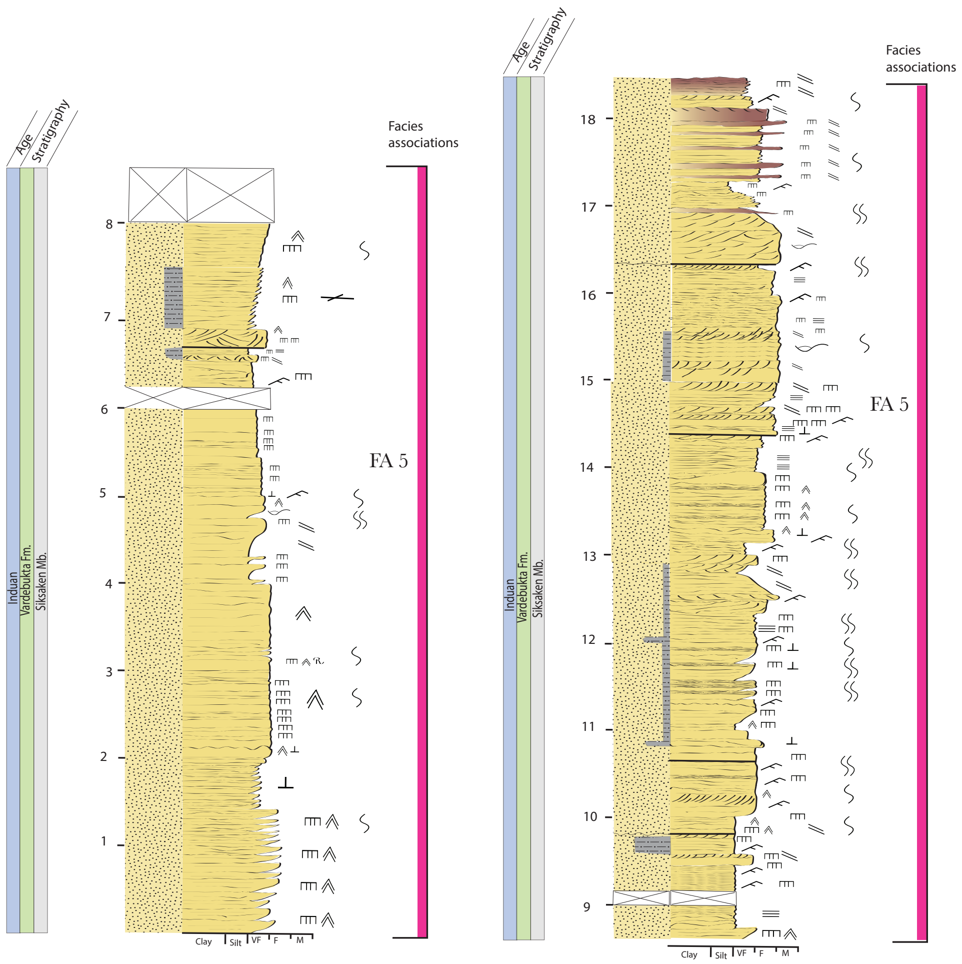



Selmaneset
Upper section (2.0)
Age
Stratigraphy
Induan
Vardebukta Fm.
Siksaken Mb.
Facies associations
FA 7
FA 5
Clay Si VF F M C

