Acknowledgements

Fieldwork on Svalbard has been an experience. I already look forward to new adventures in the north.

I wish to thank my supervisor Atle Mørk at NTNU/SINTEF for making the fieldwork possible, and for being patient and helpful during the entire process. Also, thanks to my supervisor Maria Jensen at UNIS. I have learned much about sedimentary structures and processes during days in field with you. I would also like to thank participants of the cruises to eastern Svalbard summer 2008 and 2009 for guiding and helping me during data collection. It is no doubt that being a field assistant summer 2008 was important teaching prior to more independent work the following summer. And thanks to my friend and field collaboration partner Rita Sande Rød and our field assistant Marianne Ask for making cold days in field more fun.

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And thanks to my family for motivation and inspiration.

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Abstract

Sedimentological data were obtained for the De Geerdalen Formation (Upper Triassic) from outcrop studies at Edgeøya, Hopen and central Spitsbergen to reconstruct the palaeo-depositional environment of the formation. Data from fieldwork 2009 in addition to earlier studies makes it possible to assess the formations changing sedimentation pattern. Lateral variations were mapped by logging several vertical sections in adjacent areas and helicopter based LIDAR-scans were taken at Edgeøya to be used for later spatial studies of sandstone bodies. Good exposures, especially in the eastern part of the Svalbard archipelago give important information on unit thicknesses, lateral and vertical facies variations and spatial distributions of sand bodies. This investigation is a part of the Longyearbyen CO_2 project, aiming to store CO_2 in bedrock below Longyearbyen, where sandstones from De Geerdalen Formation are the expected target.

Earlier studies, using sedimentological data, have suggested the De Geerdalen Formation to represent a shallow marine to prograding delta deposit (Mørk et al. 1982). Recent studies of the Middle and Late Triassic succession show prograding clinoforms from ESE, likely to represent De Geerdalen Formation east of Svalbard, (Riis et al. 2008). Our data support the later studies indicating a dominating ESE source.

On central Spitsbergen the lower part of De Geerdalen Formation contains fine-grained sandstone units with thicknesses about 5 m, showing storm (hummocky) and shoreline structures. Sandstones in the upper part have greater thicknesses up to 25 m, displaying both channel systems and tidally influenced shoreface deposits. The coarsest grain-sizes found in the sections are medium-grained. Measured sections on the eastern part of Svalbard contain sand units representing channel, tidal and shoreface environment. Growth faults are evident in some areas on Edgeøya. Sandstone thicknesses up to 30 m are present, and it shifts laterally between fine to medium-grained channel sands and fine-grained shallow marine sandstones. Thin coal layers, some with rootlets, are developed in the eastern sections, and channel sands are present more frequently. The data indicates an earlier development of proximal facies associations on eastern Svalbard than on central Spitsbergen, generally with a regressive pattern in both areas.

1. Introduction

1.1 Purpose

The object of this work is to make a depositional model for the De Geerdalen Formation on Svalbard, based on sedimentary properties, thicknesses and spatial distribution of sandstone bodies. Earlier work has recognized a changing appearance of the formation from eastern to western areas on Svalbard. By focusing on the eastern areas (Edgeøya and Hopen) in addition to central Spitsbergen it is possible to investigate this changing sedimentation pattern.

1.2 Study area

The Svalbard archipelago is located 74-81ºN, 10-35ºE on the northernmost corner of the Barents Shelf (Dallmann 1999), and includes a number of small islands in addition to Spitsbergen, Nordaustlandet, Barentsøya, Hopen and Edgeøya (Worsley 1986). Study areas include Edgeøya and Hopen on eastern Svalbard, and Botneheia to Sassendalen on central Spitsbergen (see Chapter 2).

Botneheia and mountains in Sassendalen are located 20-30 km from Longyearbyen, the main settlement on the Svalbard archipelago. This area is generally poorly glaciated and comprises broad glacial valleys with fluvial plains and mountains rarely exceeding 1000 msl (Dallmann et al. 2001). The choice of study area was relatively good exposure of continuous lateral sections of De Geerdalen Formation and vicinity to possible CO_2 injection location in Adventdalen. Edgeøya and Hopen are located respectively E and SSE of Spitsbergen, and comprise glacially eroded mountains up to about 600 msl and good exposures of the formation.

