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A spatial analysis of sandstone bodies in the De Geerdalen Formation on Edgeøya, Svalbard

Master's thesis in Geology
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Abstract

This study investigates sandstone bodies of the Upper Triassic De Geerdalen Formation, exposed on the Arctic island of Edgeøya, Eastern Svalbard. During the Triassic period, Svalbard and the Barents Sea were located at the northern margin of Pangea, as a large shallow embayment between the Baltic shield and Greenland. The De Geerdalen Formation was deposited as a prograding delta, filling this embayment during the Carnian to Early Norian period.

Six localities were visited, and 18 sedimentological logs were collected during a monthlong expedition to Edgeøya during the field season of 2018. This study builds upon previous research, fieldwork, shallow explorational drilling and seismic mapping in the region. The study presents detailed sedimentological descriptions and interpretations of the spatial deposition and extent of sandstone bodies found within the De Geerdalen Formation on Edgeøya. This thesis contributes to the local understanding of this formation with more localised and higher resolution data than previous work.

Facies analysis of the measured sections from the De Geerdalen Formation on Edgeøya indicates an overall coarsening upwards trend, typically associated with regressive depositional systems. Interpretations of the depositional environments of these deposits range from open marine environments at the base, to delta plain at the top of the logged sections.

Palaeocurrent measurements from the De Geerdalen Formation on Edgeøya concurs with previous suggestions of a western progradation direction. Lateral data from multiple transects through extensive sandstone bodies have been compared, revealing rapid lateral changes over short distances.

Sammendrag

Denne oppgaven undersøker triassiske sandsteinslegemer i De Geerdalsformasjonen, eksponert på den arktiske Edgeøya på den østlige delen av Svalbard. I trias befant Svalbard og Barentshavregionen seg på en nordlig del av superkontinentet Pangea, under en stor grunn havbukt mellom det Baltiske skjoldet og Grønland. De Geerdalsformasjonen ble avsatt som et prograderende delta som fylte denne bukten i løpet av karn til tidlig nor alder.

Seks lokaliteter ble besøkt og 18 sedimentologiske logger ble målt opp i løpet av en ekspedisjon til Edgeøya i 2018. Studien bygger på tidligere forskning, feltarbeid, grunne boringer og seismisk kartlegging i regionen. Denne oppgaven presenterer detaljerte sedimentologiske beskrivelser og tolkninger av den romlige avsetningen og omfanget av sandsteinslegemene i De Geerdalsformasjonen på Edgeøya. Oppgaven bidrar til å bedre forstå de lokale variasjonene av De Geerdalsformasjonen gjennom detaljert data innsamling og høyere oppløsning på dataene enn tidligere arbeid.

Faciesanalyse av de undersøkte sekvensene av De Geerdalsformasjonen indikerer en samlet oppovergrovende trend, typisk knyttet til regressive avsetningssystemer. Avsetningsmiljøene i disse sekvensene er tolket til å variere fra åpne marine miljø i bunnen til deltaslette i toppen.

Paleostrøm- og retningsmålinger av De Geerdalsformasjonen på Edgeøya stemmer overens med tidligere forslag til en vestlig progradieringsretning. Laterale data fra flere oppmålinger gjennom omfattende sandsteinslegemer har blitt sammenlignet, noe som indikerer raske laterale endringer over korte avstander.

Acknowledgement

First and foremost, I would like to thank my supervisor, Atle Mørk. Your help, feedback and weekly meetings have been invaluable during the work with this thesis. Moreover, I would like to thank you, Nina, Cathinka and Bård for introducing me to Svalbard and the fantastic sandstones of the De Geerdalen Formation three years ago.

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J.R.

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1 Introduction

1.1 Study area

The Svalbard archipelago is in the north-western corner of the Barents Sea, halfway between Northern Norway and the North Pole (Figure 1). Due to the region's long and complex geological history and wild exotic landscape it has received great interest from geoscientists. The history of geological research on Svalbard has a long history, from Keilhau led the first Norwegian geological expedition to the archipelago in 1827, and up to modern times (Keilhau 1831; Sysselmannen 2012).

The archipelago is an exhumed part of the geology found in large areas offshore in the Barents Sea (Worsley 2008; Dallmann and Elvevold 2015). Svalbard offers excellent onshore outcrops as the land is mostly free of vegetation.

Svalbard consists of several islands, the larger ones being Spitsbergen, Nordaustlandet, Edgeøya, Barentsøya, Wilhelmøya, Hopen and Bjørnøya. This study focuses on the Upper Triassic strata found on Edgeøya. Edgeøya is located in the south-eastern part of the Svalbard archipelago. The geography of the island consists of flat-topped plateau mountains with steep sides towards the sea.

1.2 Purpose of the study

This thesis aims to gain knowledge of the lateral evolution in sandstone bodies in the Triassic De Geerdalan Formation on Edgeøya. High-resolution sedimentological logs have been collected and analysed to present vertical and lateral facies variations within the sandstone bodies. Lateral transects have been observed to document the horizontal transition between depositional environments. In addition, this study aims to analyse structural and synsedimentary elements in the De Geerdalen Formation and document their effect on the deposited sandstones.

The work conducted in this thesis is a detailed continuation of Rød et al. (2014) and Lord et al. (2017a).

1.3 Previous research

The study of Triassic rocks on Svalbard dates to the 19th century and can be grouped into three epochs (Vigran et al. 2014). The first epoch lasting from the first pioneers in the early 1800s up to the end of the Second World War, was initially dominated by Swedish scientists. This Swedish domination lasted until Norwegian independence from Sweden in 1905. Norwegian interest in Svalbard grew substantially during a political game for the sovereignty of Svalbard, and eventually led to Norwegians dominating the scientific activity on the archipelago.

After the Second World War, Norwegian scientists mapped large portions of the outcropping geology, while eastern European and British scientists conducted extensive research on the stratigraphic succession.

The last epoch was fuelled by the onset of petroleum exploration on Svalbard and the Barents Sea in the 1970s. First, in search of onshore petroleum (Elvevold et al. 2007). This search resulted in 20 petroleum exploration drill sites, including two explorational wells drilled on Edgeøya in 1972 (Granberg et al. 2017). Later with onshore outcrops of Svalbard as analogues for potentials in the Barents Sea (Worsley 2008; Lundschien et al. 2014; Vigran et al. 2014).

Much of the present sedimentological model of Edgeøya and the eastern regions of Svalbard stems from stratigraphic and sedimentological research conducted by Flood et al. (1971), Lock et al. (1978), Pčelina (1980), Mørk et al. (1982) and Pčelina (1983). Facies development of the Upper Triassic succession on Edgeøya was extensively covered by Rød et al. (2014) and Lord et al. (2017a).

Large, Triassic fluvial sandstone bodies have previously been described in the eastern and south-eastern part of Svalbard (Rød 2011; Klausen and Mørk 2014; Lord et al. 2014b) as analogues for potential reservoirs in the Snadd Formation in the Barents Sea.

2 Regional Geological setting

The Svalbard geology consists of a geological record raging from the Precambrian to resent, with repeated tectonic and magmatic events as well as longer periods of sedimentary deposition. Svalbard was located at the equator in the Ordovician period and have since drifted to its present arctic location of 77 – 80°N (Dallmann et al. 2015). Through this time, there has been deposited an almost continuous rock record of different climatic zones (Figure 1).

The sedimentary rocks of Svalbard have been deposited onto a Precambrian to Silurian basement, commonly referred to as "Hecla Hoek". This basement, consisting of gneisses, metamorphosed supracrustal and intrusive rocks, is exposed in large areas in the Western and Northern part of the archipelago.

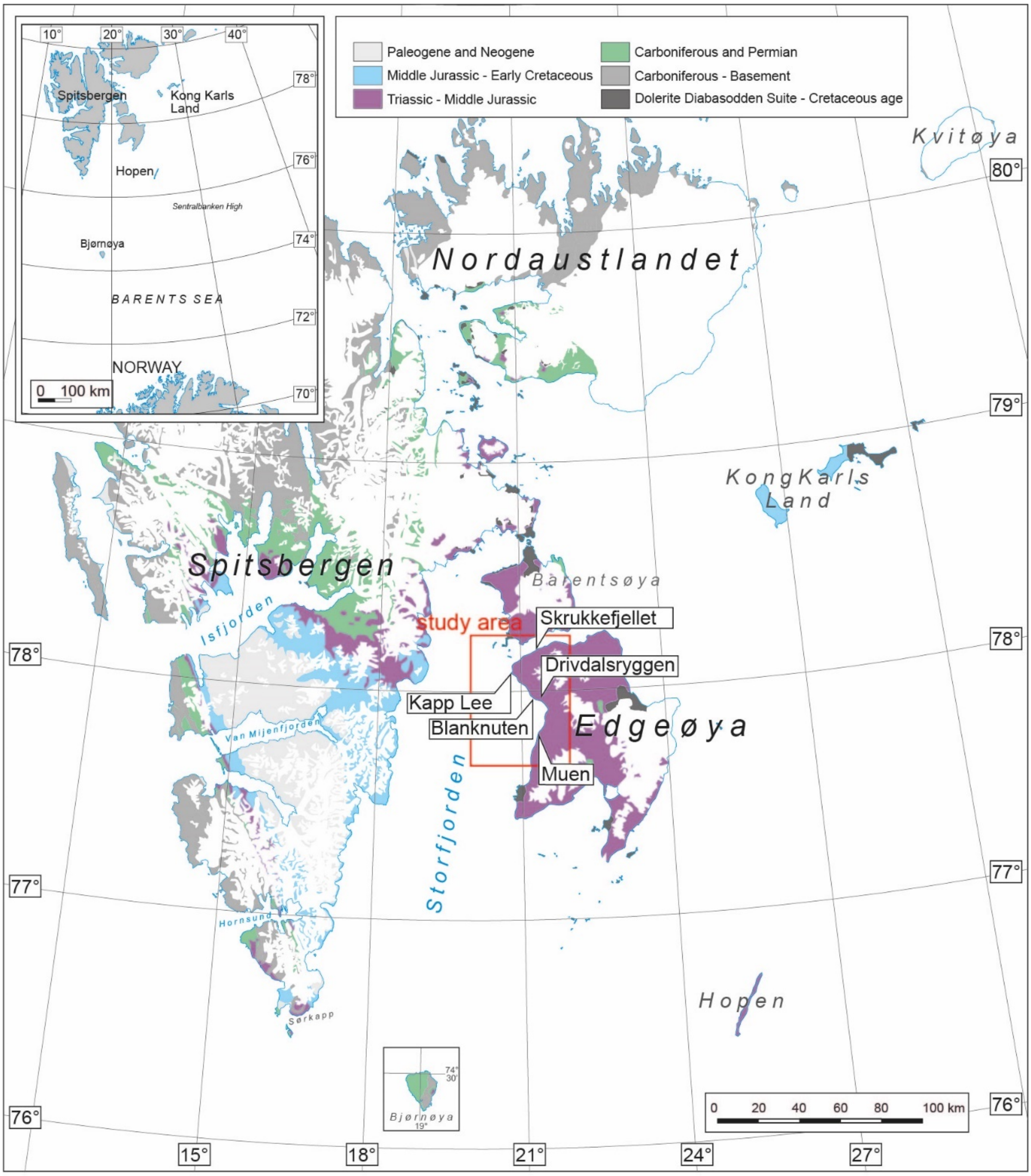


Figure 1. Simplified geological map of Svalbard. Inset map shows the position in relation to mainland Northern Norway. Map from Dallmann and Elvevold (2015).

2.1 Late Paleozoic

The post-Caledonian geological history of Svalbard has been presented in detail by Steel and Worsley (1984) and Worsley (2008).

2.1.1 Permian

The Gipsdalen Group of the lower Permian is made up of carbonates, evaporites and marls deposited in a warm and arid climate (Stemmerik and Worsley 2005). In some areas of Svalbard and the Barents Sea, these carbonates constitute thick build-ups of *Palaeoaplysina* reef-carbonates. Between the deposition of the Gipsdalen Group and the overlying Tempelfjorden Group, a major hiatus with an extensive karst landscape developed on Svalbard (Dallmann et al. 2015).

The Tempelfjorden Group represent an open marine to nearshore environment with marine clastic sediments and highly fossiliferous limestones (Stemmerik and Worsley 2005). The Middle and Upper Permian deposits on Svalbard and the Barents Sea are characterised by chert cementation due to massive production of sponge spicules in the cold open-marine water at the time (Worsley 2008). In addition to sponges, the preserved Permian biota on Svalbard was diverse and plentiful. A large number of these species went extinct as the Permian ended in one of the most severe extinction events of the history of the planet (Dallmann et al. 2015).

On Edgeøya, the only non-Triassic sedimentary rocks are two windows of Permian outcrops in the centre of the island (Figure 1).

2.2 Mesozoic

Svalbard and the Barents Sea was in the Permian and Mesozoic a relatively stable, slowly subsiding platform (Worsley 2008). The onset of Mesozoic clastic deposition on Eastern Svalbard and the Barents Sea is marked by soft siliciclastic shales on top of hard Permian cliff-forming cherts. This top Permian boundary is also recognised as an excellent, easy to recognise, seismic reflector in the Barents Sea (Glørstad-Clark et al. 2010; Lundschien et al. 2014; Eide et al. 2018).

2.2.1 Triassic

During the Triassic period, Svalbard and the Barents Sea were located at the northern margin of Pangea, as a large shallow embayment between the Baltic shield and Greenland (Figure 2) (Buiter and Torsvik 2007; Riis et al. 2008; Worsley 2008; Lord et al. 2017a). The climatic conditions in the region changed from a subtropical climate in the Permian, to a dry, temperate climate in the Triassic (Dallmann et al. 2015).

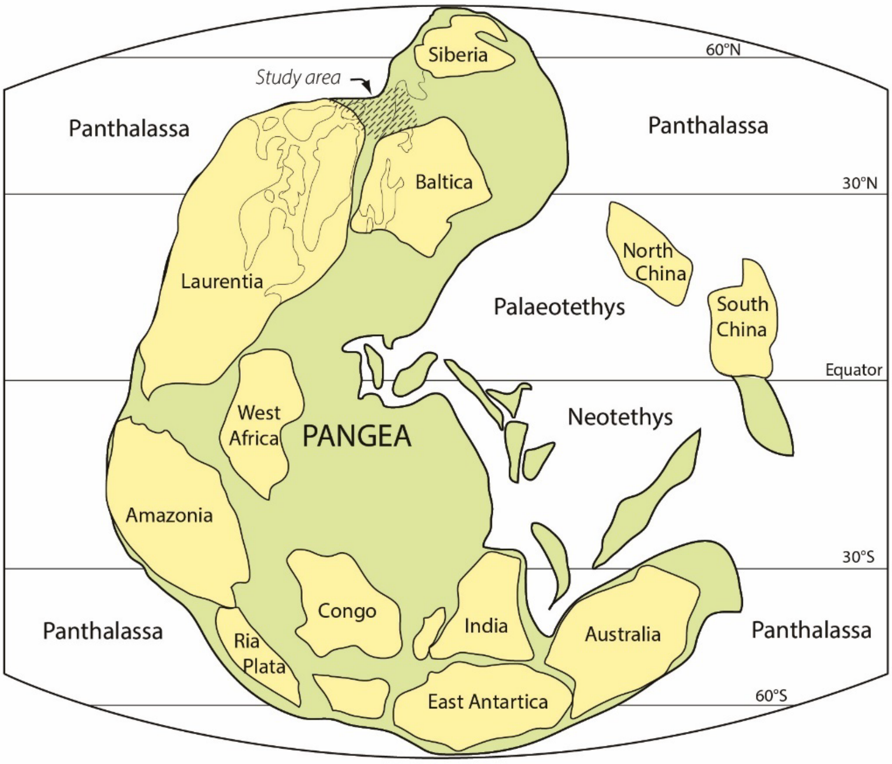


Figure 2. Palaeogeographic recreation of Pangea from Lundschien et al. (2014) based on Torsvik and Cocks (2005).

Cycles of transgressive and regressive episodes started filling this embayment, with siliciclastic sediments from hinterlands around the basin, during the Early and Middle Triassic (Glørstad-Clark et al. 2010; Klausen et al. 2016). On Edgeøya, the start of the Triassic succession is represented by a hiatus. The entire Induan stage is missing, and the oldest Triassic sediments on the island stem from the Olenekian (Vigran et al. 2014).

Phosphatic black shales represent anoxic or periodic oxic bottom conditions in most of the basin in the Middle Triassic (Mørk et al. 1993; Lundschien et al. 2014).

Overlaying these black shales are clinoforms of deltaic sediments marking the shift of sediment coming from a new sediment source, Fennoscandia and the rising Uralian orogeny in the south-east to east (Glørstad-Clark et al. 2010; Høy and Lundschien 2011; Lundschien et al. 2014; Eide et al. 2018). This prograding delta filled the entire embayment during the Carnian to Early Norian period.

On Edgeøya, the stratigraphy younger than the Carnian has been lost due to uplift and Quaternary erosion (Lord et al. 2014a; Rød et al. 2014; Paterson et al. 2016).

2.2.2 Jurassic

The Early Jurassic represents a continuation of the Triassic epicontinental basin with shallow shelf and periodically flooded low-lands. Deposited sandstones are of considerably more mature characteristics, representing a slowing down in the basin subsidence from the Triassic to Jurassic (Bergan and Knarud 1993; Mørk et al. 1999a; Dallmann et al. 2015). On Svalbard, the Early Jurassic to Middle Jurassic sedimentary succession is condensed and includes several hiati.

The Late Triassic to Cretaceous Adventdalen Group is characterised by high global sea- and atmospheric CO_2-levels. These climatic conditions resulted in mudstone-dominated and organic-rich deposition (Faleide et al. 1984). This High TOC-rocks is known as the Agardfjellet Formation on Svalbard and the Hekkingen Formation in the Barents Sea.

2.2.3 Cretaceous

Early Cretaceous magmatism resulted in the formation of the High Arctic Large Igneous Province (HALIP). These events are preserved along great areas of the Arctic Ocean margins. Far east on the Svalbard archipelago, on Kong Karls Land, there are associated lava flows (Senger et al. 2014). The rest of the Barents Sea and Svalbard was at the peripheral edge of the HALIP, where the igneous events resulted in a large number of mafic intrusions. At Edgeøya, these intrusions are commonly found as sills following the soft shales of the Early to Middle Triassic strata (Senger et al. 2013; Senger et al. 2014).

3 Stratigraphy of the Triassic to Mid-Jurassic succession

The Triassic to Mid-Jurassic succession of Svalbard and the Barents Sea is divided into two lithostratigraphic groups: the Sassendalen Group and the Kapp Toscana Group (Figure 4)(Mørk et al. 1982; Mørk et al. 1999a). These rocks are outcropping on central and eastern parts of Svalbard, where they are relatively horizontal (Figure 3), and along the western coast of Spitsbergen, where they are folded and faulted in the West Spitsbergen Fold-and-Trust Belt. These two groups represent two different sedimentological regimes and have different source areas. A brief description of these groups follows.

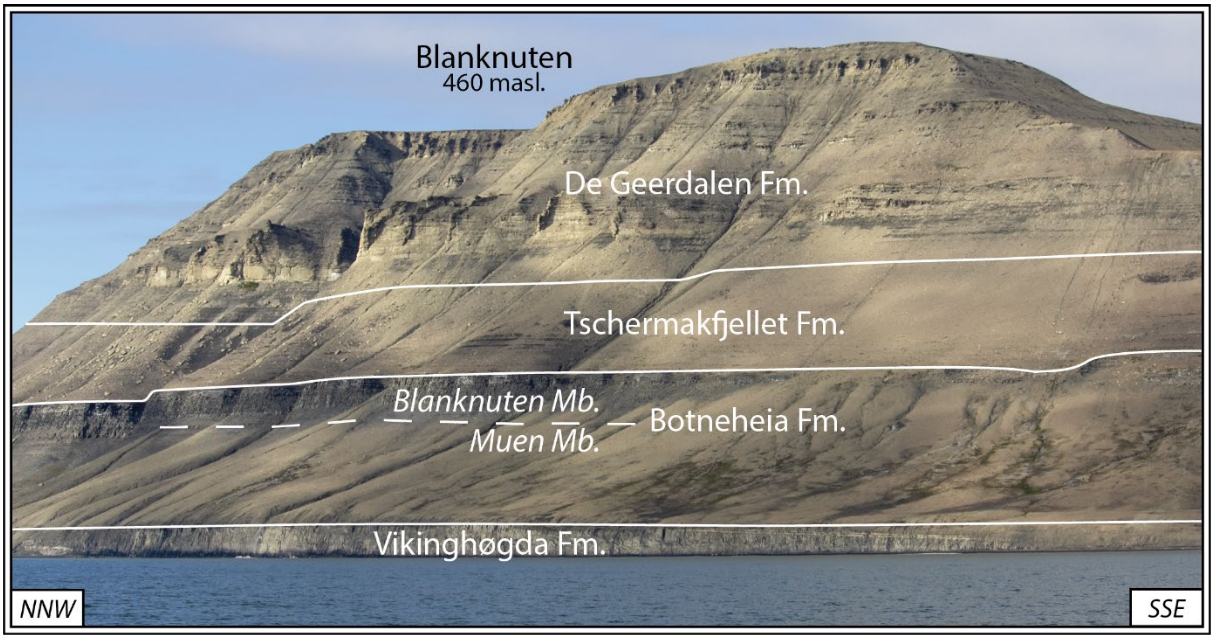


Figure 3. A photograph of Blanknuten at Edgeøya, showing the distribution of stratigraphic units.

3.1 The Sassendalen Group

The Early to Middle Triassic Sassendalen Group (Figure 4) consists of fine-grained sediments with a predominantly western sediment source. In Eastern Svalbard, the group consists of the Early Triassic Vikinghøgda Formation and the Middle Triassic Botneheia Formation. These rocks are comprised of open shelf mudstones, while the more proximal, time equivalent on the west coast, Vardebukta, Tvillingodden and Bravaisberget formations represents coastal to shallow shelf environments (Mørk et al. 1999a,b). The Mid-Triassic rocks on eastern Svalbard and the Barents Sea are organic- and phosphate-rich and reflect periodically oxic and anoxic bottom water conditions (Mørk and Bjorøy 1984; Krajewski 2008; Mørk and Bromley 2008; Vigran et al. 2014).

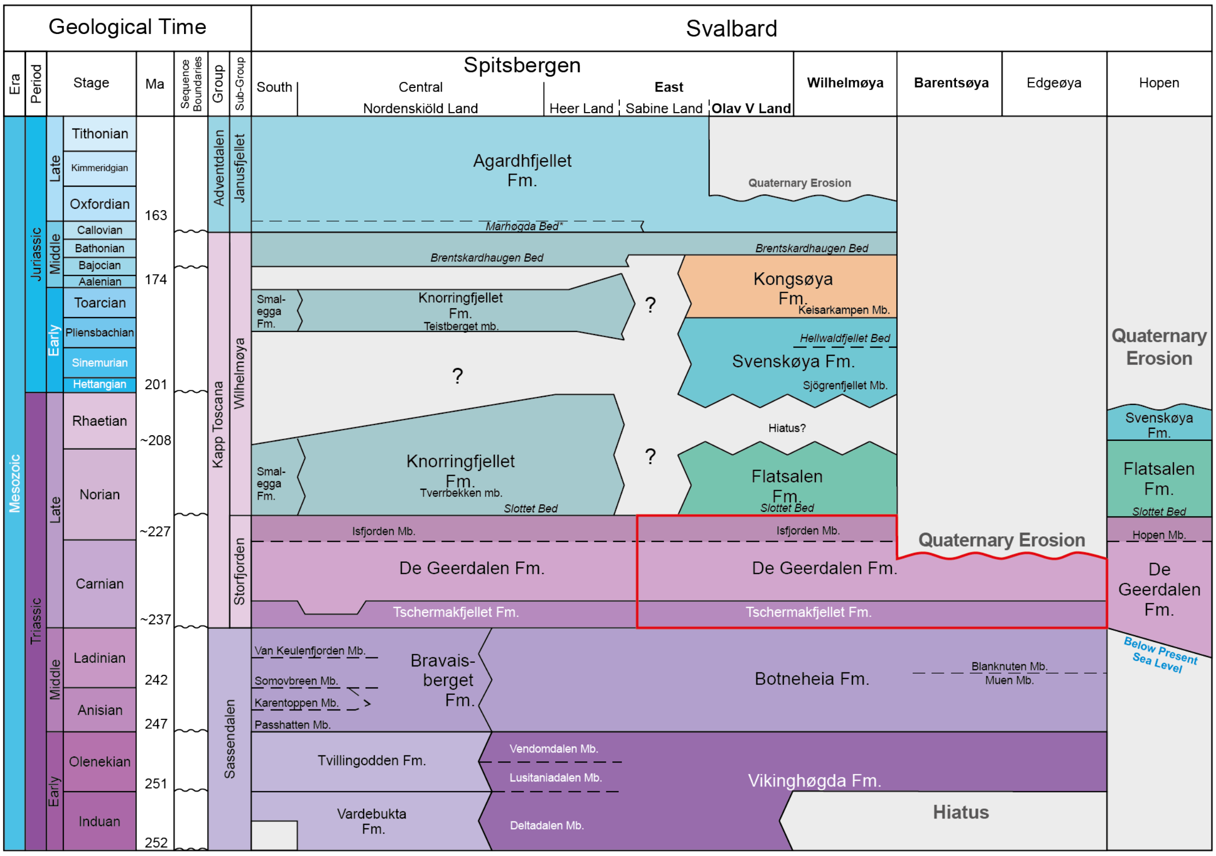


Figure 4. Triassic and Jurassic lithostratigraphy on Svalbard. From Lord et al. (2017b).

3.2 The Kapp Toscana Group

The Kapp Toscana Group consists of Storfjorden Subgroup and the Wilhelmøya Subgroup. The Storfjorden Subgroup on Edgeøya consists of the Tschermakfjellet and De Geerdalen formations (Buchan et al. 1965; Mørk et al. 1999a).

3.2.1 Tschermakfjellet Formation

The early Carnian Tschermakfjellet Formation consists of dark grey prodelta shale and siltstones (Mørk et al. 1982). The base of the Tschermakfjellet Formation marks the initiation of sedimentation from the south-east. The formation is easily recognised in the field by its red colour due to a high content of weathered siderite nodules. The prodelta shales of the Tschermakfjellet Formation coarsen upwards into the De Geerdalen Formation.

3.2.2 De Geerdalen Formations

The base of the De Geerdalen Formation is defined as the base of the first prominent sandstone above the Tschermakfjellet Formation (Buchan et al. 1965; Lock et al. 1978; Mørk et al. 1999a). The deposition consists of stacked upwards coarsening sequences of shale and immature sandstone of Carnian to Early Norian age (Mørk et al. 1999a; Vigran et al. 2014). The formation has been interpreted to represent a dynamic environment ranging from shallow marine to deltaic and coastal planes (Klausen and Mørk 2014; Lord et al. 2014b; Rød et al. 2014). The uppermost part of the formation in western and central Svalbard is called Isfjorden Member. This member consist mostly of shale with occasional red and green lagoonal deposits (Haugen 2016).

On the south-eastern island of Hopen, the correlative top of the De Geerdalen Formation consists of the Hopen Member. This member is made up of alternating layers of mud and sandstone, large distributary channels and no palaeosols (Klausen and Mørk 2014; Lord et al. 2014a). The stratigraphic level of these two members is missing due to uplift and Quaternary erosion from Edgeøya (Lord et al. 2014a; Rød et al. 2014; Paterson et al. 2016).

3.2.3 The Wilhelmøya Subgroup

The overlaying Wilhelmøya Subgroup is divisible into the Flatsalen, Svenskøya and Kongsøya formations on Eastern Svalbard and the time equivalent Knorrinfjellet Formation in the west (Mørk et al. 1999a). The Wilhelmøya Subgroup is condensed and texturally mature in the west and thickens towards the east into the Barents Sea (Worsley 2008).

4 Methodology and Data

4.1 Fieldwork

Sedimentological fieldwork was conducted during a geological expedition to Edgeøya from the 23rd of July to the 25th of August 2018. The entire expedition was accommodated in a sailboat with short stays on land in a trapper cabin. Seventeen days were spent on land conducting geological fieldwork. In this time six localities along the western and northern coast of Edgeøya were visited.

The field party operated in two groups, one studying the Botneheia Formation and the other the overlaying De Geerdalen Formation. The group studying the Botneheia Formation consisted of one master student (Bernhardsen 2019) and two PhD candidates (Victoria S. Engelschiøn and Fredrik Wesenlund). The latter group studying the De Geerdalen Formation consisted of two geologists from the Norwegian Petroleum Directorate and one master student responsible for this thesis. In addition, the expedition included a professor/supervisor, an assistant and two captains.

4.2 Methods

4.2.1 Logging procedure

The sedimentological observations recorded for this thesis was obtained according to standard sedimentological field methods (Tucker 2011). This thesis focuses on sandstones in the De Geerdalen Formation; hence, the main focus of the observations has been on sandstones found in this formation with alternating deposition of mud and sand. Mudstone, in the De Geerdalen Formation, are often partly or entirely covered by soil or scree material due its lower resistance to erosion compared to sandstone. Observations recorded during fieldwork included; lithology, sedimentary structures, grain sizes, bed thicknesses, colour, stratigraphic relationships, bed contacts and textures. The grain size was visually estimated with the help of a standard grain size comparator. Digital cameras were used to document the outcrops.

GPS-measurements in standard UTM-coordinates were measured at the base and top of all logs, as well as at significant levels within the logged sections (Appendix C). A meter stick was used to measure the thickness of sections with reference to the base of the logs. Additional GPS-measurements were made at the top of the cliffs of the Blanknuten Member as a stratigraphic reference for the collected material. The logs were recorded at a scale of 1:20 or 1:100.

4.3 Sources of error

The primary sources of error are linked to observations, interpretations and measurements made in the field. All the visited locations have a large degree of scree-cover. The scree-covered sections are interpreted as having a high mud content, if no sign of coarser material is observed. This interpretation may have led to an overestimation of the appearance and thickness of mudstones. The identification of coal shale within the formation was often problematic and required removal of scree-cover in order to verify the observations. Steep terrain may also have affected the quality of the data collected.

Steep terrain is typical in the thicker sandstone bodies of the De Geerdalen Formation. In these sections of the slope, there would often be only one possible route to log, limiting the possibility of making lateral observations of the sandstones.

The thickness measurements of logged sections and altimetry is another source of error. Two different methods were used: 1) measuring with a meter stick. 2) measuring with handheld GPS with barometric altimeter.

A GPS and altimeter measurement were made at the base of every sedimentary log. A meter stick was then used during logging and to measure the thickness of individual beds. Points in the logs were recorded with reference to the start of the log, measured with the meter stick. The altitude difference between measurement made at the start of logs and the top of logs was, in general, longer than the elevation measured with the meter stick. The GPS difference in elevation was, on average, 27.6 % longer than the length of logs measured with meter sticks.

The meter stick measurements were considered the most accurate due to the rapid changes in air pressure experienced during the fieldwork and the high latitude. Due to the high geographic latitude, a higher standard deviation on the vertical precision of any GPS measurements needs to be considered (Quincey and Luckman 2009).

5 Facies in the De Geerdalen Formation

Interpretations made in the field, for this thesis, have been made on the basis of facies defined by Rød et al. (2014) and Lord et al. (2017a). Their defined facies are presented below (Table 1). New contributions on the intra-facies variation will be presented in this chapter. These facies have been grouped in facies associations and depositional environments presented at the end of this chapter.

Table 1. Overview of the 14 facies defined for the De Geerdalen Formation on Edgeøya. Abbreviations for grain size: vf=very fine-, f=fine-, m=medium-grained sand. Based on Rød et al. (2014) and Lord et al. (2017a).

	Description	Interpretation
A	**Mudstone (0.1 - 10's m)** Clay and silt, laminated (shale) or non-laminated (mudstone). Thickness varies from a few centimetres to tens of meters. Laminated mudstones are most common and may encase thin beds of silty to vf sandstone. Colour is dominantly grey or black, but may also be yellow, white or purple colour with weathering of siderite cement. Facies is characterised by horizontal and gently undulating laminae. Load structures and irregular lamination are occasionally observed. Concretions of calcite or siderite are common. Organic content may be high at some intervals.	Pelagic shale and mudstone deposited from suspension in low-energy environments where clay and silt flocculate and settle on the sea floor (Collinson et al. 2006). Also forms background sedimentation in shallow-marine environments closer to the shoreline.
B	**Heterolithic Bedding (0.01 - 10's m)** Heterolithic bedding is observed as thin beds of vf to f sandstone and siltstone alternating with mudstones often forming coarsening-upwards units. The thickness of mud and sand layers generally range from 1 mm to a few centimetres, however thicker packages are evident. Units are up to 10-15 m thick. Sedimentary structures preserved in the sandstones of heterolithic successions are commonly hummocky cross-stratification and ripple cross-stratification. Sparse to heavy bioturbation is common towards the top of units.	Heterolithic bedding indicates alternating flow regime where sand and mud are available (Davis 2012). Mud is deposited from suspension, while sand is deposited during current or wave activity (Reineck and Singh 1980). This facies can form in the transition zone when mud interacts with sand introduced by periods of higher flow and sedimentation.
C	**Hummocky Cross-Stratified Sandstone (0.1 - 1 m)** Vf to f-grained sandstones featuring hummocky and swaley cross-stratification. Consists of 10 cm to 1 m thick sandstone beds and are characterised by cross-laminae in undulating sets. Individual laminae sets are commonly between 5 and 20 cm thick. The sandstones are typically grey to yellow or orange to reddish brown colour. Hummocky cross-stratified sandstones are typical in upwards coarsening sequences in the lower part of the De Geerdalen Formation throughout the study area. Little cementation and organic material observed.	Hummocky cross-stratification shows a distinct undulating geometry of lamination formed by the migration of low-relief bed forms in one direction due to wave surge and unidirectional currents (Nøttvedt and Kreisa 1987). This facies is widely recognised as being characteristic of tempestite deposition in shallow marine, storm-dominated inner shelf, to lower shoreface settings (Midtgaard 1996; Yang et al. 2006).
D	**Sandstone with Soft Sediment Deformation (0.3 - 2 m)** Erosive based, vf to f-grained sandstones characterised by abundant soft-sediment deformation. Units can be laterally restricted, but also extensive. Irregular lamination seen within the sandstone bodies is also present in the upper parts of the underlying, deformed, mudstones. Sandstones are typically green-grey in colour and lack bioturbation.	Soft-sediment deformation structures typically generate from gravitational processes such as downslope sliding and slumping or rapid loading of sediment (Reineck and Singh 1980; Bhattacharya and Maceachern 2009). Likely form the base of distributary mouth bar deposits, where large volumes of sediments are deposited rapidly in front of distributary systems and reworked by wave or fluvial processes.

Table 1. Continues

E	**Wave Rippled Sandstone (0.1 - 7 m)** Vf to f-grained sandstone with symmetrical ripple lamination. Thicknesses range from tens of cm up to ca 0.5 m, individual beds can be 10 to 30 cm in thickness. Sandstones have grey, yellow or red weathering colour. Fresh surfaces are light grey. Carbonate cement (calcite/ dolomite) or siderite is common. Sandstone beds of this facies are normally graded and wave ripples are often observed on the upper surfaces in coarsening-upwards successions. The crests tend to be continuous and straight. Mud drapes are common and expose ripple foresets. Facies is commonly found interbedded with heterolithic bedding or overlying horizontally bedded sandstone.	Wave ripples are commonly found in shallow-marine settings. They are formed by the oscillatory movement of currents at normal wave base (upper shoreface) where swash and backwash currents produce symmetrically shaped ripples (Boggs 2011c). Mud drapes on the foresets of ripples indicate a tidal influence.
F	**Current Rippled Sandstone (0.1 - 4 m)** Vf to f-grained sandstone with asymmetric ripples forming individual beds or units composed entirely of ripple cross-stratification up to 4 m in thickness. Sandstones are yellow, orange and brownish in colour. Sandstone beds in this facies are typically normally graded and have sharp lower contacts, whereas contacts to upper facies are gradual. In some instances, this facies may fine upwards. This facies is often observed to overlay large-scale cross-bedded and small-scale cross-bedded, normally graded sandstones and itself is overlain by fining-upwards beds of horizontally bedded sandstone.	Current ripples occur with the aggradation of ripples under contemporary downstream migration during unidirectional flow. Sets arranged into climbing ripples form under the same regime but with the angle of climb reflecting rate of aggradation(Collinson et al. 2006). Current ripples are commonly found in environments such as fluvial floodplains, with sub-environments such as; crevasse splays and point bars. They are also present in seasonally flooded river deltas (Reading and Collinson 1996; Boggs 2011c). In marine environments, they are usually formed in the shoaling wave zone.
G	**Carbonate-rich Sandstone (0.2 - 2 m)** Vf to f-grained, normally graded, sandstones characterised by structures formed during diagenesis. Sandstone units are commonly hard and heavily cemented with calcite, dolomite or siderite, can preserve primary sedimentary structures, such as rippled lamination, thickness is typically 0.2 – 2 m. Secondary sedimentary structures include cone-in-cone, siderite beds and calcareous concretions. Colour variation between grey, brown, yellow and red are observed. Scarce to heavy bioturbation is noticed. Cemented sandstone forms benches in the topography or distinctive layers, that may be laterally continuous for several tens of meters prior to pinching out.	Sources of calcite cement may be dissolved bivalves and coquinas. Siderite occurs in organic-rich brackish to meteoric pore-waters depleted of SO_2 and is commonly found in f-grained deltaic to coastal sediments (Morad 1998). Siderite concretions and layering might indicate a continental influence on marine sedimentation with organic-rich stagnant waters close to the delta front (Pettijohn et al. 1972).
H	**Plane Parallel Laminated Sandstone (0.3 - 15 m)** Sandstones with horizontal, plane parallel lamination or plane parallel stratification. Mostly vf to f-grained sand, but can also be silty and medium grained. Stratification varies from lamination to bedding. Colour is grey to pale yellow, but weathers brown to red. Lower boundaries are typically sharp, while the upper are commonly more gradual. Units are often observed towards the top of sandstone benches. Bioturbation is rare in lower parts but occurs towards the upper part of units. *Skolithos, Diplocraterion* and *Rhizocorallium* also observed.	Plane parallel stratification occurs in various environments and is not a unique environmental indicator (Boggs 2011c). The structure form by settling of fine grains from suspension or traction of sand as bed-load in the upper flow regime (Collinson et al. 2006; Boggs 2011c). It is commonly found in rivers and streams with high flow (Boggs 2011c).
I	**Undulating Fractured Sandstone (0.1 – 3 m)** Often erosive based. They appear massive with undulating fractures. Possible primary structures are large-scale cross-stratification or low angle cross-stratification. Mud flakes are often found close to the base of the units, as well as load structures. Colour from light grey to red to brown.	Massive or structureless sand can form by liquefaction or rapid deposition from suspension. Mud flakes, erosive boundaries and load structures are often found associated.

Table 1. Continues

J	**Low Angle Cross-Stratified Sandstone (0.5-1.5m)** Vf to f-grained sand, forming gently inclined sets of planar parallel stratification or lamination, with wedge-shaped set boundaries. The colour is usually grey to red-brown when weathered and grey on fresh surfaces. Unit thickness is usually between tens of cm to 1.5 m, while set thickness range between 5 and 15 cm. Individual sets are composed of both beds and lamina, where the former is the most common. These sandstones are commonly bioturbated and contain plant fragments and rare fish remains. It is frequently found overlying or interbedded with wave rippled sandstones, or heterolithic bedding.	Low angle cross-stratification is not considered a diagnostic sedimentary structure as it can be seen occurring in a range of depositional environments. However, the presence of bioturbation and plant fragments are interpreted as indicators of a proximal position in the shallow marine environment, most likely the upper shoreface or beach foreshore (Reading and Collinson 1996). Low angle cross-stratified sandstones typically exhibit a gentle dip seawards when found in foreshore and backshore settings.
K	**Tabular Cross-Stratified Sandstone (0.1 - 1.5 m)** Vf to f-grained sandstones with tabular cross-stratification or cross-lamination, arranged in foresets with bedforms of 2 to 10 cm thickness and stacked in units that are up to 1.5 m thick. Sparse bioturbation is occasionally observed towards the top of units, and plant fragments are common. Grey, yellow, brown and reddish colours are observed. Weathering of finer material on sandstone bounding surfaces is interpreted as draping mud or finer sand. This facies is commonly found overlying large-scale cross-bedded sandstones in fining upwards units. It is also often found within heterolithic bedded units.	Tabular cross-stratification forms by unidirectional currents of the lower flow regime in shallow waters (Collinson 1996; Boggs 2011c). Environments of formation are fluvial and shallow marine where rip-currents, longshore currents, tidal currents and breaking waves creates unidirectional currents (Reading and Collinson 1996). Plant fragments, low abundance of trace fossils and close proximity to palaeosols in upper sections indicates that this facies is most likely associated with terrestrial depositional environments.
L	**Trough Cross-Stratified Sandstone (0.2 - 4 m)** F to m-grained trough cross-stratified sandstones with sharp erosive base, displaying a fining upwards trend. Cross set thicknesses range from 20 to 80 cm, whereas stacking of sets results in unit thicknesses of 0.2 to 4 meters. Rip-up clasts and plant fragments are frequent in the basal parts of units and scours. Observed colours are grey, yellow and brown, with reddish and dark colours appearing occasionally on weathered surfaces. Upper parts of sandstones may be sparsely bioturbated, whereas lower parts are essentially free of traces. Trace fossils observed within this facies are *Skolithos* and *Diplocraterion*.	Formed by migration of 3D dunes, in unidirectional currents in the lower flow regime (Reading and Collinson 1996; Boggs 2011c). Complexity of dune morphology is thought to increase at higher current velocities and shallower waters (Collinson et al. 2006; Boggs 2011c) and stacking of co-sets represent superimposed bed-forms (Reineck and Singh 1980). Facies is interpreted as migrating dunes in a subaqueous environment due to unidirectional current. Mud drapes are attributed to slight changes in current velocity, possibly implemented by tidal activity or seasonal changes in stream discharge.
M	**Coal and Coal Shale (0.5 - 10 cm)** Units of coal and coal shale are from 0.5 to 10 cm thick. The units often appear laterally continuous over tens of meters. Coal and coal shales are usually found in close proximity to the top of larger sandstones. Coal and coal shales are commonly associated with palaeosols, but coal shale surrounded by grey shale is observed.	Coal seams found in the De Geerdalen Formation is typically associated with palaeosols, indicating they are formed in place (Retallack 1991). Coal and coal shale beds found in the De Geerdalen Formation are thin and laterally discontinuous. Coal and coal shales are here interpreted to originate from mires on a dynamic delta plain setting in a humid paleoclimate with seasonal variations in precipitation, following the conclusions of Enga (2015).
N	**Palaeosols (0.1 – 0.5 m)** The thickness is in the range of 0.1 to 0.5 meters. Roots and wood fragments, up to 20 cm in diameter, can be found. The colour varies from brown to reddish brown and yellow. Palaeosols are composed of mudstone and weather red or green and are 0.2 to 1 m in thickness. The structure of these mudstones is blocky or gravelly with weathering and mottles being common. Palaeosols occur both in grey mudstone and on top of sandstone beds. A gradual contact at the base and sharper contact at the top is typical for palaeosols (Boggs 2011c) and is frequently observed in the outcrops. The palaeosols are commonly associated with coal or coal shale.	Palaeosols form due to physical, biological and chemical modification of soil during periods of subaerial exposure. Palaeosols are continental (Boggs 2009) but can form in marine strata following sea level fall and sub-aerial exposure (Webb 1994). Palaeosols represent an unconformity, formed in a degrading landscape (Kraus 1999).