Appendix D

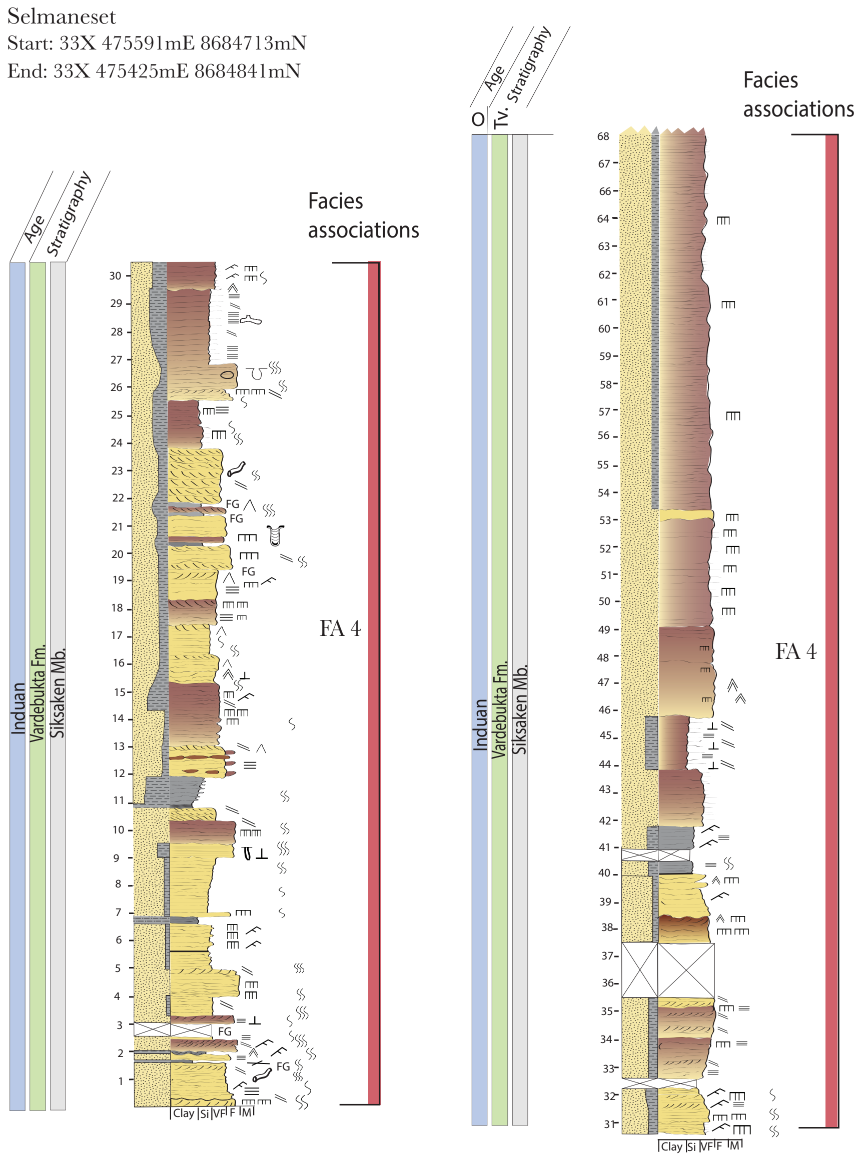
SEL17-3.0

Selmaneset
33X 475407mE
8683520mN



Appendix E

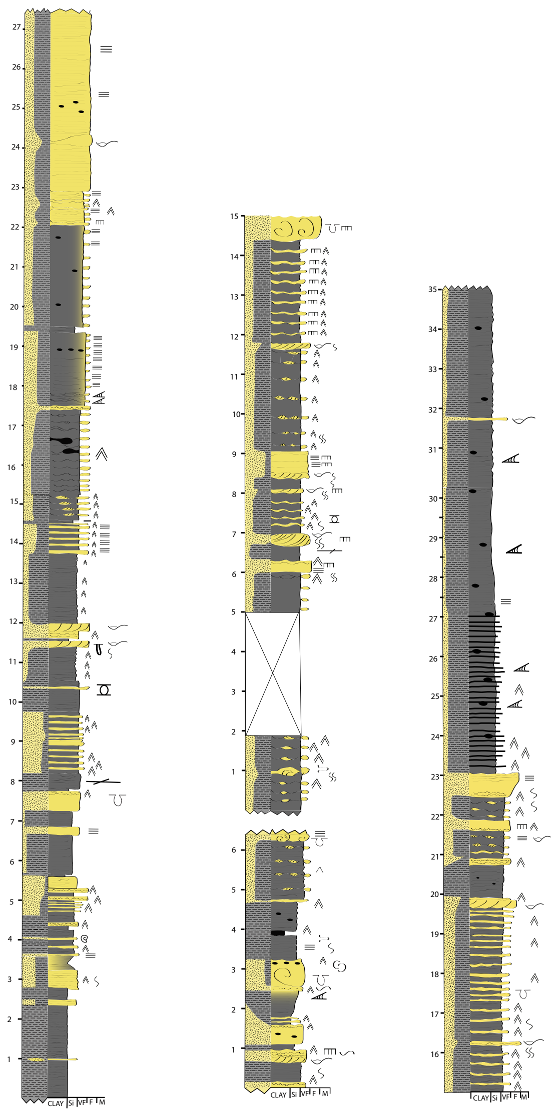
SEL17-4.0



Appendix F

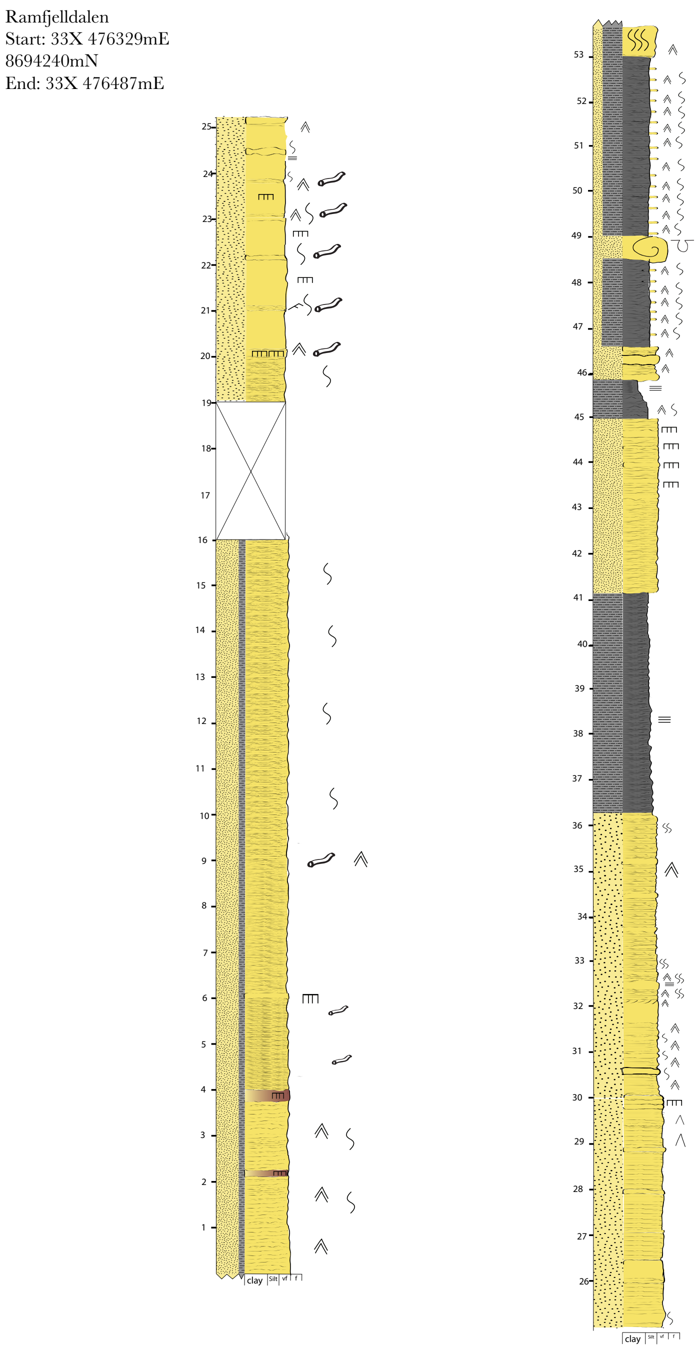
BERT17-1.0

Bertilryggen
Start: 33X 476487mE
8694298mN
End: 33X 489420mE
8724853mN



Appendix G

RAM17-1.0



Bibliography

A.Buatoisa, L., Lindsey J.N.Wesolowski, Gabriela Mánganoa, M., B.Carmonab, Ponce, J. J., and B.Carmona, N. (2018). Trace fossils, sedimentary facies and parasequence architecture from the Lower Cretaceous Mulichinco Formation of Argentina: The role of fair-weather waves in shoreface deposits. *Sedimentary Geology*, 367.

Bergh, S., Braathen, A., and Andresen, A. (1997). Interaction of Basement-involved and thin-skinned Tectonism in the tertiary fold-thrust belt of central spitsbergen.

Bhattacharya, J. P. (2006). Deltas. In Posamentier, H. W. and Walker, R. G., editors, *Facies Models Revisited*, chapter 5. SEPM Special Publication 84.

Boggs, S. J. (1987). *Priciples of Sedimentology and Stratigraphy.* Merrill Publishing Company. 784pp.

Boggs, S. J. (2011). *Principles of Sedimentology and Stratigraphy.* Pearson Prentice Hall, 5 edition. 585 pp.

Boyd, R., Dalrymple, R., and Zaitlin, B. (1992). Classification of clastic coastal depositional environments. *Sedimentary Geology*, 80(3-4):139–150.

Braathen, A., Bergh, S., Karlsen, F., Maher, H., Andresen, A., Hansen, A. I., and Bergvik, A. (1999). Kinematics of the Isfjorden-Ymerbukta Fault Zone: A dextral oblique-thrust ramp in the Tertiary fold-thrust belt of Spitsbergen. *Norsk Geologisk Tidsskrift*, 79(4):227–239.