1.3 Previous work and researches

The first work on Triassic rocks was carried out from the mid 19th century by Swedish expeditions led mainly by A. E. Nordenskiöld, and later G. De Geer and A. G. Nathorst. Early focus of investigation was macropalaeontology, and collection of fossils was made at different localities within the Svalbard archipelago. Based on this early work the foundation of stratigraphical nomenclature was made in the 20th century (Buchan et al. 1965). Several publications and reports came as a result of the expeditions and field work in this period (Buchan et al. 1965). Buchan et al. (1965) contributed to extended work on lithostratigraphy of the Triassic succession, and several stratigraphical sections where measured together with sampling of rocks *in situ* (Buchan et al. 1965; Mørk et al. 1982). Biostratigraphical studies were made by Tozer and Parker (1968) and Korcinskaja (1971) (Mørk et al. 1982).

Detailed sedimentological and stratigraphic studies of the De Geerdalen Formation were carried out in the period 1977-1984, representing the present stratigraphic understanding of the unit (Knarud 1980; Mørk et al. 1982, 1999).

Later studies on De Geerdalen Formation have been carried out on Edgeøya in a cooperating project between Norwegian Petroleum Directorate (NPD) and SINTEF Petroleum Research during fieldwork summer 2007, 2008 and 2009. Focus of study has been the sedimentology and growth faults in the area, aiming to reconstruct the palaeogeography and for comparisons with offshore areas (Riis et al. 2008).

1.4 Regional geological setting

The Svalbard archipelago is a segment of the Eurasian Plate, which was uplifted by late Mesozoic and Cenozoic tectonics (Dallmann 1999). Continuous northward movement during the post-Caledonian time led to changing tectonic and climatic controls during the journey from a equatorial position in late Devonian to the present position in the high Arctic (Worsley 2008). Striking features at the present configuration of Svalbard are NNW-SSE trending lineaments, probably formed during the Caledonian orogeny with subsequent re-activation in Devonian/Carboniferous and Tertiary tectonic events (Steel and Worsley 1984; Fossen et al. 2006) . The most evident lineaments are Lomfjorden/Agardhbukta, Inner Hornsund, Palaeo-Hornsund and Billefjorden, where the varying movement style has affected the sedimentation pattern during the geological history (Steel and Worsley 1984). The geological history of the archipelago is displayed in continuous successions of sedimentary rocks, and can contribute to better understanding of the subsurface of neighboring Barents Shelf geology (Hjelle 1993; Worsley and Nøttvedt 2006).

The basement rocks (Hekla Hoek) of the archipelago is composed of Precambrian to early Silurian rocks, metamorphosed during the Caledonian orogeny in late Silurian and possibly older orogenic events of Precambrian age (Dallmann et al. 1999; Worsley 2008). There are uncertainties about how the Caledonian orogeny affected Svalbard, but it is believed to involve large-scale lateral movements gathering three structural provinces of basement rocks (Worsley 2008). Hekla Hoek are found in three tectonostratigraphic basement provinces; the NE province, the north-central and westerly province (Dallmann 1999; Worsley 2008).

In the Devonian there was a shift to an extensional regime on Svalbard, with deposition of continental rift basin sediments, often referred to as “Old Red Sandstone” (Fossen et al. 2006). The sediments are mainly found in the northern part of Spitsbergen in down faulted blocks between Raudfjorden Fault to the west and the Billefjorden Fault to the east (Fossen et al. 2006). The succession has a thickness of approximately 8 km in total, and display a shift in depositional environment from the characteristic “Old Red” clastic alluvial and fluvial deposits to more marine and tidewater influenced grey deposits in younger strata (Worsley 1986; Fossen et al. 2006). The change likely reflects a transition from the southern arid zone to more humid climate conditions (Worsley 2008). In late Devonian “Svalbardian event” there was a re-activation of older faults from the Caledonian orogeny contemporaneously with compression across the faults (transpresion), resulting in deformation of the sediments localized close to these zones (Fossen et al. 2006).

Carboniferous sediments where deposited in a changing graben setting, and during the time period the rift basins got narrower with increased subsidence (Steel and Worsley 1984; Worsley and Nøttvedt 2006). The succession is laying unconformably on top of Hekla Hoek basement or the “Old Red Sandstone” (Steel and Worsley 1984). Climatic conditions changed considerably throughout the period reflected in deposits varying from fluvial sandstone, shale and coal early in Carboniferous (Billefjorden Group), to carbonates, evaporites and red-sandstone sediments from the mid-Carboniferous (Gipsdalen Group) (Worsley and Nøttvedt 2006). The changing deposits tell about a transition from humid to semi-arid climate, and a decrease in tectonic activity during the late Carboniferous (Steel and Worsley 1984; Worsley and Nøttvedt 2006).