5.1 Mudstone – A

The mudstone facies consist of fine-grained sediments (clay and silt) and constitute the bulk of the logged sections at all visited locations on Edgeøya. The facies is classified as laminated (shale) or non-laminated (mudstone) (Lundegard and Samuels 1980). Horizontal to gently undulating, laminated shale is the most common form of mudrock found in the De Geerdalen Formation. Non-laminated mudstones were common at the Muen and Skrukkefjellet localities and were found in sections of the stratigraphy with no alteration with coarser sediments.

Mudstones are, for the most part, covered by scree in the De Geerdalen Formation. The scree is usually made up of either loose blocks of overlying sandstones, shortly travelled mudstone fragments or weathered material similar to soil (Figure 5.B and C). The scree-cover thickness can vary from zero to a meter, and make the process of logging mudstone in the De Geerdalen Formation difficult and time-consuming. The non-laminated mudstones found at the Muen and Skrukkefjellet localities were the only rocks of this facies found in-situ and without scree-cover (Figure 5.A).

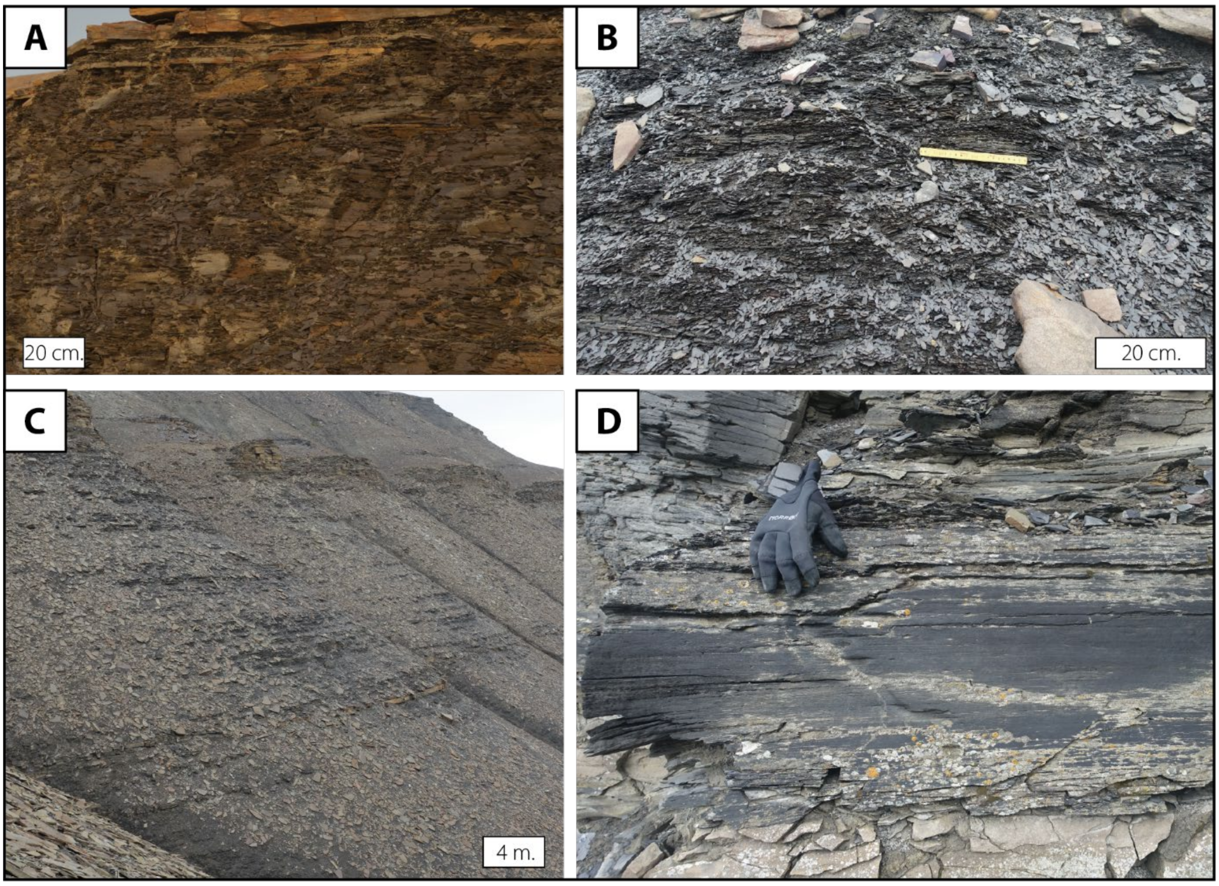


Figure 5. Mudstones facies. A. in-situ laminated shale at Muen. B. Non-laminated mudstone at Muen. C. Thick, partly scree-covered horizontally laminated shale at Drivdalsryggen. D. Paper shale from the Blanknuten Member at Blanknuten.

The colour of the mudrocks is, for the most part, grey to black. White, yellow and purple mudrocks are also found and interpreted to be the result of weathering of cement.

As the focus of this thesis has not been on the mudrocks, there has been little time put into distinguishing between different mudrocks. The term "fines" have been used to describe mud- and siltstone together with coal and palaeosol when undifferentiated.

5.2 Heterolithic Bedding – B

Heterolithic bedding is characterised by thin beds of siltstone to fine-grained sandstone alternating with shale (Figure 6). The facies thickness was found to vary from 10 cm to tens of meters at all the visited localities. The facies was found in all levels of the De Geerdalen Formation. However, it was most common in the lower part. The thickness of individual sand- or mudstone layers were between 1 mm and 30 cm. Sedimentary structures found in this facies include hummocky cross-stratification (facies C), swaley cross-stratification, rippled cross-stratification (facies E and F) and bioturbation.

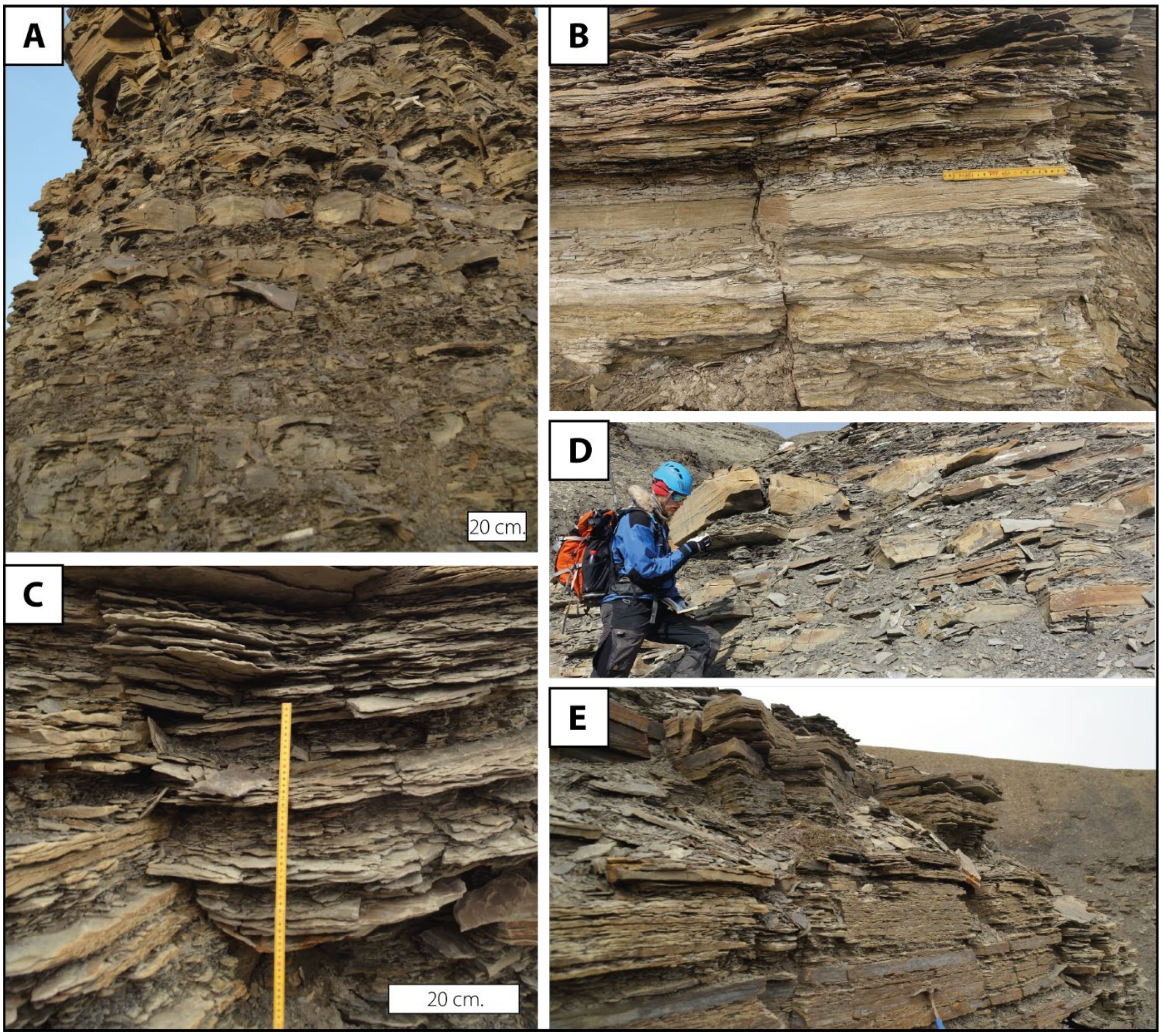


Figure 6. Heterolithic bedding facies. A. Heterolithic, coarsening upwards bedding with an increasing amount of sand at Muen. B. Heterolithic bedding with varying mud content showing cross-stratification and gutter casts at Blanknuten. C. Wavy bedding at Muen. D. Thick intervals of alternating shale and fine-grained sandstone beds showing hummocky cross-stratification at Drivdalsryggen. E. Flaser bedding with wave ripples at Muen.

5.3 Hummocky Cross-Stratified Sandstone – C

This facies is characterised as silt- or sandstone displaying hummocky or swaley cross-stratification. Units were often erosive based with thicknesses from 0.1 to 2 meters. Individual sets of cross-laminae were from 1 to 20 cm. The colour was grey to yellow. Bioturbation occurred in the upper parts of units but was not common.

The facies was observed as; 1) individual sets of hummocky cross-stratified sandstone within heterolithic sequences (Figure 7.E and H), 3) a single set in planar parallel laminated sandstone (Figure 7.D) 3) amalgamated sets in thick sandstone sequences (Figure 7.B). Individual sets were commonly found towards the top of heterolithic sequences in the bottom part of the De Geerdalen Formation. Amalgamated sets could be found immediately above this, while singular sets in a planar parallel laminated sandstone were common in the middle part of the formation.

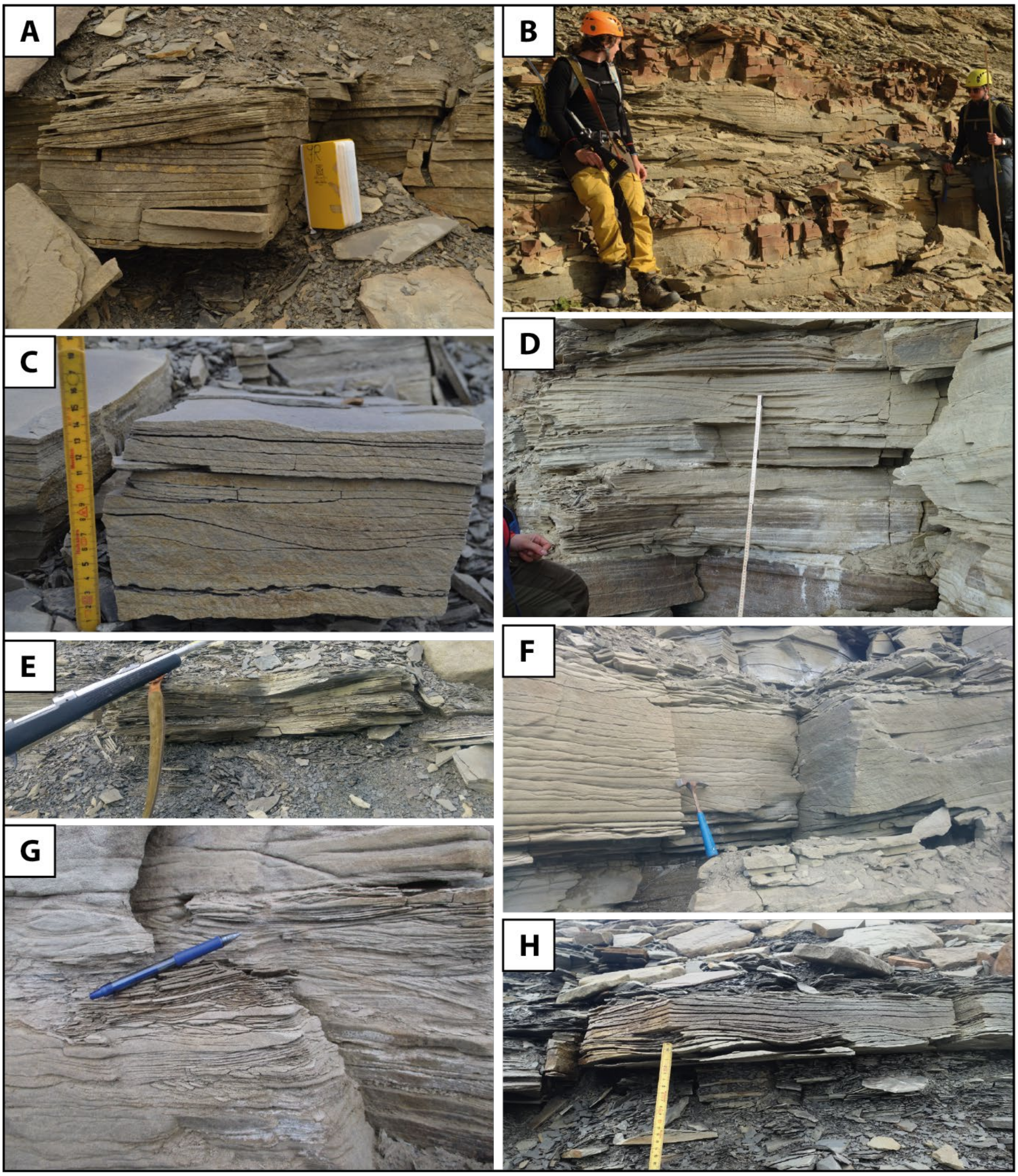


Figure 7. Hummocky cross-stratified sandstone facies. A. Block exposure showing the three-dimensional structure of isotropic small-scale HCS, at Muen. B. Multiple amalgamated sets of large-scale HCS at Blanknuten. C. Small-scale HCS with a wavelength of only 14 cm, at Palibinranten. D. Large-scale HCS with plane parallel stratification over and under. E. A single bed of small-scale HCS at the top of a package of tempestites, at Blanknuten. Rifle for scale. F. Swaley cross-stratified bed at Palibinranten. G. Small-scale HCS at Drivdalsryggen. H. Very fine-grained sandstone bed, with erosive base, small-scale HCS, plane parallel lamination and ripples on top, at Drivdalsryggen.

In this thesis, hummocky cross-stratification has been divided into and recorded as large or small-scale. Large-scale hummocky cross-stratification is characterised by a spacing of hummock and swell greater than 50 cm. The relief of this size varies from 1 to a few tens of centimetre. The largest hummocky cross-stratification observed during the fieldwork, had a spacing from hummock to swell of 2.40 cm. Small-scale hummocky cross-stratification has been classified as hummocky cross-stratification with a spacing from hummock to swell of less than 50 cm.

Hummocky cross-stratification is a result of oscillatory flow combined with unidirectional flow (Nøttvedt and Kreisa 1987). It is believed to be formed by waves and is typical for storm deposit. It is often used as an indicator of sediments deposited below fair-weather wave base and above, but near storm-weather wave base due to its low potential for preservation above fair-weather wave base (Dumas and Arnott 2006).

5.4 Sandstone with Soft Sediment Deformation – D

This facies is characterised by sandstones displaying different forms of soft sediment deformation. Soft sediment deformation includes a wide array of deformation structures. Units can have deformation structures restricted to its lower boundary or throughout the thickness of the unit. The deformation can be laterally extensive over tens of meters or laterally restricted to a sandstone lens of a few tens of centimetres in width. The deformed sediment was found to be very fine- and fine-grained sand. The deformed sandstones were green, grey or yellow in colour.

Sandstones with soft sediment deformation were found at all visited localities but was more frequent at Muen, Skrukkefjellet and Palibinranten than the others. This may be associated with the syn-sedimentary faulting observed at these localities (see Section 6.3.5 and 6.6.4).

Soft sedimentary deformation structures found in the Tschermakfjellet Formation and the lower part of the De Geerdalen Formation were often in sandstone lenses with erosive or irregular lower boundaries, capsulated in mud (Figure 8.C, D, E, and G). These lenses were often found as weathered out “mounds” in the landscape (Figure 8.D).

These deformation structures may have been the result of gravitational downslope sliding or slumping, or from loading into the underlying sediments. This type of structures are commonly associated with depositional environments with high sedimentation rates (Boggs 2011a). Combined with marine indicators found in adjacent sediment, this facies can be argued to fit into an delta front setting (Reineck and Singh 1980; Boggs 2009). The sandstones classified within this facies have been interpreted to represent different lengths of post depositional transport. Loading structures are interpreted as not having been gravitationally transported while sandstone lenses capsuled by mudstone were found to have entirely lost the original internal lamination, and thus were interpreted to have been transported the furthest. The sandstone lenses found in the Tschermakfjellet Formation on Muen have been interpreted as more distal than other sandstones in this facies and placed in a prodelta setting.

This facies is not included in Rød et al. (2014), however rocks of similar characteristics as this facies are described at the base of several large sandstone bodies presented in the paper.

Figure 8. Sandstone with soft sediment deformation facies. A. An almost 2-meter thick package of convolute bedding in very fine-grained sandstone, at Skrukkefjellet. The bed was ca 20 meters wide and had planar upper and lower contacts. B. Heavily deformed sandstone body, with a loading contact to the underlying mudstone, at Skrukkefjellet. C. A lens of slump folded sandstone, capsuled in mud, at Palibinranten. D. A two-meter-wide sandstone lens, with a lower loading contact and upper planar contact, is capsuled by mudstone. It forms a small hill in the terrain due to subaerial erosion, at Muen. E. A single slump deformed sandstone lens capsuled in mud, at Palibinranten. F. Deformed lamination at Blanknuten. G. Slump deformed sandstone lens in a horizon of similar lenses, at Muen. H. Intensely deformed lower part of sandstone bed at Blanknuten.

5.5 Wave Rippled Sandstone – E

The wave rippled sandstone facies consists of very fine- to medium-grained sandstone with symmetrical rippled lamination. Sandstone units with thicknesses from 0.1 to seven meters were observed displaying this facies. Individual set thicknesses range from 1 to 4 cm. The facies was often observed in sandstone beds that also had characteristics from facies B, D, H or G. When possible, the shape of the crests of the ripples was observed. Only straight ripple crests were observed in the visited localities, some bifurcation occurred (Figure 9.A). Weathering colours of the sandstones were yellow to grey and brow. Fresh cut surfaces displayed light grey colours. Mud and coal drapes were common (Figure 9.B). The units displaying this facies were normally bioturbated in a sparse to moderate degree.

Single sets of symmetrical rippled lamination could only be followed laterally for a few meters, while sandstone layers displaying symmetrical rippled lamination could be followed more than 100 meters in the large outcrops at Blanknuten and Drivdalsryggen, making this facies one of the more laterally extensive.

The crest of ripples can be peaked (Figure 9.C), rounded (Figure 9.E) or flat (Figure 9.A). The formation processes of ripples are complicated, however they may be indicative of what depth the ripples formed at. Rounded wave ripples are commonly believed to be deposited at deeper water than peaked crested ripples (Collinson et al. 2006). Flat-top ripples can be formed as the formation of an eroding current truncates the crest of ripples and moves the sand into adjacent ripple troughs (Pilkey et al. 2011). This crest form is interpreted to be formed in active water with breaking waves (Collinson et al. 2006).

Symmetrical ripple lamination is found in a range of depositional environments. They are deposited by oscillatory currents formed when waves interact with the seabed (Nichols 2009a).

This facies is included in both Rød et al. (2014) and Lord et al. (2017a). The facies description are similar except for the dimensions of sandstones with wave ripples. Rød et al. (2014) describe units with wave ripples up to 0.5 meters thick. Lord et al. (2017a) describe units up to four meters thick and individual sets of up to 10 centimetres. The largest unit with wave ripples as the dominant sedimentary structure found during the fieldwork was seven meters high, and the thickest set height was four centimetres.

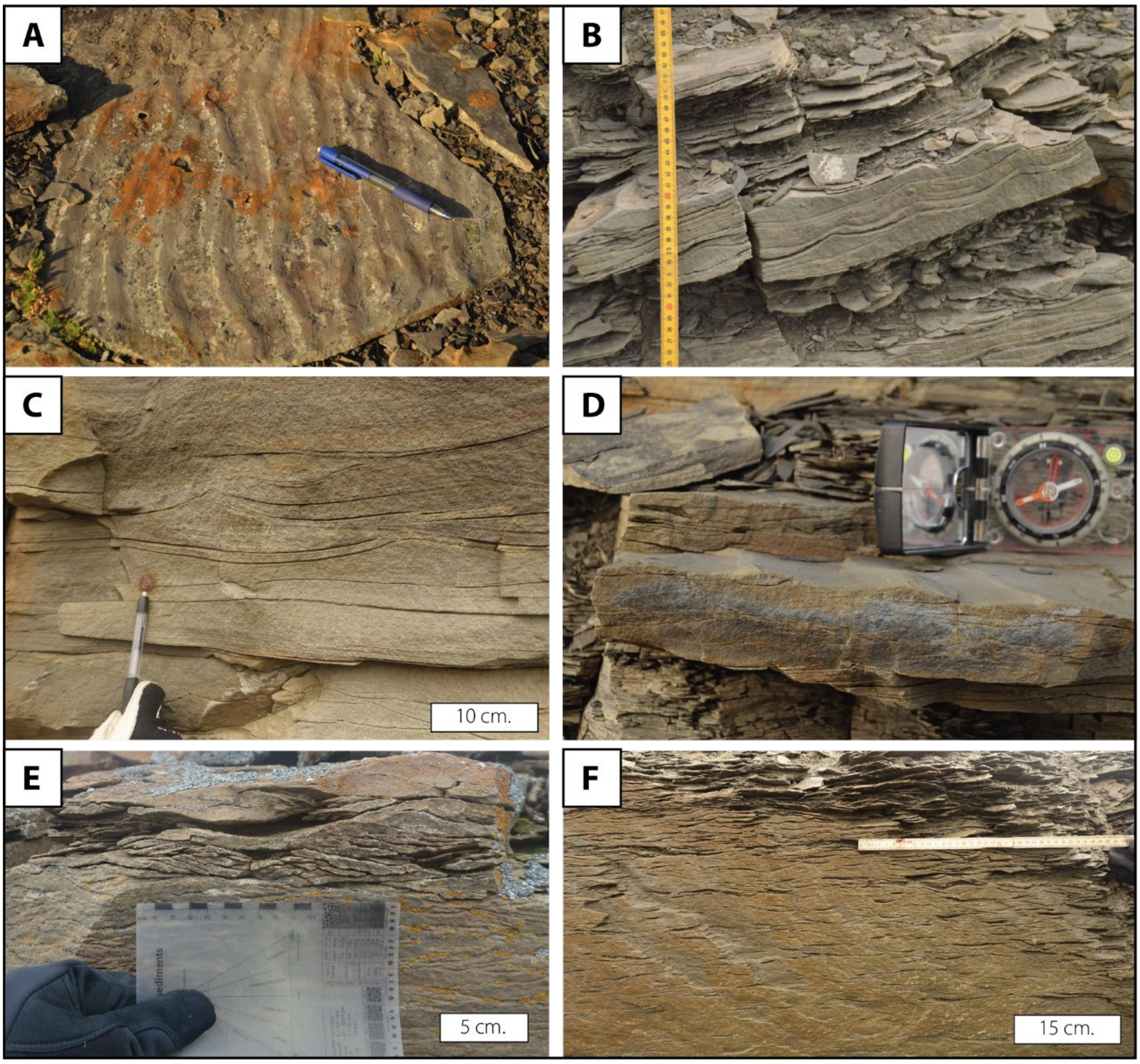


Figure 9. Wave rippled sandstone facies. A. Flat-topped ripple crests at Muen. B. Wave ripple cross-lamination in heterolithic bedding at Palibinranten. C. Wave ripples with peaked crests at Blanknuten. D. Symmetrical ripple lamination in heterolithic bedding at Muen. E. Wave ripples of increasing size with round crests at Drivdalsryggen. F. Massive, thick, calcite-cemented, wave rippled sandstone at Drivdalsryggen.

5.6 Current Rippled Sandstone – F

The current rippled sandstone facies consist of very fine- to medium-grained sandstone with asymmetrical rippled lamination. Sandstone units with thicknesses from 0.1 to 3 meters were observed displaying this facies. Individual set thicknesses range from 1 to 8 cm. The facies was often observed in sandstone beds that also had characteristics from facies B, C or G. The colour of the sandstones were yellow, brown or grey. Mud draping, coal draping and plant fragments were common on the foresets of ripples. Bioturbation was sparse.

Units with current ripple structures had sharp lower boundaries and were often underlying plane parallel laminated sandstones (facies H). The current rippled sandstone facies include climbing ripples and herringbone lamination.

Sandstone with asymmetrical rippled lamination is regarded as deposits of ripples migration downstream under unidirectional current. Current ripples are often recognised to have formed in shallow water in marine or fluvial environments, but can also be produced by ocean-bottom currents such as turbidities (Collinson et al. 2006). Ripples form in the lower flow regime (Figure 11). The highest angle of climb found at the visited localities was 25^{o} at Blanknuten (Figure 10.D). These ripples were characterised as supercritically climbing ripples.

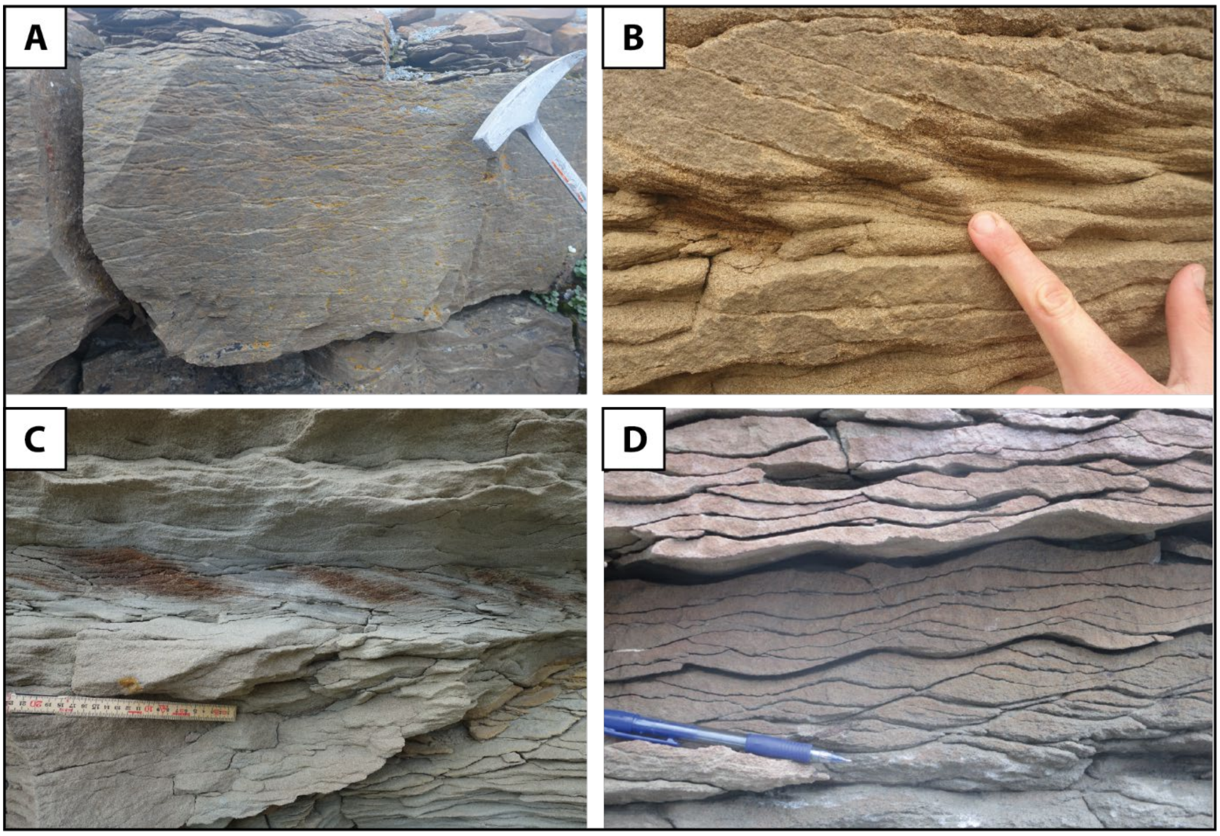


Figure 10. Current rippled sandstone facies. A. A one-meter thick sandstone of amalgamated sets of sinuous monodirectional ripples, at Drivdalsryggen. B. Medium-grained sand forming an 8 cm high set current ripples with mud drapes. C. Climbing ripples at Drivdalsryggen visible due to the deposition of grains with higher iron content on the stoss side of the ripples. D. Climbing ripples at Blanknuten visible due to fractures following the lamination.

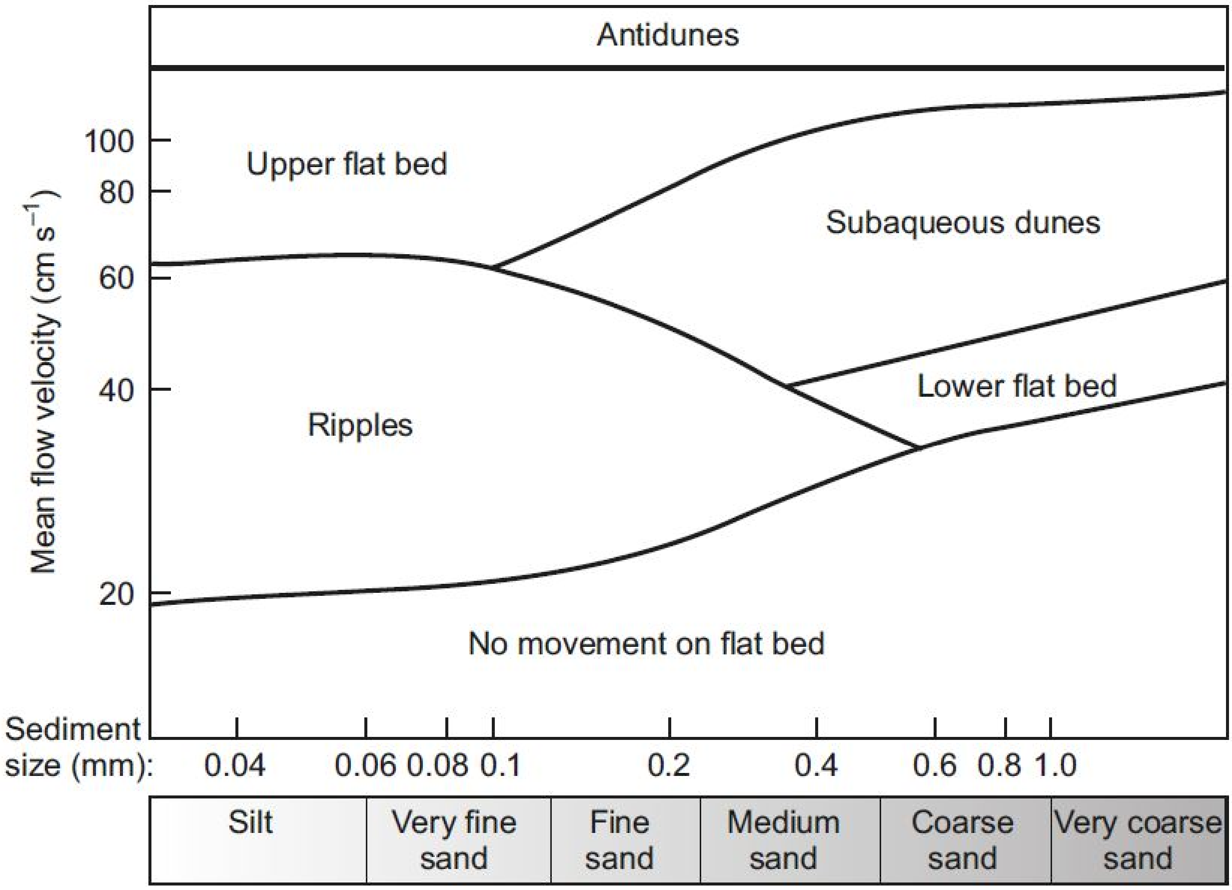


Figure 11. Bedform stability diagram showing which bedforms that are stable with variations in both sediment grain size and flow velocity. From Nichols (2009).

5.7 Carbonate-rich Sandstone – G

This facies was found at all visited localities on Edgeøya. It is a facies composed of sandstones with structures formed during diagenesis. It is characterised as very fine- to fine-grained, hard sandstone with a higher degree of cementation than the surrounding sandstone. This heavy cementation may cause challenges in observations of primary sedimentary structures by making the rock seem massive and uniform (Figure 12.A, C and D). Primary sedimentary structures can, however, be preserved by heavy cementation in beds where the host rock is so severely fractured that no primary sedimentary structures are visible (Figure 12.F). The colours in this facies include yellow, orange, purple, red, grey and brown.

Heavily cemented sandstone benches are typical as single beds in sequences of heterolithic bedding (Figure 12.C) or in larger sandstone bodies (Figure 12.D). Beds found in heterolithic bedding are typically laterally extensive and can be traced from ridge to ridge for hundreds of meters. Heavily cemented beds, often red, in larger sandstone bodies were observed to pinche out after 5 to 50 meters (Figure 15.E).

This facies includes sandstones with secondary sedimentary structures such as cone-in-cone structures (Figures 12B and C), siderite beds and concretions (Figures 12.A and 13). Cone-in-cone structures were common in the Tschermakfjellet Formation and the lower part of the De Geerdalen Formation. In the Tschermakfjellet Formation, it was found in laterally extensive layers that could be traced for up to 50 meters, as well as in lenses of sandstone. In the De Geerdalen Formation, cone-in-cone structures were only observed in lenses. All of the observed cone-in-cone structures were planar in shape, except one found at Muen with a radial structure (see Section 5.3). The formation of cone-in-cone structures is believed to occur during early diagenesis in a shallow marine environment. Tugarova and Fedyaevsky (2014) suggest that the formation of these structures is caused by biochemical precipitation from micro-organisms; this includes cone-in-cone "fouling" or overgrowth on microbial carbonate mats. Maher et al. (2017) have, after investigations of cone-in-cone structures on Eastern Svalbard, suggested that carbonate nucleation formed at small tensile fractures and carbonate shell fragments within unconsolidated sediments.

The equivalent facies is in Lord et al. (2017a) named "Carbonate Cemented Sandstone", and "Carbonate-rich sandstone" in Rød et al. (2014). The facies is similar and describes (0.2-2 m) benches of sandstone characterised by structures formed during diagenesis.

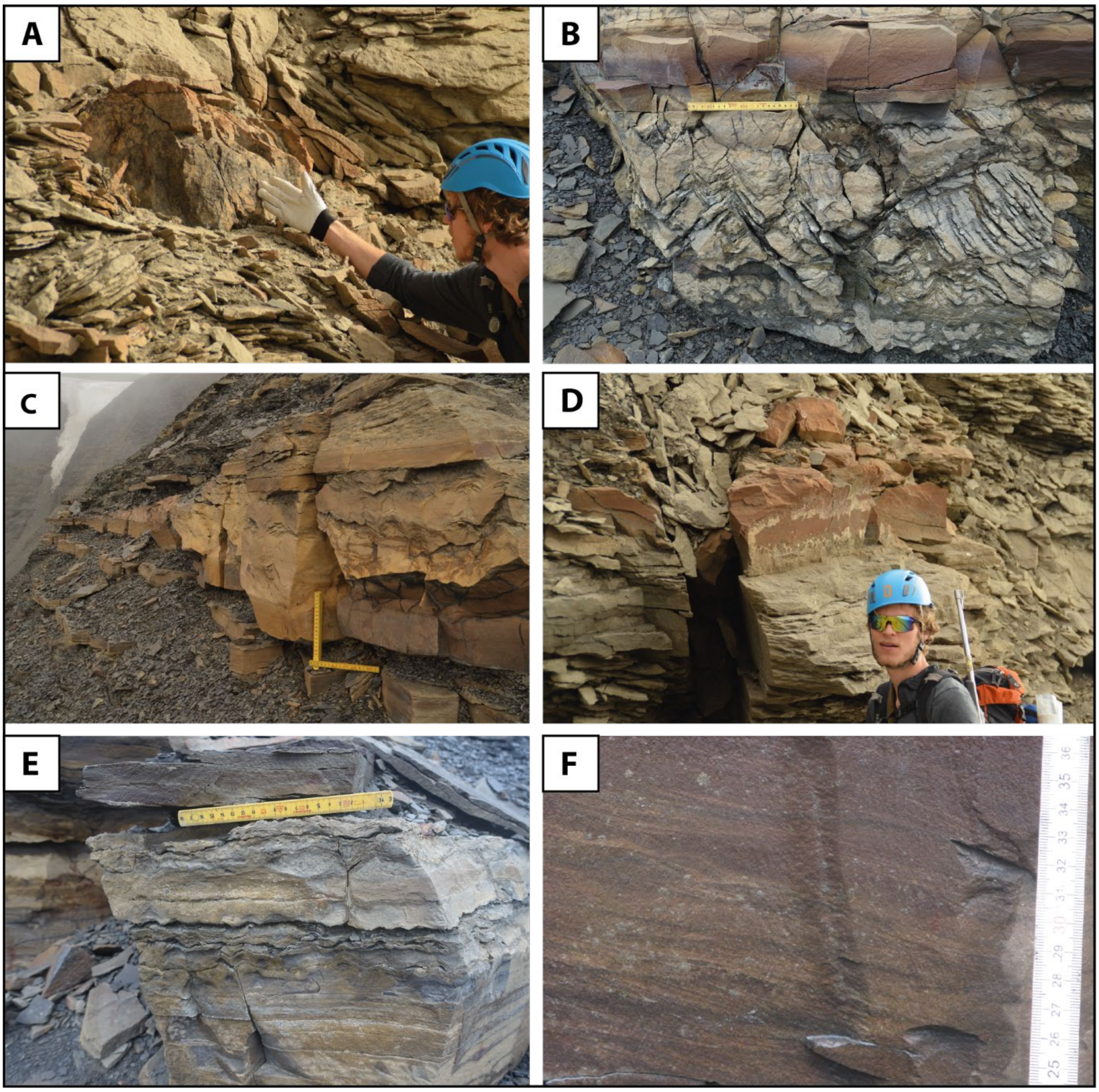


Figure 12. Carbonate-rich sandstone facies. A. Large carbonate concretion at Blanknuten. B. Cone-in-cone at Drivdalsryggen. C. Laterally extensive carbonate-rich sandstone bench with cone-in-cone structure at Muen. D. Red, confined, carbonate-rich sandstone that could be traced laterally no more than 5 meters, at Blanknuten. E. Calcite-cemented very fine-grained sandstone with cone-in-cone structures at Blanknuten. F. Red, confined, carbonate-rich sandstone, of the same character as in (D), containing preserved climbing ripples, while the adjacent quartz-cemented sandstone was too weathered and fractured to see any primary structures.

Ball-shaped structures were common in the upper part of the De Geerdalen Formation (Figure 13). The structures were found weathering out of thick sandstone bodies. The structures were highly spherical and often found in horizons with spherical structures every few meters. These horizons were possible to follow for hundreds of meters at the largest visited outcrops. The structures were found as singular ball-like shapes (Figure 13.A and D) or amalgamated spheres (Figure 13.B, C and E). The host rocks of these structures were either planar parallel laminated sandstone or intensely fractured sandstone without visible primary sedimentary structures. In both cases, the planar bedding was seen in the spheres, and where parallel bedding was found in the host rock, it could be traced through the spheres.

These structures may be calcite-cemented, sandstone concretions, only slightly better cemented than the host rock. Thin section analyses of the ball structures have not found any significant differences in the cementation compared to the host rock at the locality in Figure 13.C (Figure 13.F). The spherical shape of the concretions and the planar parallel bedding that could be traced through them, indicates that the concretions were formed after compaction, similar to concretions described by Marshall and Pirrie (2013). These structures were only observed in host rocks of the plane parallel stratified sandstone facies (facies H) and massive sandstone facies (facies I). These two facies may be the preferred facies for the formation of these structures or the only facies allowing them to weather out and be recognisable. Horizons with similar concretions have been used to correlate logs over short distances at the same locality.

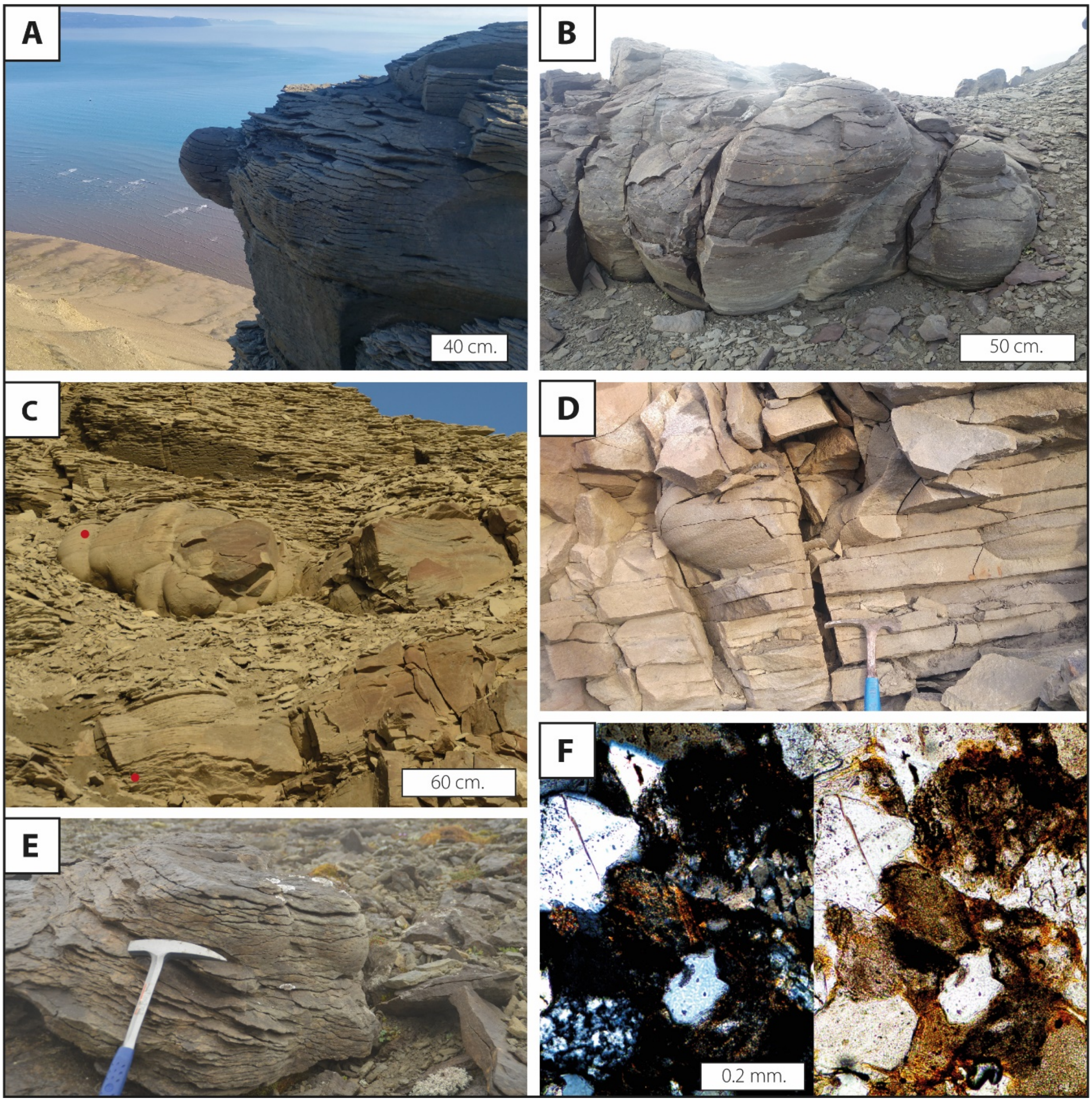


Figure 13. Ball structures. A. Single ball structure in plane parallel stratified sandstone at Blanknuten. B. Large structure of amalgamated ball shapes in plane parallel stratified sandstone at Blanknuten. C. Large formation of amalgamated ball structures in heavily fractured sandstone at Blanknuten. Red dots mark location of thin section samples. D. Single elongated ball structure at Skrukkefjellet. E. Structure of amalgamated spheres forms the largest fragment left of entirely fragmented sandstone bed at Drivdalsryggen. F. Micro image from sample within the ball structures in (C) showing carbonate-cementation and a high clay content in the sandstone. In cross and plane polarised light.