Buchan, S., Challinor, A., Harland, W., and Parker, J. (1965). The Triassic stratigraphy of Svalbard. *Norsk Polarinstitutt Skrifter*, 135(135):18âĂŞ94.

Clifton, H. (2006). A reexamination of facies models for clastic shorelines. In Posamentier, H. and Walker, R., editors, *Facies Models Revisited*, pages 293–337. Society for Sedimentary Geology.

Daidu, F., Yuan, W., and Min, L. (2013). Classifications, sedimentary features and facies associations of tidal flats. *Journal of Palaeogeography*, 2(1):66–80.

Dallman, W. K., Andresen, A., Bergh, S. G., Jr., H. D. M., and Ohta, Y. (1993). *Tertiary fold-and-thrust belt of Spitsbergen, Svalbard*, volume 128.

Dallmann, W., Blomeier, D., Elvevold, S., Grundvåg, S., Mørk, A., Olaussen, S., Bond, D., and Hormes, A. (2015). Historical geology. In Dallmann, W., editor, *Geoscience Atlas of Svalbard*, volume 6 edition, chapter 6, pages 89–131. Norsk Polarinstitutt.

Dallmann, W. and Elvevold, S. (2015). Bedrock Geology. In Dallmann, W., editor, *Geoscience Atlas of Svalbard*, chapter 7, pages 133–174. Norsk Polarinstitutt, Tromsø, reposrt se edition.

Dallmann, W. K. (1999). Lithostratigraphic Lexicon of Svalbard: review and recommendations for nomenclature use: Upper Paleozoic to Quaternary Bedrock. Committee on the Stratigraphy of Svalbard. page 318.

Dalrymple, R. W. and 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(3-4):135–174.

Dashtgard, S. E., MacEachern, J. A., Frey, S. E., and Gingras, M. K. (2012). Tidal effects on the shoreface: Towards a conceptual framework. *Sedimentary Geology*, 279:42–61.

Doré, A. (1995). Barents Sea Geology, Petroleum Resources and Commercial Potential. *Arctic*, 48(3):207–221.

Elliot, T. (1989). Siliciclastic Shorelines. In Reading, H. G., editor, *Sedimentary Environments and Facies*, chapter 7, pages 155–188. Blackwell Scientific Publications, 2nd edition.

Fleming, E. J., Flowerdew, M. J., Smyth, H. R., Scott, R. A., Morton, A. C., Omma, J. E., Frei, D., and 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.

Grundvåg, S. A. and Olaussen, S. (2017). Sedimentology of the Lower Cretaceous at Kikutodden and Keilhaufjellet, southern Spitsbergen: Implications for an onshore-offshore link. *Polar Research*, 36(2017).

Hasiotis, S. (2014). KU Ichnology: Studying the Traces of Life. URL: http://ichnology.ku.edu/tracefossils.html

Johansen, S. K. (2016). *Sedimentology and facies distribution of the Upper Triassic De Geerdalen Formation in the Storfjorden area and Wilhelmøya , eastern Svalbard*. Masters thesis, Norwegian University of Science and Technology.

Johnson, H. and Baldwin, C. (1996). Shallow clastic seas. In 3, editor, *Sedimentary Environments: Processes, Facies and Stratigraphy*, chapter 7, pages 232–280. Blackwell Scientific Publications.

Komar, P. and Miller, M. (1975). The initiation of oscillatory ripple marks and the developement of plane-bed at high shear stresses under waves. *Journal of Sedimentary Petrology*, 45(3):697–703.

Loon, A. V. (2009). Soft-sediment deformation structures in siliciclastic sediments: an overview. *Geologos*, 15(1):3–55.

Lord, G. S., Johansen, S. K., Støen, S. J., and Mørk, A. (2017a). Facies development of the Upper Triassic succession on Barentsøya , Wilhelmøya and NE Spitsbergen , Svalbard. 97(1):33–62.

Lord, G. S., Johansen, S. K., Støen, S. J., and Mørk, A. (2017b). Facies development of the Upper Triassic succession on Barentsøya , Wilhelmøya and NE Spitsbergen , Svalbard. *Sedimentary Environments and Facies*, 97(3):33–62.

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

Manby, G. and Lyberis, N. (1996). State of stress and tectonic evolution of the West Spitsbergen Fold Belt. *Tectonophysics*, 267:1–29.