In early Permian Svalbard developed into a stable carbonate platform, with sediments shifting from marine limestone to evaporites deposited in sabkha environment (Worsley 1986; Dallmann 1999). The rhythmic depositions can possibly be explained by glaciation of Gondwanaland (Worsley and Nøttvedt 2006). Changing tectonic and climatic conditions in late Permian, with development of a intracratonic seaway on the western shelf and transition into the temperate climate zone, resulted in renewed clastic sediment depositions (Worsley and Nøttvedt 2006; Worsley 2008). In southern Barents Sea the sedimentation was affected by development of the Uralides (Riis et al. 2008; Worsley 2008). Typical of late Permian sediments are the high silica content, showing in outcrops as cliff-forming layers (Worsley 1986).

Humid climate conditions continued into the Triassic and remained throughout most of the Mesozoic, while the platform moved from 50º-70º N during the period (Worsley 1986).
The stable platform conditions developed in late Permian prevailed into the Mesozoic (Steel and Worsley 1984). Triassic at Svalbard was a relative quiet period regarding tectonic activity, except from some movements along existing lineaments (Steel and Worsley 1984; Riis et al. 2008). Exposures are mainly found on eastern Spitsbergen, Edgeøya and Barentsøya, where they are relatively flat-lying (Mørk et al. 1982). Folded or thrusted Triassic rocks can be found in the western fold-and thrust belt on Spitsbergen (Mørk et al. 1982). The succession are divided into two lithostratigraphical groups; Sassendalen Group and lower part of Kapp Toscana Group (Mørk et al. 1999).

Sedimentation in early to mid-Triassic was dominated by shale and mudstone deposition, representing delta to shallow marine environment (Dallmann 1999; Worsley 2008). Coarser units from this period are found to the west on Svalbard, where positive areas on the platform existed (Worsley 1986). Transgressive-regressive sequences, representing sea-level change and varying sediment input, are characteristic for the succession and correlative to other Triassic basins (Mørk et al. 1999; Riis et al. 2008). Deposition of shale and mudstone continued in Late Triassic, grading into riverplane and prograding delta deposits in the De Geerdalen Formation.

Jurassic at Svalbard was a time of mainly shallow marine deposition of mudstone and sandstone in a transgressive coastal environment, unaffected by the rifting in the Norwegian Sea (Johannessen and Nøttvedt 2006).

Deposition of mudstone continued into the Early Cretaceous, gradually changing into more sandy sediments caused by uplift and following regression (Rurikfjellet Fm.) (Brekke and Olaussen 2006). Global rise in sea level resulted in alternating sandy and coal bearing layers divided into the Helvetia Fm. and Carolinefjellet Fm. (Brekke and Olaussen 2006). The episodes of uplift during the Cretaceous was caused by opening of the Arctic Ocean, and resulted in eroded and tilted units northwards (Brekke and Olaussen 2006).

In Paleogene Svalbard experienced increased tectonic activity with development of the Tertiary compressive belt in West Spitsbergen, before the final opening of the Norwegian-Greenland Sea in Eocene/Oligocene (Dallmann 1999; Worsley 2006). Paleogene sediments are found in foreland basins developed on central Spitsbergen, east of the fold-and-thrust belt (Martinsen and Nøttvedt 2006). Dominating clastic infill from this period is included into the lithostratigraphical Van Mijenfjorden Group (Dallmann et al. 1999). The deposits show structures indicative of paleotransport direction changing from west to east during Paleogene, suggesting varying source area during development of the Tertiary mountain chain caused by different tectonic movements (Martinsen and Nøttvedt 2006).

During Neogene and Quaternary time repeated glaciation cycles took place, resulting in clastic sedimentation on the shelf edge and later uplift and erosion related to isostatic rebound (Worsley 2008). Volcanic rocks are found on NW Spitsbergen, related to volcanic activity in Neogene and Quaternary (Dallmann 1999). Suggested source for the late Quaternary volcanism is a hot spot on Yermak plateau NW of Spitsbergen, while the Neogene volcanites are plateau basalts (Dallmann 1999; Worsley 2008).

This post-Triassic development on Svalbard can be important to consider when dealing with deformation and diagenesis of the Triassic sediments. One example is the earlier mentioned different dip of the exposures from west to east on Svalbard, caused by decreased influence of the fold-and-thrust belt eastwards on the archipelago. The Tertiary deformation pushed pre-Tertiary sediments in from a westerly direction, resulting in folding and thrusting of the sediments (Knarud 1980). According to Knarud (1980) some of the westerly profiles on Spitsbergen can be misleading regarding thickness because of faults in the area. During Jurassic, Cretaceous and Tertiary time there have also been tectonic movements along the Billefjorden/Flowerdalen and Lomfjorden/Agardhbukta lineaments affecting the Triassic sediments (Knarud 1980; Steel and Worsley 1984).