5.8 Plane Parallel Stratified Sandstone – H

The plane parallel stratified sandstone facies made up 0.1 to 15 meters thick sandstone units. The stratification can be both laminated (Figure 14.C and D) and bedded (Figure 14.A, B and E). The thickest individual bed found was 7 cm thick. The grain-size of sandstones with these structures was mostly between very fine- and fine-grained sand, however medium-grained sand also occurred. Sparse and moderate bioturbation (Figure 14.D), mud flakes and organic fragments occurred. Carbonate cementation and concretions were common (Figures 14 and 13). The colour was grey to yellow and orange on weathered surfaces. Parting lineation was not observed. Plane parallel stratification was often found in combination with heterolithic bedding (facies B), rippled sandstone (facies E and F) and tabular cross-stratified sandstone (facies K).

Plane parallel stratification can be formed in several different depositional environments. The plane parallel stratification sandstones observed in this thesis are interpreted to have been deposited in the upper flow regime (Figure 11), under shallow water with high velocity.

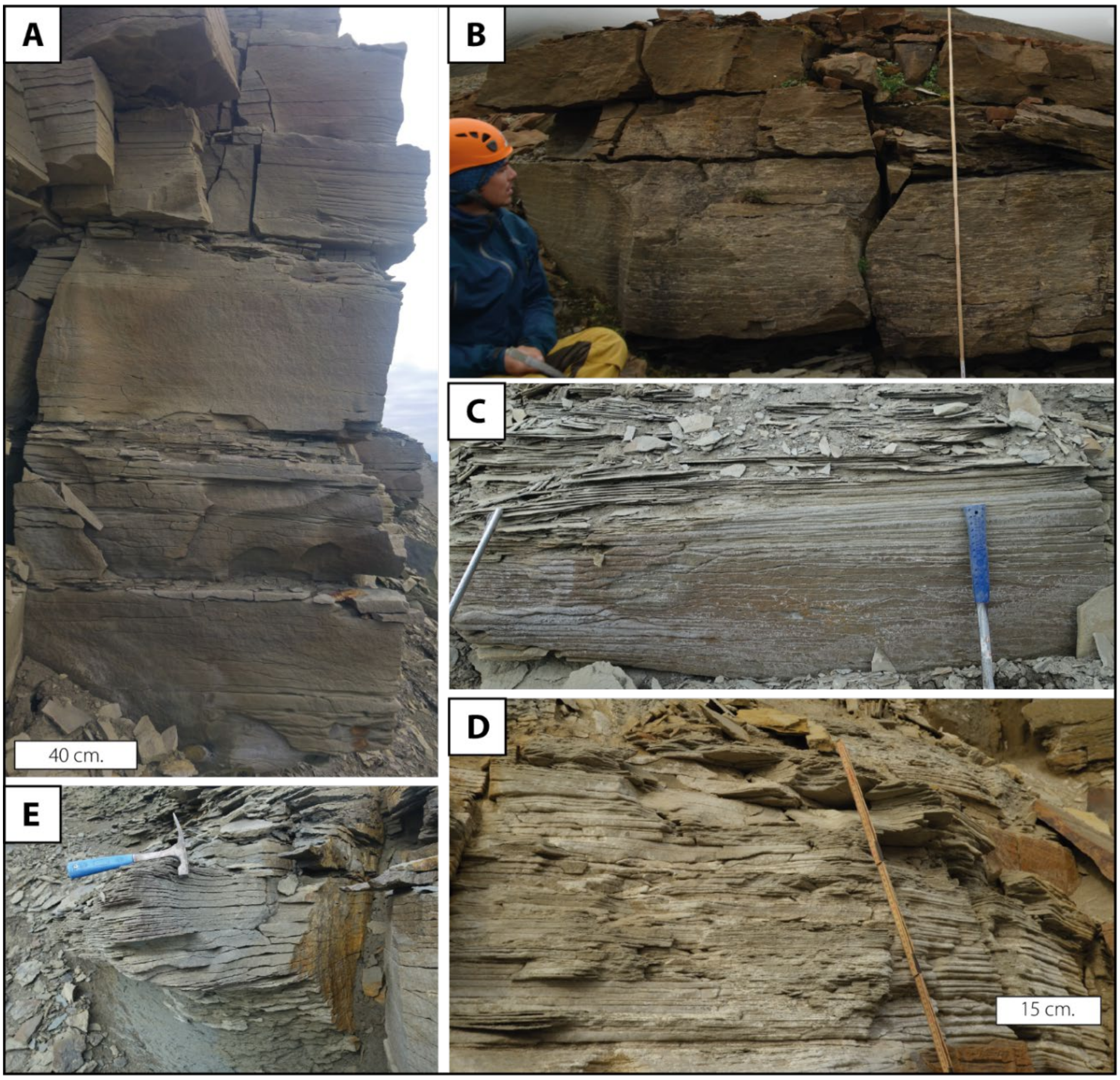


Figure 14. Planar parallel laminated sandstone facies. A. Plane parallel stratified sandstone with siderite concretions at the base, at Palibinranten. B. Planar parallel laminated, calcite-cemented sandstone at Drivdalsryggen. C. Planar parallel lamination at Drivdalsryggen. D. Planar parallel lamination at Blanknuten. E. Planar parallel stratification splitting into lamination towards the left in the picture, at Blanknuten.

5.9 Massive Sandstone – I

The massive sandstone facies include structureless massive sandstones and sandstones that appear structureless due to being entirely defined by undulated fractures, weathering or calcite cementation. The grain size of this facies range from very fine- to medium-grained sand. Typical colours are grey, brown, yellow and orange. Units are thick and laterally extensive. They could be up to 9 meters thick and 180 meters in lateral extension (Figure 15.B). Sandstones in this facies are often found with erosive bases.

The apparent structureless sandstone may initially have had soft sediment deformation, ripples or large-scale cross-stratification. The structureless sandstones may have gotten this appearance due to heavy bioturbation, very rapid deposition or rapid liquefaction (Collinson et al. 2006).

The facies is not defined in Lord et al. (2017a) or Rød et al. (2014). However, the latter has described the facies "undulation fractured sandstone" with similar characteristics. At Blanknuten, there were no visible sedimentary structures in the largest sandstone body in the outcrop, making this facies essential for this thesis.

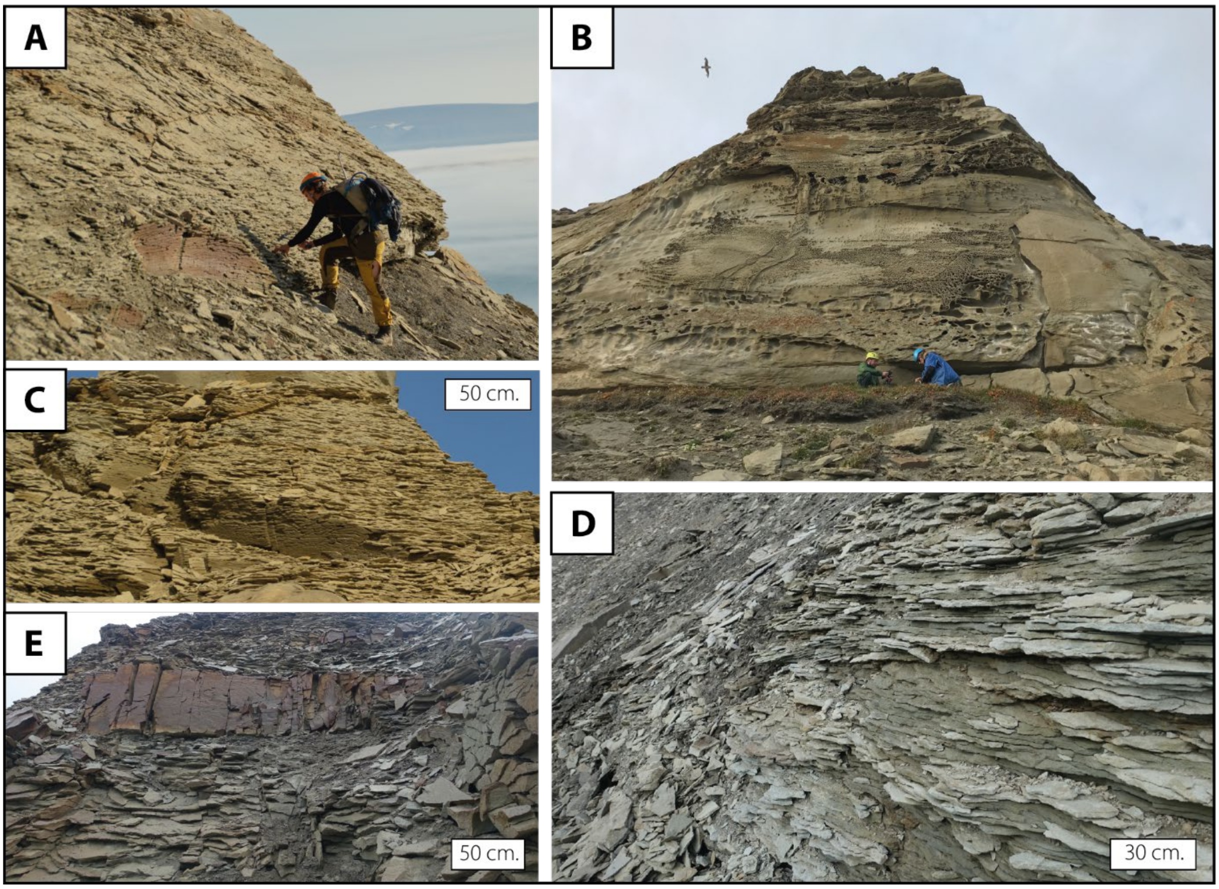


Figure 15. Massive sandstone facies. A. Heavily fractures sandstone, apparently structureless, at Blanknuten. B. The thickest sandstone body at Blanknuten, apparently massive, with tafoni weathering. C. Undulating fractured, apparently massive sandstone, with no visible primary structures, at Blanknuten. D. Undulating fractured sandstone with no visible primary structures, at Skrukkefjellet. E. Undulating fractured apparently massive sandstone, with a one-meter thick calcite-cemented bed in the middle, preserving and revealing tabular cross-stratification, at Blanknuten.

5.10 Low Angle Cross-Stratified Sandstone – J

The low angle cross-stratified sandstone facies made up 0.5 to 1.5 meters thick beds of gently dipping parallel stratification with wedge shape set boundaries, within larger sandstone units (Figure 16). The stratification could be laminated or bedded. The thickest set found was 1.5 meters thick (Figure 16.B). The grain-size of sandstones with these structures was very fine- to fine-grained sand. Sparse and moderate bioturbation occurred (Figure 16.D). Mud flakes, mud drapes or organic fragments were not observed within this facies. The colour was grey, yellow, orange or brown. The low angle cross-stratified beds were often found in larger sandstone units with wave ripples (facies E), current ripples (facies F) or plane parallel stratification (facies H). Low angle cross-stratified sandstone is not diagnostic for one sedimentary environment and can stem from the upper shoreface, beach foreshore or fluvial environments (Reading and Collinson 1996).

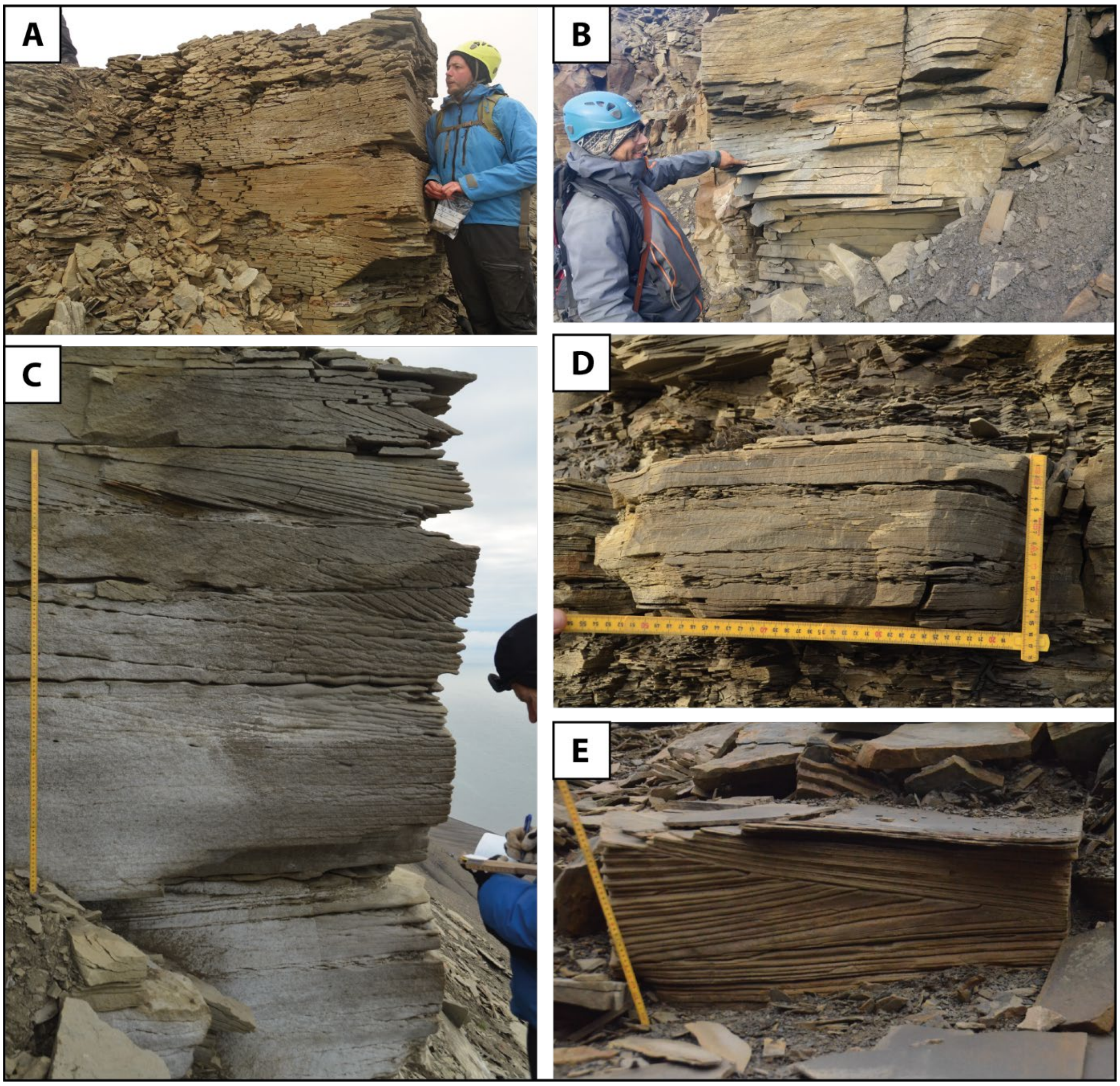


Figure 16. Low angle cross-stratified sandstone facies. A. Multiple stacked sets of low angle cross-stratified sandstone with siderite cemented horizons, at Blanknuten. B. Low angle cross-bedded sandstone where the foresets dip 7^{o} and each set thins in the down-dip direction, at Skrukkefjellet. C. Sets of cross-stratification with different angles, all dipping in the same direction with foresets thinning in the up-dip direction, at Palibinranten. D. Wave rippled sandstone with low angle cross-stratification on the top, at Drivdalsryggen. E. Low angle cross-stratified, fine-grained sandstone with sets dipping in opposing directions, at Drivdalsryggen.

5.11 Tabular Cross-Stratified Sandstone – K

The tabular cross-stratified sandstone facies consist of very fine- to medium-grained sandstone with cross-bedding and planar bounding surfaces. Sandstone units with thicknesses from 0.3 to 5 meters were observed displaying this facies (Figure 17). Individual foresets were between 0.2 and 1 meters thick. The colour of the sandstones was yellow, brown or grey. Mud draping, coal draping and plant fragments were common on the foresets. Bioturbation was sparse but occurred towards the top of some units. Plant fragments and mud clasts also occurred. The facies was often found interbedded or overlaying wave ripples (facies E) or planer parallel stratified sandstone (facies H).

Tabular cross-bedding is formed mainly by the migration of large-scale, straight-crested dunes in unidirectional flow of the lower flow regime (Boggs 2011a)(Figure 19).

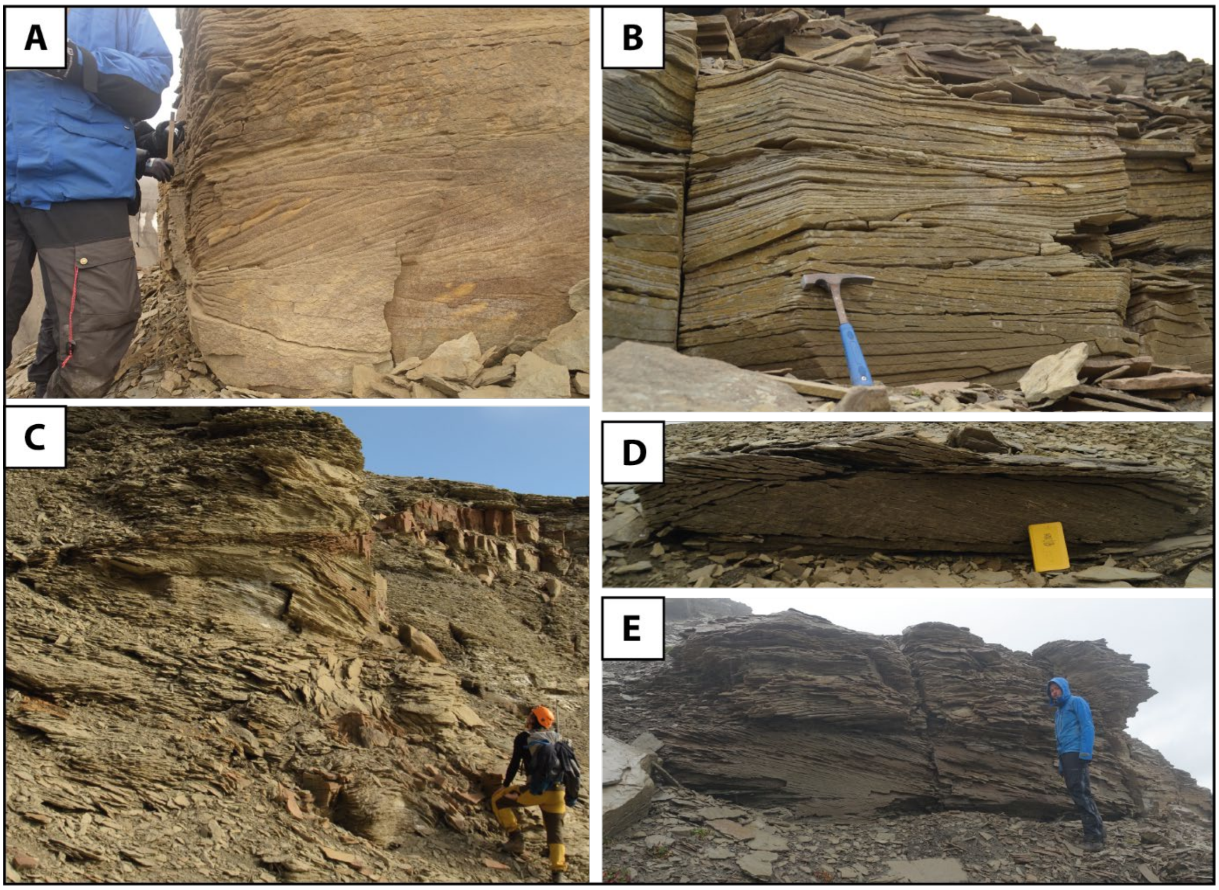


Figure 17. Tabular cross-stratified sandstone facies. A. Medium-grained, planar cross-bedded sandstone, with 35 cm high foresets, at Blanknuten B. Planar cross-bedded sandstone at Muen. C. Stacked sets of tabular cross-stratified sandstone at Blanknuten D. A 25 cm high set of calcite-cemented, tabular cross-bedded sandstone at Drivdalsryggen. E. Large-scale planar cross-bedding in fine-grained sandstone, in the lower part of the De Geerdalen Formation, at Blanknuten.

5.12 Trough Cross-Stratified Sandstone – L

The trough cross-stratified sandstone facies consist of fine- to medium-grained sandstone with foreset beds tangentially bent towards the lower boundary of the bed and one or two curved bounding surfaces. Sandstone units with thicknesses from 0.2 to 5 meters were observed displaying this facies (Figure 18). Individual foreset beds were between 0.2 and 1.2 meters thick. The colour of the sandstones was yellow, orange, brown or grey. Mud clasts, organic fragments and coal draping were common. Bioturbation was sparse but occurred towards the top of some units. The facies was often found underlying planer parallel stratified sandstone (facies H).

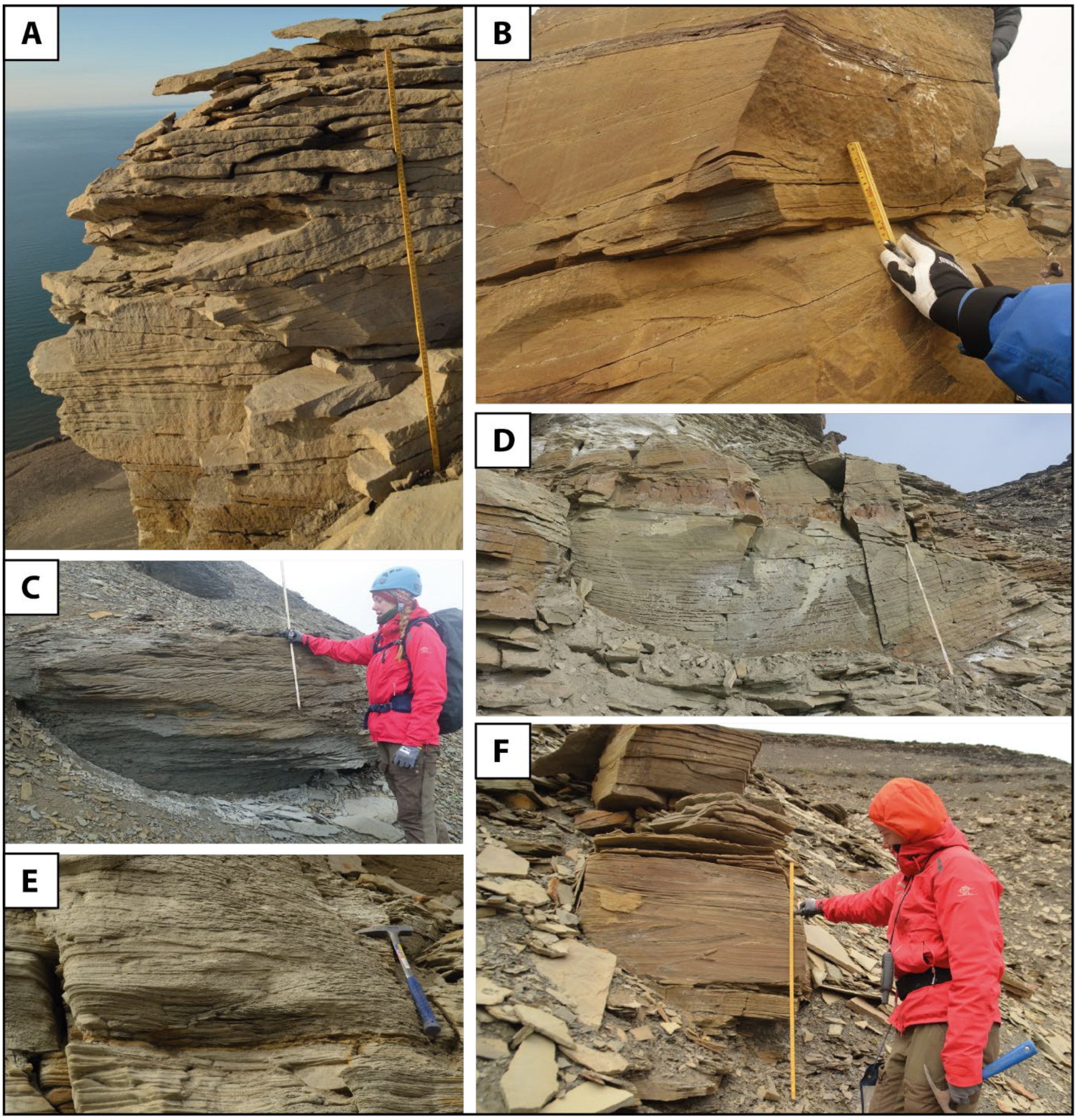


Figure 18. Trough cross-stratified sandstone facies. A. Trough cross-bedded, medium-grained sandstone, with 35 cm high foresets at Muen. B. 45 cm high foresets at Palibinranten. C. Trough cross-bedded, poorly cemented sandstone, with an increasing amount of bioturbation, at Blanknuten. D. Cross-bedded sandstone interpreted to have been formed by subaqueous dunes migrating out of the picture, with 1-meter high foresets, at Blanknuten. E. Trough cross-lamination in fine-grained sandstone at Drivdalsryggen. F. Trough cross-bedded, calcite-cemented sandstone at Muen.

Trough cross-bedding is formed by the migration of sinuous subaqueous dunes (Figure 19). These dunes can be formed in river channels, deltas, estuaries and shallow marine environments where there are relatively strong, sustained flows (Nichols 2009a).

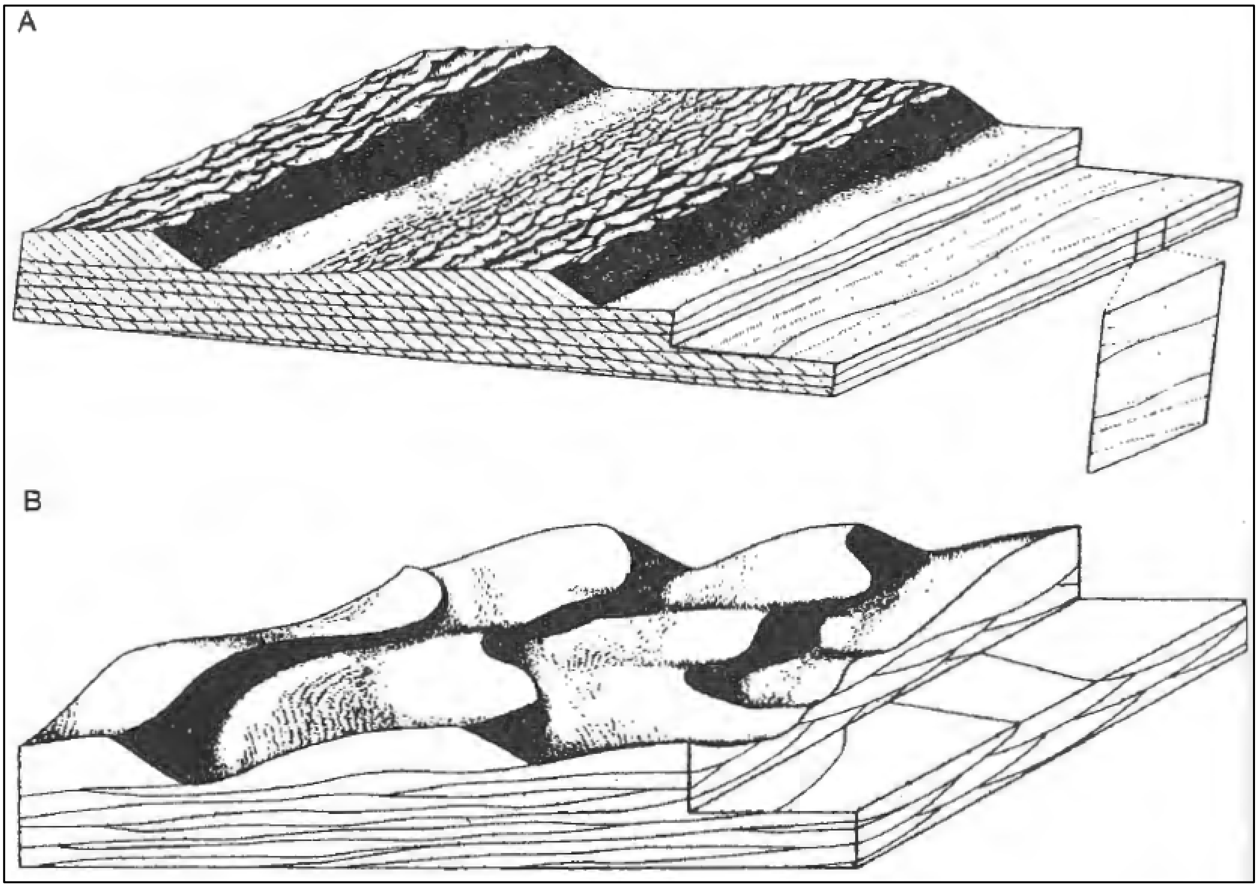


Figure 19. Diagram illustrating the deposition of: A. Tabular cross-stratified sandstone. B. Trough cross-stratified sandstone. From Harms et al. (1982).

5.13 Coal and palaeosols – M and N

The coal and coal shale facies consist of thin beds between 0.5 and 10 cm thick. The beds were often associated with the top of large sandstone bodies. The observed palaeosols were between 0.1 and 0.5 meters thick and were always associated with coal. The palaeosols were grey to green in colour, had a mottled appearance and consisted of clay (Figure 20).

Thin coal layers (>2 cm) that extended laterally for up to 5 meters were frequently found within larger sandstones. The thicker coal layers that extended laterally for tens of meters were found within grey mudstones or palaeosols directly above large sandstones. Coals and palaeosol beds were common at Blanknuten and Drivdalsryggen. The facies were not present at any of the other visited localities, which may be due to the fact that Blanknuten and Drivdalsryggen were situated highest in the stratification. The observed palaeosols were thinner and did not have the red or yellow colour typical for the Isfjorden Member (Haugen 2016). Neither calcrete nor peds were observed. The term "fines" have been used to describe coal and palaeosol together with mud- and siltstones when undifferentiated.

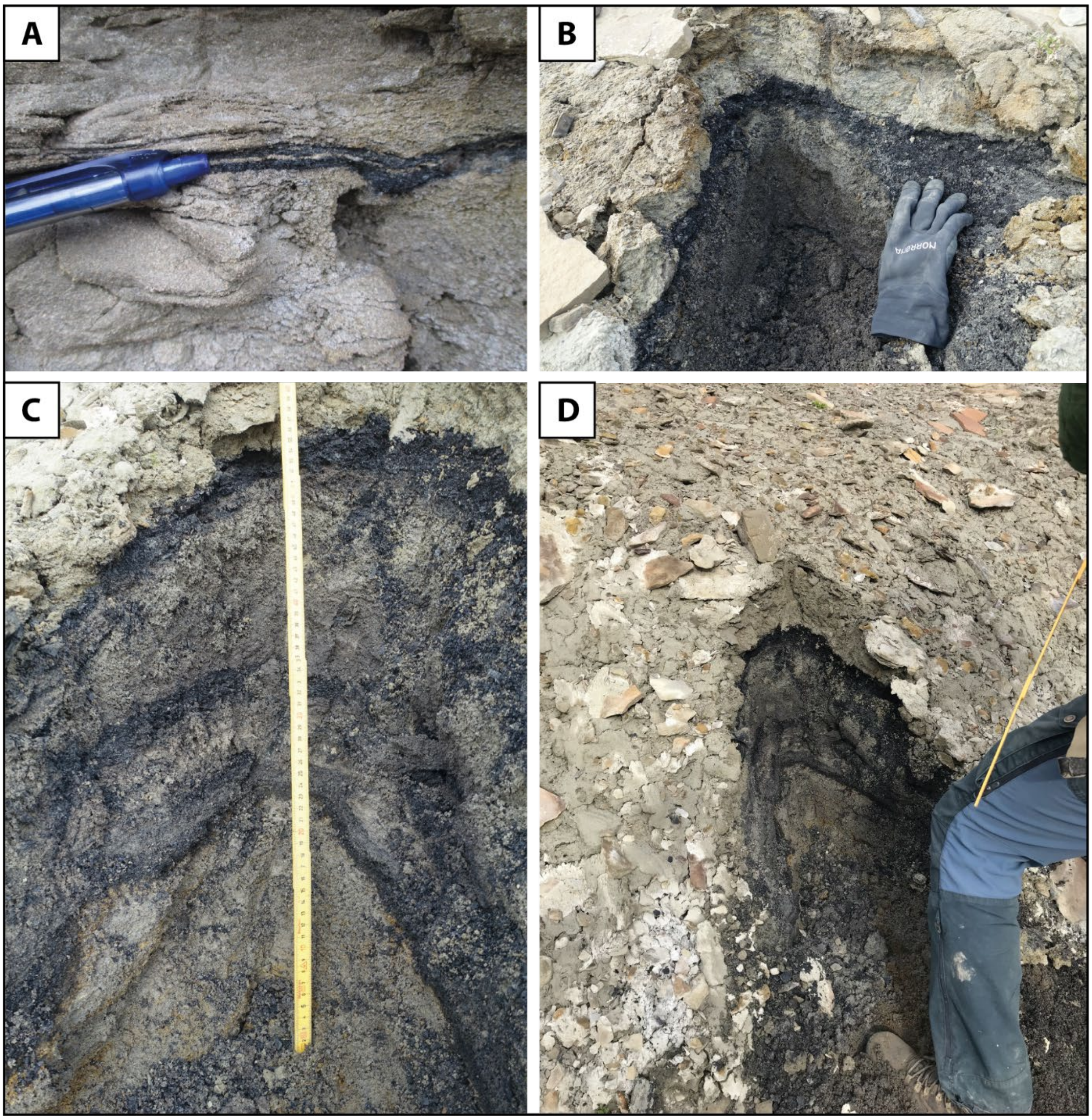


Figure 20. Coal and paleosol facies. A. Two approximately one-meter-wide bands of coal lamina at Drivdalsryggen. B. Coal bed interbedded with paleosol over and under at the top of a para-sequence at Blanknuten. C. Three coal beds interbedded with palaeosols at Drivdalsryggen. D. Coal bed excavated from scree at Blanknuten.

5.14 Facies associations

Facies are commonly grouped together into a facies association (Collinson 1969). A facies association is a collection of sedimentary facies that reflects a depositional environment (Nichols 2009b).

Facies have been grouped in facies associations to present the evolution of general depositional environments at the visited locations. The facies associations used in this study were presented by Lord et al. (2017a) (Table 2). The facies association and depositional environment have been used to correlate within and between datasets (see Chapter 8).

Table 2 Facies associations recognised in the De Geerdalen Formation by Lord et al. (2017a). The incorporated facies have been adjusted to facies observed at Edgeøya and presented previously in Chapter 5.

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

5.14.1 Open marine shelf – DE 1

Open marine shelf deposits - FA 1

The open marine facies association is defined as pelagic deposition of clay-size particles over a prolonged time period (Stow et al. 1996). Mudstone is the only incorporated facies in this facies association (facies A). In this study, the open marine facies association is only found in the Botneheia Formation and the lower part of the Tschermakfjellet Formation.

5.14.2 Shallow marine – DE 2

Prodelta slope deposits – FA 2

The prodelta slope deposits overlay open marine shelf deposits, with a boundary at the first onset of deltaic sediments (Reading and Collinson 1996). It consists predominantly of shale unaffected by tidal and wave processes (Coleman et al. 1983). Mudstone, heterolithic bedding, hummocky cross-bedding and sandstones with soft sediment deformation are incorporated facies in this facies association (facies A, B, C and D).

This facies association is found as grey mud- and siltstones of the Tschermakfjellet Formation coarsening upwards towards the De Geerdalen Formation.

Offshore transition deposits – FA 3

The offshore transition zone extends between the storm weather wave base to mean fair weather wave base (Boggs 2011b). Offshore transition deposits consist of mud- and siltstone with heterolithic bedding and occasional thin sandstone beds. The sandstone beds found within these deposits typically exhibit hummocky cross-bedding and wave ripples on the upper surface (Lord et al. 2017a). The sediment distribution in the coarser facies is generally controled by storm erosion in shallower water, while fines are deposited through settling from suspension under fair weather conditions (Reading and Collinson 1996; Eide et al. 2015).

Mudstone, coarsening upwards heterolithic bedding, hummocky cross-bedding, carbonate-rich and wave rippled sandstone are incorporated facies in this facies association (facies A, B, C, G and E). Carbonate-rich sandstones in this facies association often exhibit cone-in-cone structures.

This facies association is commonly found in the upper part of the Tschermakfjellet Formation and the lower part of the De Geerdalen Formation.

Lower shoreface deposits – FA 4

The lower shoreface zone extends from mean fair weather wave base to the upper shoreface zone (Reading and Collinson 1996).

Lower shoreface deposits are found as sandy intervals in the upper part of DE 2, where oscillatory wave currents have reworked very fine- to fine-grained sand under fair weather conditions. Coarser sediments of up to pebble grain size can be transported to the lower shoreface during storm events resulting in a characteristic bimodal grain-size distribution (Clifton 2006).

Mudstone, heterolithic bedding, swaley cross-bedding, carbonate rich-, wave rippled- and planar parallel sandstones are incorporated facies in this facies association (facies A, B, C, E, G and H).

5.14.3 Delta front – DE 3

Upper shoreface deposits – FA 5

The upper shoreface zone extends from the base of the surf zone to the swash zone and the back of the beach (Lord et al. 2017a). This facies association is dominated by high wave energy.

Hummocky cross-bedding, carbonate rich-, wave rippled-, current rippled-, low angle cross-stratified and trough cross-stratified sandstones are incorporated facies in this facies association (facies C, E, F, G, J and L). Low angle cross-stratification is common in a beach environment, exhibiting a gentle dip towards the sea. It is also found in other depositional environments and is thus not a diagnostic sedimentary structure for FA 5 (Reading and Collinson 1996).

Mud draping ripple-troughs are interpreted as a tidal influence (Davis 2012). The trace fossils *Diplocraterion* and *Skolithos* are used as indicators for high energy environments, typically the upper shoreface (Droser 1991).

Distributary mouth bar deposits – FA 6

Distributary mouth bars forms as river bedload stop moving at the point of flow expansion, while suspended fines continue to be transported basinward

(Bhattacharya 2006). Mouth bars are thus comprised of sediments of very fine-grained sand and coarser. The formation of mouth bars requires that the sediments are not redistributed by wave processes (Reading and Collinson 1996). Distributary mouth bars occur thus more frequently in river-dominated deltas than in wave- and tide influenced deltas (Bhattacharya 2006).

Distributary mouth bar deposits are often overlaid by distributary channel deposits (Rød et al. 2014). The two facies associations have similar characteristics, and both have erosive bases (Bhattacharya, 2006). Marine trace fossils and the lack of mud flake conglomerate can be used to differentiate distributary mouth bars and distributary channel deposits.

Sandstone with soft sediment deformation, current rippled sandstone, plane parallel stratified sandstone, massive sandstone, low angle, tabular and trough cross-stratified sandstones are incorporated facies in this facies association (facies D, F, H, I, J, K and L).

Barrier bar deposits – FA 7

Barrier bar deposits in the De Geerdalen Formation consists of fine- to medium-grained sand often with tidal signatures such as herringbone cross-stratification and mud-draped foresets (Lord et al. 2017a).

The facies association, barrier bar, is often found overlaying FA 4 and 5, and underlying finer delta plain deposits. The boundary between barrier bars and the underlying sediments are gradual and upwards-shallowing, opposed to the lower boundary of FA 6 and 8 (Bhattacharya 2006; Clifton 2006). Upwards coarsening lower boundaries and overlying lagoonal deposits, for sandstone bodies are clear indicators of these sandstones being deposited as barrier bars. Both upwards coarsening lower boundaries and lagoonal deposits are prone to be covered by scree. This masking limits the accurate interpretation of barrier bar deposits.

Wave rippled sandstone, current rippled sandstone, plane parallel stratified sandstone, massive sandstone, low angle and trough cross-stratified sandstones are incorporated facies in this facies association (facies E, F, H, J and L).

5.14.4 Delta plain – DE 4

Sediments assigned to the delta plain depositional environment are only found on the visited localities, Blanknuten and Drivdalsryggen. These two localities are interpreted to contain more proximal deltaic sediments than found on the other visited localities to the south and north.

Distributary channel deposits – FA 8

Distributary channel deposits are typically recognised as fining upwards sandstone bodies with erosive basal lags of plant fragments or mud clast conglomerate (Knarud 1980). Trough cross-bedding is often observed in the lower part of these sandstones, overlaid by planar cross-bedding, and then ripple lamination on the top. These sandstone bodies are also often found to be capped by coal and palaeosol layers. These capping facies are interpreted as the result of the emergence or abandonment of the channel.

Distributary channels have a lower slope gradient on the delta plain, compared to more fluvial dominated channels further inland (Nichols 2009a). This gentle gradient results in avulsion, bifurcation and anastomosing of channels, which forms thin (< 10 meters thick) amalgamated laterally extensive sandstone bodies (Reineck and Singh 1980).

Current rippled sandstone, plane parallel stratified sandstone, massive sandstone, tabular cross-stratified sandstones, trough cross-stratified sandstones, coal and palaeosols are incorporated facies in this facies association (facies F, H, I, K, L, M and N).

Floodplain deposits – FA 9

Floodplain deposits consist of predominantly fines with occasional horizontally laminated or rippled silt- and sandstone beds. The coarser deposits on these floodplains might be deposited as levees and crevasse splays (Nichols 2009c).

Floodplain deposits are found as one to five-meter-thick sections immediately overlaying FA 8, or as up to 30-meter think intervals in the upper parts of the exposed De Geerdalen Formation on Edgeøya. These thick sections are often covered by thick scree.

Mudstone, wave rippled sandstone, current rippled sandstone, plane parallel stratified sandstone, coal and palaeosols are incorporated facies in this facies association (facies A, E, F, M and N).

Interdistributary area – FA 10

Interdistributary areas are considered as standing bodies of water such as lagoons, lakes, marshes and swamps (Lord et al. 2017a). The interdistributary area facies association differ from FA 9 with a higher marine influence and lower sand content.

Mudstone, coal shale, coal and palaeosols are incorporated facies in this facies association (facies A, M and N), but wave rippled sandstone, current rippled sandstone and plane parallel stratified sandstones occur as wash-over sands (facies E, F and H).