Mørk, A., Dallmann, W. K., Dypvik, H., Johannessen, E. P., Larssen, G. B., Nagy, J., Nøttvedt, A., Olaussen, S., Pcelina, T. M., and Worsley, D. (1999a). 3.Mesozoic Lithostratigraphy. In *Lithostratigraphic Lexicon of Svalbard*, chapter 3. Norsk Polarinstitut.

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

Mørk, A., Embry, A., and Weitschat, W. (1989). Triassic transgressive-regressive cycles in the sverdrup basin, svalbard and the barents shelf. *Correlation in hydrocarbon exploration*, pages 113–130.

Mørk, A., Knarud, R., and Worsley, D. (1982). Depositional and diagenetic environments of the Triassic and Lower Jurassic succession of Svalbard. *Artic Geology and Geophysics*.

Mørk, A. and Worsley, D. (2006). Triassic of Svalbard and the Barents shelf. *Boreal Triassic*.

Morsilli, M. and Pomar, L. (2012). Internal waves vs. surface storm waves: a review on the origin of hummocky cross-stratification. *Terra Nova*, 24:273–282.

Nicols, G. (2009). *Sedimentology and Stratigraphy*. Wiley-Blackwell, 2 edition.

Nøttvedt, A., Cecchi, M., Gjelberg, J. G., Kristensen, S. E., Lønøy, A., Rasmussen, A., Rasmussen, E., Skott, P. H., and van Veen, P. M. (1993). Svalbard-Barents Sea correlation: A short review. *Norwegian Petroleum Society Special Publications*, 2(C):363–375.

Posamentier, H. W. and Walker, R. G. (2006). *Facies Models Revisited*. SEPM Special Publication 84.

Quin, J. G. (2011). Is most hummocky cross-stratification formed by large-scale ripples? *Sedimentology*, 58(6):1414–1433.

Reading, H. and Collinson, J. (1996). Clastic Coasts. In Reading, H., editor, *Sedimentary Environments: Processes, Facies and Stratigraphy*, chapter 6, pages 154–231. Blackwell Scientific Publications, 3 edition.

Reading, H. G. (2001). Clastic facies models, a personal perspective. *Bulletin of the Geological Society of Denmark*, 48(2):101–115.

Reineck, H.-E. and Singh, I. (1980). *Depositional Sedimentary Enviroments*. Springer-Verlag, Berlin Heidelberg, 2 edition.

Riis, F., Lundschien, B. A., Høy, T., Mørk, A., and Mørk, M. B. E. (2008). Evolution of the Triassic shelf in the northern Barents Sea region. In *Polar Research*, volume 27, pages 318–338.

Rød, R. S., Hynne, I. B., and 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*, 11:21–38.

Solvang, O.-m. (2017). *Sedimentological and petrographical investigations of the Early Triassic Vardebukta Formation on western Spitsbergen*. Masters thesis, University of Bergen.

Sysselmannen (2012). Svalbards Geologi. https://www.sysselmannen.no/Toppmeny/Om-Svalbard/Geologi/

Tucker, M. E. (2015). *Sedimentary Rocks in the Field.* Wiley-Blackwell, 4 edition.

van de Meene, J., Boersma, J., and Terwindt, J. (1996). Sedimentary structures of combined flow deposits from the shoreface-connected ridges along the central Dutch coast. *Marine Geology*, 131(3-4):151–175.

Vigran, Mangerud, Mørk, Worsley, and Hochuli (2014). Palynology and geology of the triassic succession of svalbard and the barents sea. *Norsk Geologisk Undersøkelse Special Publication*, 14:1–65.

Wentworth, C. K. (1922). A Scale of Grade and Class Terms for Clastic Sediments. *The Journal of Geology*, 30(5):377–392.

Wignall, P. and Twitchett, R. J. (1996). Oceanic Anoxia and the End Permian Mass Extinction. *Science (New York, N.Y.)*, 272:1155–8.

Wignall, P. B., Bond, D. P. G., Sun, Y., Grasby, S. E., Beauchamp, B., Joachimski, M. M., and Blomeier, D. P. G. (2016). Ultra-shallow-marine anoxia in an Early Triassic shallow-marine clastic ramp (Spitsbergen) and the suppression of benthic radiation. *Geological Magazine*, 153:316–331.

Wignall, P. B., Morante, R., and Newton, R. (1998). The Permo-Triassic transition in Spitsbergen: δ13C chemostratigraphy, Fe and S geochemistry, org facies, fauna and trace fossils. *Geological Magazine*, 135(1):47–62.

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

Yang, B., Dalrymple, R. W., and 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(1):2–8.