In addition to faulting of some of the Triassic sediments, a number of dike and sills cut the Mesozoic strata in many areas on Svalbard (Mørk et al. 1999). There have been discussions regarding age of these intrusions, but resent dating tells about an Early Cretaceous age (pers.com. K. Krajewski 2008). The influence of these intrusions on the Triassic sediments are observed to be hornfelsing and calcification of host rocks, most commonly shale and siltstone (Mørk et al. 1999).

1.5 The Kapp Toscana Group

The Kapp Toscana Group includes sediments of Carnian (Late Triassic) to Bathonian (Middle Jurassic) age at Svalbard, and is named after the locality Kapp Toscana on the south coast of Van Keulenfjorden (Mørk et al. 1982, 1999). Type area are central eastern Spitsbergen, and the group are exposed along the Cenozoic fold-and-thrust belt on Western Spitsbergen, on central and eastern Spitsbergen, on Barentsøya, Hopen, Edgeøya, Kong Karls Land and Bjørnøya (Mørk et al. 1999, Riis et al. 2008).

Lithostratigraphy of the Kapp Toscana Group

The unit was first defined by Buchan et al. (1965) as a formation, with Tschermakfjellet and De Geerdalen ranked as members. Harland et al. (1974) later revised this division by upgrading Kapp Toscana as a group equal to the underlying Sassendalen Group and the overlying Adventdalen Group (Mørk et al. 1982). There have been several contributions to the discussion concerning the stratigraphical nomenclature on this unit; Worsley 1973; Knarud 1980; Mørk et al. 1982, 1999.

The most resent edition of the lithostratigraphical division of this time period is described by Mørk et al. (1999) (Figure 1). This work accept the definition of Kapp Toscana as a group made by Harland et al. (1974), and suggest a subdivision into the subgroups; Storfjorden Subgroup (Mørk et al. 1999), Realgrunnen Subgroup (Worsley et al. 1988), Wilhelmøya Subgroup (introduced as a formation by Worsley 1973) (Mørk et al. 1999). Tschermakfjellet and De Geerdalen are established as formations like the previous definition made by Mørk et al. (1982). The Kapp Toscana Group includes several formations and members of younger ages (Jurassic age), none of which have continuous lateral extension throughout the Svalbard archipelago.

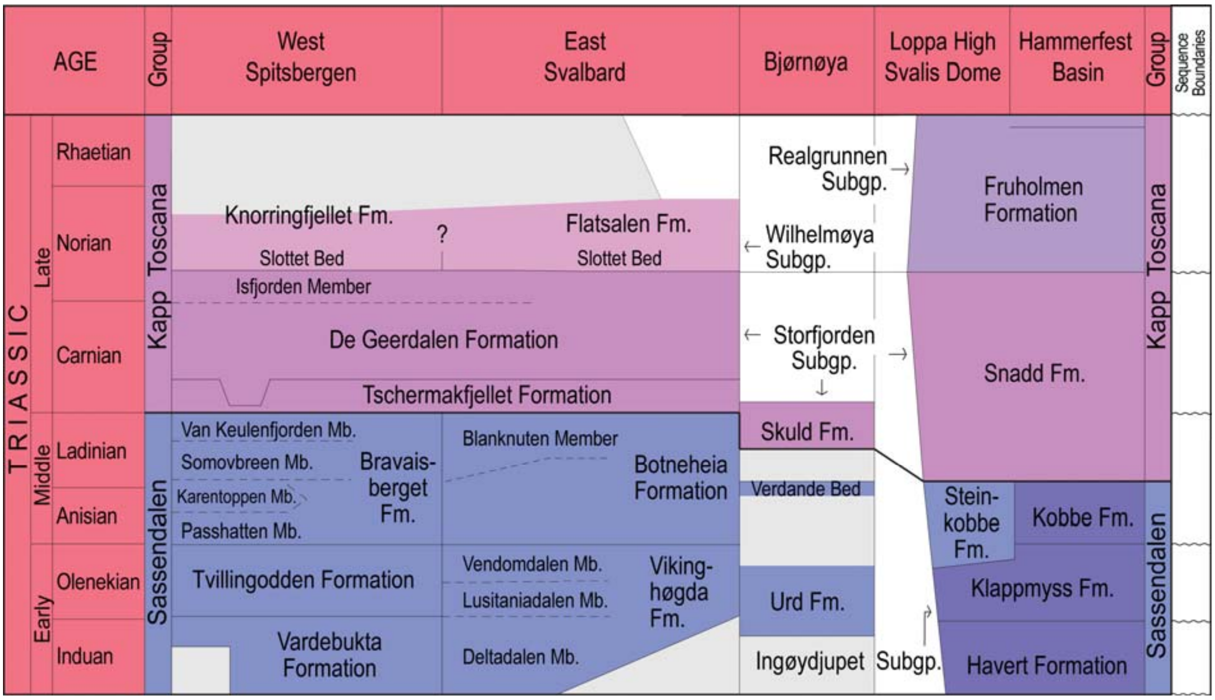


Figure 1: The Triassic lithostratigraphy of Svalbard and the southern Barents Sea. Figure from Riis et al. (2008), simplified from Mørk et al. (1999).