6 Logged sections

Six locations along the western and northern coast of Edgeøya were visited. The six localities are Blanknuten, Drivdalsryggen, Muen, Kapp Lee, Palibinranten and Skrukkefjellet (Figure 21). Between one and seven days were spent at each locality. The amount of time spent at each locality and varying accessibility to outcrops have resulted in significant variations in the amount of data collected at each locality. In this chapter, the visited localities and logged sections will be described along with a short interpretation of each interval. A more thorough interpretation is presented in Chapter 7. Blanknuten and Drivdalsryggen are the most important localities for this thesis and will be presented first.

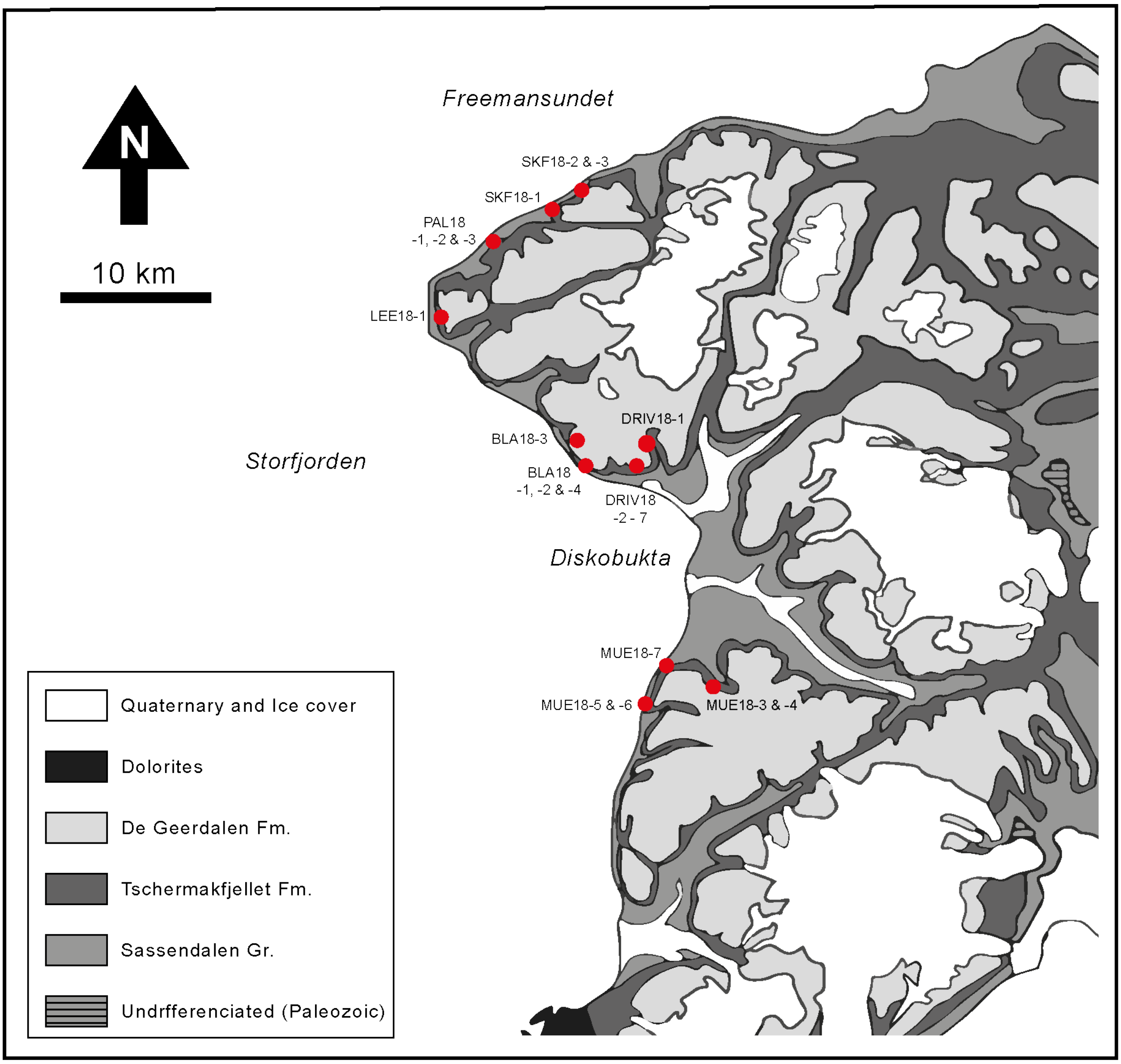


Figure 21. Schematic geological map of the western coast of Edgeøya with the location of different logs (redrawn from Osmundsen et al. (2014).

6.1 Blanknuten

Blanknuten is a 481 meter high plateau mountain at the northern end of Diskobukta (Figure 21). It presents a 5 km long steep mountainside made up of multiple ridges and gullies towards Storfjorden, exposing strata assigned to the Vikinghøgda-, Botneheia-, Tschermakfjellet- and De Geerdalen formations. Blanknuten is the type locality for the Blanknuten Member of the Botneheia Formation, which forms cliffs due to carbonate cementation (Mørk et al. 1999a). In addition to the cliff-forming interval in the Botneheia Formation, there are large cliff-forming sandstone bodies of the De Geerdalen Formation exposed towards the top of the steep mountainside. These steep stratigraphic intervals have made large parts of the mountainside inaccessible. The inaccessible sections of the cliff face have been observed from adjacent ridges. Five days were spent making observations at Blanknuten, and four logs recorded, three on the south-eastern side of the mountain (Figure 22) and one on the north-western (BLA18-3). Our field party stayed on land in a trapper cabin next to the mountain while working at this location.

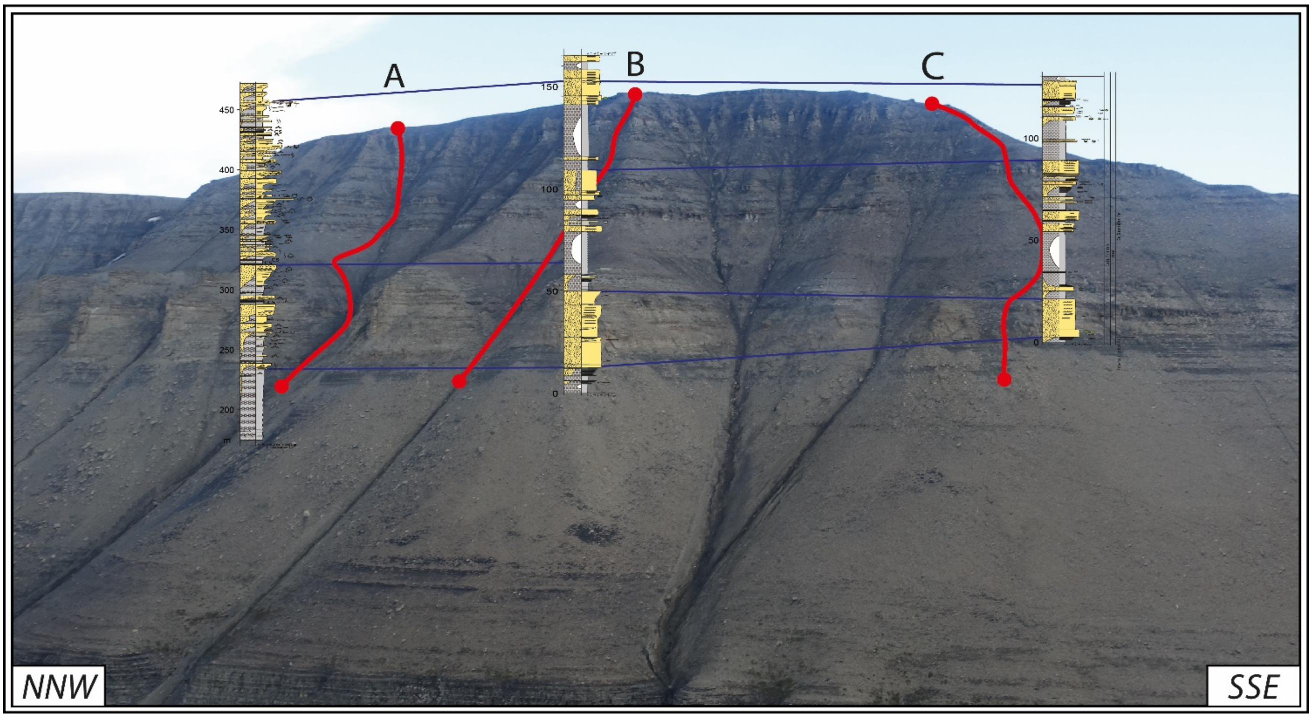


Figure 22. Overview photo of Blanknuten, with three logs. The log traces are marked with a red line. A. Log 22b Blanknuten recorded by Knarud (1980) as presented by Vigran et al. (2014). B. Log BLA18-2. C. Log BLA18-4.

6.1.1 BLA18-1

The BLA18-1 log was recorded from the base of the steepest sandstone cliff on Blanknuten (Figure 23). Samples, lateral observations and a four-meter-long log were collected five ridges to the north-west of BLA18-2. The steepness of the terrain prohibited continued logging and more extensive lateral observation. The massive sandstone body has an ellipsoid geometry and is estimated (from photographs) to be 9 meters thick and 180 meters wide (Figure 23.B). The slope below the sandstone consists of a coarsening upwards section with heterolithic bedding exhibiting hummocky cross-stratification and wave ripples (Figure 23.D). The outcropping surface of the sandstone is affected by tafoni weathering and appear massive (Figure 23.C). Structures that can be seen are 10-12 planar parallel beds, measuring from 0.5 to 1.5 meter in thickness. Planar cross-bedding can be seen in these beds towards the top of sandstone with foresets dipping towards the south.

Interpretation: This prominent sandstone has earlier been described based on observations from a distance and adjacent ridges (Knarud 1980; Hynne 2010; Rød et al. 2014; Lord et al. 2017a). The origin of the sandstone body has been debated to represent deposits from a delta lobe (Knarud 1980; Lord et al. 2017a). This interpretation is in agreement with data and observations conducted in this study. The massive planar beds at the base of the sandstone exhibit flaking and surface fractures with a horizontal orientation (Figure 23.D). This flaking may be oriented along the foresets of large-scale cross-bedding formed by dunes migrating out of the outcrop towards the south-east. This orientation parallel to the outcrop can be hard to observe. A shift in the migration direction towards the south might be the reason the only visible foresets can be seen towards the top.

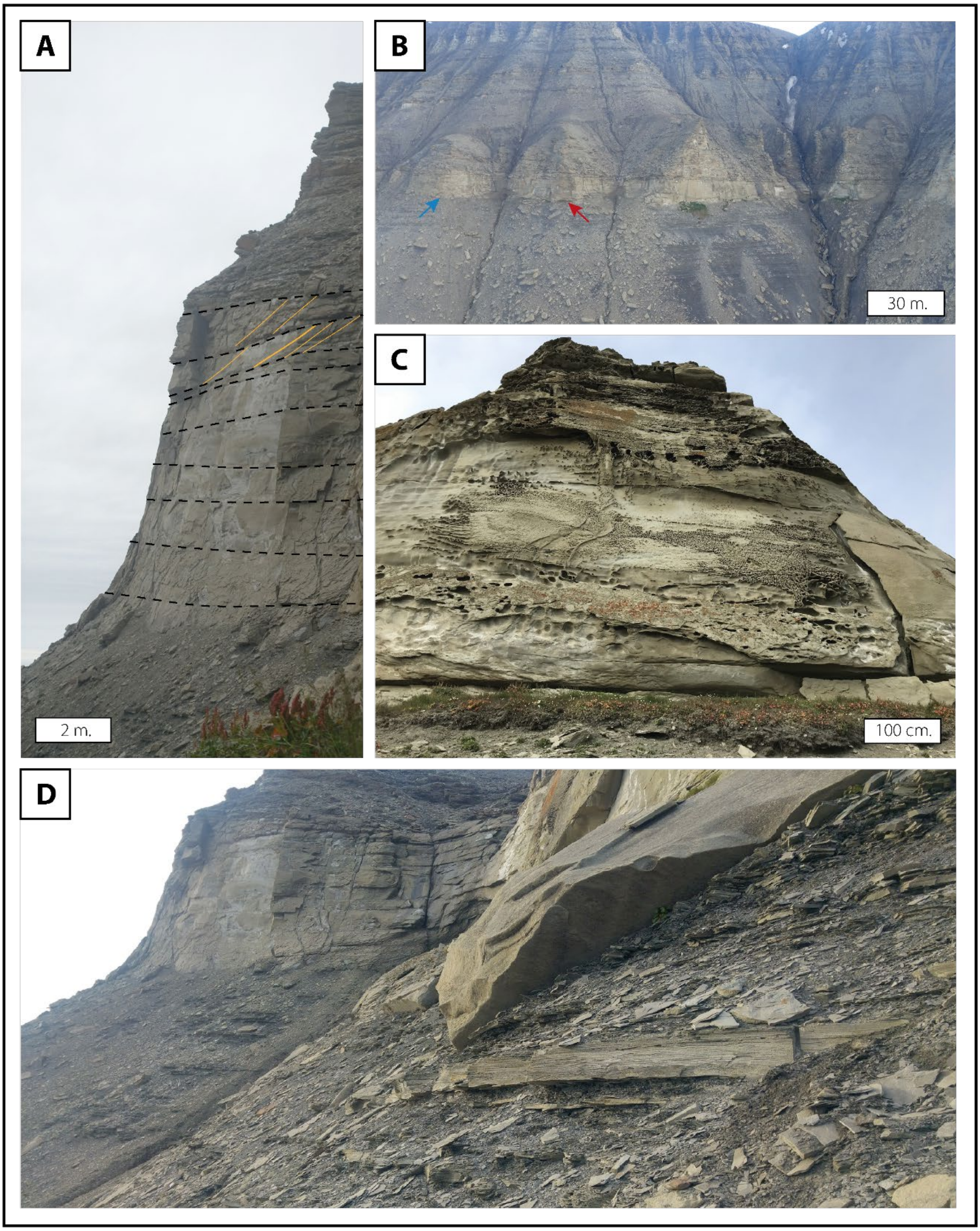


Figure 23. A. The 9-meter thick vertical sandstone cliff with planar bounding surfaces and foresets. B. Overview photo of the large ellipsoid sandstone body on Blanknuten. The blue arrow is marking the location of the cliff in (A). The red arrow is marking the location of (C) where BLA18-1 was recorded. D. Hummocky cross-stratification below the sandstone. The cliff face seen in the background is the same as in (A).

6.1.2 BLA18-2

The BLA18-2 log (Appendix B.1 and Figure 25) is the complete log recorded closest to the large ellipsoid sandstone body on Blanknuten, during the fieldwork for this thesis. It was recorded along a gully, five ridges to the south-east of BLA18-1, and ca 150 meters to the south-east of the 22b Blanknuten log, recorded by Knarud (1980) (Figure 22). The largest sandstone bodies recorded in this log are heavily fractured and locally very steep (Figure 24.B). The top of the Botneheia Formation was recorded 76 meters below the base of this log, making the Tschermakfjellet Formation 88 meters thick at this location.

Interval 1 (0 – 12.5 m)

Description: The lowermost interval of this log consists of 12 meters of shale and heterolithic bedding with hummocky cross-stratification in an upwards coarsening succession (facies A, B and C).

Interpretation: This interval is interpreted as offshore transition prodelta deposits of the Tschermakfjellet Formation (FA 2 and 3). The upwards coarsening nature of the deposits supports this interpretation.

Interval 2 (12.5 – 50 m)

Description: This interval consists of a 37-meter thick sandstone body made of three amalgamated coarsening-upward units (Figure 25). The sandstone body is heavily fractured by undulating fractures, masking possible primary structures. Sedimentary structures include hummocky cross-stratification, large-scale trough cross-stratification and ripple lamination (facies C, G, F, I and L).

Interpretation: The large sandstone body in this interval is interpreted to have been deposited in amalgamating distributary channels (FA 8). This interpretation is supported by the upwards coarsening nature of the sand, large-scale trough cross-bedding at the base, ripple lamination at the top and the occurrence of channel-shaped lenses within the sandstone.

Interval 3 (50 – 79 m)

Description: This interval consists of a coarsening upwards sequence of heterolithic bedding and a thick (> 20 meters) sequence of scree-covered slope, interpreted as mudstone (facies A and B).

Interpretation: The scree-covered section and heterolithic bedding of this interval are interpreted as fines deposited in an interdistributary setting (FA 10). Coal and palaeosol beds are found at this stratigraphic level in BLA18-4 and the 22b Blanknuten log from Knarud (1980) and might be covered under the scree at this location as well.

<u>Interval 4 (79 – 109 m)</u>

Description: This interval consists of a 37-meter thick sequence of sandstones. The sandstone sequence has been divided into three separate sandstones. The lowermost is made of medium-grained trough cross-bedded sandstone (facies L). The middle sandstone is a coarsening upwards section with heterolithic bedding, marine fossils, moderate bioturbation, hummocky cross-bedding and a coal-shale horizon (facies B, C, L and M). The uppermost sandstone body is made up of very fine- to fine-grained sand and contain hummocky cross-bedding, planar parallel lamination, sparse bioturbation and trough cross-bedding in the lower part. The upper 11 meters of this sandstone has a high silt content, are heavily fractured and appear structureless (facies B and I).

Interpretation: The three sandstones of this interval are interpreted to represent three episodes of progradation in a delta front to upper shoreface environment (DE 3). More specifically, barrier bars or shallow subaqueous banks (FA 7). Lateral extensive thin sandstone layers are typical for such deposits (Rød et al. 2014; Lord et al. 2017a). The shale heterolithic bedding and coal shale topping each of the bars are interpreted as lagoonal fines (FA 10). The thin sandstones may have formed during storm episodes as wash-over fans. The overall interpretation of this interval is regressive.

<u>Interval 5 (109 – 141 m)</u>

Description: This interval consists of shale, a 1.5-meter-thick layer of fine-grained sand and a thick (> 20 meters) sequence of scree-covered slope, interpreted as mudstone (facies A).

Interpretation: The scree-covered slope in the top half is therefore interpreted as fines deposited in an interdistributary area (FA 10). The planar parallel stratified sandstone bed within these shales could also reflect wash-over fans or a small channel on a mud-dominated tidal flat (Reineck and Singh 1980).

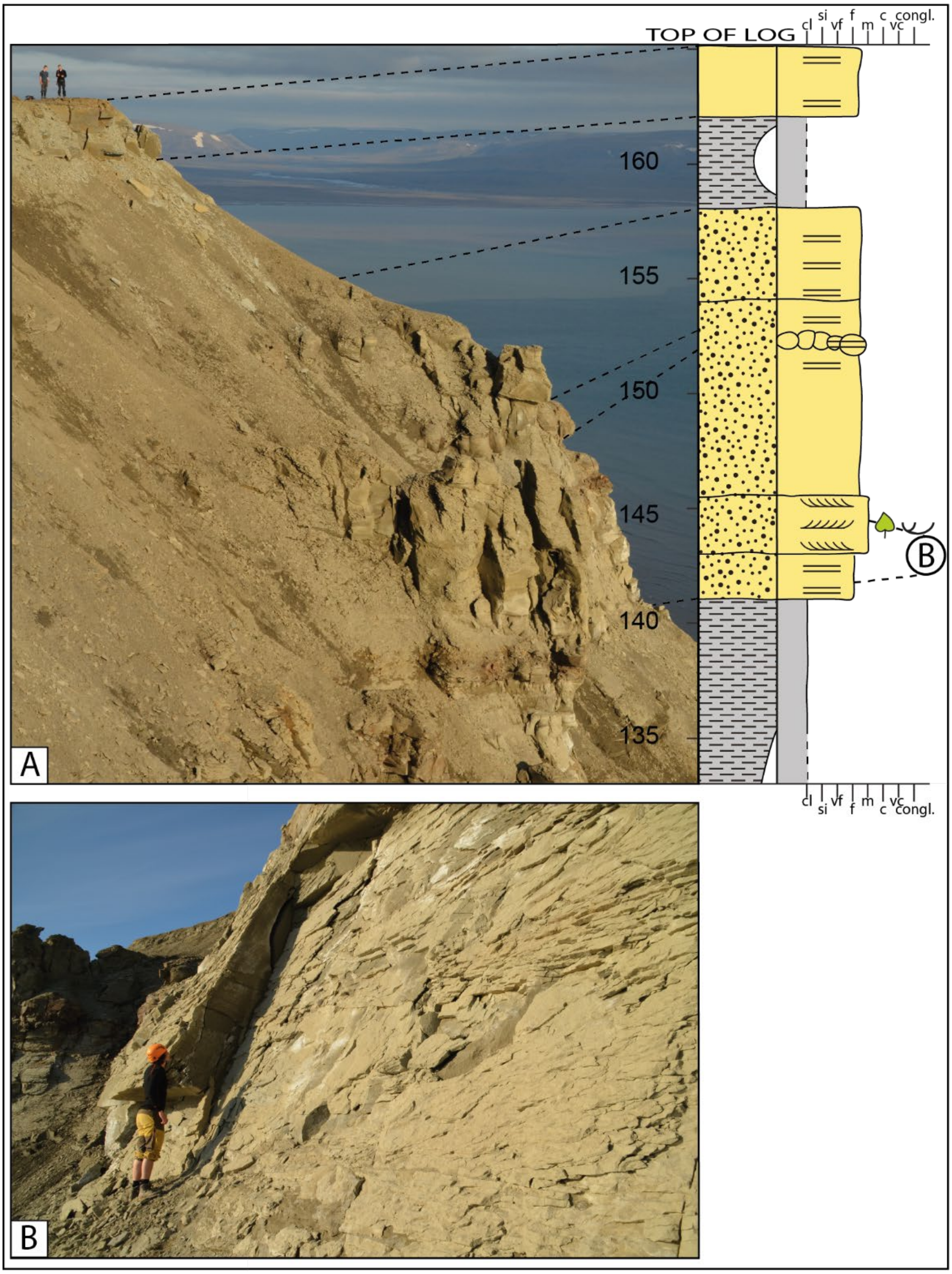


Figure 24. A. The top of the ridge logged in BLA18-2 corresponding to Interval 6. B. Close up of the base of the sandstone unit in (A).

Interval 6 (141 – 165 m)

Description: This interval is 24 meters long and consists of fine- to medium-grained, planar and cross-stratified sandstone (facies H and L). Plant fossils and coal fragments are draping the foresets of cross-bedding that occur frequently. Large sections of this sandstone appear massive with undulating fractures on the surface (Figure 24). The middle part of this interval has a horizon of large sandstone concretions (facies G). The sandstone cliffs in this interval are the steepest of the BLA18-2 log, limiting the quality of sedimentary observations made at this location. The geometry of this sandstone body is sheet-like and does not exhibit the lenticular geometry of the BLA18-1 sandstone body. It is also wider than the BLA18-1 sandstone body with a lateral extent over hundreds of metres.

Interpretation: The sandstone composing this top cliff of the Blanknuten mountainside is interpreted to have been deposited as amalgamated distributary channels (FA 8). This interpretation is likely due to its lateral extension, organic fragments and large-scale cross-bedding.

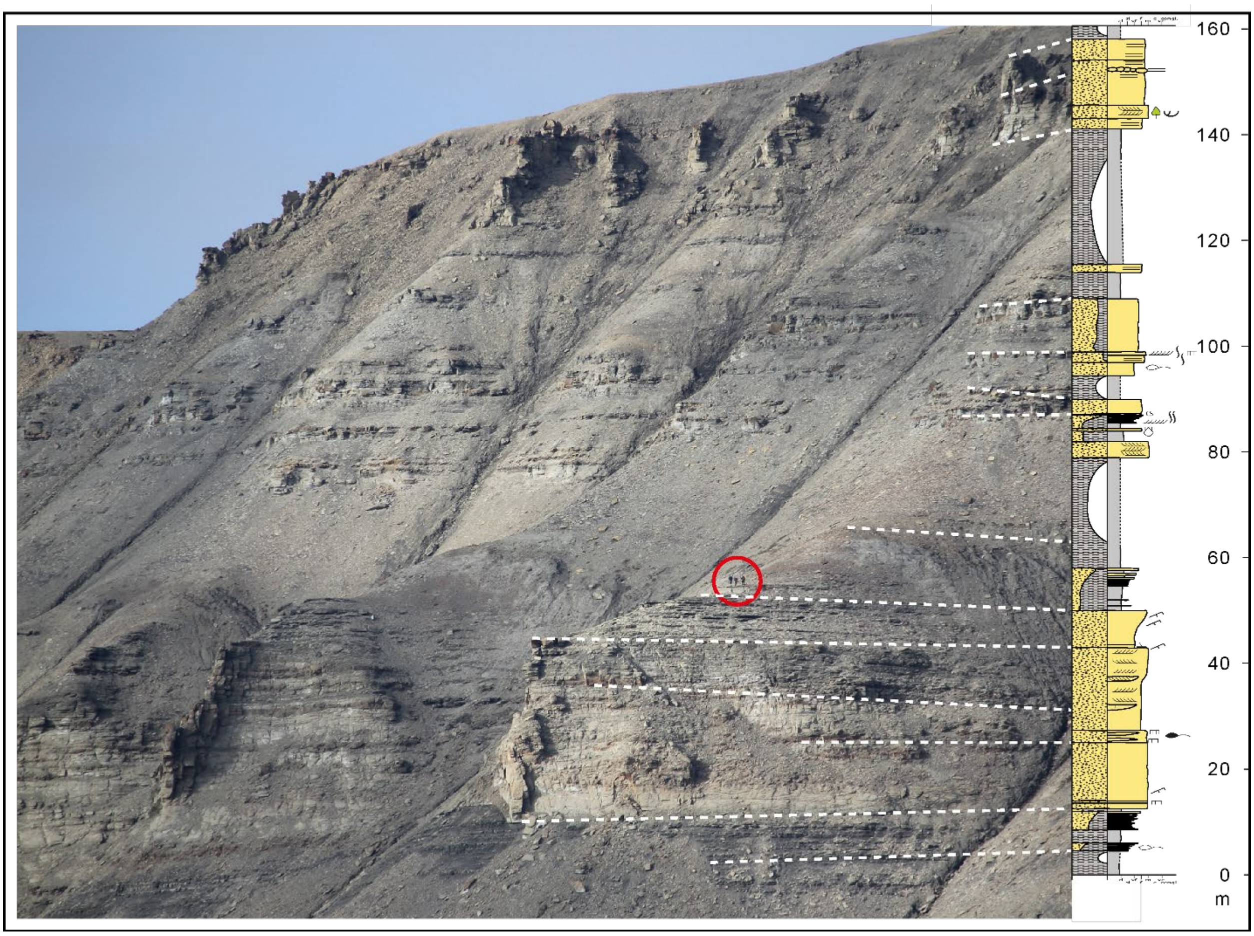


Figure 25. Log correlation of the entire BLA18-2 log. The red circle marks three geologists for scale.

6.1.3 BLA18-3

The BLA18-3 log (Appendix B.2) was logged at the southern side of the most prominent gully on Blanknuten, two kilometres to the north of BLA18-1. This area is the area of the mountain where Hynne (2010) measured two logs in 2009. The section measure 172 meters, where the base of the log is a 2.4-meter thick sandstone, interpreted as the base of the De Geerdalen Formation. This section contains a significantly smaller fraction of sand compared to equivalent strata logged further south on Blanknuten. The observed sandstone benches in this section are thinner and with more mudstone between them.

Interval 1 (0 – 38 m)

Description: The first 38 meters of the log, above the 2.4-meter thick sandstone, consists of mostly shale and scree-cover. Occasional very fine- to fine-grained sandstone benches protrude the scree slope, the thickest measuring 2.4 meters in thickness. Plant fragments, mud flakes and hummocky cross-stratified lamination are present.

Interpretation: This interval is interpreted to represent lower shoreface to prodelta deposits close to shore (DE 2). The sandstone benches within the interval are likely storm deposits. This interpretation is supported by the high amount of plant fragments and hummocky cross-stratification found in the sandstones.

Interval 2 (38 – 68 m)

Description: This interval consists of three coarsening upwards sequences. The sequences have shale and heterolithic bedding at the base, and current rippled or planar laminated sandstone on the top. One of these sequences are capped by coal shale (facies A, B, C, D, E, F, H, K and M).

Interpretation: Repetitive or cyclic successions similar to this interval may form as a result of repeated progradation and abandonment of deltaic lobes or the entire delta (Reading and Collinson 1996). This progradation and abandonment occur at different scales governed by different processes (Reading and Collinson 1996). Sequences formed due to deltaic progradation, are characterised by an upward coarsening facies succession with coarser upper shoreface deposits building out over finer sediments deposited in deeper water (Bhattacharya 2006). The three coarsening upwards units of this interval are therefore interpreted as delta lobes prograding before being abandoned (DE 3).

Interval 3 (68 – 86 m)

Description: This interval consists of one sequence of coal and palaeosol beds underlying a ca 10-meter-thick scree-covered slope (facies A, M and N).

Interpretation: Interval 3 in the BLA18-3 log can be correlated to Interval 3 of the BLA18-2 log. Coal and palaeosol beds are also found at this stratigraphic level in BLA18-4 and the 22b Blanknuten (Knarud 1980). This interval in the BLA18-3 log is therefore interpreted as fines deposited in an interdistributary setting (FA 10).

Interval 4 (86 – 109 m)

Description: This interval consists of four coarsening upwards sequences. The interval shows similarities to Interval 2, but have coarser grain sizes, less shale and more large-scale trough cross-bedding. The mud flakes, organic fragments, mud drapes and coal drapes on foresets are found throughout this upwards coarsening sequences. Hummocky and swaley cross-bedding are found at the base and trough cross-bedding at the top. One sequence is topped by a coal layer, and one is topped by wave ripples (facies B, C, E, F, H, L, M and N)

Interpretation: Similar to Interval 2, this interval has been interpreted as cyclic successions deposited by the progradation and abandonment of delta lobes (DE 3). The delta lobe deposits of this interval show signs of higher energy levels compared to Interval 2. This interpretation is supported by the higher flow regime in Interval 3, a lower percentage of shale and coarser sands in the top of the sequences.

Interval 5 (109 – 172 m)

Description: The uppermost 60 meters of the section consists of thin sandstones (1-3 m thick) with mudstones between. The sandstones have a grey colour and are dominantly made up of medium-grained sand. They are generally poorly cemented. Sedimentary structures observed in the sandstones are low angle cross-stratification, trough cross-stratification, moderate to high bioturbation, plant fragments, wave- and current ripples (facies A, B, C, E, F, G, H, J, K, L and

M). The large sandstone concretions found in the top interval of logs on the southern end of Blanknuten and Drivdalsryggen were not found at this location.

Interpretation: This interval is interpreted to have been deposited in upper shoreface settings (FA 5). This interpretation is supported by the large-scale cross-bedding found at the base of the sandstones and the wave- and current ripples found at the top.

6.1.4 BLA18-4

The BLA18-4 log (Appendix B.3) was recorded along the southernmost ridge of the steep mountainside of southern Blanknuten (Figure 22), two ridges to the east of BLA18-2. It represents 130 meters of logged section in total. The log has been divided into six intervals.

<u>Interval 1 (0 – 2.5 m)</u>

Description: This interval consists of heterolithic bedding forming a coarsening-upwards unit towards the first prominent sandstone (facies B). Sedimentary structures found in the interval include hummocky cross-stratification and ripple cross-stratification. A unit of coarsening-upwards heterolithic bedding underlying a thick sandstone at the base of the De Geerdalen is common at Blanknuten. This unit in the BLA18-4 log is significantly thinner than found elsewhere on Blanknuten (Figure 26.C).

Interpretation: This interval is assigned to the Tschermakfjellet Formation and interpreted as shallow marine offshore transition deposits grading into the lower part of the De Geerdalen Formation (FA 3).

<u>Interval 2 (2.5 – 21 m)</u>

Description: This interval consists of a 19-meter-thick sandstone body, made from fine- to occasional coarse-grained sand. The sandstone body is showing large-scale planar cross-stratification, planar parallel lamination, wave ripples and climbing ripples (facies E, F, H and K). The lowermost parts of the sandstone body consist of heavily fractured sandstone (facies I) with unspecified organic fragments and wood fragments. The base of the sandstone body is covered by scree.

Interpretation: The interpretation of this interval has a significant degree of uncertainty due to large parts of the sandstone being heavily fractured. The base of the sandstone is interpreted as the base of the De Geerdalen Formation. This interval has been correlated to the sandstone in Interval 2 of the BLA18-2 log. The sandstone body is twice as thick in the BLA18-2 log compared to the -4 log. This is due to the ellipsoid geometry thinning towards the south-east (Figure 22).

The sandstone itself is interpreted as having been formed by amalgamating distributary channels (FA 8) (see Section 6.1.2). This interpretation is supported by the sandstones apparent high sedimentation rate, indicated by climbing ripples, and large-scale planar cross-stratification. The large-scale planar cross-stratification surfaces have been used to interpret the migration direction of the uppermost of these channels towards the south-west.

Interval 3 (21 – 54 m)

Description: This interval consists of heterolithic bedding, shale, coal shale, palaeosol and scree-covered slope between the two sandstones. This section of the outcrop is more sand-dominated in the lower part, below the coal and palaeosol, at the adjacent ridge to the northwest. The shale in this section has a darker grey colour than the shale found in Interval 1. The outcropping shale in the lower half (facies A, B, E, M and N).

Interpretation: The interpretation of this interval has a significant degree of uncertainty due to large parts of it being scree-covered. This scree-covered slope has been interpreted as shale deposited in an interdistributary or delta plain setting (DE 4). The dark grey colour of the sediment may be the result of a high organic content, preserved due to poor water circulation. The colour and associated palaeosol layer support the interpretation of this interval representing a marginal marine to delta plain depositional setting.

Interval 4 (54 – 89 m)

Description: This interval consists of coarsening-upwards sandstone units, up to nine meters thick, made of fine- to medium-grained sand. All the sandstones display large-scale cross-stratification as the most common sedimentary structure. Other structures include mud draping, mud clasts, plane parallel stratification and hummocky cross-stratification. There are also occasional bioturbation and marine trace fossils. Sections of mudstone with coal and coal-shale beds topped with palaeosols were found between the sandstones (facies A, M and N).

At 76 meters in the log, there is a 2.8-meter-thick sandstone package (Figure 26.A). The package is divided into three distinct beds. The lowermost bed contains large-scale hummocky cross-stratification, small siderite nodules and mud clasts at the base.

The middle bed is made of fine-grained sand and has hummocky cross-stratification at the base, however, higher in the bed heavy bioturbation overprint these structures. Trace fossils recognised includes *Skolithos, Arenicolites* and multiple unknown burrows. The unknown burrows can be described as spherical hollows in the rock connected with a vertical pipe underneath (Figure 26.B).

The uppermost bed also consists of fine-grained sand, however, the only structure observed in this bed are large-scale trough cross-stratification. All the bioturbation and burrows, seen in the underlying bed, stops at the base of this bed. This surface has been interpreted as representing a drowning event.

Interpretation: Multiple coals, coal-shale beds and in-situ up right fossilised large tree trunks found at this level in the stratigraphy can represent prolonged periods of non-deposition or abandonment surfaces (Enga 2015). These levels are interpreted as delta plains (DE 4) due to the time of non-deposition needed for tree trunks of up to 0.8 meters in diameter to grow. The sandstones in this interval have been interpreted to represent a barrier bar (FA 7) and distributary channel (FA 8) deposits due to their large-scale cross-bedding and erosional surfaces.

<u>Interval 5 (89 – 108 m)</u>

Description: This interval consists of a thick sequence of mudstone with two fine-grained sandstone benches protruding. The shale in this interval has a lighter grey colour than the shale in Interval 3 and have almost no scree-cover. The two sandstone benches are less than 0.5 meters thick and contain cone-in-cone structures, *Diplocraterion* burrows and tabular cross-stratification (facies A, G and K).

Interpretation: Diplocraterion burrows are made up of vertical U-shaped tunnels with spreite; it is commonly associated with high energy environments (Hampson and Howell 2005). *Diplocraterion* have also been used to indicate deposition in brackish-water conditions (Ichaso and Dalrymple 2009). The two sandstone benches are therefore interpreted to reflect wash-over fans or a small channel on a mud-dominated tidal flat (FA 10).

Interval 6 (108 – 130 m)

Description: This interval consists of three fine-grained sandstones separated by thin sections of clay. The two lower sandstones are up to 3.6 meters thick and dominated by trough cross-bedding and current ripples (facies L and F). Mud drapes, plant fragments and heavy bioturbation are also found.

Between the two lower sandstones and the uppermost, there are a four-meter thick section of heterolithic bedding, two thin coal shale beds and a thin palaeosol bed (facies (B, M and N).

The uppermost sandstone is ca 10 meters thick, fine-grained and is displaying trough cross-stratification, planar lamination and two horizons of large concretions (facies L, H and G). The sandstone body is laterally extensive and can be walked out for more than 500 meters along the steep mountainside at the top of Blanknuten. It can be correlated to both BLA18-2 and the 22b Blanknuten log (Knarud 1980).

Interpretation: This interval has been interpreted to represent deposition in a marginal marine (DE 3) to delta plain environment (DE 4). The uppermost sandstone is interpreted as amalgamated distributary channel deposits (FA 8) due to the lateral extent, and high content of organic fragments and planar/trough cross-bedding.

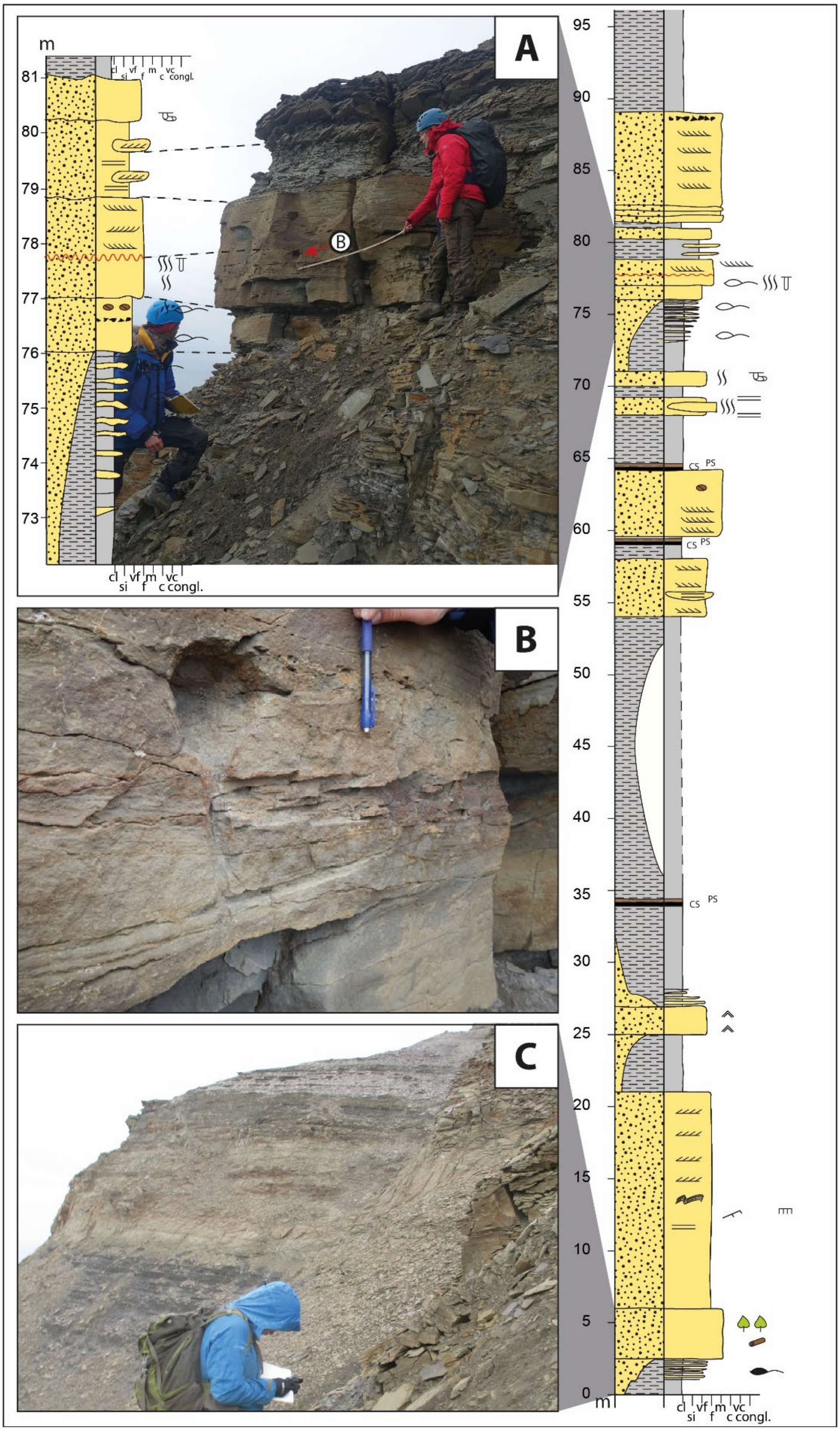


Figure 26. Log correlation for the BLA18-4 log. A. Close-up of the interpreted drowning surface at 78 meters in the log. The location of the burrow from (B) is marked with a red arrow. B. Golf ball sized trace fossil shaped like a bowl with a pipe under it. C. The base of the lowermost sandstone in the De Geerdalen Formation seen in the next ridge over from the logged ridge in BLA18-4.

6.2 Drivdalsryggen

Drivdalsryggen is a 453 meter high mountain directly to the east of Blanknuten (Figure 21). It features a 1.5-kilometre wide slope toward Diskobukta exposing the Botneheia-, Tschermakfjellet- and De Geerdalen formations (Figure 27). Six logs were collected from the south-facing slope and one from the north-eastern slope on the other side of the mountain. Four days were spent conducting observations at Drivdalsryggen. Our field party stayed on land in the trapper cabin next to Blanknuten and reached Drivdalsryggen on foot.

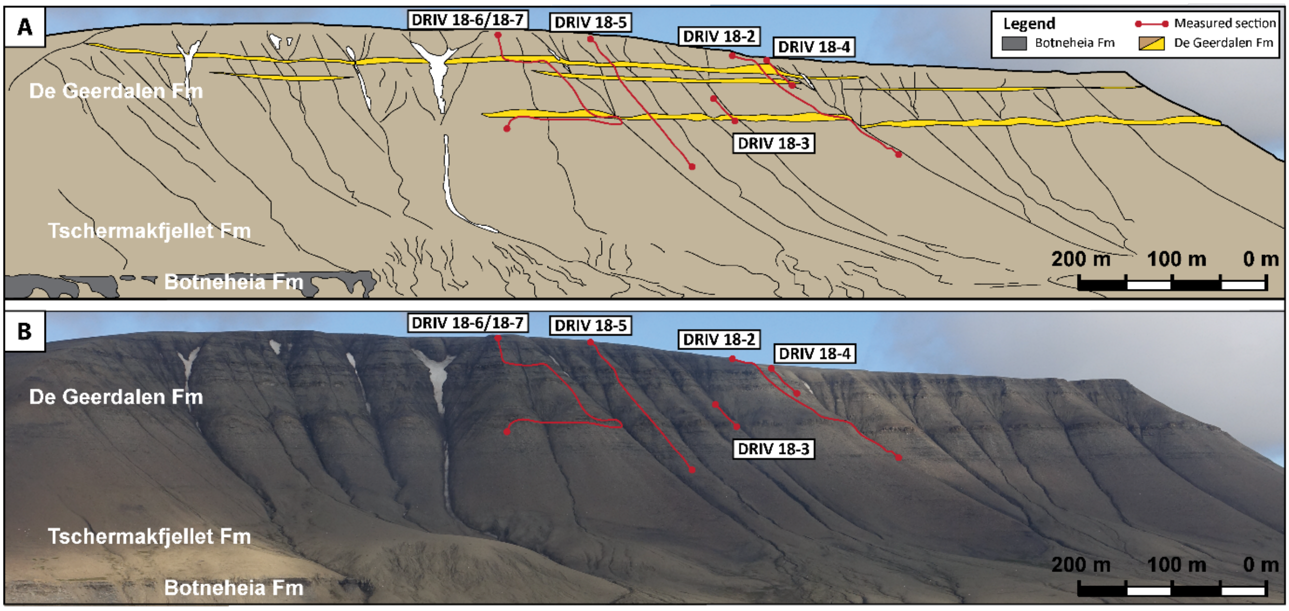


Figure 27. Overview of the south-facing slope of Drivdalsryggen with log traces marked. A. Geological sketch of the mountainside. Yellow areas mark major sandstone bodies within the De Geerdalen Formation. B. Corresponding overview photo of the mountainside.

6.2.1 DRIV18-1

The DRIV18-1 log was collected on a north-eastern slope of Drivdalsryggen towards Drivdalen (Figure 21). This side of the mountain has a gentler inclination of the slopes than the south-facing side. The slopes are covered in mud, dirt and scree with the occasional in-situ sandstone bench. Fourteen sandstone benches were studied in 114 meters of log. None of the sandstones is thicker than two meters. They generally exhibit heavy carbonate cement. The benches are also only outcropping along ridges, so lateral observations were not possible due to scree- and dirt-cover. Only one horizon has been interpreted to be useful for correlation to the other side of the mountain. It contained large (>0.5m) amalgamated ball-shaped structures, interpreted to be concretions (see Section 5.7). Thus, the DRIV18-1 log has not been studied further in this thesis.

6.2.2 DRIV18-2

The DRIV18-2 log (Appendix B.4) was recorded along the widest ridge in the centre of the south-facing slope of Drivdalsryggen (Figure 27). It makes up 188 meters of logged section in a 1:100 scale from the base of the Tschermakfjellet Formation to the top of the cliff where the De Geerdalen Formation is eroded. Along the log trace, two more detailed logs were logged in a 1:20 scale at two thick sandstone units. These more detailed logs are DRIV18-3 and DRIV18-4.

Interval 1 (0 – 65 m)

Description: This interval was started in the upper part of the Botneheia Formation in order to record the thickness of the Tschermakfjellet Formation at this location. The Tschermakfjellet Formation found between the Botneheia and De Geerdalen formations is largely scree-covered (Figure 28.D). One thin (<80 cm) bed of orange, carbonate-cemented, very fine-grained sandstone protrude from the scree surfaces. This sandstone bed at 51 meters in the log has cone-in-cone structures at the base and top, and are visible in the next ridge over in both directions. Significantly higher concentrations of fractured siderite concretion were found in the scree at two levels in the interval. Siderite concretion horizons have been inferred at these levels.

Interpretation: The lowermost five meters of this interval was interpreted as the Botneheia Formation, due to the black, cliff-forming, carbonate-cemented, paper shale in the first five meters of the interval (FA 1). The rest of this interval is interpreted to represent shales of the Tschermakfjellet Formation, making this formation 60 meters thick in this location (DE 2).

Interval 2 (65 – 100 m)

Description: This interval consists of grey shale (facies A), heterolithic lamination (facies B) and some (>1.5 m) sandstone benches. The lowermost sandstone bench contains flaser bedding and hummocky cross-stratification (facies B and C) (Figure 28.C). This bench is the thickest sandstone in the interval at 1.3 meters. The grain size of these beds is from silt to fine-grained sand, and the lowermost contacts are erosive. Wave ripples (facies E), current ripples (facies F) and hummocky/swaley cross-bedding are found in these sandstones. They are laterally extensive and can be seen in the next ridges. The entire interval is overall not fining nor coarsening upwards.

Interpretation: The lowermost, 1.3-meter thick sandstone bench in this interval is interpreted as the first prominent sandstone above the Botneheia Formation and thus the base of the De Geerdalen Formation. The entire interval is interpreted to be deposited in an offshore transition to lower shoreface setting (FA 3 and 4). The sandstone benches with ripples and hummocky cross-stratification are interpreted as storm-generated beds. The mudstone intervals have been deposited by settling from suspension under fair weather conditions, similar to mudstones described by Eide et al. (2015).

<u>Interval 3 (100 – 114 m)</u>

Description: This interval consists of heterolithic bedding, with wave ripples, coarsening upwards into the first cliff-forming sandstone in the DRIV18-2 log. The sandstone body in this interval corresponds with the sandstone logged in the DRIV18-3 log. The sandstone consists of two separate beds. The lower is coarsening upwards with slump deposits containing a high percentage of mud at the top. The upper 6-meter thick bed of this sandstone have an erosive contact to the underlying slump deposits and consists of medium-grained sand. Sedimentary structures seen in the sand include current ripples, wave ripples with mud draping, plane parallel bedding and low angle cross-stratification. The sandstone is capped by trough cross-bedding.

Interpretation: This sandstone interval is interpreted as delta front deposits (DE 3). The upper 6-meter thick bed are interpreted as distributary mouth bar deposits (FA 6). This interpretation is based on observations of rapid lateral change in facies within a laterally extensive sandstone body when comparing the DRIV18-2 to adjacent logs.

<u>Interval 4 (114 – 149 m)</u>

Description: This interval consists dominantly of scree-covered slope. There is a siderite concretion horizon at the base of the interval. Within the interval, two ca 20-centimetre-thick coal beds were observed along with one fine-grained sandstone bench. The only observed sedimentary structures in this interval are current ripples in this bench. Both are hard to trace laterally and disappear below the scree-cover in a few meters. There is a siderite concretion horizon at the base of the interval.

Interpretation: This interval is interpreted as lower delta plain deposits (DE 4). The one sandstone bench with current ripples may be crevasse splay deposits. The scree-covered slope may be hiding palaeosols and floodplain fines. The lowermost 11 meters of this interval has been correlated to the top 11 meters of the DRIV18-3 log. No fine-grained sandstone benches were present on the ridge where the latter log was logged, but a palaeosol layer was found overlying the lowermost coal layer. These rapid lateral changes support the interpretation of floodplain deposits.

<u>Interval 5 (149 – 166 m)</u>

Description: This interval starts at the base of a 6 meter thick, medium-grained sandstone unit, containing plane parallel bedding (facies H), carbonate-rich sandstone (facies G), current ripples (facies F), wave ripples (E), tabular cross-bedding (facies K), trough cross-bedding (facies L), sparse bioturbation and a lot of plant fragments. A coal and palaeosol layer are capping the sandstone (facies M and N). This unit is also the base of the more detailed DRIV18-4 log (Figure 29). Above this sandstone unit, the interval consists of sandy mudrock with an increasing amount of sand. This sandy mudrock are coarsening upwards into a medium-grained sandstone unit with plant fragments, plane parallel bedding, and a siderite concretion horizon. The sandstone unit is topped by mud flake conglomerate and planar cross-bedding. The uppermost sandstone bed of this interval, overlaying the large-scale planar cross-bedding, are showing soft-sediment deformation (facies D).

Interpretation: The lower sandstone unit of this interval has been interpreted as distributary channel deposits (FA 8). This interpretation is supported by the presence of large-scale tabular and trough cross-bedding, current ripples, organic content and possible erosive base, which is covered by scree. Capping of the sandstone by coal and palaeosol are also good indicators for this interpretation. Similar deposits have been described and interpreted as distributary channels in Canada by Young and Reinson (1975). The upper sandstone of this interval is interpreted as barrier bar deposits (FA 7). This interpretation is supported by the upwards coarsening nature of the sandstone, the soft sediment deformation, large-scale cross-bedding and current ripples. Interpretations for this interval is combined with observations in DRIV18-4, which is more detailed.

<u>Interval 6 (166 – 187 m)</u>

Description: The lower boundary of this interval is an upwards coarsening sequence from heterolithic bedding into a seven-meter-thick very fine-grained sandstone. This sandstone has swaley cross-stratification (facies C), wave ripples (facies E), mud drapes and *Skolithos* burrows. Above this, there is a 14-meter thick sequence with four fine- to medium-grained sandstone benches alternating with mudstone. The sandstone benches are between 0.4 and 2.4 meters thick and heavily bioturbated. Other features found in these sandstones include low angle cross-stratification (facies J), wave ripples (facies E), cone-in-cone structures, siderite concretions and burrows. *Macaronicnus* occur occasionally, while *Diplocraterion* were observed to be abundant.

Interpretation: This entire interval has been interpreted as upper shoreface deposits due to the presence of swaley cross-stratification, wave ripples, normal grading and reworking of the sediments (FA 5). The lowermost very fine-grained sandstone is interpreted to have been deposited deeper than the overlying 14-meter thick package of bioturbated sandstones. These sandstones are interpreted as being deposited in high energy, shallow shoreface conditions, as indicated by low angle cross-bedding, abundant *Diplocraterion*, wave ripples and the coarser grain size.

6.2.3 DRIV18-3

The DRIV18-3 log (Appendix B.5) was logged directly to the west of the DRIV18-2 log, less than 100 meters offset from the DRIV18-2 log trace (Figure 27). The base of the DRIV18-3 corresponds to the base of the first prominent cliff-forming sandstone in the DRIV18-2 log, at 105 meters (Figure 28). The DRIV18-3 was logged in a 1:20 scale to more detailed capture the variations within this sandstone body.

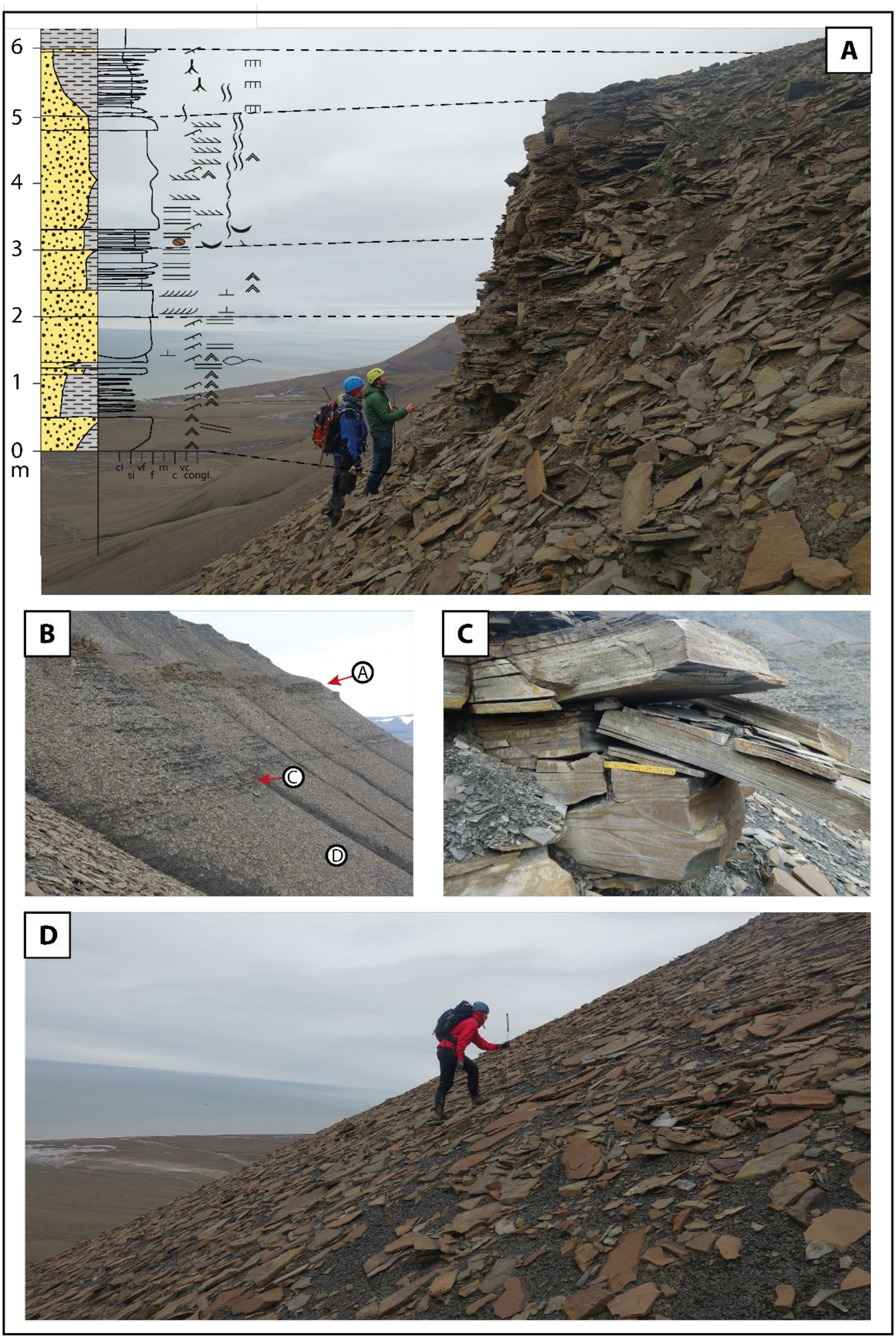


Figure 28. A. Log correlation of the sandstone cliff in the DRIV18-3 log. B. Overview photo of the lower part of the DRIV18-2 log marking the stratigraphic height of (A), (C) and (D). C. The first prominent sandstone logged in the DRIV18-2 log, interpreted as the base of the De Geerdalen Formation. D. The scree-covered lower part of the DRIV18-2 log. Typical for the Tschermakfjellet Formation on Edgeøya.

Interval 1 (0 – 3.3 m)

Description: This interval consists of fine-grained sandstone beds (ca 1 m thick) alternating with wavy and flaser bedding (facies B). Sedimentary structures found within the sandstone units go from being dominated by wave ripples and low angle cross-bedding (facies E and J) in the lower part of the sandstone to current ripples and hummocky cross-stratification (facies F and C) in the middle part. The top part of the interval is dominated by trough cross-bedding and plane parallel lamination (facies L and H). There were not found any traces of bioturbation in Interval 1 (Figure 29).

Interpretation: This lowermost interval of the DRIV18-3 log has been interpreted as upper shoreface deposits due to the presence of both hummocky cross-bedding and low angle cross-stratification (FA 5). The lack of bioturbation may be an indication of unfavourable living conditions at the time of deposition, possibly due to a rapid sedimentation rate.

Interval 2 (3.3 – 6 m)

Description: This interval has an upward increasing amount of bioturbation and is capped by two layers with root traces. The middle 1.9-meter thick sandstone of this interval is dominated by tabular cross-bedding.

Interpretation: This fining upwards interval is interpreted to reflect delta front to upper shoreface sands, due to the laterally rapid change in sedimentary structures found within a laterally extensive sandstone body (FA 5).

The presence of root traces in this sandstone body indicate that the delta front sand was occasionally exposed and colonised by plants. Although rare, similar root and plant remains have been described by Chakraborty and Sarkar (2005) and Dam et al. (1995).

Interval 3 (6 – 17 m)

Description: This interval consists of mudstone and scree-cover with two thin (<20 cm thick) coal layers (facies M). The interval is capped by two coal layers and a layer of a brown and yellow mud (facies N). Coal fragments are found in the scree throughout the scree-covered section of this interval.

Interpretation: This top interval of the DRIV18-3 log are interpreted as lower delta plain deposits and floodplain fines (FA 9). There may be hiding additional palaeosol or coal layers underneath the scree-cover in this interval.

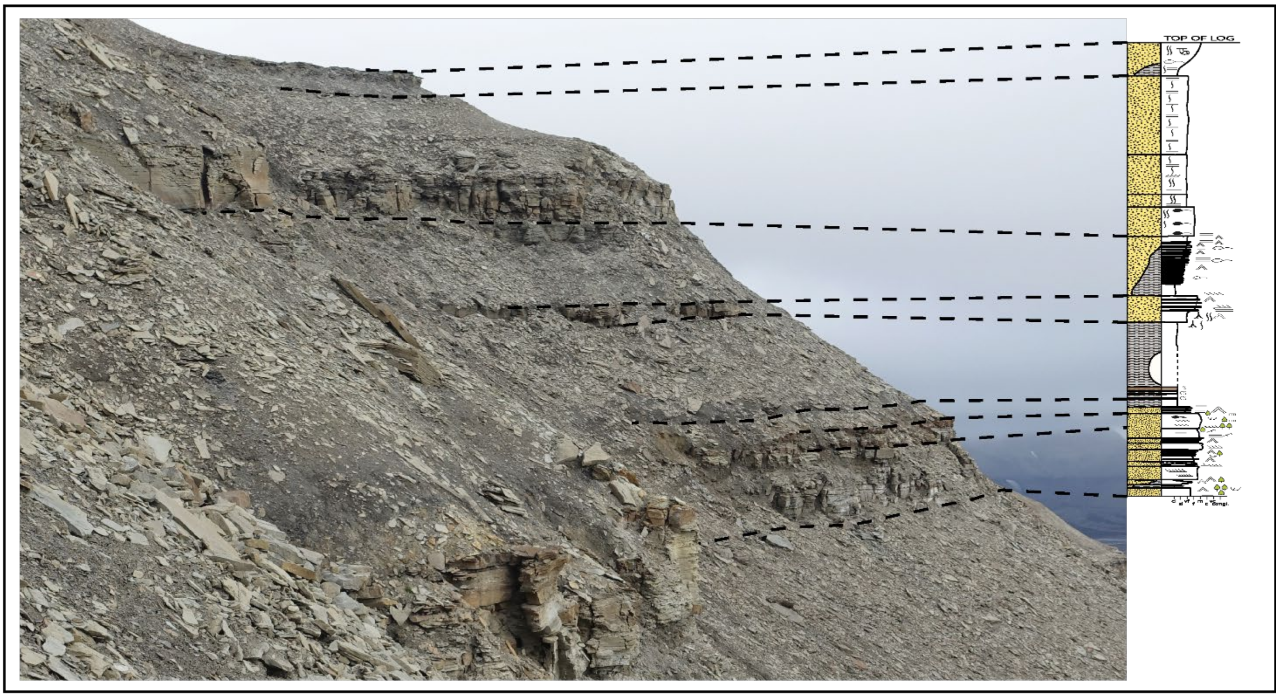


Figure 29. Log correlation of the DRIV18-4 log. The picture is taken from the DRIV18-5 log trace.

6.2.4 DRIV18-4

This log (Appendix B.6) was logged along the same broad ridge as the DRIV18-2 log, only 70 meters to the east of the DRIV18-2 log trace. The base of the DRIV18-4 corresponds to the base of the sandstone at 149 meters in the DRIV18-2 log. The DRIV18-4 log was logged in a detailed scale of 1:20, with the intention of recording more detailed observations of sedimentary structures. In addition, it revealed the rapid lateral changes that can be found within these sandstone bodies of the De Geerdalen Formation. These rapid lateral changes are apparent when comparing the DRIV18-2 to the DRIV18-3 and -4 (Figure 30).

<u>Interval 1 (0 – 5.3 m)</u>

Description: The more detailed DRIV18-4 have no concretions or bioturbation in the lowermost sandstone, which was found in the corresponding stratigraphic level in DRIV18-2. No observations of mud drapes, coal drapes, or hummocky cross-stratification were made in this sandstone. This contrasts to observations in the

DRIV18-2 log, 70 meters to the east. Large- and small-scale cross-stratification (facies E, F, K and L), organic content and heavy cementation frequently occur in the two logged sections.

Interpretation: This lower sandstone unit is, similar to the corresponding unit in the DRIV18-2 log, interpreted as distributary channel deposits (FA 8).

<u>Interval 2 (6.3 – 9 m)</u>

Description: This interval consists of mudstone, scree-covered slope, two coal layers and a palaeosol layer (facies A, M and N).

Interpretation: This 3.7-meter-thick interval is interpreted as fines deposited in a lower delta plain to an interdistributary setting (DE 4).

<u>Interval 3 (9 – 16 m)</u>

Description: This interval consists of heterolithic bedding with two upwards coarsening sandstones (< 2 meters thick). The lowermost 1.6-meter thick unit is grading from very fine- to fine-grained sand and contain root traces and moderate bioturbation. Sedimentary structures are wave ripples and planar cross-bedding (facies E and K).

The uppermost unit in this interval is 3.5 meters of sediment coarsening from shale to fine-grained sand. The dominant sedimentary structures in this interval are wave ripples and hummocky cross-stratification (facies C and E).

Interpretation: The lower sandstone in this interval is interpreted as barrier bar deposits (FA 7). This interpretation is partly supported by the soft sediment deformation found in the corresponding stratigraphic interval of the DRIV18-2 log. The top of this sandstone is interpreted as a flooding surface before the next coarsening upwards unit was deposited in an upper or lower shoreface environment (FA 4 and 5).

<u>Interval 4 (16 – 26 m)</u>

Description: Due to time constraints, only minor observations were made of this interval. The corresponding interval in the DRIV18-2 log is used in the interpretation of this interval.

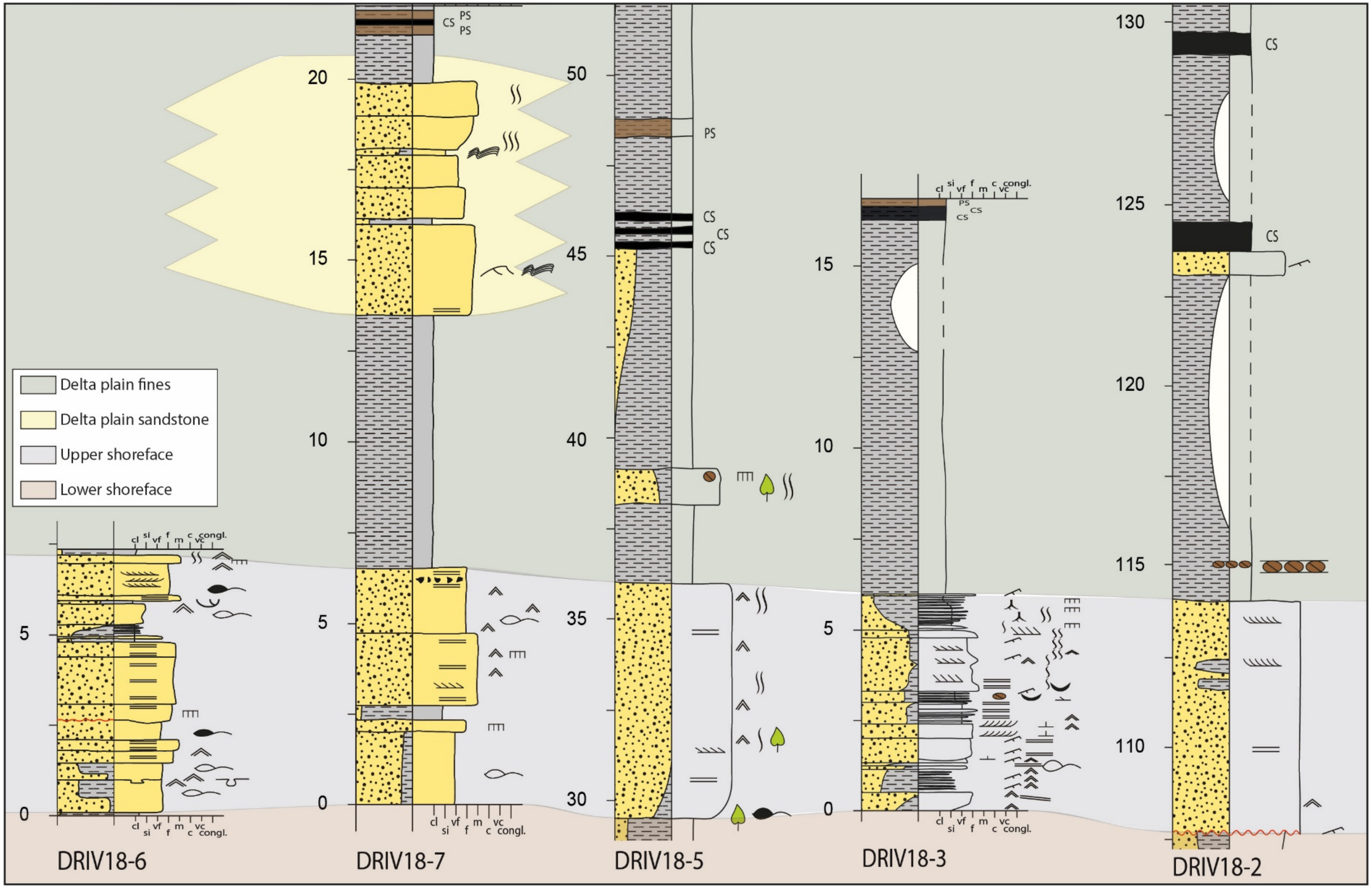


Figure 30. Log correlation of the five logs going through the lowermost sandstone body on Drivdalsryggen. The location of log traces can be seen in Figure 27.

6.2.5 DRIV18-5

The DRIV18-5 log (Appendix B.7) was logged along the westernmost of three narrow ridges in the centre of the mountainside (Figure 27). The log was logged in a 1:100 scale to capture the entire outcropping section on Drivdalsryggen. The log was started below the first prominent (> 1 m) sandstone in the section and not at the top of the Botneheia Formation, as in DRIV18-2. The top of the Botneheia Formation was recorded at 73 meters below the base of this log which makes the Tschermakfjellet Formation 75 meters thick at this location.

<u>Interval 1 (0 – 29 m)</u>

Description: This interval consists of mudrocks, heterolithic bedding (facies A and B) and thin beds (< 1.3 m) of silt to very fine-grained sand. The dominant sedimentary structures in these beds are small-scale hummocky cross-stratification, wave ripples (facies C and E) and minor bioturbation and load cast structures (facies D).

Interpretation: The lowermost 1.1 meters thick very fine-grained sandstone is interpreted as the base of the De Geerdalen Formation. This bed, as well as the other sandstone benches in this interval, are interpreted as storm beds, deposited in a prodelta to offshore transition environment (FA 2 and 3). This interpretation is supported by the occurrence of hummocky cross-bedding in all of these benches.

<u>Interval 2 (29 – 52 m)</u>

Description: This second interval of the DRIV18-5 log starts with a 5.6-meter-thick, bioturbated, medium-grained sandstone. This bed contains large-scale hummocky cross-bedding at the base, plant fragments, planar cross-bedding and planar parallel stratification (facies C, K and H) higher up. Further up in the interval overlaying this sandstone there is a 17-meter thick section dominated by mudstones with a 70 cm thick, moderately bioturbated, fine-grained sandstone protruding from the mud. There are also thin (< 20 cm) layers of coal and palaeosols in this section. Although this section contains fines along this log trace, there are sandstones with short lateral extensions outcropping at this stratigraphic level in the ridges to the east and west (Figure 31). A 6.5 meters thick, sandstone on the ridge to the west of the DRIV18-5 log trace was recorded as a part of the DRIV18-7 log (Figure 31.A).

Interpretation: This interval is interpreted as a prograding deltaic environment going from lower shoreface deposits to the lower delta plain. This interpretation is supported by the presence of hummocky cross-stratified, medium-grained sand at the base of the interval and the more proximal subaerial muds and fines towards the top of the interval. The laterally restricted sandstones in this lower delta plain setting have been interpreted as wash-over fans (DE 4).

<u>Interval 3 (52 – 81 m)</u>

Description: The transition from the underlying interval is based on a colour change in the shale, going from light grey to a darker colour. The interval also starts with a transition from mud to fine-grained planar parallel laminated sand. This sandstone is 6 meters thick and contains heavily cemented lenses. The sandstone is capped by a thin layer of palaeosol and coal. The interval consists of three coarsening upwards sandstone beds. The two uppermost beds of which are ca 2 meters thick, made of medium-grained sand and moderately to intensely bioturbated. The middle of these three sandstones is reworked by bioturbation to the degree that no other sedimentary structures are visible. The uppermost have less severe bioturbation and planar cross-bedding towards the top. Mud drapes and ripple lamination were observed in this sandstone bench. Large-scale hummocky cross-stratification are present in the few meters of the heterolithic bedding coarsening upwards into this uppermost sandstone of the interval.

Interpretation: The lower part of this interval, through the 6-meter thick sandstone and the capping coal and palaeosol, has been interpreted to have been deposited in an interdistributary area (FA 10). This interpretation is based on the colour change in the deposited muds that may have been caused by changes from a marine to a lagoonal or an interdistributary bay setting. The two lower sandstones are interpreted as delta lobe progradations, while the uppermost unit is interpreted to have been formed as a barrier bar, due to its heterolithic base with large-scale hummocky cross-stratification.

<u>Interval 4 (81 – 112 m)</u>

Description: The lower part of this interval consists of fines covered by scree with two thin (ca 50 cm thick) medium-grained sandstone benches. The uppermost of the two contain mud flake conglomerate and bioturbation. Further up in the interval, there are three sandstones. They are thicker (> 2 m) and still separated by segments of shale. These shale segments are thicker than in the corresponding height further to the east on Drivdalsryggen. The lowermost of the sandstones exhibit low angle cross-bedding, intense bioturbation, *Skolithos* burrows and small plant fragments. The middle sandstone has large-scale trough cross-bedding at the base and planar parallel stratification at the top. The uppermost, upwards coarsening sandstone have hummocky cross-bedding both at the base and top.

Interpretation: This interval is interpreted to have been deposited in a lower to upper shoreface environment (FA 4 and 5). The low angle cross-stratified, 3-meter thick sandstone in the middle is interpreted as beach deposits, due to the high energy burrows and sedimentary structures. The uppermost sandstone in this log is interpreted to have been deposited deeper on the shoreface due to its gradual, upwards coarsening, lower boundary and heterolithic bedding (DE 2).

6.2.6 DRIV18-6

The DRIV18-6 log (Appendix B.8) was logged on the same day as the -7 log on a broad ridge to the west of DRIV18-5 to get a more detailed look into lateral variations within sandstones on this ridge. The DRIV18-6 log was logged in a 1:20 scale and starts at the base of a sandstone corresponding to the 5.6 meters thick, bioturbated, medium-grained sandstone in interval 2 of DRIV18-5 (Figure 30).

Interval 1 (0 – 7.4 m)

Description: At this location, the sandstone is 7.2 meters thick and are built up of very fine- to fine-grained sand with the occasional (ca 20 cm thick) bed of medium sand. This is the thickest thickness of this sandstone recorded at Drivdalsryggen (Figure 30). The sandstone is dominated by planar parallel stratification and hummocky cross-stratification (facies H and C) throughout, except for the upper 80 centimetres which are dominated by trough cross-bedding (facies L). Other observed structures are load casts at 1 meter and cut-and-fill structures at 1.7 meters in the log. Several red, heavily cemented beds are observed in the log. These thin (< one meter thick) beds are pinching and less than 15 meters wide. Wave ripples and moderate bioturbation cap the sandstone.

Interpretation: The logged sandstone unit is interpreted as the upper shoreface to barrier island deposits (FA 5 and 7).

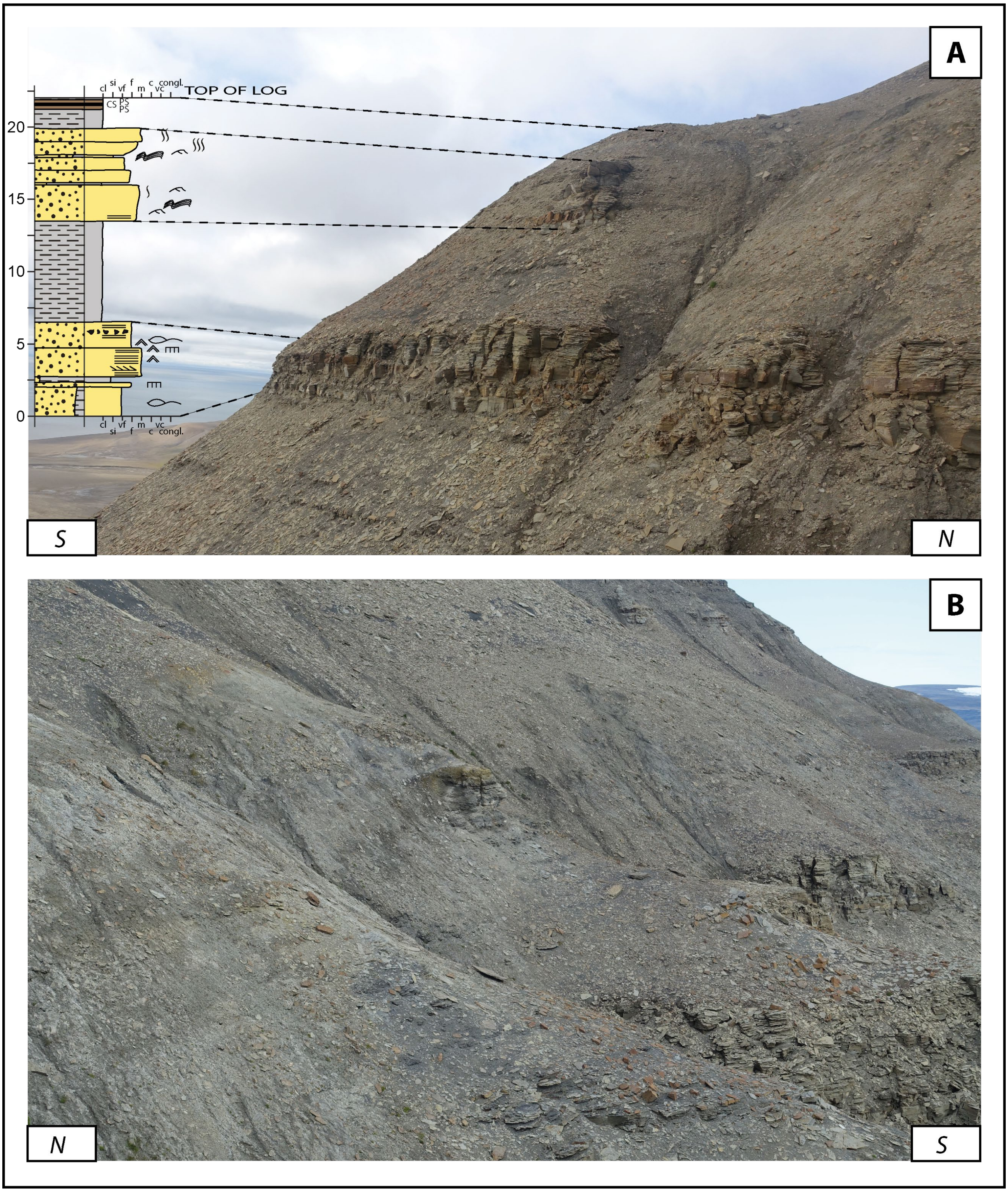


Figure 31. Two laterally restricted sandstones in the same stratigraphic elevation on Drivdalsryggen. A. Log correlation of the DRIV18-7 log. The uppermost sandstone is only outcropping in a 7 meter vide section. B. A corresponding, similarly lateral restricted sandstone two small ridges to the east of the one logged in DRIV18-7.

6.2.7 DRIV18-7

The DRIV18-7 log (Appendix B.9) was logged on the eastern side of the same broad ridge as DRIV18-6 to record lateral changes in the sandstone bodies found on this broad ridge. The log was recorded partly lateral along the lowermost sandstone cliff at a scale of 1:50. The top of the DRIV18-7 log is 90 meters to the east of the top of the DRIV18-6 log.

<u>Interval 1 (0 – 6.4 m)</u>

Description: This lowermost interval of the DRIV18-7 log consists of the lateral extensive sandstone body recorded in four other logs at Drivdalsryggen (Figure 30). The log and the interval start at the scree-covered base of the sandstone body, making it 6.4 meters thick at this location. The sandstone body has a very fine-grained, heterolithic section at the base. This section is dominated by hummocky cross-stratification (facies B and C). Above this section, there are a 30 cm thick hard, calcite-cemented bed of fine-grained sand and a 40 cm thick bed of silt. The middle 2 meter of the sandstone body consists of fine- to medium-grained sand and exhibit wave ripples, planar parallel bedding and cross-bedding (facies E, H and K). The upper 1.7 meters of the body have wave ripples, hummocky cross-stratification, planar parallel bedding and mud flake conglomerate.

Interpretation: This lower sandstone unit is interpreted to represent an upper shoreface to barrier island environment (FA 5 and 7).

<u>Interval 2 (6.4 – 13.5 m)</u>

Description: The middle interval of this log consists of seven meters of mud, partly scree-covered. No sedimentary structures were observed in the mud.

Interpretation: This interval is interpreted to have been deposited in a lower delta plain (DE 4).

<u>Interval 3 (13.5 – 22 m)</u>

Description: Third interval of this log consists of a 6.5-meter thick sandstone with one meter of clay, palaeosol and coal on the top. The grain size of the sandstone varies from very fine- to medium grained sand. The lower part consists of planar parallel bedding (facies H). The middle is dominated by current ripples, some of which are climbing (facies F). The top part of the sandstone is moderate to intensely bioturbated so that no other sedimentary features are preserved. The sandstone body is only outcropping in a 7 meter wide part of the cliff. The slope to either side is covered by scree (Figure 31). A similar lateral restricted sandstone is present two ridges to the east. The scree-covered slopes between these sandstones are interpreted to be composed of mud and fines.

Interpretation: This stratigraphic interval with isolated sandstones with fins between is interpreted as wash-over fans in a lower delta plain setting. This interpretation is supported by the occurrence of current ripples, climbing ripples and bioturbation on the top of sandstone beds. This may be a lagoonal setting.

6.3 Muen

Muen is a mountain 18 km to the south of Blanknuten, at the southern end of Diskobukta. It is famous for the Muen-plateau (Krajewski 2008), consisting of excellent outcrops, with almost no scree-cover, of the Botneheia and Tschermakfjellet formations. There are also outcrops of the lower parts of the De Geerdalen Formation. Seven logs were recorded at Muen. From the north-western, south-western and eastern side of the mountain (Figure 21). Our field party stayed on board the sailboat and reached the study sites by zodiacs and on foot.

6.3.1 MUE18-1 and -2

The MUE18-1 and -2 logs were recorded above the Muen-plateau, on the eastern side of the large gully. These two logs only contain rocks assigned to the Tschermakfjellet Formation and are therefore not emphasised in this thesis.

6.3.2 MUE18-3 and -4

The MUE18-3 and -4 logs were recorded at the eastern side of the Muen mountain, towards Mudalen (Figure 21). These logs were recorded to gain a 3D understanding of the sandstone bodies of the De Geerdalen Formation at Muen. Only the lower ca 30 meters of the formation are exposed on this side of the mountain, and no conclusive correlation surfaces have been found to the western side of Muen. These two logs have therefore not been emphasised in this thesis.

6.3.3 MUE18-5 and -6

The MUE18-5 and -6 logs (Appendix B.10 and B.11) were recorded along the south-western ridge, next to the cliff facing the sea at Muen. The two logs are overlapping, giving a continuous cover of the stratigraphy at the Muen mountain (Figure 32). The base of the MUE18-5 log is at the top of the Botneheia Formation. The thickness of the Tschermakfjellet Formation is 84 meters at this side of the mountain. Bidirectional palaeocurrent data were collected, from dominantly wave ripple crests. These measurements show a dominant direction towards the south-east or the north-west.

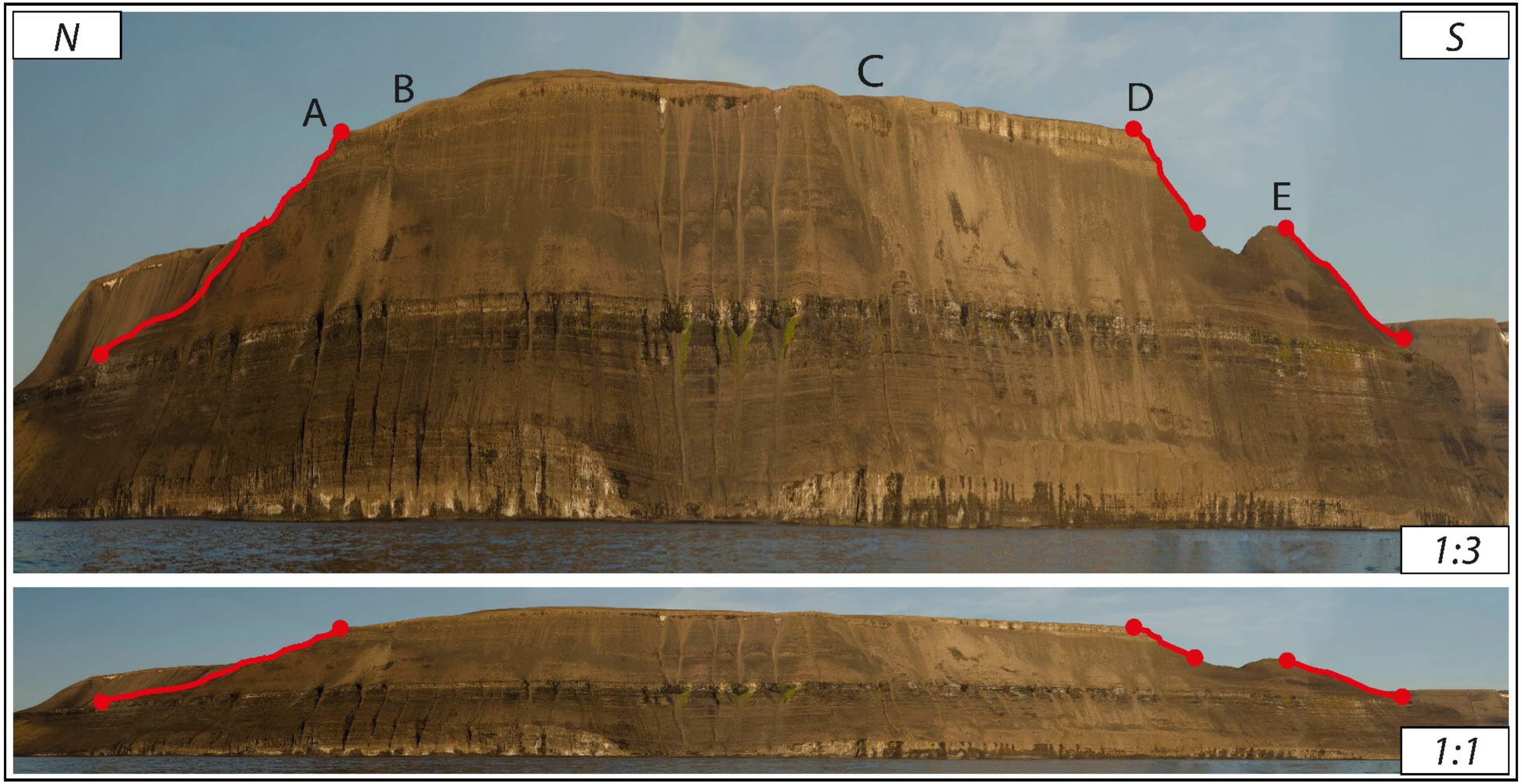


Figure 32. Panorama picture of the Muen mountain. A. Top of the MUE18-7 log. B. The northern downfaulted block. C. The southern downfaulted block. D. Top of the MUE18-6 log. E. Top of the MUE18-5 log.

Interval 1 (0 – 87 m)

Description: The top of the Botneheia Formation forms a ca 100 meters wide plateau at this side of the mountain, similar to the more famous Muen-plateau on the northern side. The log starts at this plateau and reaches the base of the Tschermakfjellet Formation two meters above it. The next 85 meters are black to grey shale, predominantly without scree-cover and in-situ. Within this shale, there are horizons of siderite nodules, up to 0.7-meter-thick sand lenses and thin sheets of very fine-grained sand. At 60 – 72 meters in the log there is a sandier section of the interval, the thickest of the sands are 1.2 meters of rust-red silt to very fine-grained sand. This section may be the reason the mound at the top of MUE18-5 formed (Figure 32). The corresponding sequence at the base of the MUE18-6 log, ca 100 meters to the north, consists of finer sediments.