The De Geerdalen Formation is of Carnian to early Norian age (Late Triassic), bounded by the underlying Tschermakfjellet Formation and the overlying Wilhelmøya Subgroup (Figure 2) (Mørk et al. 1999). The formation consists of repeated coarsening-upwards successions, with fine sandstone and shale as the main lithology (Mørk et al. 1999). Appearance of the cliff forming sandstone units varies form massive- to upwards fining sandstones with different weathering surfaces (Mørk et al. 1999). Deposit thickens increase to the east and northeastwards, from about 230-300 m on central and eastern Spitsbergen to 400 m on Edgeøya (Mørk et al. 1999; Mørk and Worsley 2006). On Edgeøya there has been erosion on top of the De Geerdalen Formation, and younger deposits are mainly missing (Mørk et al. 1982; Mørk et al. 1999). The sand-content of the unit is increasing towards SW and NE, principally texturally and mineralogically immature (Mørk et al. 1982; Mørk and Worsley 2006). The lower boundary is defined at the base of the first pronounced sandstone bed (Mørk et al. 1999).

Botneheia was suggested as type section by Buchan et al. (1965), later changed to Storfjellet located in central Sabine Land (Mørk et al. 1982; Mørk et al. 1999). The reason for defining a new type section was an incomplete section at Botneheia (Mørk et al. 1982). Dalsnuten is regarded as hypostratotype, earlier argued by Mørk et al. (1982) to represent a more complete section with good exposure.

On Central Spitsbergen the upper part of De Geerdalen Formation contains the *Isfjorden Member*, first defined by Pcelina (1983) as a formation (Mørk et al. 1999). It mainly contains interbedded shale, siltstone and sandstone, with abundant wave and ripple lamination (Mørk et al. 1999). The lower boundary of the member is defined at the base of a siltstone bivalve coquina bed, and can be recognized in lithological work made by Knarud (1980) at Storfjellet, Festningen and Dalsnuten-Breikampen (Mørk et al. 1999).

The Wilhelmøya Subgroup contains texturally mature sandstone, shale, mudstone and conglomerate (Mørk et al., 1999). Typical for the subgroup are phosphatic nodular beds, occurring both at the base (Slottet Bed) and in the upper part of the section (Brentskardhaugen Bed) (Mørk et al. 1999).The Slottet bed occurs both on eastern Svalbard, Hopen, Wilhelmøya and central Spitsbergen (Mørk et al. 1999). The lateral variations are significant, with a varying condensed development and a decrease in thickness towards west/northwest (Mørk et al. 1999).

Figure 2: Outcrop of the Botneheia, Tschermakfjellet and De Geerdalen formations on Klinkhamaren (Edgeøya). Growth faults are present in the Tschermakfjellet Formation and lower part of the De Geerdalen Formation, described by Edwards (1976) on southern Edgeøya and later studied during cruises organized by the Norwegian Petroleum Directorate in summer seasons 2007-2009. Picture is taken by A. Mørk.

Palaeogeography

The Kapp Toscana Group has a different sedimentation pattern from the underlying Sassendalen Group, and varying sediment sources during the period created complex sedimentary units (Mørk et al. 1999; Riis et al. 2008). The group's lower boundary is time-transgressive, with an earlier development in the southern Barents Sea than at Svalbard (Riis et al. 2008). The Snadd Formation (Ladinian) to the south are correlative to the

Tschermakfjellet and the De Geerdalen Formation (Carnian) developed at Svalbard (Figure 3) (Riis et al. 2008).