Interpretation: The lowermost three meters of this log is interpreted as the upper part of the Botneheia Formation (DE 1). The upper 84 meters of the interval is interpreted as prodelta to offshore transition deposits of the Tschermakfjellet Formation with a prograding nature towards the De Geerdalen Formation (FA 2 and 3).

Interval 2 (87 – 99 m)

Description: The base of this interval corresponds to the base of the De Geerdalen Formation and the base of the MUN09 log recorded by Hynne (2010). It starts at the base of an 11 meters thick sandstone body, with an upwards coarsening base grading from shale to heterolithic bedding and fine-grained sand. The base and the top of the sandstone are exhibiting loading structures (facies D). The rest of the sandstone is dominated by wave ripples and planar parallel lamination (facies E and H).

Interpretation: This interval is interpreted as delta front deposits, more specifically of the upper shoreface (DE 3).

Interval 3 (99 – 109 m)

Description: This interval consists of seven meters of shale and heterolithic bedding separating the two sandstone bodies in this log (facies A and B). Sedimentary structures seen in the thin sandstone layers in this interval include moderate bioturbation, wave ripples and current ripples (facies E and F). There is an angular unconformity between Interval 2 and Interval 3 (Figure 33.B). This angular unconformity causes the fines of Interval 3 not to be present 50 meters to the north of the log trace of the MUE18-6 log.

Interpretation: This interval is interpreted as lower shoreface deposits with storm-generated beds (FA 4).

Interval 4 (109 – 118 m)

Description: This uppermost interval consists of one six-meter and one 4.5-meter-thick sandstone, separated by one meter of scree-cover (Figure 33). The lower six-meter-thick grey sandstone have current ripples at the base, planar cross bedding with mud drapes in the middle and trough cross-bedding at the top (facies F, K and L). The top sandstone is heavily fractured and apparently massive.

Interpretation: This interval is interpreted as upper shoreface deposits, more specifically, barrier bars or migrating shallow subaqueous bank deposits (FA 7).

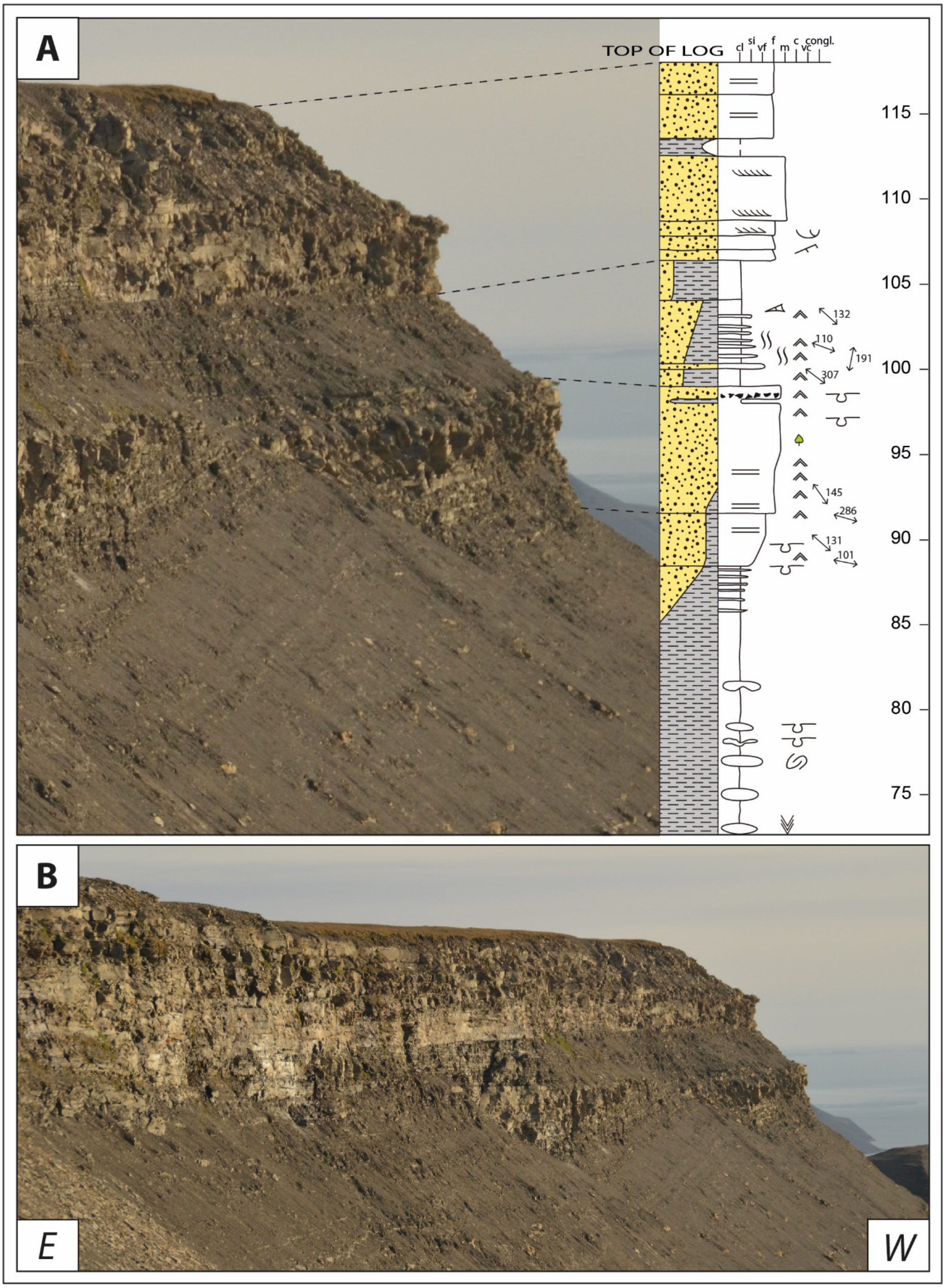


Figure 33. A. Log correlation to a picture of the two sandstone bodies at the top of the MUE18-6 log. B. The same picture as is (A) but including more of the lateral extent of the sandstone bodies to show the unconformity between Interval 3 and Interval 4.

6.3.4 MUE18-7

The MUE18-7 log (Appendix B.12) was recorded along the north-western ridge next to the cliff facing the sea at Muen (Figure 32).

Description: The MUE18-7 starts at the 700-meter-long and 200-meter-wide Muen-plateau formed at the top of the Botneheia Formation. Similar to the MUE18-5 and -6 logs, the -7 log records the entirety of the Tschermakfjellet Formation. The formation is 120 meters thick along this side of the mountain. The De Geerdalen Formation is not outcropping along this ridge, but the base of the formation was found 90 meters onto the plateau on the top of the mountain (Figure 34). These sandstones, assigned to the De Geerdalen Formation, are interpreted as a downfaulted block.

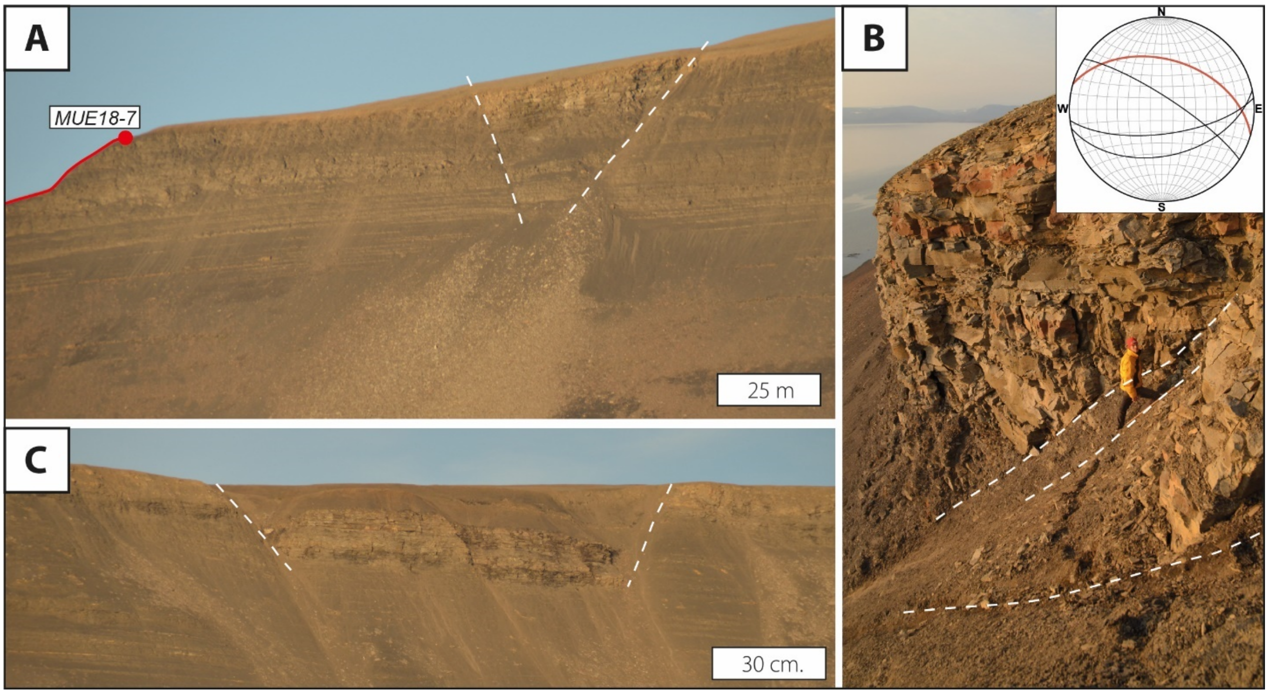


Figure 34. Faults at Muen. A. The northern downfaulted block and the top of the MUE18-7 log trace. B. Close up of the southern side of the northern downfaulted block seen in (A). Geologist for scale. With the orientation of fault plains. The great circle of the main fault plane with 1 – 2 cm thick mud gauge is marked in red. Measurements of shear surfaces with slickensides are marked with black great circles. C. The southern downfaulted block at Muen.

Interpretation: The lower five meters of this log is interpreted as the upper part of the Botneheia Formation based on the carbonate cementation, plateau forming nature of the sediments (DE 1). The rest of the log is interpreted as prodelta to offshore transition deposits of the Tschermakfjellet Formation (FA 2 and 3).

6.3.5 Faults at Muen

The southern side of the northern fault block on Muen is exposed and was examined in more detail. It consists of a main fault plane with 1 – 2 cm of mud gouge and a surrounding fault zone. The fault zone in the hanging wall consists of folding of the sandstone host rock towards the main fault plane. In the footwall, the fault zone is ca 1.5 meters wide and heavily affected by faults with slickensides (Figure 34). These faults are interpreted as shear surfaces.

All the studied faults on Muen appear planar, but the top of the underlying Botneheia Formation is horizontal and not affected by the faults (Figures 32 and 34).

The MUE18-7 log contains two zones where silty mudrocks assigned to the Tschermakfjellet Formation lose the lamination of the surrounding rock and exhibit a grey to orange and rust-red colour. These two zones are interpreted as fault zones (Appendix B.12). The colour changes are likely the effects of chemical reactions with pore fluids due to enhanced permeability along the fault zone. These two zones are marked at 33 and 52 meters in the log.

6.4 Kapp Lee

Stretehamna is a sheltered harbour just to the south of Kapp Lee, beneath the mountain Leehovden, at the north-western corner of Edgeøya. The slope of Leehovden towards Stretehamna has outcrops assigned to the Botneheia, Tschermakfjellet and the De Geerdalen formations. In addition, several dolerite sills and dykes are cross-cutting across the mountainside. One log was collected here. Our field party stayed on board the sailboat and reached the study sites by zodiacs and on foot.

6.4.1 LEE18-1

The LEE18-1 log (Appendix B13) represents 68 meters of log, collected from the interpreted base of the De Geerdalen Formation to the top of the mountain

Leehovden. The log was started 44 meters above the top of the Botneheia Formation, making the Tschermakfjellet Formation 45 meters thick at this location. Palaeocurrent measurements show a western orientation.

Interval 1 (0 – 23 m)

Description: The log starts directly below a one-meter thick bed of very fine-grained sandstone. The lower interval consists of heterolithic bedding with occasional thicker sandstone beds of up to 1.2 meters in thickness. Some of these beds have an undulating variation in thickness, where the sandstones are half the thickness less than 50 meters to the sides. Sedimentary structures in this interval include flute casts, current ripples, planar parallel lamination and wave ripples (facies B, E, F and H).

Interpretation: This interval is interpreted to be offshore transition deposits where gravity-driven currents coming down the slope has formed current ripples and flute casts (FA 3).

Interval 2 (23 – 43 m)

Description: The lower five meters of this interval consists of two (ca three meters wide) slump deformed lenses of fine-grained sandstone (facies A and D). The upper 11 meters of this interval consists of heterolithic bedding with occasional very fine- to fine-grained sandstone beds. Sedimentary structures in this interval include soft sediment deformation, hummocky cross-stratification, current ripples and organic fragments (facies B, C, D and F). The uppermost four-meter-thick sandstone of this interval forms a (ca 10 meters wide) plateau in the slope and contains fossilised leaves and mud clast conglomerate.

Interpretation: This second interval of the LEE18-1 log are interpreted to be deposited as a prograding system slightly shallower on the slope than the underlying interval. This interpretation is supported by a lack of current ripples and the existence of large slump deformed sandstones with shorter lateral extent (DE 2).

Interval 3 (43 – 68 m)

Description: The lower 20 meters of this interval consists of three (1 - 3-meter-wide) slump deformed lenses of very fine-grained sand (facies A and D). At the top of the log there are three thin (< 1 m) beds of very fine- to fine-grained sand. These beds exhibit soft sediment deformation and low-angle cross-bedding.

Interpretation: This interval is interpreted to represent another prograding system from an offshore transition setting to the upper shoreface (FA 3, 4 and 5). This interpretation is supported by the occurrence of low angle cross-bedding at the top and the coarsening upwards base of the sandstones.

6.5 Palibinranten

Palibinranten is a 237 meter high mountain halfway between Kapp Lee and Skrukkefjellet along the northern coast of Edgeøya. The northern mountainside facing Freemansundet, exposes rocks assigned to the Botneheia and Tschermakfjellet formations. The mountain top consists of two peeks made of sandstone, assigned to the De Geerdalen Formation. Both of these capping sandstones were logged. The eastern sandstone is four-meter-thick and consists of very fine- to fine-grained sand. The western sandstone is five meters thick and consists of the same grain size. Palaeocurrent data was collected on Palibinranten, measured from current ripples/forests, groove and flute marks, and wave ripple crests (Figure 35). The logs recorded on Palibinranten have not been emphasised in this thesis.

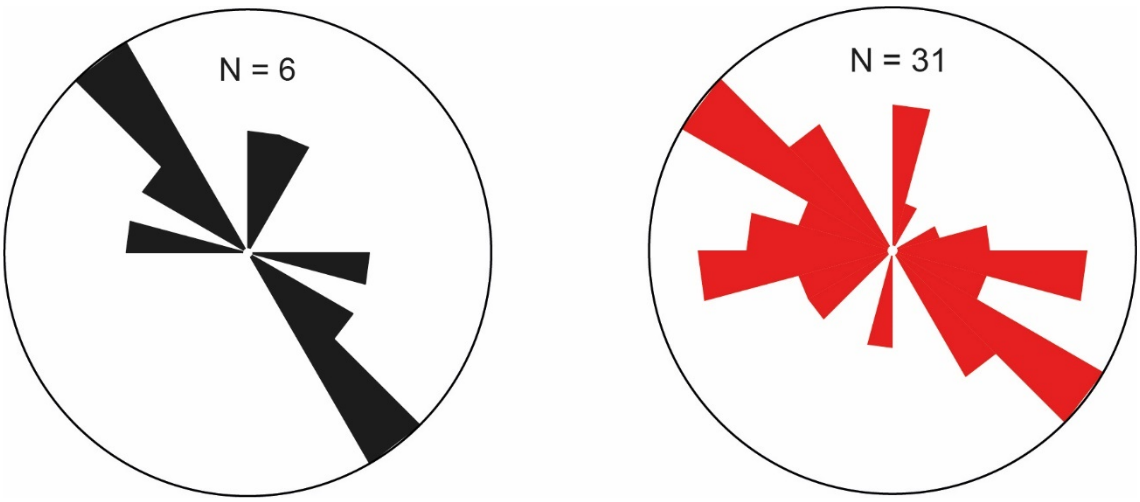


Figure 35. Palaeocurrent data, measured from current ripples/forests, groove and flute marks, and wave ripple crests. The left rose diagram is from Palibinranten. The right is a combination of all measurements recorded at the northern coast of Edgeøya.

6.6 Skrukkefjellet

Skrukkefjellet is a mountain on the northern coast of Edgeøya. It is exposing sections of faulted De Geerdalen Formation in a slope towards Freemansundet (Figure 36). Three days were spent at this location. Two logs were collected at the faulted slope and one at the westernmost ridge of the mountain (Figure 21). Our field party stayed on board the sailboat and reached the study sites by zodiacs and on foot.

6.6.1 SKF18-1

The SKF18-1 log was recorded along the westernmost ridge on Skrukkefjellet, ca 1.2 kilometres to the west of the SKF18-2 log. This log only contains rocks assigned to the Botneheia and Tschermakfjellet formations and are therefore not emphasised in this thesis.

6.6.2 SKF18-2

The SKF18-2 log (Appendix B.14) was logged in a slope towards Freemansundet 1.2 kilometres to the east of the SKF18-1 log. This slope is affected by a shallow-rooted normal fault downfaulting rocks assigned to the De Geerdalen Formation (Osmundsen et al. 2014) (Figure 36). The SKF18 log starts 12 meters above the top of the horizontal undisturbed Botneheia Formation, making the Tschermakfjellet Formation 51 meters thick at this location.

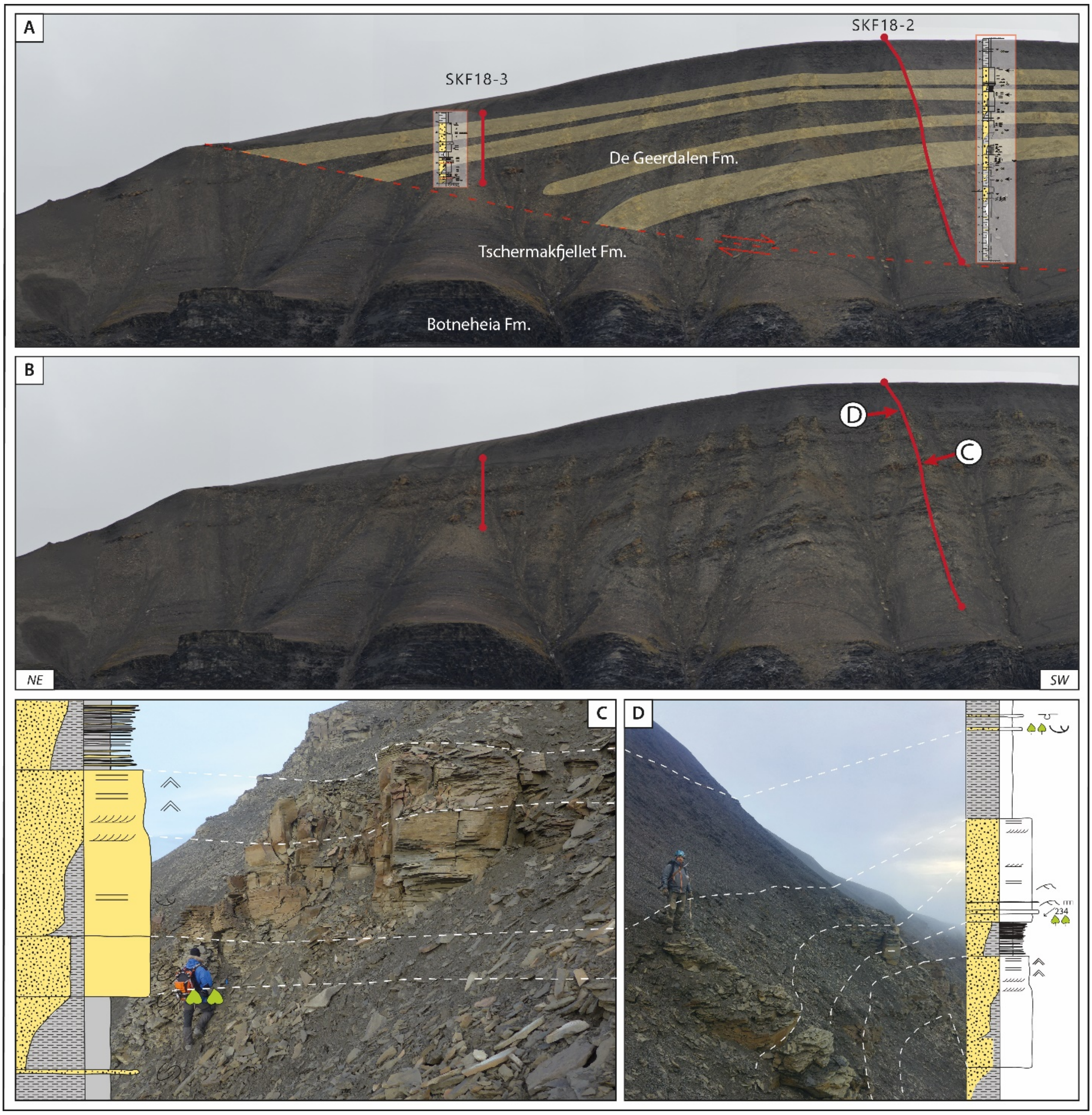


Figure 36. A. Geological sketch of Skrukkefjellet with the logs and long traces of SKF18-2 and -3. Yellow areas within the De Geerdalen Formation mark major sandstone intervals. B. the corresponding overview photo with log traces and the location of the picture in (C) and (D). C. Log correlation of sandstone in Interval 3 in SKF18-2. D. Log correlation to the top of SKF18-2.

Interval 1 (0 – 39.5 m)

Description: The lowermost 40 meters of this log consists of scree-cover and occasional thin (< 0.5 meters thick) siltstone benches. *Skolithos* burrows, sparse undifferentiated bioturbation and cone-in-cone structures are found within these silt benches. The top of the interval is coarsening upwards into heterolithic bedding leading to the lowermost prominent sandstone of the log. Sparse bioturbation, current ripples and minor loading structures were observed in this heterolithic sequence (facies A, B, C, D and F).

Interpretation: This interval is interpreted as offshore transition prodelta deposits of the Tschermakfjellet Formation (FA 2 and 3).

Interval 2 (39.5 – 67 m)

Description: The interval starts with a 1.6-meter-thick, very fine-grained and heavily fractured sandstone. Overlaying the sandstone is a 10-meter thick interval of shale with two slump-deformed sandstone lenses (facies A and D). The two lenses are ca 1.5 meters thick and two to three meters wide. They contain mud flakes and plant fragments. This type of slump-deformation and convoluted bedding are found throughout the rest of the interval and log, constituting more of the lower De Geerdalen Formation than observed at any other locality. Above the shale sequence, there is a sequence of heterolithic bedding and up to four-meter thick, fine-grained sandstone beds. Current ripples, wave ripples, mud drapes, planar parallel bedding and trough cross-bedding, are observed within this sequence.

Interpretation: The 1.6-meter thick sandstone at the base of this interval is interpreted as the base of the De Geerdalen Formation. This sandstone and the sediments in this interval have been interpreted to have been deposited in an upper shoreface setting (FA 5).

Interval 3 (67 – 110 m)

Description: This Interval consists of three coarsening upwards sandstone bodies. The sandstones consists of fine-grained sand, have gradual lower boundaries, exhibit plane parallel stratification, a moderate amount of plant fragments and trough cross-stratification. The lowermost of these three sandstones also exhibit low angle cross-bedding and a horizon with ball-shaped structures, interpreted to be concretions (see Section 5.7). The middle sandstone also exhibits convoluted bedding and wave ripples. The uppermost sandstone exhibit current ripples and planar cross-bedding.

Interpretation: This interval has been interpreted to represent a delta front setting of distributary mouth bars or migrating subaqueous dunes (FA 6).

Interval 4 (110 – 127 m)

Description: This entire top interval of the SKF18-2 log consists of outcropping, in-situ clay with two very fine-grained sandstone benches (Figure 36.C). The two benches are 0.2 and 0.3 meters thick and contain mud drapes, organic fragments and minor load structures.

Interpretation: The base of this interval has been interpreted as a drowning surface, and the sediments of this interval represent a significantly deeper depositional setting than Interval 3. The sediments are interpreted to represent a prodelta setting (FA 2).

6.6.3 SKF18-3

The SKF18-3 log (Appendix B.15) was logged along a ridge 170 meters to the north-east of the SKF18-2 log trace (Figure 36.A). It is within the same interpreted downfaulted block as the SKF18-2 log, and similar facies were found during the logging of the two logs. A 1:50 scale was used during the recording of this log with the intention of recording more detailed observations of sedimentary structures.

Interval 1 (0 – 11 m)

Description: This interval consists of sandstones and contains two erosional surfaces capped by mud flake conglomerate. The main cliff-forming sandstone of this interval is 10.5 meters thick and can be correlated to the 11.5-meter-thick middle sandstone in Interval 3 of the SKF18-3 log.

Interpretation: This orange 1.6-meter-thick convoluted, heavily carbonate-cemented sandstone can be followed and correlated to the middle sandstone in Interval 3 of the SKF18-2 log (Figure 37.B). The interval has been interpreted to represent a delta front setting with possible beach and fluvial channel/bar deposits (DE 3).

Interval 2 (11 – 15.5 m)

Description: This interval consists of scree-covered slope between two sandstone bodies (facies A).

Interpretation: This scree-covered slope has been interpreted as fines deposited in a lagoonal or interdistributary setting (FA 10).

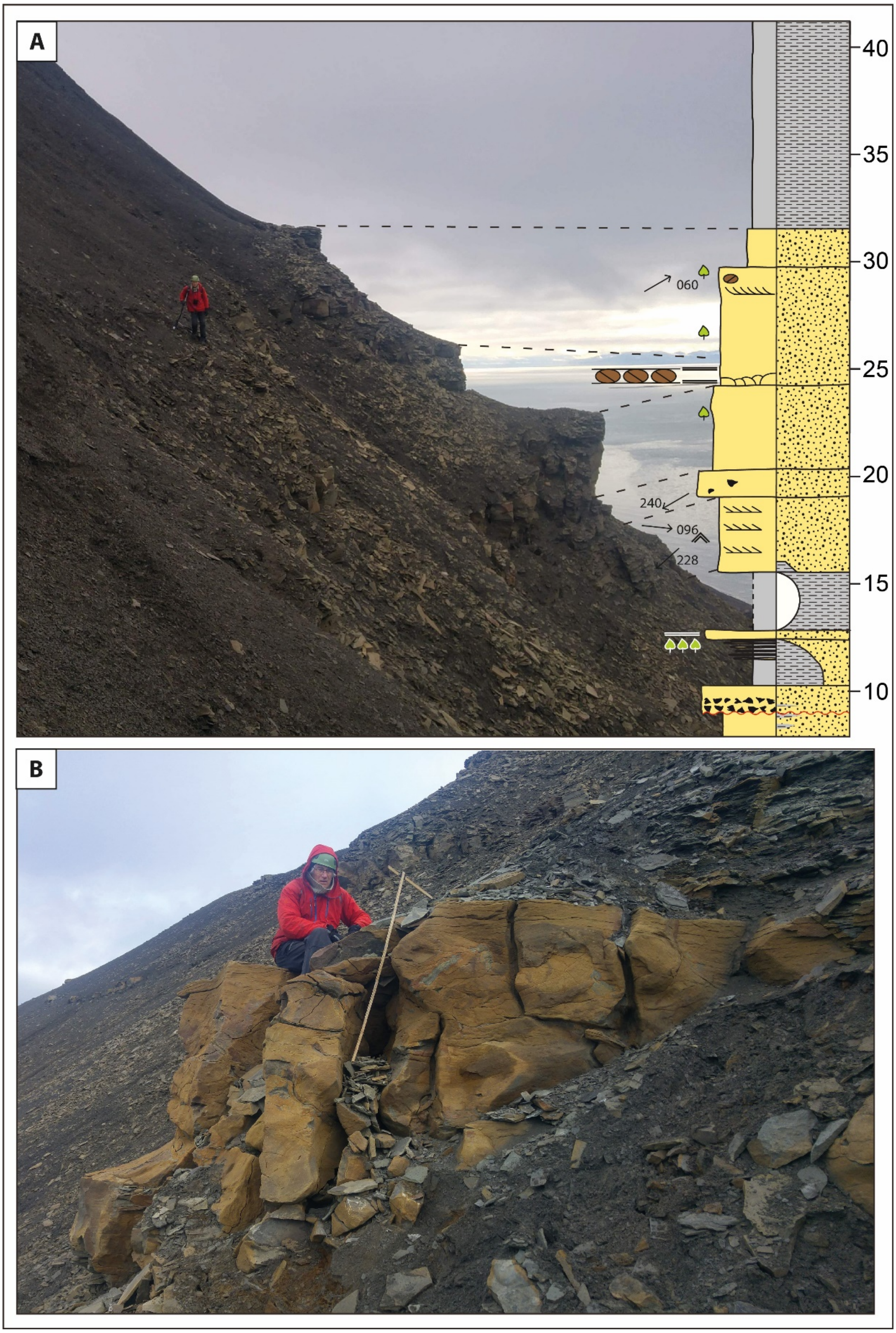


Figure 37. A. Log correlation to the top of the SKF18-3 log. B. The convoluted sandstone at four meters in the SKF18-3 log.

Interval 3 (15.5 – 30 m)

Description: This interval consists of a 14-meter-thick sandstone that can be correlated to the 10.3-meter-thick uppermost sandstone in the SKF18-2 log. This interval has been divided into four beds. The lowermost consists of very fine-grained sandstone with wave ripples and planar cross-bedding (facies E and K). The overlaying 1.3-meter-thick bed consists of heavily fractured medium-grained sandstone with apparently randomly intermixed mud clasts. No other sedimentary features were observed.

The second uppermost four-meter-thick bed consists of fine-grained sandstone with large (> 1 cm) organic fragments. This bed is less cemented than the underlying beds, and the outermost surface of the sandstone bed is creeping down the slope as fractured scree fragments (Figure 37.A).

The uppermost 5.5-meter-thick bed are made up of very fine-grained sand and have similarly fractured, and creeping characteristics as the underlying bed, but are more coherent. Large sandstone concretions, planar parallel bedding and large-scale trough cross-bedding, were observed within this bed.

Interpretation: The change in thickness of this sandstone when comparing it in the SKF18-3 and -2 logs indicates that it is wedging towards the north-east (Figure 36).

The sediments within this interval are interpreted to have been deposited as a migrating barrier bar in a delta front setting (DE 3).

Interval 4 (30 – 31.5 m)

Description: This entire top interval of the SKF18-3 log consists of outcropping, in-situ clay similar to Interval 4 of the SKF18-2 log. The two sandstone benches found in the -3 log are not present along the -3 log trace.

Interpretation: The base of this interval has been correlated to the base of Interval 4 of the SKF18-2 log and interpreted as a drowning surface. The sediments are interpreted to represent a prodelta setting (FA 2).

6.6.4 Faults at Skrukkefjellet

The south-west dipping listric fault plane of Skrukkefjellet coincide with similarly oriented listric faults on Klinkhamaren and Kvalpynten described by Rød (2011), Osmundsen et al. (2014) and Ogata et al. (2018).

Similar to the faults at Muen, the underlying Botneheia Formation is horizontal and appear unaffected by the fault. Unlike the faults at Muen, the fault plane is listric, flattening in the lower parts and terminates somewhere in the underlying shales of the Tschermakfjellet Formation.

Two sandstones can be correlated and compared between the SKF18-2 and -3 logs to understand the geometry of the sandstones. The lowermost of the two are uniform in thickness with a difference in thickness of only one meter in the 170 meters between the two logs. The uppermost of the two have a wedge-shaped geometry thickening towards the north-east and the fault plane. The increase in thickness is 3.7 meters between the two logs. This geometry can be interpreted as a rollover structure, typically associates with growth fault deposits (Edwards 1976).

7 Discussion

The following chapter will present a discussion on the findings and implications from the De Geerdalen Formation on Edgeøya. The depositional environment and facies distribution will be described and compared relative to earlier models (Lock et al. 1978; Rød et al. 2014; Lord et al. 2017a; Ogata et al. 2018).

7.1 Log correlation

Six datasets have been collected from the six visited locations on Edgeøya. These six datasets have a varying degree of spatial resolution. The two datasets with the highest resolution, Blanknuten and Drivdalsryggen, only have a couple of hundred meters between the logs, and a couple of kilometres between the two datasets. Previous sedimentological work on the De Geerdalen Formation have presented single logs, from a few, to several tens of kilometres apart, and correlated them to offer a regional understanding of the formation (Lock et al. 1978; Knarud 1980; Riis et al. 2008; Rød et al. 2014; Lord et al. 2017a,b). A similar regional correlation will be presented in this chapter. The two new datasets from Blanknuten and Drivdalsryggen offer an opportunity to better understand local variations within the De Geerdalen Formation. Facies, facies associations and depositional environments (discussed in Chapter 5) have been used to correlate within and between datasets (Figures 38 and 39).

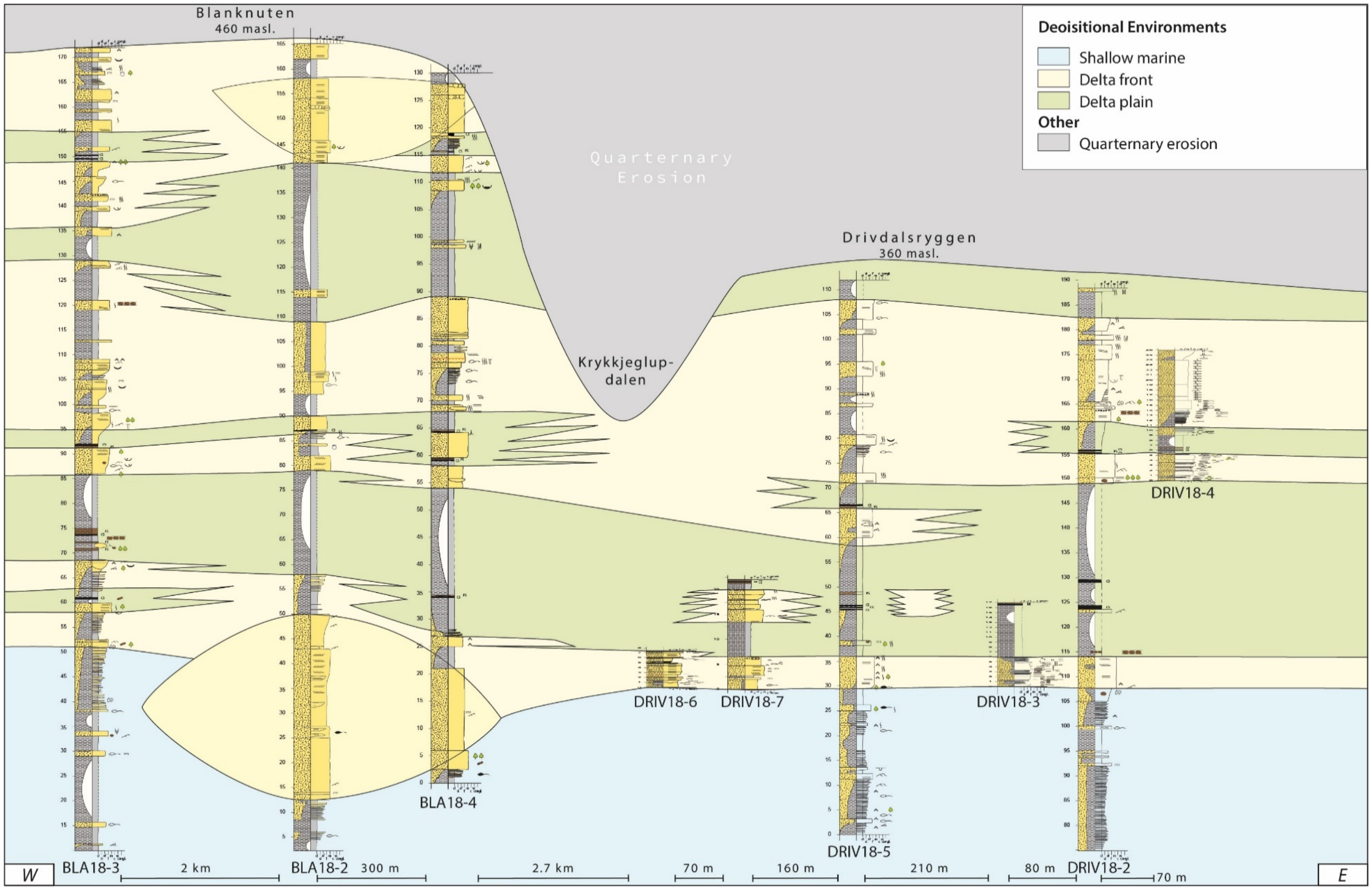


Figure 38. Local correlation panel of measured sections at Blanknuten and Drivdalsryggen with interpreted depositional environment.

Log correlation on a local level is far more intuitive than correlation on a regional level. During local level correlation, it is possible to correlate on individual sandstone bodies extending between the logs. No individual layers have been observed to extend between the visited localities. Thus, the correlated depositional environments in Figure 39 does not represent individual sandstone layers, but rather sandstone events.

The local correlation in Figure 38 reveals alternations between delta front and delta plain depositional environments. Subareal deposited coal, palaeosol and floodplain layers are immediately overlaid by sandstones with hummocky cross-stratification, interpreted as lower shoreface deposits. This indicates a dynamic environment with substantial sea level fluctuations. This interpretation is concurrent with interpretations of the upper part of the exposed stratigraphy on Blanknuten and Klinkhamaren made by Rød et al. (2014).

The local correlation in Figure 30 and Figure 38 also show rapid lateral changes with different facies at the same hight within a sandstone body. Facies differences are found even when comparing logs less than a 100 meters apart. Other sandstone bodies are laterally restricted to almost a 1:1 geometry. This type of characteristics has been used to recognise deposition in existing accumulation space, opposed to scour and fill (Dam et al. 1995; Chakraborty and Sarkar 2005; Rød et al. 2014). Rød et al. (2014) described the De Geerdalen Formation on Edgeøya as a more proximal and fluvial dominated delta system compared to deposits of the De Geerdalen Formation found further to the west. The rapid lateral changes found on Edgeøya concur with these interpretations, where facies are restricted to point sources and not spread by wave and tide processes. No similar high-resolution dataset exists further to the west, but if recorded, more lateral continuity would be expected.

Previous regional log correlation on Spitsbergen has used the regionally extensive base of the Isfjorden Member, as a reference horizon (Forsberg 2017; Mc Cabe 2018). This bed is removed by quaternary erosion on Edgeøya, and thus cannot be used as a reference horizon for this thesis. Instead, the top of the Botneheia Formation has been chosen as a correlation horizon and flattened (Figure 39). The use of the lithological equivalent of the top Botneheia Formation as a flattening horizon is widespread in the Barents Sea and Svalbard (Riis et al. 2008; Glørstad-Clark et al. 2010; Lundschien et al. 2014; Vigran et al. 2014; Forsberg 2017).

The choice of this horizon as a correlation surface has highlighted the thickness variations of the Tschermakfjellet Formation. The thickness of the formation varies from 44 meters at Kapp Lee to more than 120 meters at Muen, which is concordant with previous measurements of the Tschermakfjellet Formation (Lock et al. 1978). The widespread thickness variation may be due to the somewhat arbitrary boundary between the Tschermakfjellet and De Geerdalen formations (Lord et al. 2017a). The thickness variations of the basal sandstone of the De Geerdalen Formation is also varying greatly, contributing to the thickness variations of the Tschermakfjellet Formation (see Section 3.2.2).

On Muen, Skrukkefjellet and possibly Kapp Lee, the base of the De Geerdalen Formation is affected by normal faults, reducing the thickness of the Tschermakfjellet Formation. This tectonic control is limited to the vertical throw and the locations of the faults. A more significant process controlling the thickness of the formation is therefore needed. The leading process is believed to be delta switching, where delta lobes and distributaries move with a cyclic rhythm (Reading and Collinson 1996). The overall trend for the visited localities is a thickening of the formation toward the south (Figure 39).

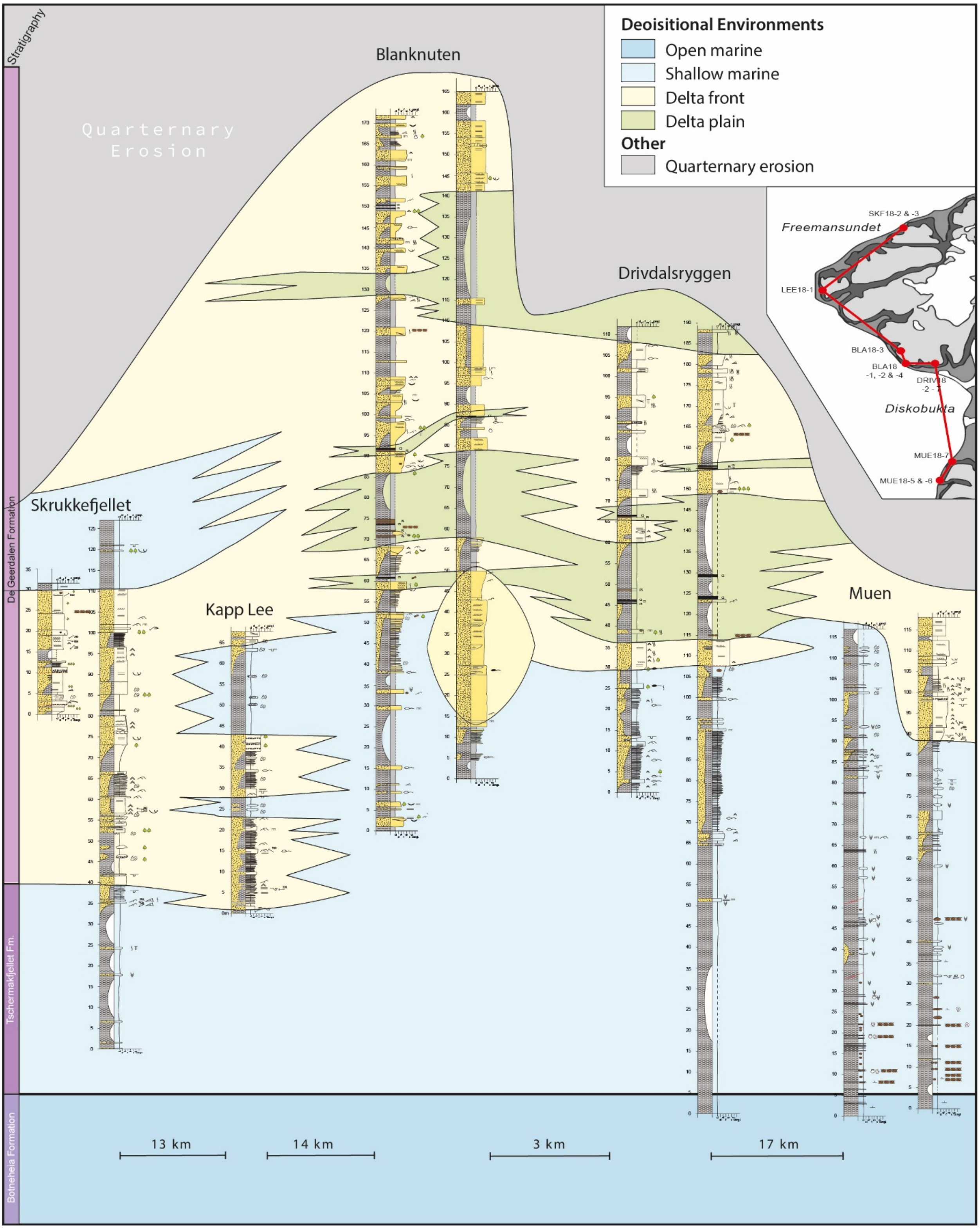


Figure 39. Regional correlation panel of five localities.