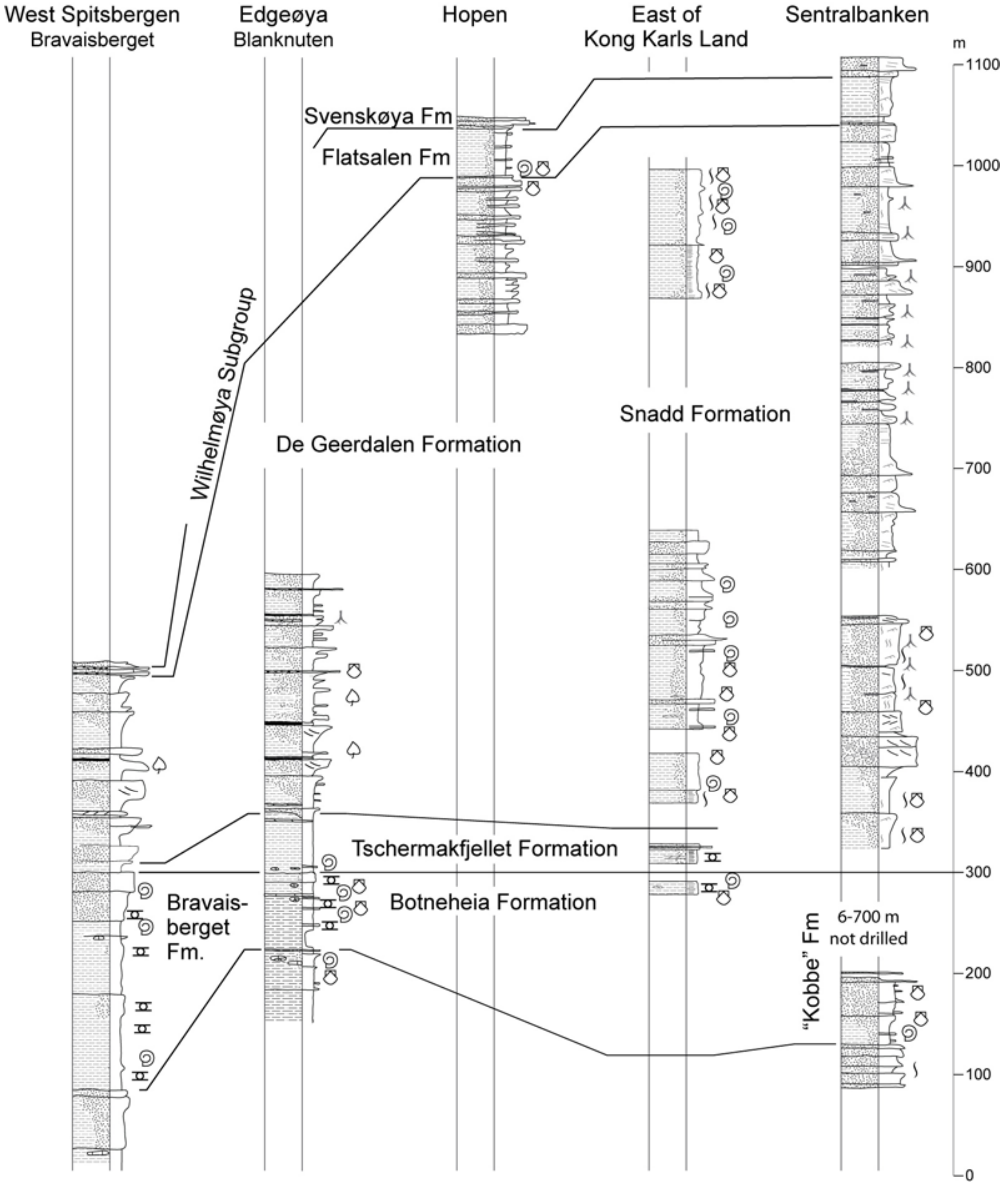


Figure 3: Interpreted correlation of Middle and Upper Triassic strata from Svalbard to southern Barent Sea based on sedimentological data. Outcrop sections are measured on Bravaisberget, Blanknuten and Hopen, and core sections are from north-east of Kong Karls Land and Sentralbanken High. Figure from Riis et al. 2008.

The sedimentation pattern changes from deltaic progradations with different provenance area in Ladinian to coastal and shallow marine environments when moving into the Jurassic (mid-Norian-Bathonian) (Mørk and Worsley 2006). Sediment thickness of the group is about 400 m at Svalbard, increasing to about 2000 m south in the Barents Sea (Nøttvedt et al. 2008).

Riis et al. (2008) discusses the palaeogeography of Svalbard and the Barents Sea when the Kapp Toscana Group was deposited (Figure 4). Svalbard was positioned on the northern rim of the supercontinent Pangea, inundated by the epicontinental Boreal Sea (Nystuen et al. 2006; Nøttvedt et al. 2008). Ladinian to early Norian was marked by high subsidence and sediment input, decreasing later in Norian time (Mørk and Worsley 2006).