7.2 Geometry of sandstone bodies

The apparent massive, nine meters thick and 180 meters wide sandstone body, described in Section 6.1 is found at the base of the bigger, more heterolithic ellipsoid sandstone body marked in Figure 38 and Figure 40. This bigger ellipsoid sandstone body is ca 30-meter-thick and 1.1 kilometres wide.

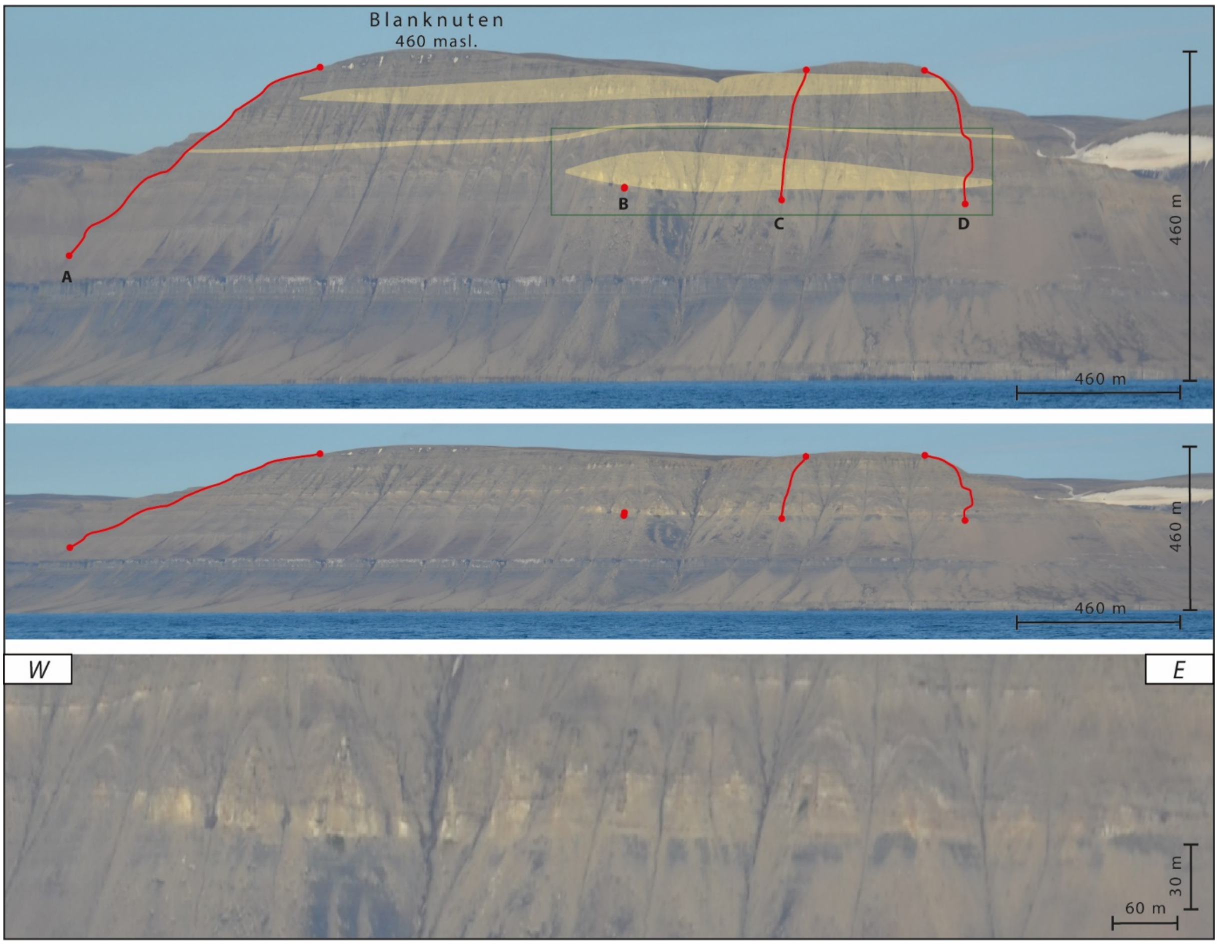


Figure 40 Vertically exaggerated and normal overview photos of Blanknuten with marked log traces, large sandstone bodies and an incised photo of the large ellipsoid sandstone body. A. Log BLA18-3 B. Log BLA18-1. C. Log BLA18-2. D. Log BLA18-4.

The interpretation of the progradation directions of these deltaic deposits has been one of the aims of this thesis. In the northern Barents Sea, Triassic clinoforms have been recognised to have been filling in a basin towards the north-west and west-north-west (Riis et al. 2008; Glørstad-Clark et al. 2010; Høy and Lundschien 2011; Anell et al. 2014; Lundschien et al. 2014).

Onshore studies of the De Geerdalen Formation have used paleocurrent measurements to interpret progradation directions (Knarud 1980; Hynne 2010; Høy and Lundschien 2011; Rød et al. 2014; Ogata et al. 2018).

The monodirectional measurements made by Hynne (2010) at Blanknuten indicates sediment transport with southern to north-western progradational directions (Figure 41). The measurements range mainly between 160° and 330°, with a dominant western component. These findings are concurrent with measurements made by Knarud (1980) at the eastern end of the mountain, showing large variation in measured directions, with a predominantly western to north-western direction.

Monodirectional palaeocurrent measurements from locations along the northern coast of Edgeøya show a dominant western progradational direction (Figure 41).

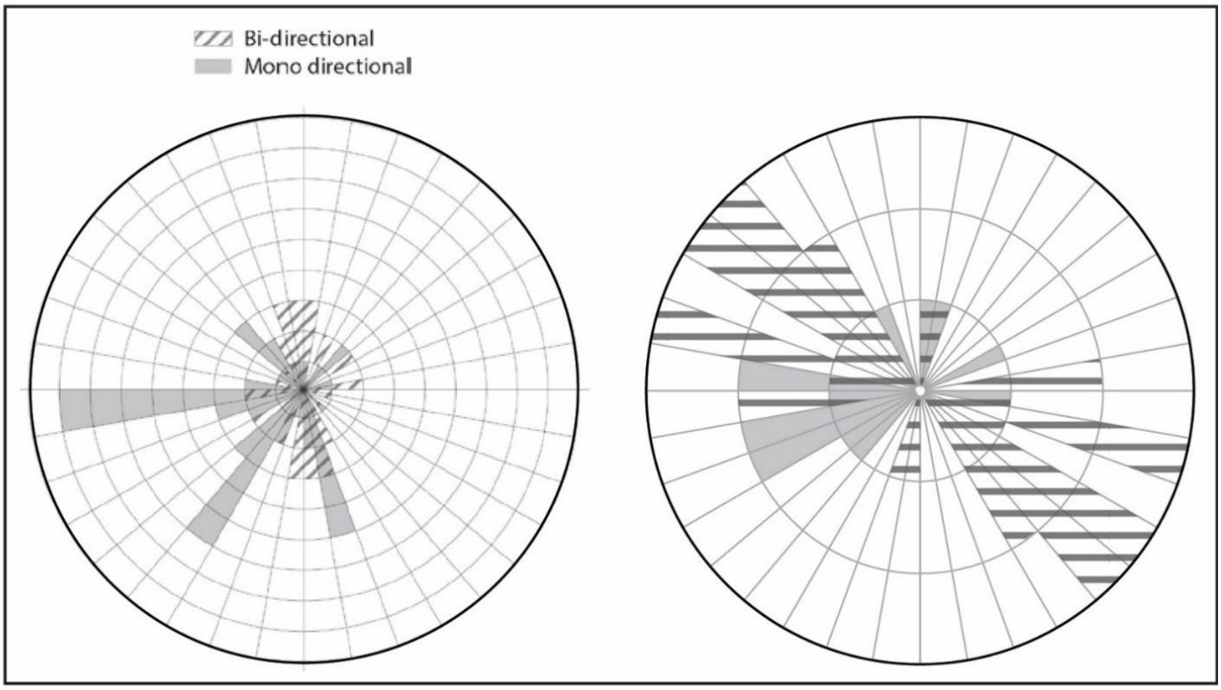


Figure 41. Palaeocurrent data from (Hynne 2010) to the left and from this study to the right. This study includes 17 bidirectional and 14 monodirectional measurements.

The observed sandstone bodies at Blanknuten and Drivdalsryggen are for the most part horizontal, except for one. The middle marked lateral extensive sandstone body on Blanknuten has a bent geometry with a dip towards the west (Figure 40). This geometry may be the result of differential compaction induced by higher resistance to compaction at the eastern side of Blanknuten. This higher resistance to compaction may stem from the underlying large ellipsoid sandstone body. The difference in sand content in the north-western side compared to the south-eastern side of Blanknuten can be seen when comparing log BLA18-2 and log BLA18-3 (Appendix B.1 and B.2). The geometry of this sandstone body has thus not been used to indicate the progradation direction of these sediments.

7.3 Faults

The listric fault of Skrukkefjellet has been described as shallow rooted growth faults by Osmundsen et al. (2014). Growth faults are defined as normal faults with a listric geometry that were active during deposition (Bhattacharya and Davies 2001). Osmundsen et al. (2014) recognised a possible unconformity, from photographic analysis, at a level intermediate between the top of the Botneheia Formation and the top of the exposed section. This unconformity has not been found in the field as a part of this study.

The two correlated sandstone bodies of the Skrukkefjellet fault have significant dissimilarities in geometry (see Section 6.6.4). The lowermost of the two has a uniform thickness, indicating a pre-fault deposition. The uppermost sandstone has a wedge-shaped geometry, thickening towards the fault plane, indicating synsedimentary movement along the fault plane (Ogata et al. 2018). The uniform thickness of the lowermost sandstone indicates that this unit was deposited without synsedimentary movement. The wedge-shaped geometry of the uppermost sandstone body was not found in any of the other sandstone bodies at this location, through photographic analysis. From these observations, the fault is interpreted as a late synsedimentary growth-fault with the majority of the tectonic movement occurring after the deposition of the second top sandstone body.

The faults at Muen have a different geometry with apparent planar fault planes and conjugate faults forming graben structures. These faults have a west to west-north-west strike, differing from the north-western strike of the fault on Skrukkefjellet. The studied fault plane on Muen is also characterised as more brittle than the fault on Skrukkefjellet, due to the mud gauge on the main fault plain and the occurrence of slickensides in the damage zone.

The faults on Muen are interpreted to have formed on a later stage than the fault on Skrukkefjellet, after lithification of the sediments. This interpretation concurs with the third generation of faults at Edgeøya, presented by Osmundsen et al. (2014), while the fault on Skrukkefjellet concurs with descriptions of the second generation.

8 Summary and conclusion

- An overall coarsening upwards trend has been recognised and described at all the studied localities. The sediments assigned to the Tschermakfjellet and De Geerdalen formations at Blanknuten and Drivdalsryggen range from offshore deposits to shallow marine, delta front and delta plain deposits. The sediments described at Skrukkefjellet, Kapp Lee and Muen have been interpreted to represent deeper depositional environments ranging from offshore deposits to shallow marine and delta front. No delta plain deposits have been interpreted at Skrukkefjellet, Kapp Lee or Muen.
- Rapid lateral facies changes within sandstone bodies have been documented throughout the study area owing to a high-resolution local dataset. These rapid lateral changes indicate deposition in a deltaic setting with a low wave and tidal influence, and more accommodation space than found on Spitsbergen.
- Palaeocurrent directions concur with previous suggestions of a western and north-western progradation direction from provenance areas in Fennoscandia and the Uralian orogeny. Sparse data from this work can be applied as supportive data to previous seismic and sedimentological studies.
- The fault described at Skrukkefjellet is a late synsedimentary listric fault.
- The faults described at Muen are of a later brittle generation.
- The data presented in this thesis agree with other stratigraphic sections measured on Edgeøya (Lock et al. 1978; Knarud 1980; Rød et al. 2014; Lord et al. 2017a).

9 References

Anell, I., Midtkandal, I. & Braathen, A. 2014. Trajectory analysis and inferences on geometric relationships of an Early Triassic prograding clinoform succession on the northern Barents Shelf. *Marine and Petroleum Geology,* 54, 167-179.

Bergan, M. & Knarud, R. 1993. Apparent changes in clastic mineralogy of the Triassic–Jurassic succession, Norwegian Barents Sea: possible implications for palaeodrainage and subsidence. *In:* Vorren, T.O., et al. (eds.) *Norwegian Petroleum Society Special Publications.* 2, 481-493.

Bernhardsen, S. 2019. *A sedimentological study of the organic-rich Botneheia Formation (Middle Triassic) with emphasis on the ichnogenus Thalassinoides, Edgeøya, Svalbard.* Master Thesis, Norwegian University of Science and Technology, Trondheim, 150 pp.

Bhattacharya, J.P. 2006. Deltas. *In:* Posamentier, H.W. & Walker, R.G. (eds.) *Facies models revisited.* Tulsa, Oklahoma: Society for Sedimentary Geology Special Publication, 84, 237–292.

Bhattacharya, J.P. & Davies, R.K. 2001. Growth faults at the prodelta to delta-front transition, Cretaceous Ferron sandstone, Utah. *Marine and Petroleum Geology,* 18, 525-534.

Bhattacharya, J.P. & Maceachern, J. 2009. Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America. *Journal of Sedimentary Research,* 79, 184-209.

Boggs, S. 2009. *Petrology of sedimentary rocks.* 2nd ed, Cambridge, Cambridge University Press, 600 pp.

Boggs, S. 2011a. Chapter 4: Sedimentary Structures *In:* Boggs, S. (ed.) *Principles of sedimentology and stratigraphy.* 5th ed. Upper Saddle River, New Jersey: Pearson Prentice Hall, 65-98.

Boggs, S. 2011b. Chapter 10: Marginal-Marine Environments. *In:* Boggs, S. (ed.) *Principles of sedimentology and stratigraphy.* 5th ed. Upper Saddle River, New Jersey: Pearson Prentice Hall, 279-314.

Boggs, S. 2011c. *Principles of sedimentology and stratigraphy.* 5th ed, Upper Saddle River, New Jersey, Pearson Prentice Hall, 586 pp.

Buchan, S., Challinor, A., Harland, W. & Parker, J. 1965. The Triassic stratigraphy of Svalbard. *Norsk Polarinstitutt Skrifter,* 135, 92 pp.

Buiter, S.J.H. & Torsvik, T.H. 2007. Horizontal movements in the eastern Barents Sea constrained by numerical models and plate reconstructions. *Geophysical Journal International,* 171, 1376-1389.

Chakraborty, T. & Sarkar, S. 2005. Evidence of lacustrine sedimentation in the Upper Permian Bijori Formation, Satpura Gondwana basin: Palaeogeographic and tectonic implications. *Journal of Earth System Science,* 114, 303-323.

Clifton, H.E. 2006. A reexamination of facies models for clastic shorelines. *In:* Posamentier, H.W. & Walker, R.G. (eds.) *Facies models revisited.* Tulsa, Oklahoma: Society for Sedimentary Geology Special Publication, 84, 293-337.

Coleman, J.M., Prior, D.B. & Lindsay, J.F. 1983. Deltaic influences on shelfedge instability processes. *In:* Stanley, D.J. & Moore, D.T. (eds.) *The Shelfbreak: Critical Interface on Continental Margins.* Tulsa, Oklahoma: Society for Sedimentary Geology Special Publication, 33, 121-137.

Collinson, J.D. 1969. The Sedimentology of the Grindslow Shales and the Kinderscout Grit: A Deltaic Complex in the Namurian of Northern England. *Journal of Sedimentary Petrology,* 39, 194-221.

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

Collinson, J.D., Mountney, N. & Thompson, D.B. 2006. *Sedimentary Structures.* 3rd ed*,* Dunedin, Dunedin Academic Press, 304 pp.

Dallmann, W.K., Blomeier, D., Elvevold, S., Mørk, A., Olaussen, S., Grundvåg, S.-A., Bond, B. & Hormes, A. 2015. Chapter 6: Historical geology. *In:* Dallmann, W.K. (ed.) *Geoscience Atlas of Svalbard.* Tromsø: Norsk polarinstitutt, 89-131.

Dallmann, W.K. & Elvevold, S. 2015. Chapter 7: Bedrock Geology. *In:* Dallmann, W.K. (ed.) *Geoscience Atlas of Svalbard.* Tromsø: Norsk polarinstitutt, 133-174.

Dam, G., Surlyk, F., Mathiesen, A. & Christiansen, F.G. 1995. Exploration significance of lacustrine forced regressions of the Rhaetian-Sinemurian Kap Stewart Formation, Jameson Land, East Greenland. *In:* Steel, R.J., et al. (eds.) *Norwegian Petroleum Society Special Publications.* 5, 511-527.

Davis, R.A. 2012. Tidal signatures and their preservation potential in stratigraphic sequences. *In:* Davis, R.A. & Dalrymple, R.W. (eds.) *Principles of tidal sedimentology.* Dordrecht: Springer Netherlands, 35-55.

Droser, M.L. 1991. Ichnofabric of the Paleozoic Skolithos ichnofacies and the nature and distribution of Skolithos piperock. *Palaios,* 6, 316-325.

Dumas, S. & Arnott, R.W.C. 2006. Origin of hummocky and swaley cross-stratification—The controlling influence of unidirectional current strength and aggradation rate. *Geology,* 34, 1073-1076.

Edwards, M.B. 1976. Growth faults in upper Triassic deltaic sediments, Svalbard. *AAPG Bulletin,* 60, 341-355.

Eide, C.H., Howell, J.A. & Buckley, S.J. 2015. Sedimentology and reservoir properties of tabular and erosive offshore transition deposits in wave-dominated, shallow-marine strata; Book Cliffs, USA. *Petroleum Geoscience,* 21, 55-73.

Eide, C.H., Klausen, T.G., Katkov, D., Suslova, A.A. & Helland-Hansen, W. 2018. Linking an Early Triassic delta to antecedent topography: Source-to-sink study of the southwestern Barents Sea margin. *Geological Society of America Bulletin,* 130, 263.

Elvevold, S., Dallmann, W. & Blomeier, D. 2007. *Geology of Svalbard.* Tromsø, Norwegian Polar Institute, 36 pp.

Enga, J. 2015. *Paleosols in the Triassic De Geerdalen and Snadd formations.* Master Thesis, Norwegian University of Science and Technology, Trondheim, 127 pp.

Faleide, J.I., Gudlaugsson, S.T. & Jacquart, G. 1984. Evolution of the western Barents Sea. *Marine and Petroleum Geology,* 1, 123-150.

Flood, B., Nagy, J. & Winsnes, T.S. 1971. *The Triassic succession of Barentsøya, Edgeøya, and Hopen (Svalbard).* Oslo, Norwegian Polar Institute, 25 pp.

Forsberg, C.S. 2017. *A sedimentological study of the deltaic De Geerdalen Formation in Fulmardalen and of fluvial deposits in the Snadd Formation on the Finnmark Platform.* Master Thesis, Norwegian University of Science and Technology, Trondheim, 166 pp.

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

Granberg, M.E., Ask, A. & Gabrielsen, G.W. 2017. *Local contamination in Svalbard: overview and suggestions for remdiation actions.* Tromsø, Norwegian Polar Institute, 48 pp.

Hampson, G.J. & Howell, J.A. 2005. Sedimentologic and geomorphic characterization of ancient wave-dominated deltaic shorelines: examples from the Late Cretaceous Blackhawk Formation, Book Cliffs, Utah. *In:* Giosan, L. & Bhattacharya, J.P. (eds.) *River Deltas – Concepts, Models, and Examples.* Society for Sedimentary Geology Special Publication, 83, 133–154.

Harms, J.C., Southard, J.B. & Walker, R.G. 1982. *Structures and Sequences in Clastic Rock.* 2nd ed, Society of Economic Paleontologists and Mineralogists, 249 pp.

Haugen, T. 2016. *A Sedimentological Study of the De Geerdalen Formation with Focus on the Isfjorden Member and Palaeosols.* Master Thesis, Norwegian University of Science and Technology, Trondheim, 129 pp.

Hynne, I.B. 2010. *Depositional environment on eastern Svalbard and central Spitsbergen during Carnian time (Late Triassic): a sedimentological investigation of the De Geerdalen Formation.* Master Thesis, Norwegian University of Science and Technology, Trondheim, 143 pp.

Høy, T. & Lundschien, B.A. 2011. Chapter 15: Triassic deltaic sequences in the northern Barents Sea. *Geological Society, London, Memoirs,* 35, 249-260.

Ichaso, A.A. & Dalrymple, R.W. 2009. Tide- and wave-generated fluid mud deposits in the Tilje Formation (Jurassic), offshore Norway. *Geology,* 37, 539-542.

Keilhau, B.M. 1831. *Reise i Öst-og Vest-Finmarken: samt til Beeren-Eiland og Spitsbergen : i Aarene 1827 og 1828.* Christiania, Cappelen, 247 pp.

Klausen, T.G. & Mørk, A. 2014. The Upper Triassic paralic deposits of the De Geerdalen Formation on Hopen: Outcrop analog to the subsurface Snadd Formation in the Barents SeaThe De Geerdalen Formation on Hopen. *AAPG Bulletin,* 98, 1911-1941.

Klausen, T.G., Ryseth, A., Helland-Hansen, W., Gjelberg, H.K. & Hampson, G. 2016. Progradational and backstepping shoreface deposits in the Ladinian to Early Norian Snadd Formation of the Barents Sea. *Sedimentology,* 63, 893-916.

Knarud, R. 1980. *En sedimentologisk og diagenetisk undersøkelse av Kapp Toscana Formasjonens sedimenter på Svalbard. (A sedimentological and diagenetic study of the sediments of the Kapp Toscana Formation in Svalbard).* Cand. real., University of Oslo, Oslo, 221 pp.

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

Kraus, M.J. 1999. Paleosols in clastic sedimentary rocks: their geologic applications. *Earth-Science Reviews,* 47, 41-70.

Lock, B., Pickton, C., Smith, D., Batten, D. & Harland, W. 1978. The geology of Edgeøya and Barentsøya, Svalbard.

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

Lord, G.S., Mørk, A. & Høy, T. 2017b. Sequence patterns in the Triassic Succession of Svalbard and the Northern Barents Sea. *In:* Lord, G.S. (ed.) *Sequence stratigraphy and facies development of the Triassic succession of Svalbard and the northern Barents Sea*, PhD. Thesis: Norwegian University of Science and Technology, Trondheim, 185-223.

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

Lord, G.S., Solvi, K.H., Klausen, T.G. & Mørk, A. 2014b. Triassic channel bodies on Hopen, Svalbard: Their facies, stratigraphic significance and spatial distribution. *Norwegian Petroleum Directorate Bulletin,* 11, 41-59.

Lundegard, P.D. & Samuels, N.D. 1980. Field Classification of Fine-Grained Sedimentary Rocks. *SEPM Journal of Sedimentary Research,* 50, 781-786.

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

Maher, H.D., Ogata, K.E.I. & Braathen, A. 2017. Cone-in-cone and beef mineralization associated with Triassic growth basin faulting and shallow shale diagenesis, Edgeøya, Svalbard. *Geological Magazine,* 154, 201-216.

Marshall, J.D. & Pirrie, D. 2013. Carbonate concretions—explained. *Geology Today,* 29, 53-62.

Mc Cabe, C.P. 2018. *Sedimentology and diagenesis of the Late Triassic De Geerdalen Formation in Oscar II Land, Spitsbergen, Svalbard.* Master Thesis, Norwegian University of Science and Technology, Trondheim, 128 pp.

Midtgaard, H.H. 1996. Inner-shelf to lower-shoreface hummocky sandstone bodies with evidence for geostrophic influenced combined flow, Lower Cretaceous, West Greenland. *Journal of Sedimentary Research,* 66, 343-353.

Morad, S. 1998. Carbonate cementation in sandstones: distribution patterns and geochemical evolution. *In:* Morad, S. (ed.) *Carbonate cementation in sandstones: distribution patterns and geochemical evolution.* Oxford, England: Blackwell Science, 26, 1-26.

Mørk, A. & Bjorøy, M. 1984. Mesozoic source rocks on Svalbard. *In:* Spencer, A.M., et al. (eds.) *Petroleum geology of the North European margin.* London: Graham and Trotman, 371-382.

Mørk, A. & Bromley, R.G. 2008. Ichnology of a marine regressive systems tract: the Middle Triassic of Svalbard. *Polar Research,* 27, 339-359.

Mørk, A., Dallmann, W.K., Dypvik, H., Johannessen, E.P., Larssen, G.B., Nagy, J., Nøttvedt, A., Olaussen, S., Pchelina, T.M. & Worsley, D. 1999a. Chapter 3: Mesozoic lithostratigraphy. *In:* Dallmann, W.K. (ed.) *Lithostratigraphic lexicon of Svalbard. Review and recommendations for nomenclature use. Upper Palaeozoic to Quaternary bedrock.* Tromsø: Norsk Polarinstitutt, 127-214.

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

Mørk, A., Knarud, R. & Worsley, D. 1982. Depositional and diagenetic environments of the Triassic and Lower Jurassic succession of Svalbard. *Canadian Society of Petroleum Geologists Memoir,* 8, 371-398.

Mørk, A., Vigran, J.O., Korchinskaya, M.V., Pchelina, T.M., Fefilova, L.A., Vavilov, M.N. & Weitschat, W. 1993. Triassic rocks in Svalbard, the Arctic Soviet islands and the Barents Shelf: bearing on their correlations. *In:* Vorren, T.O., et al. (eds.) *Arctic Geology and Petroleum Potential.* Amsterdam: Norwegian Petroleum Society Special Publications, 2, 457-479.

Nichols, G. 2009a. Chapter 4: Processes of Transport and Sedimentary Structures. *In:* Nichols, G. (ed.) *Sedimentology and stratigraphy.* 2nd ed. Chichester: Wiley-Blackwell, 44-68.

Nichols, G. 2009b. Chapter 5: Field Sedimentology, Facies and Environments. *In:* Nichols, G. (ed.) *Sedimentology and stratigraphy.* 2nd ed. Chichester: Wiley-Blackwell, 69-86.

Nichols, G. 2009c. Chapter 12: Deltas. *In:* Nichols, G. (ed.) *Sedimentology and stratigraphy.* 2nd ed. Chichester: Wiley-Blackwell, 179 - 198.

Nøttvedt, A. & Kreisa, R.D. 1987. Model for the combined-flow origin of hummocky cross-stratification. *Geology,* 15, 357-361.

Ogata, K., Mulrooney, M.J., Braathen, A., Maher, H., Osmundsen, P.T., Anell, I., Smyrak-Sikora, A.A. & Balsamo, F. 2018. Architecture, deformation style and petrophysical properties of growth fault systems: the Late Triassic deltaic succession of southern Edgeøya (East Svalbard). *Basin Research,* 30, 1042-1073.

Osmundsen, P.T., Braathen, A., Rød, R.S. & Hynne, I.B. 2014. Styles of normal faulting and fault-controlled sedimentation in the Triassic deposits of eastern Svalbard. *Norwegian Petroleum Directorate Bulletin,* 11, 61-79.

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

Pčelina, T.M. 1980. Novye dannye po pograničnym slojam triasa i jury na arhipelage Svalbard.(New data on the Triassic/Jurassic boundary beds in the Svalbard Archipelago.). *In:* Semevskij, D.V. (ed.) *Geologija osadočnogo čechla arhipelaga Svalbard. NIIGA. (Geology of the sedimentary cover of the Svalbard archipelago).* Leningrad: NIIGA, 44-60.

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

Pettijohn, F.J., Potter, P.E. & Siever, R. 1972. *Sand and Sandstone.* 1st ed*,* New York, Springer US, 583 pp.

Pilkey, O.H., Neal, W.J., Cooper, J.A.G. & Kelley, J.T. 2011. *The World's Beaches: A Global Guide to the Science of the Shoreline.* 1st ed*,* Los Angeles, University of California Press, 284 pp.

Quincey, D.J. & Luckman, A. 2009. Progress in satellite remote sensing of ice sheets. *Progress in Physical Geography,* 33, 547-567.

Reading, H.G. & Collinson, J.D. 1996. Chapter 6: Clastic coasts. *In:* Reading, H.G. (ed.) *Sedimentary environments : processes, facies and stratigraphy.* 3rd ed. Oxford: Blackwell Science, pp. 37–82.

Reineck, H.E. & Singh, I.B. 1980. *Depositional sedimentary environments : with reference to terrigenous clastics.* 2nd ed*,* Berlin, Springer, 504 pp.

Retallack, G.J. 1991. Untangling the effects of burial alteration and ancient soil formation. *Annual Review of Earth and Planetary Sciences,* 19, 183-206.

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

Rød, R.S. 2011. *Spatial occurrences of selected sandstone bodies in the De Geerdalen Formation, Svalbard, and their relation to depositional facies.* Master Thesis, Norwegian University of Science and Technology, Trondheim, 103 pp.

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

Senger, K., Roy, S., Braathen, A., Buckley, S.J., Bælum, K., Gernigon, L., Mjelde, R., Noormets, R., Ogata, K. & Olaussen, S. 2013. Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-offshore magmatic province with implications for CO2 sequestration. *Norwegian Journal of Geology,* 93, 143–166.

Senger, K., Tveranger, J., Ogata, K., Braathen, A. & Planke, S. 2014. Late Mesozoic magmatism in Svalbard: A review. *Earth-Science Reviews,* 139, 123-144.

Steel, R.J. & Worsley, D. 1984. Svalbard's post-Caledonian strata. An atlas of sedimentational patterns and palaeogeographic evolution. *In:* Spencer, A.M., et al. (eds.) *Petroleum geology of the North European margin. Norwegian Petroleum Society.* London: Graham & Trotman Ltd., 109-135.

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

Stow, D.A.V., Reading, H.G. & Collinson, J.D. 1996. Chapter 10: Deep seas. *In:* Reading, H.G. (ed.) *Sedimentary environments: processes, facies and stratigraphy.* 3rd ed. Oxford: Blackwell Science, 395 - 453.

Sysselmannen. 2012. *Geology* [Online]. [Accessed 09.01.2019]. Available at: https://www.sysselmannen.no/en/Toppmeny/About-Svalbard/Geology/

Torsvik, T.H. & Cocks, L.R.M. 2005. Norway in space and time: A Centennial cavalcade. *Norwegian Journal of Geology,* 85, 73-86.

Tucker, M.E. 2011. *Sedimentary rocks in the field: a practical guide.* 4th ed, Hoboken, Wiley-Blackwell, 275 pp.

Tugarova, M.A. & Fedyaevsky, A.G. 2014. Calcareous microbialites in the Upper Triassic succession of eastern Svalbard. *Norwegian Petroleum Directorate Bulletin,* 11, 137-152.

Vigran, J.O., Mangerud, G., Mørk, A., Worsley, D. & Hochuli, P.A. 2014. Palynology and geology of the Triassic succession of Svalbard and the Barents Sea. *Geological Survey of Norway Special Publication 14*, 1–269.

Webb, G. 1994. Paleokarst, paleosol, and rocky-shore deposits at the Mississippian-Pennsylvanian unconformity, northwestern Arkansas. *Geological Society of America Bulletin,* 106, 634-648.

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

Yang, B., Dalrymple, R. & Chun, S. 2006. The significance of hummocky cross-stratification (HCS) wavelengths: Evidence from an open-coast tidal flat, South Korea. *Journal of Sedimentary Research,* 76, 2-8.

Young, F. & Reinson, G. 1975. Sedimentology of Blood Reserve and adjacent formations (Upper Cretaceous), St. Mary River, southern Alberta. *In:* Shawa, M.S. (ed.) *Guidebook to selected sedimentary environments In southwestern Alberta, Canada.* Canadian Society of Petroleum Geologists, 10-20.

Appendix A: Legend

Lithology

- Sandstone
- Mud and siltstone
- CS Coal/Coal Shale
- PS Palaeosol
- Covered/partly covered

Fossiles

- Ammonoids
- Bivalves

Concretions/nodules

- Siderite concretion
- Siderite concretion horizon
- Large sandstone concretions

Trace fossils

- *Skolithos*
- *Rhizocorallium*
- *Diplocraterion*

Cements

- Dolomite cementation
- Calcite cementation
- Siderite cementation
- Unspecified cementation

Sedimentary structures

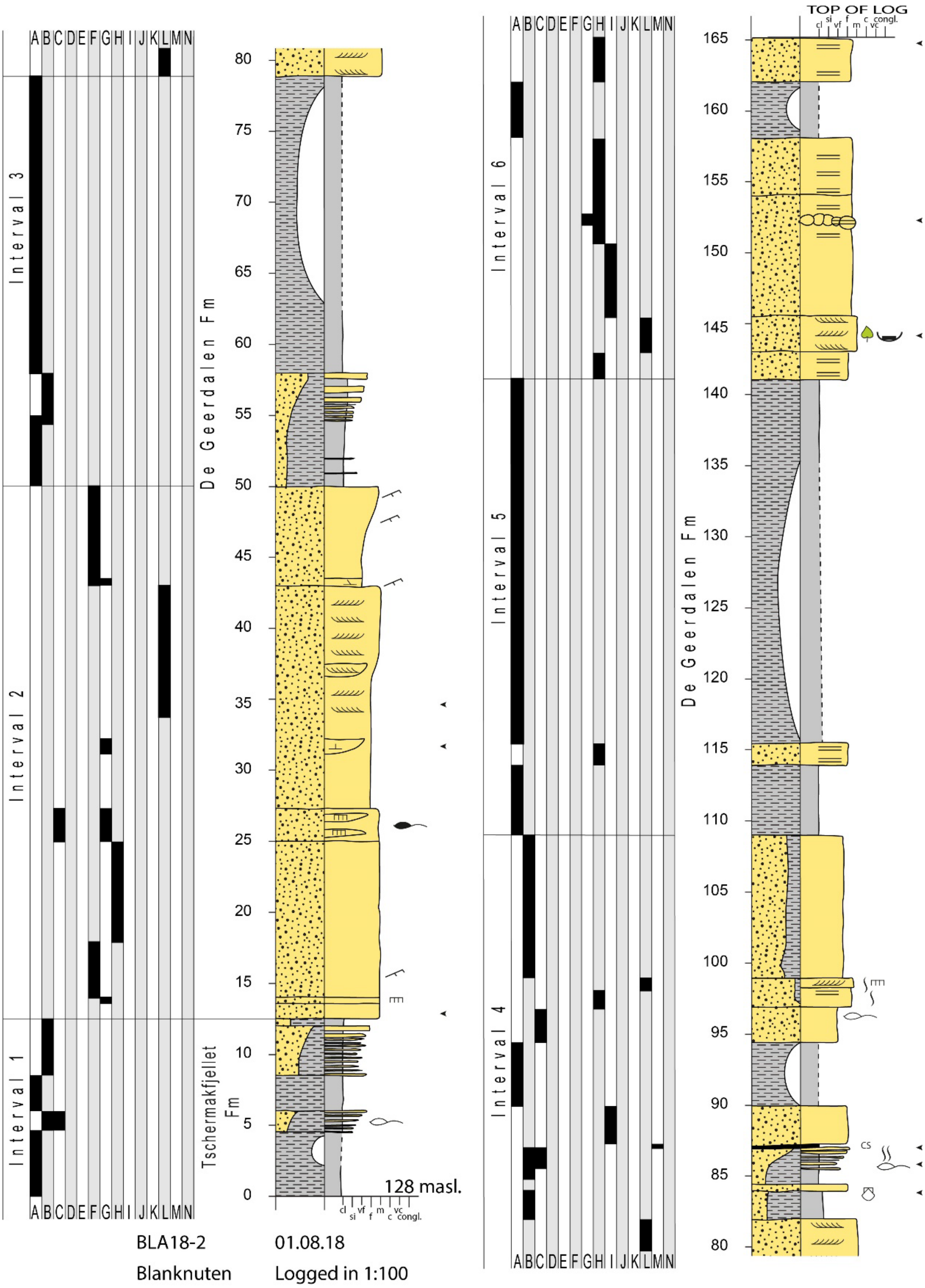
- Planar parallel lamination/stratification
- Low-angle cross-stratification
- Hetrolitic lamination
- Current ripples
- Ripple lamination
- Wave ripples
- Hummocky cross-stratification (smal scale)
- Hummocky cross-stratification (large scale)
- Swaley cross-stratification (large scale)
- Flute casts
- Loading/deformation structure (minor)
- Loading/deformation structure (major)
- Climbing ripples
- 300 Bidirectional palaeocurrent measurement
- 120 Monodirectional palaeocurrent measurement
- Herringbone cross-stratification
- Planar / angular cross-stratification
- Trough cross-stratification
- Wood fragment
- Plant fragmnet
- Coal fragment
- Coal drape
- Mud flake
- Mud clast conglomerate
- Mud drape
- Roots
- Bioturbation (sparse - intense)
- Cone-in-cone
- Erosional surface
- Sample

Log authors

AJ - André F. Jensen
AM - Atle Mørk
FT - Frida Tronbøl
FW - Fredrik Wesenlund
JR - Jostein Røstad
SJ - Sondre K. Johansen

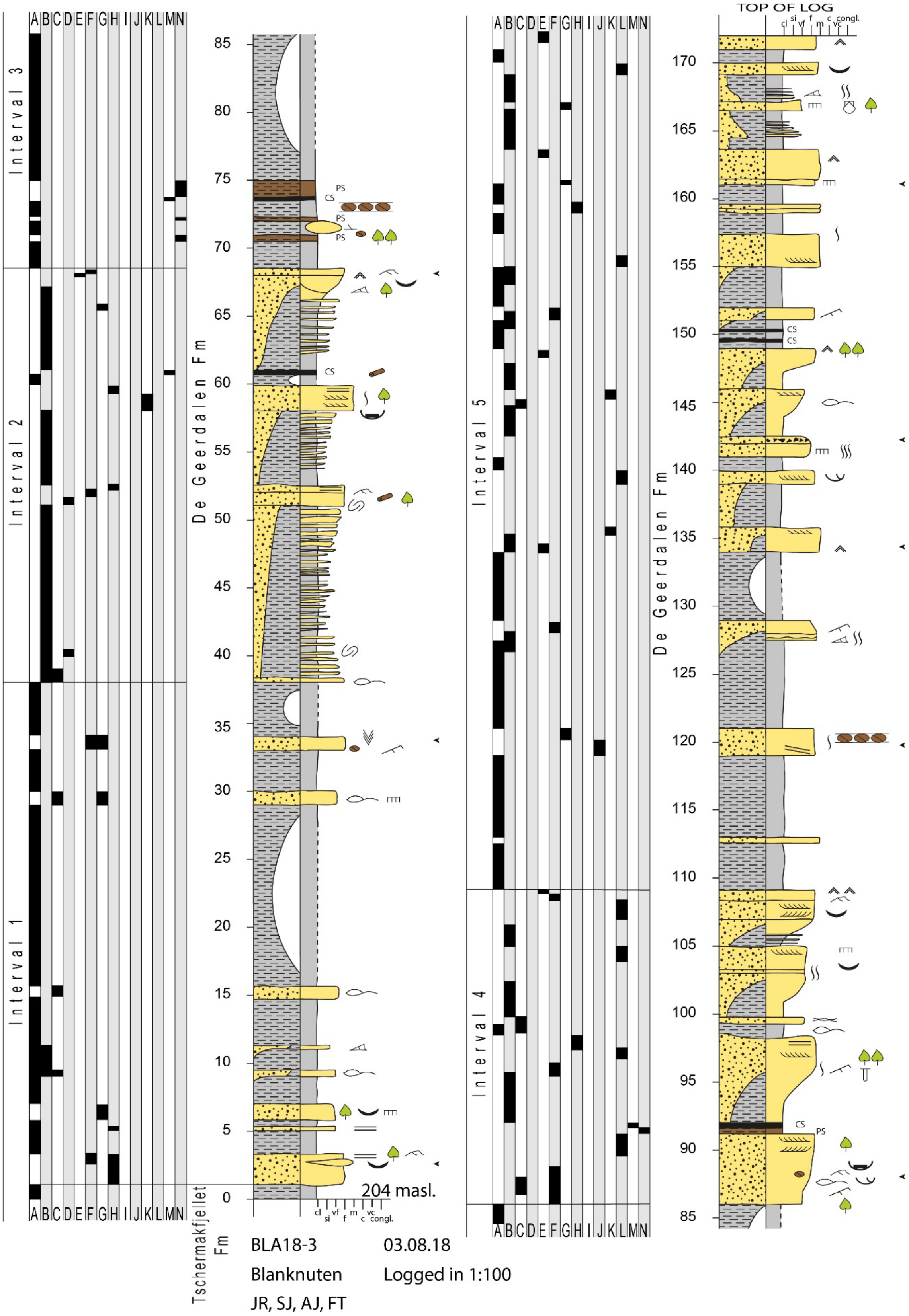
Appendix B: Logs

Appendix B.1: BLA18-2



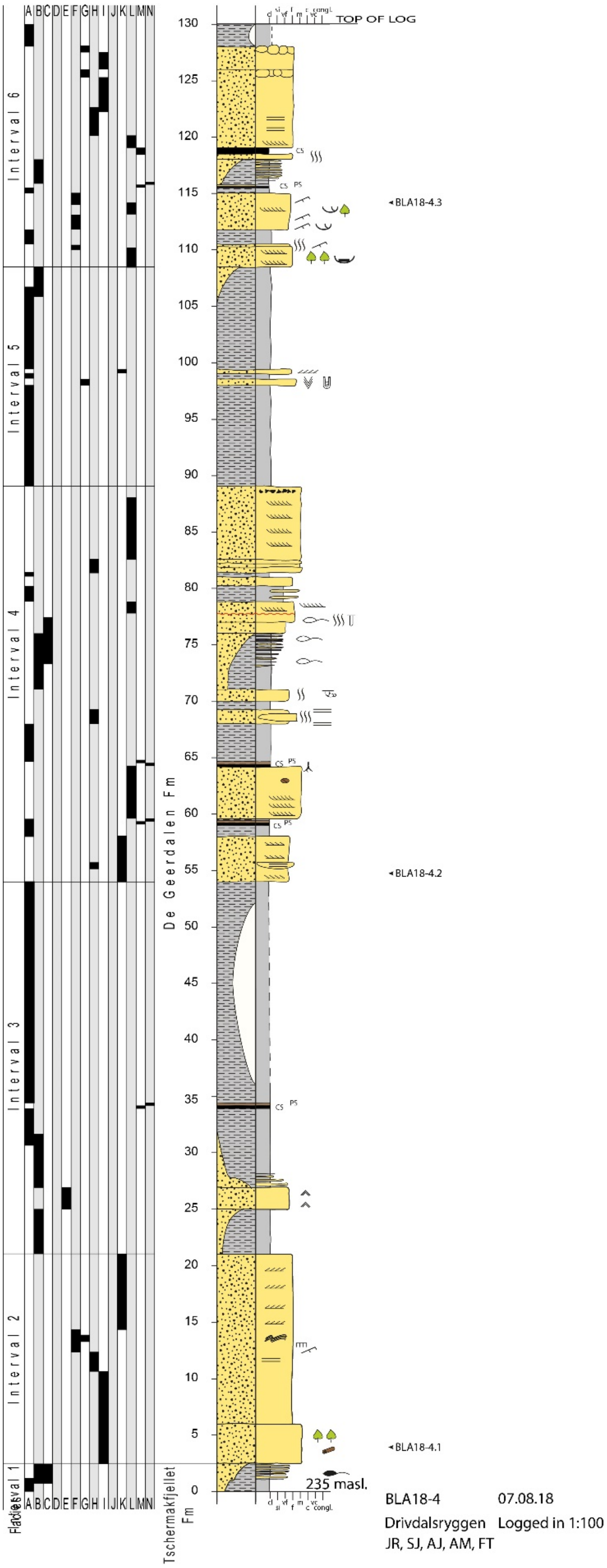
BLA18-2 01.08.18
Blanknuten Logged in 1:100
JR, SJ, AJ, FT