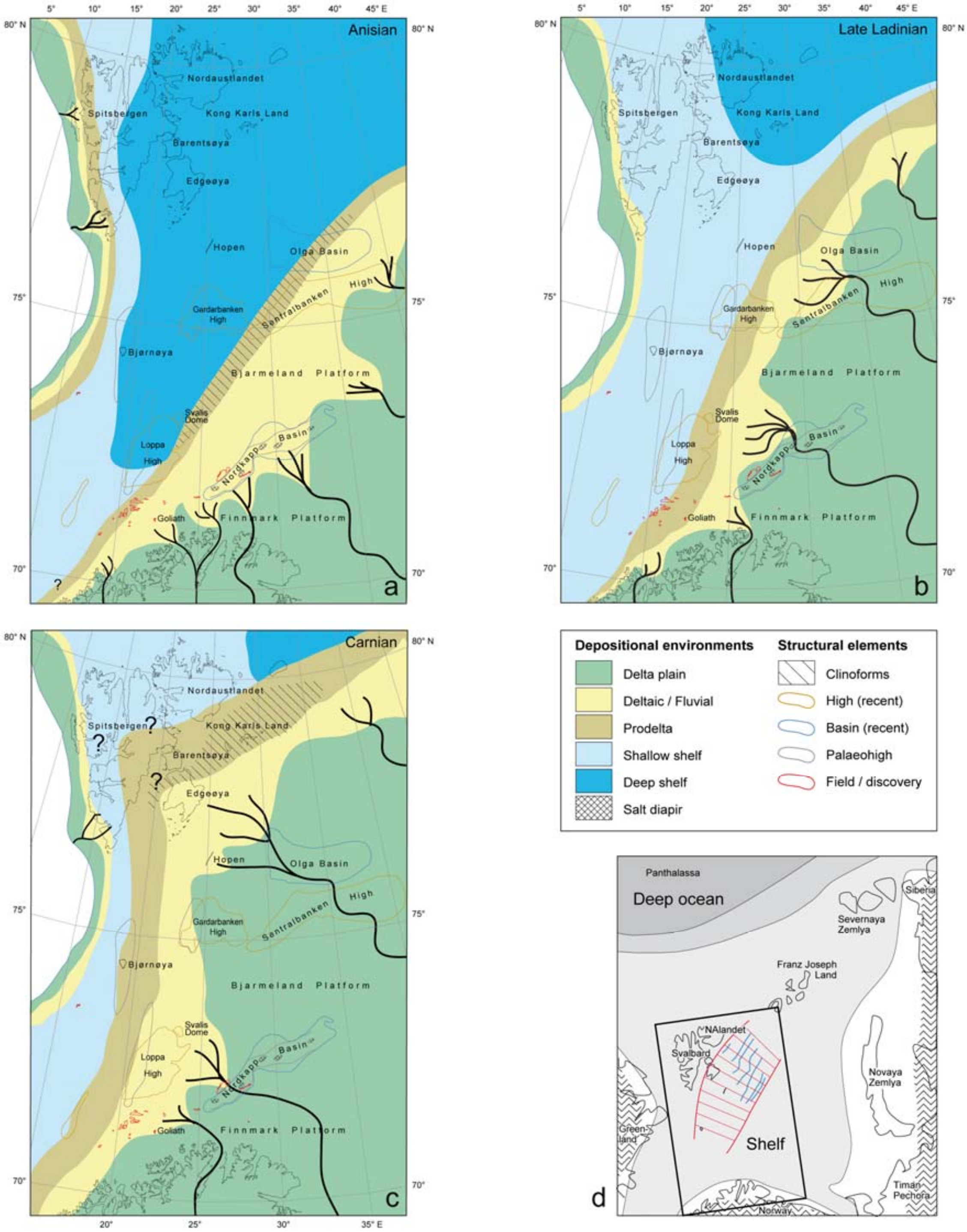


Figure 4: (a-c) Palaeogeographical maps showing sedimentation pattern into the Middle Triassic. (d) Interpreted progradation of shallow shelf/delta front areas from Anisian to Carnian times. Continent positions redrawn from Cocks & Torsvik (2007). Figure from Riis et al. (2008).

The transition from the lowermost Tschermakfjellet Formation to the overlying De Geerdalen Formation is visible by a pronounced increase in sandstone content from the shale dominated pro-delta depositions of Tschermakfjellet Formation (Mørk et al. 1999; Mørk and Worsley 2006). While Tschermakfjellet Formation represents sediments mainly developed on eastern and central Spitsbergen, the De Geerdalen Formation can be recognized in most of the outcrops on Spitsbergen and eastwards on the archipelago (Mørk et al. 1982). Lateral thickness variations have been described both in the Tschermakfjellet Formation and De Geerdalen Formation (Lock et al. 1978).