Appendix B.2: BLA18-3

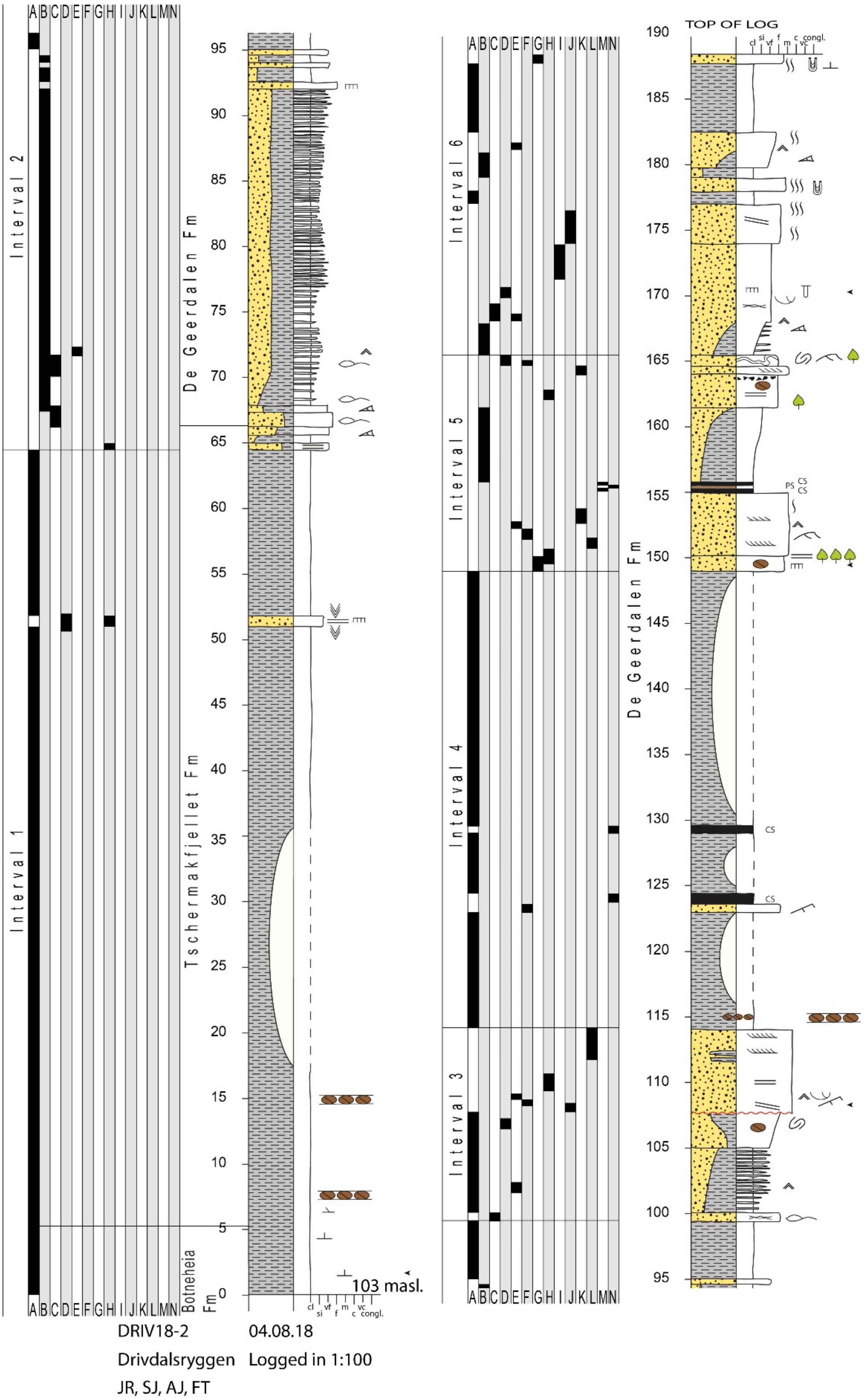


BLA18-3 03.08.18
Blanknuten Logged in 1:100
JR, SJ, AJ, FT

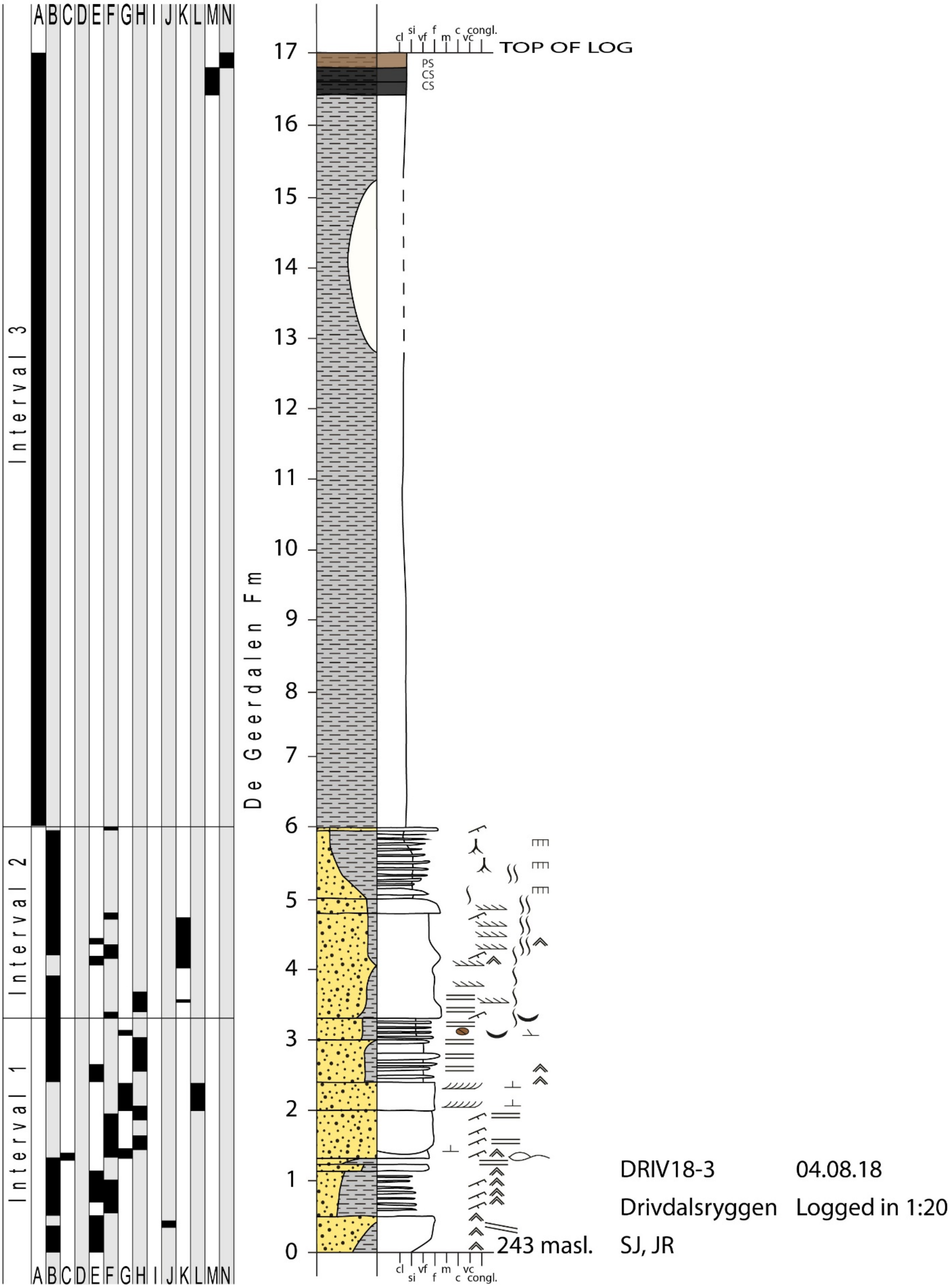
Appendix B.3: BLA18-4



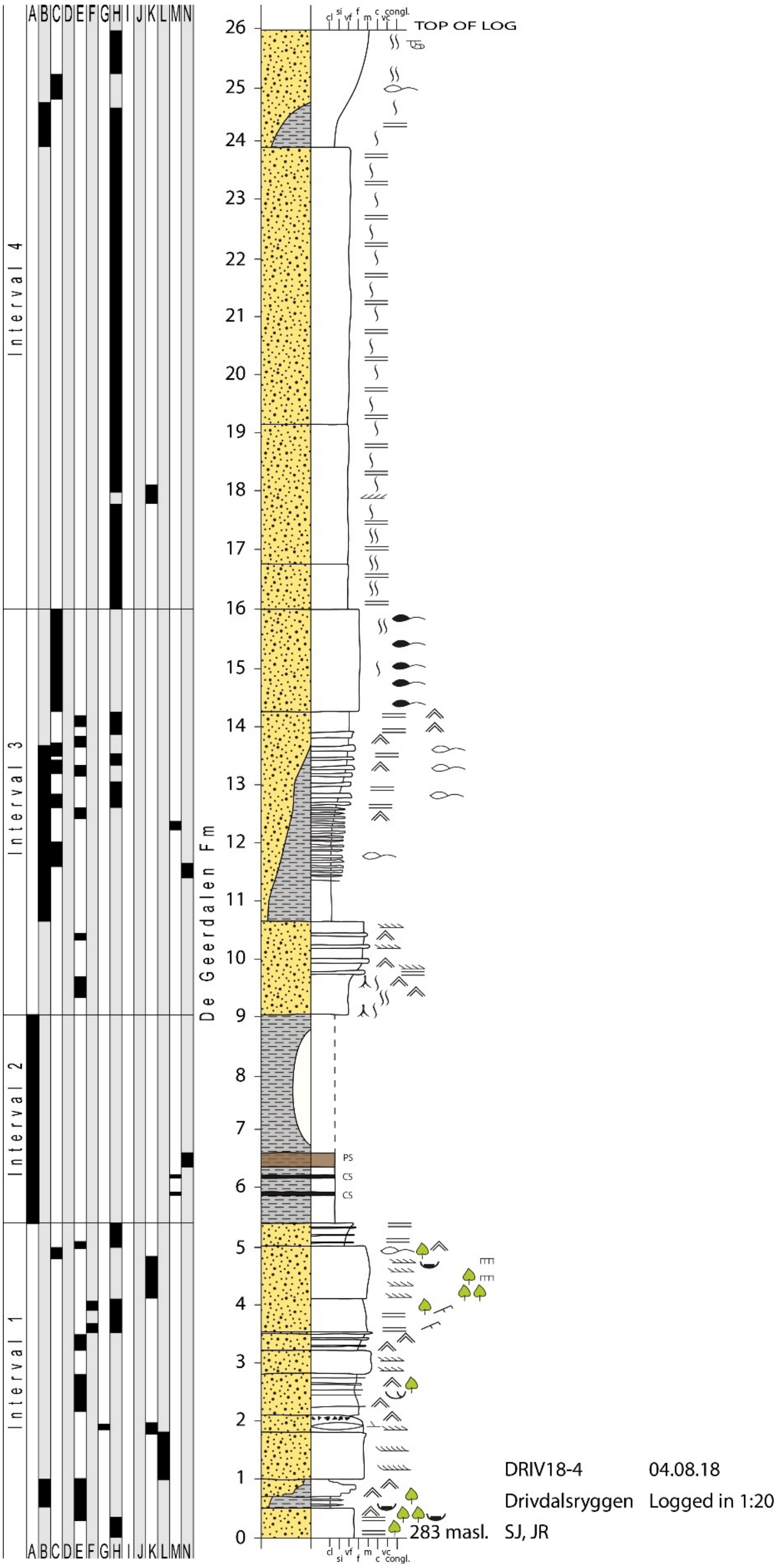
Appendix B.4: DRIV18-2



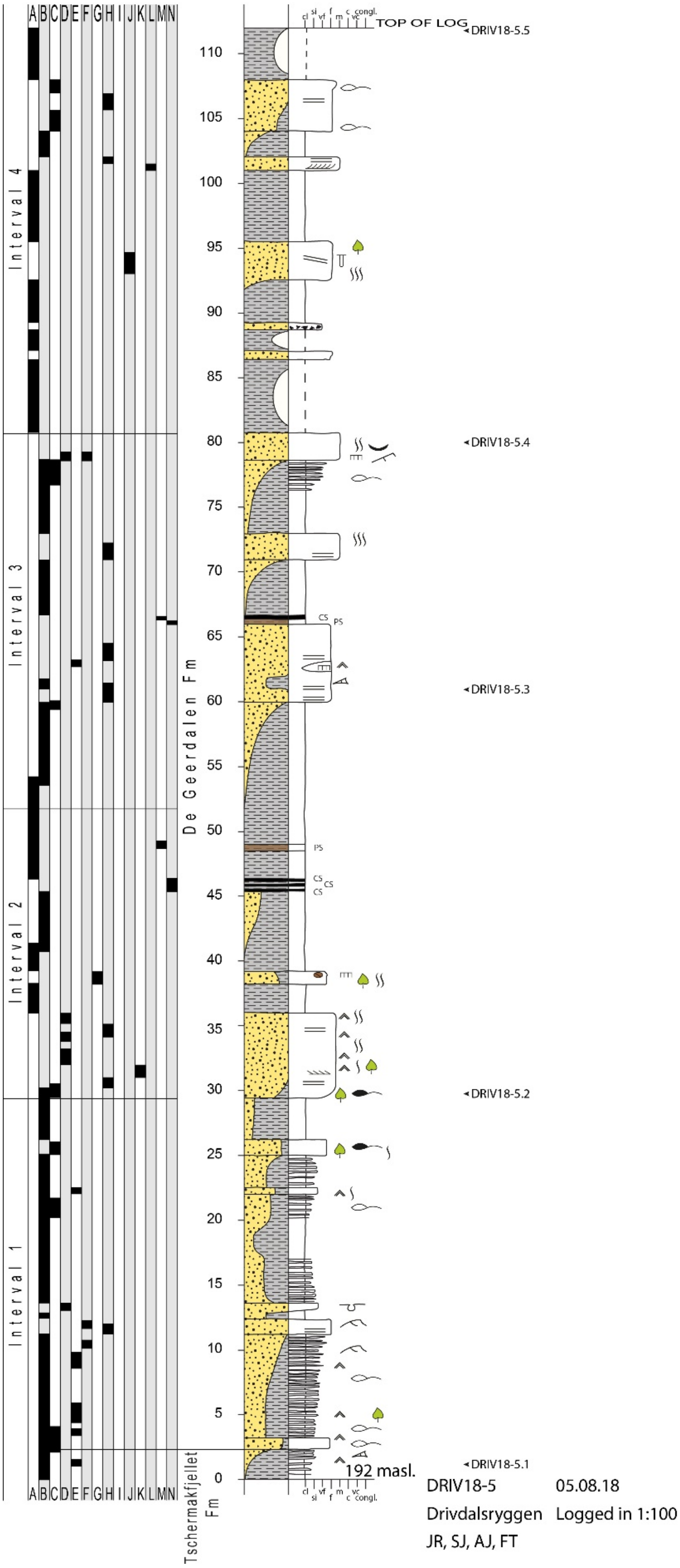
Appendix B.5: DRIV18-3



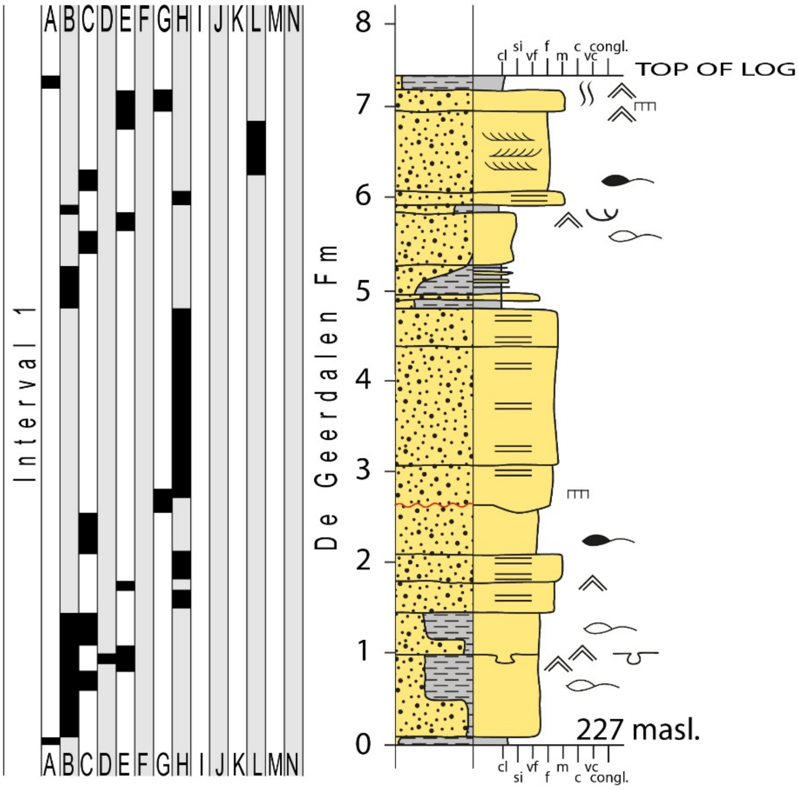
Appendix B.6: DRIV18-4



Appendix B.7: DRIV18-5

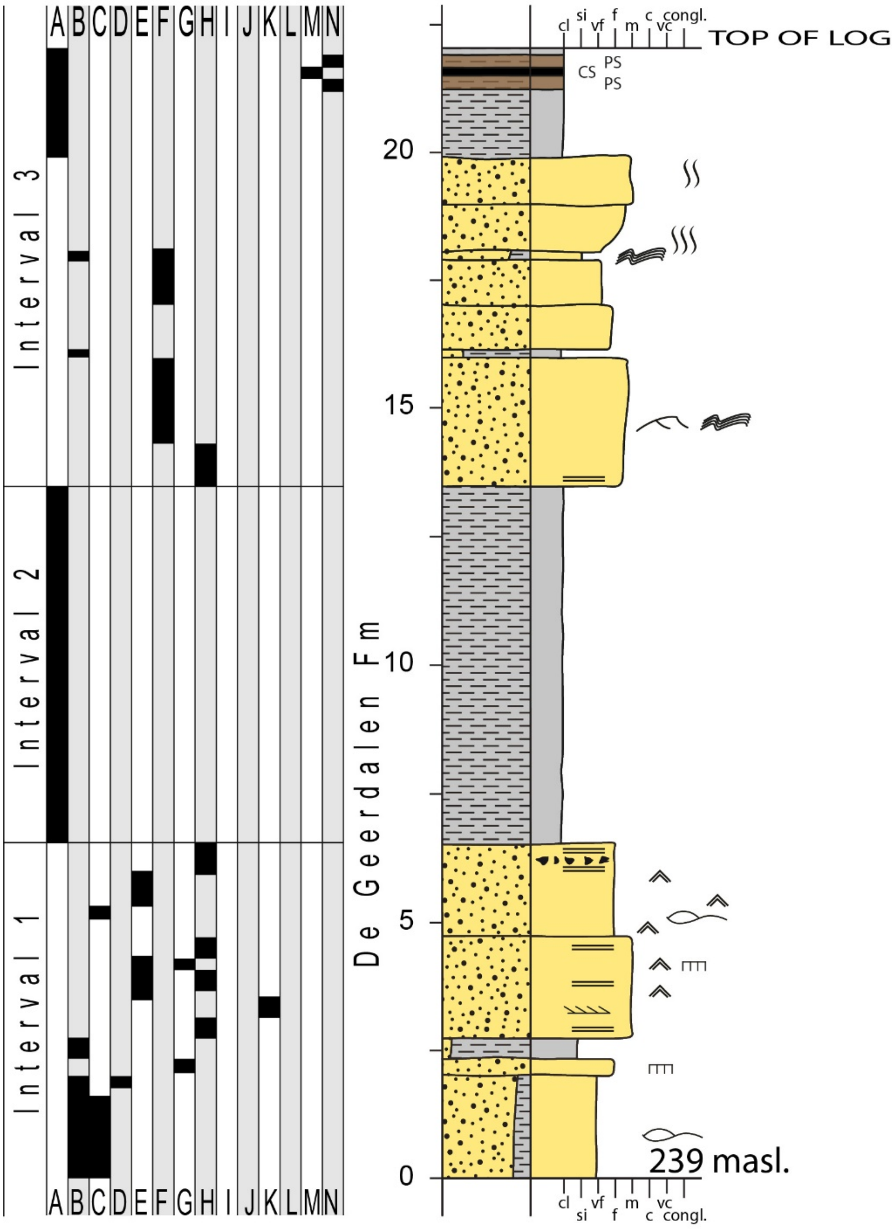


Appendix B.8: DRIV18-6



DRIV18-6 08.08.18
Drivdalsryggen Logged in 1:20
AJ, FT, SJ, JR

Appendix B.9: DRIV18-7

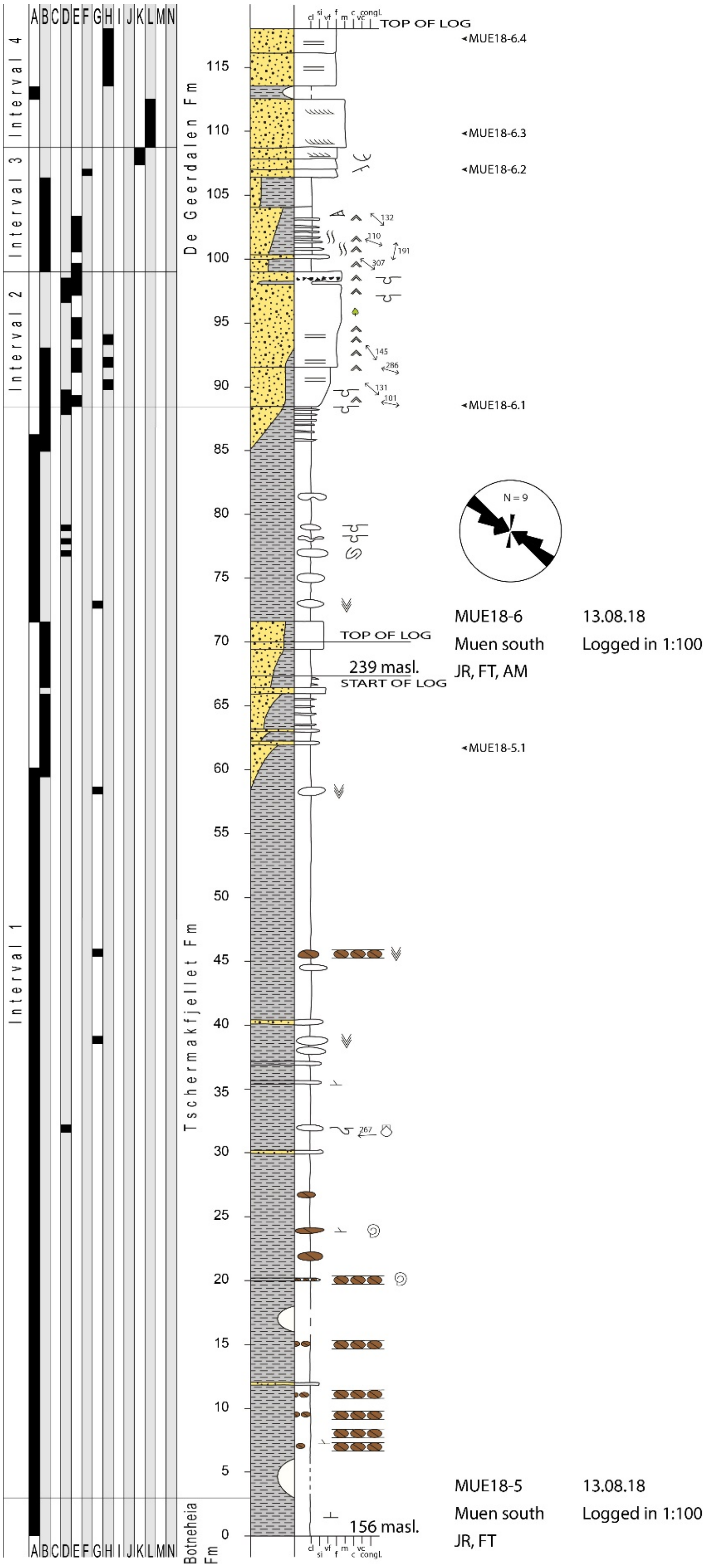


DRIV18-7 06.08.18

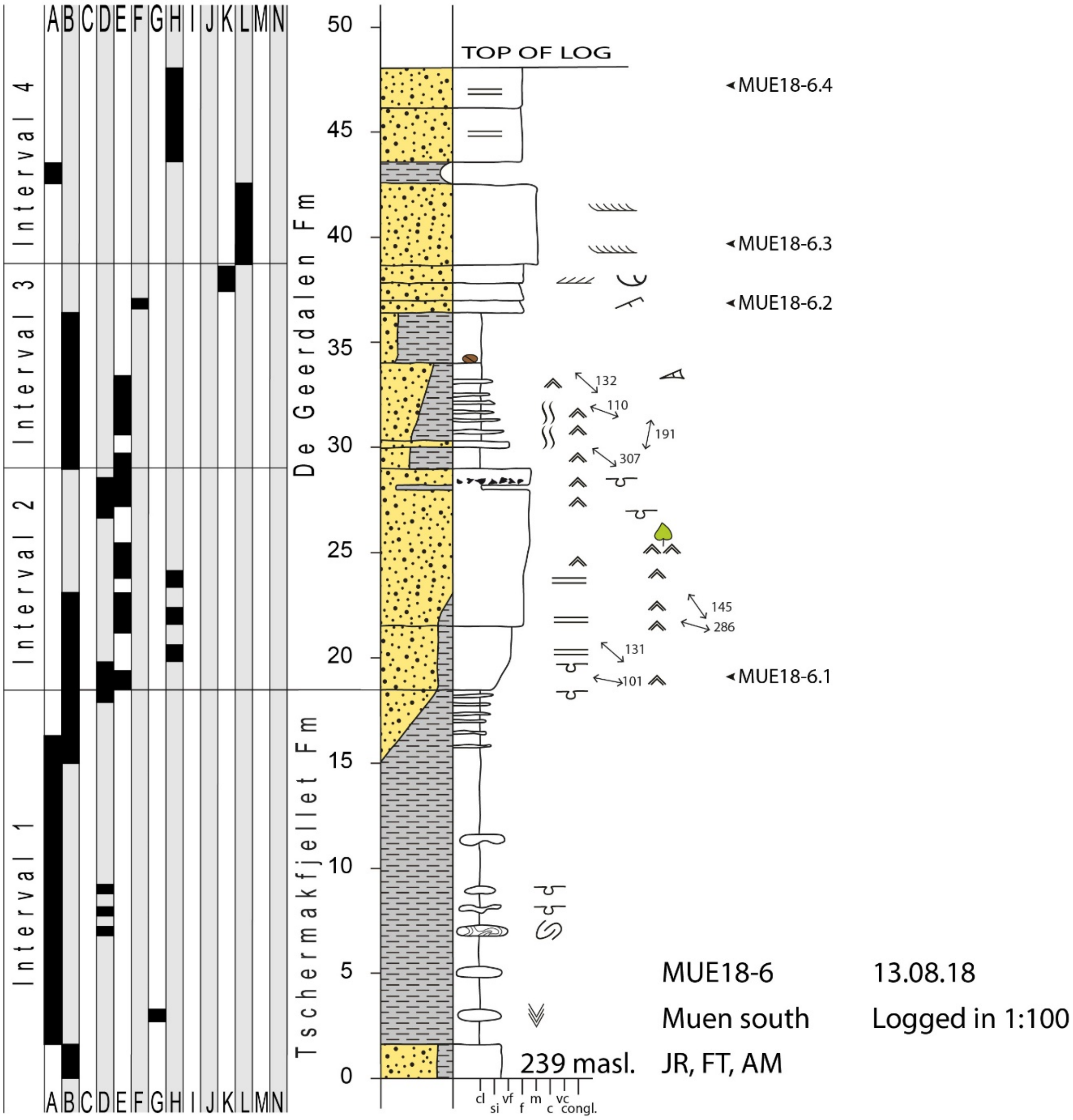
Drivdalsryggen Logged in 1:50

AJ, FT, SJ, JR

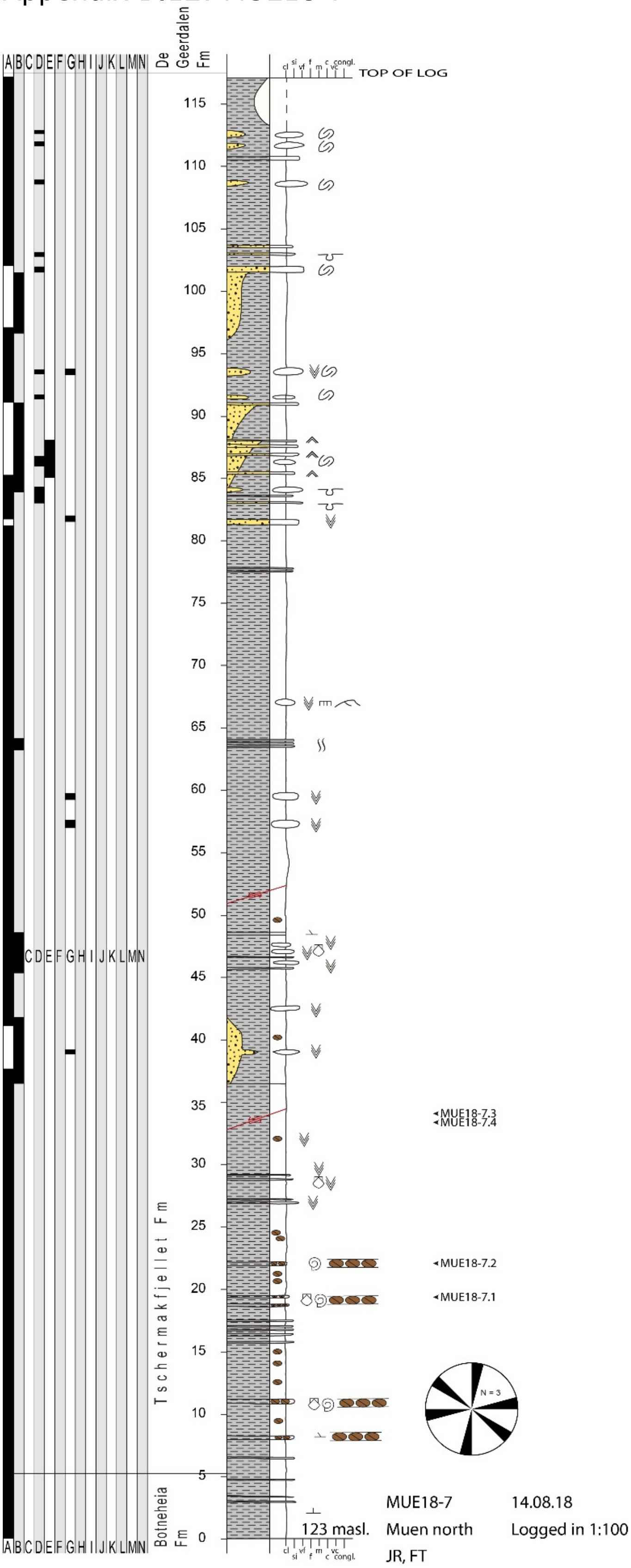
Appendix B.10: MUE18-5 and -6



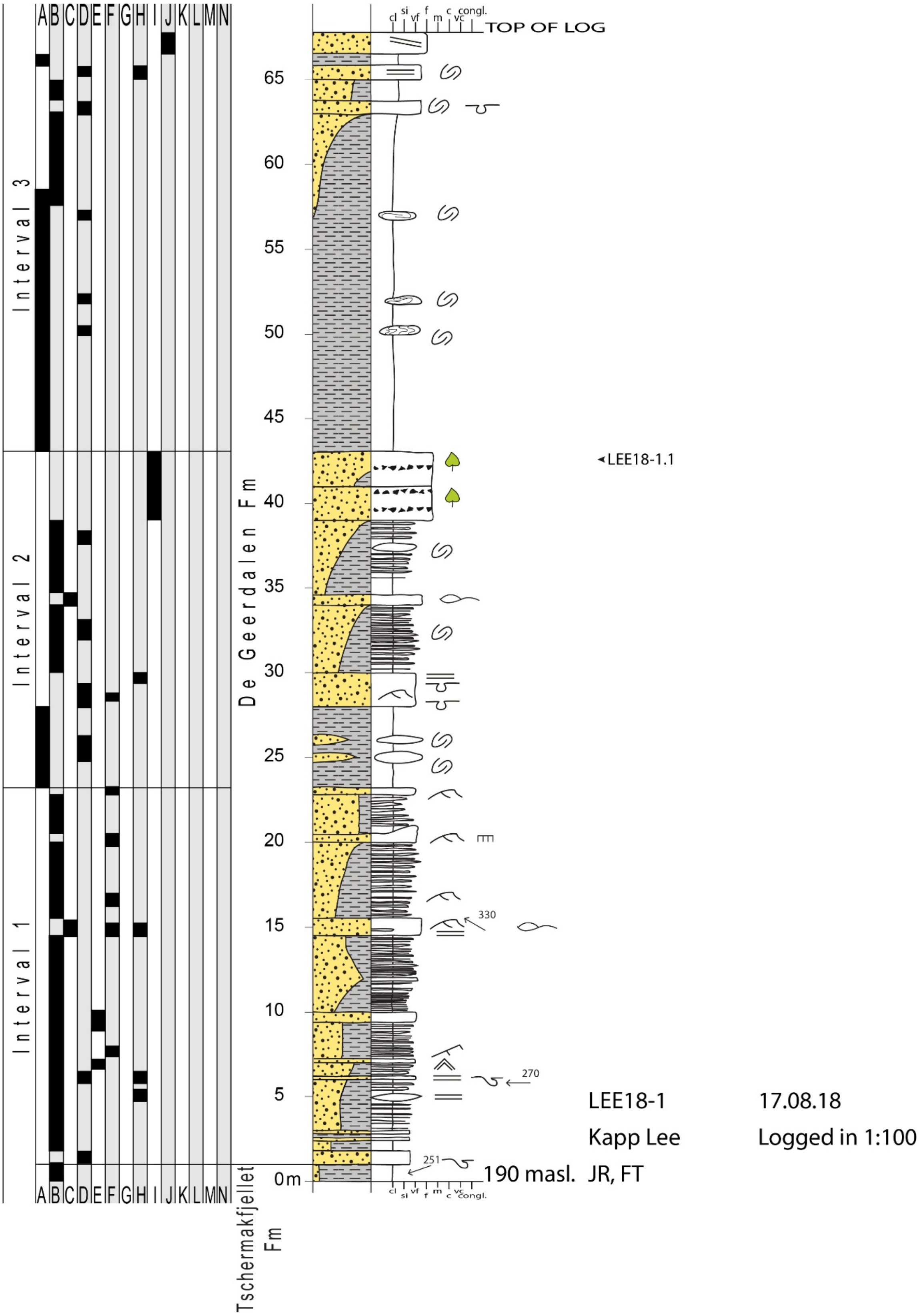
Appendix B.11: MUE18-6



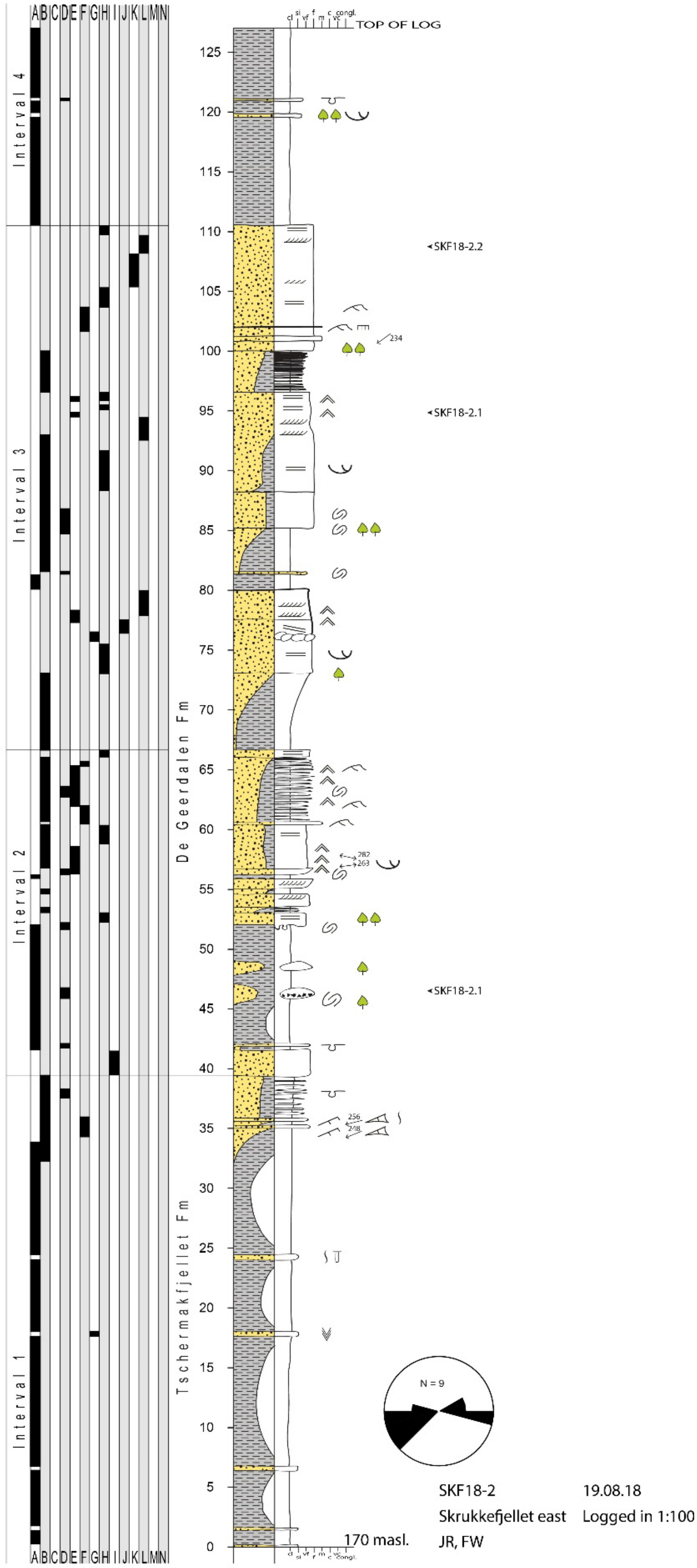
Appendix B.12: MUE18-7



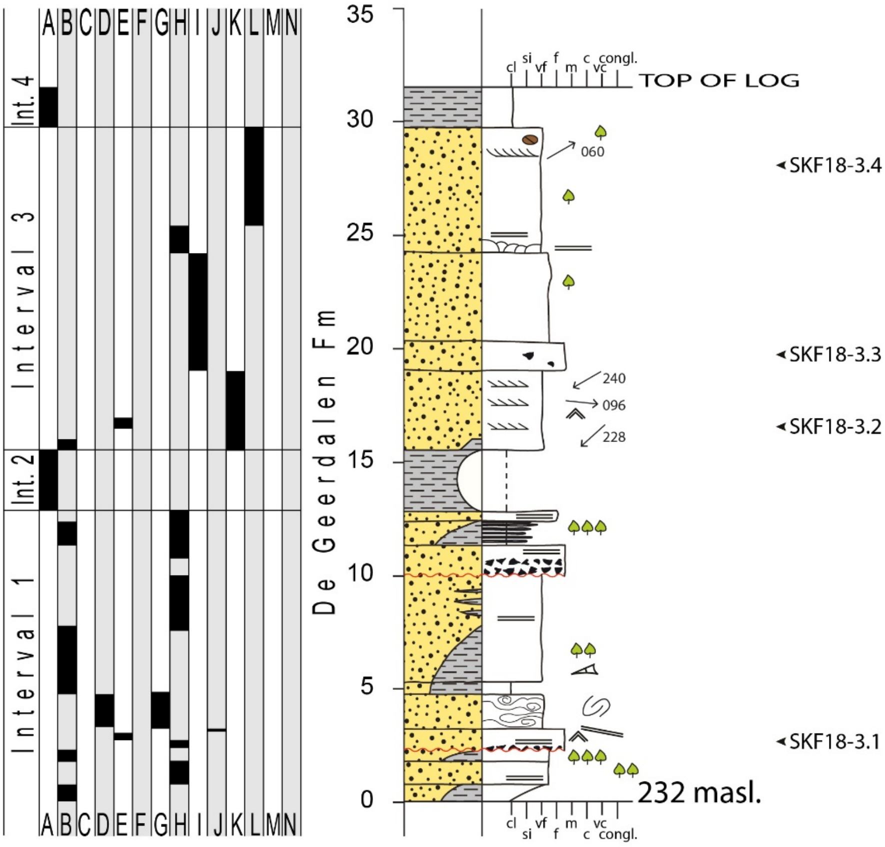
Appendix B.13: LEE18-1



Appendix B.14: SKF18-2



Appendix B.15: SKF18-3



SKF18-3 20.08.18

Skrukkefjellet east Logged in 1:50

JR, AM

Appendix C: Overview of measured sections

		Start of log UTM-coordinates				Top of log UTM-coordinates			
Name of log	**Location**	**Zone**	**Longitude**	**Latitude**	**Altitude**	**Zone**	**Longitude**	**Latitude**	**Altitude**
BLA18-1	Blanknuten	35x	0366139	8662463	246				
BLA18-2	Blanknuten	35x	0366399	8661908	128	35x	0366678	8662187	369
BLA18-3	Blanknuten	35x	0365681	8664361	204	35x	0365852	8663918	437
BLA18-4	Blanknuten	35x	0366700	8661904	235	35x	0366821	8662086	400
DRIV18-1	Drivdalen	35x	0369962	8663200	179	35x	0369337	8663205	425
DRIV18-2	Drivdalsryggen	35x	0369791	8661356	130	35x	0369725	8661659	327
DRIV18-3	Drivdalsryggen	35x	0369722	8661512	243	35x	0369718	8661526	249
DRIV18-4	Drivdalsryggen	35x	0369722	8661595	283	35x	0369731	8661640	325
DRIV18-5	Drivdalsryggen	35x	0369513	8661537	192	35x	0369576	8661733	340
DRIV18-6	Drivdalsryggen	35x	0369397	8661608	227	35x	0369392	8661616	240
DRIV18-7	Drivdalsryggen	35x	0369436	8661590	239	35x	0369479	8661603	246
MUE18-3	Muen	35x	0370441	8643451	263	35x	0370395	8643478	313
MUE18-4	Muen	35x	0370505	8643924	270	35x	0370443	8643932	313
MUE18-5	Muen	35x	0366109	8642080	156	35x	0366372	8642331	245
MUE18-6	Muen	35x	0366506	8642544	239	35x	0366594	8642623	295
MUE18-7	Muen	35x	0367496	8644717	123	35x	0367265	8644103	270
LEE18-1	Kapp Lee	33x	0634120	8675550	190	33x	0634209	8675603	287
PAL18-1	Palibinranten	35x	0364594	8682025	127	35x	0364018	8681641	232
PAL18-2	Palibinranten					35x	0364018	8681641	232
PAL18_3	Palibinranten	35x	0363889	8681550	225	35x	0363880	8681538	235
SKF18-1	Skrukkefjellet	35x	0368132	8683100	184	35x	0368417	8683115	244
SKF18-2	Skrukkefjellet	35x	0369172	8683421	170	35x	0369245	8683251	326
SKF18-3	Skrukkefjellet	35x	0369375	8683395	232	35x	0369382	8683350	261