Western areas of Spitsbergen show exposures of small-scale coarsening-upwards sequences directly on top of the Sassendalen Group, lacking the Tschermakfjellet Formation (Mørk et al. 1982). Knarud (1980) have described and interpreted sections from different locations on the Svalbard archipelago, and recognizes this rhythmic coarsening-upwards facies association at different levels in the formation from the western area towards east. The sequences are interpreted as minor delta progradations, and the presence of sedimentary structures like low angled cross-stratification tells about marine reworking of the unit (Knarud 1980; Mørk et al. 1982; Mørk and Worsley 2006). In the western profiles made by Knarud (1980) the coarsening-upwards sequences are found in the lowermost 150-200 m of the Kapp Toscana Group. Further up in the De Geerdalen Formation in the western area Mørk et al. (1982) suggest less influence by delta activity, indicated by increasing shale dominance (Mørk et al. 1982). A possible explanation could be increased distance to the delta lobe, or a reduced presence of the entire delta system (Mørk et al. 1982).

This development of the lowermost De Geerdalen Formation in the western area is consistent with a delta system building out from land areas in Northern-Greenland (Nystuen et al. 2006). Observations made by Knarud (1980) support an early western provenance area.

Both the De Geerdalen Formation and the underlying Tschermakfjellet Formation thickens to the east and northeast, where the De Geerdalen Formation shows a fluvial-dominated delta sedimentation (Mørk et al. 1982; Mørk and Worsley 2006). Profiles measured on Edgeøya tells about marine reworking similar to what is observed in the western areas of Spitsbergen (Mørk et al. 1982).

Looking at exposures in eastern areas of Svalbard they display sediments with evident delta influence, supporting the presence of a new provenance area during Carnian (Mørk et al. 1982). It has been discussed whether this provenance area was situated on the northern part of Spitsbergen and Nordaustlandet or further SE as recently suggested by Riis et al. (2008). Knarud (1980) point out tectonics and uplift of the eastern areas as an explanation of the changing main source of sediments, which also could mean a closure of the basin after earlier open marine conditions (Knarud 1984). The high energy coastal environment to the west and east in Late Triassic can support the theory of an open seaway through the depositional basin in Carnian and early Norian time, making an northern source and basin closure less likely (Mørk et al. 1982). Knarud (1980) also measured cross-bedding in fluvial channels indicating a W/NW trending sedimentation pattern in the eastern areas of Spitsbergen in the upper parts of De Geerdalen Formation during his studies. The depositions are probably the result of a coastal plain building out from the Russian Timan-Pechora area and northwards, extending westwards on to the eastern parts of the Svalbard archipelago (Larssen et al. 2006). Riis et al. (2008) present the hypothesis that infill of the Barents Sea and Svalbard came from the south and east (Ural orogeny), also supporting an open seaway to the north.

Growth faults at Kvalpynten, south-west on Edgeøya, have also been used as indicators of transport directions and environmental setting. They where fist described by (Edwards 1976), and further investigations have been performed during fieldwork in 2007, 2008 and 2009, organized by the Norwegian Petroleum Directorate. Edwards (1976) observed a southerly dip direction of the faults, and indicated rapid deposition on underlying clay as cause of the failure. Recently investigations have revealed a more widely distribution of growth faults on Edgeøya, with faults also dipping to the north (Riis et al. 2008). The growth faults make lateral correlation of sandstone bodies challenging in current areas. Correlation can in general be difficult in these sediments, one reason being difficulties with palynological dating on Carnian sediments (pers.com. J.O.Vigran 2010).

2. Material

2.1 Fieldwork

Fieldwork was carried out during two period's summer 2009 (June and August-September) on central Spitsbergen and eastern Svalbard. The fieldwork on eastern Svalbard was stationed on the vessel M/S Kongsøy, organized by the Norwegian Petroleum Directorate. Sections were measured with help from participant attending the cruise. The survey on central Spitsbergen was accomplished in collaboration with Rita Sande Rød and field assistant Marianne Ask, with tent and a cabin as accommodation during the work. Localities in the different areas were chosen based on degree of exposure and accessibility. Several sections and photos were collected in the current area (Appendix 5 and 8), and samples for later thin-section work were taken from several sandstone units. GPS were used to measure height of extensive units, and a standard meterstick to measure units possessing thicknesses less than about 5 m.

Localities on central Spitsbergen include Botneheia and several mountains in Sassendalen (Figure 5 and Appendix 8).

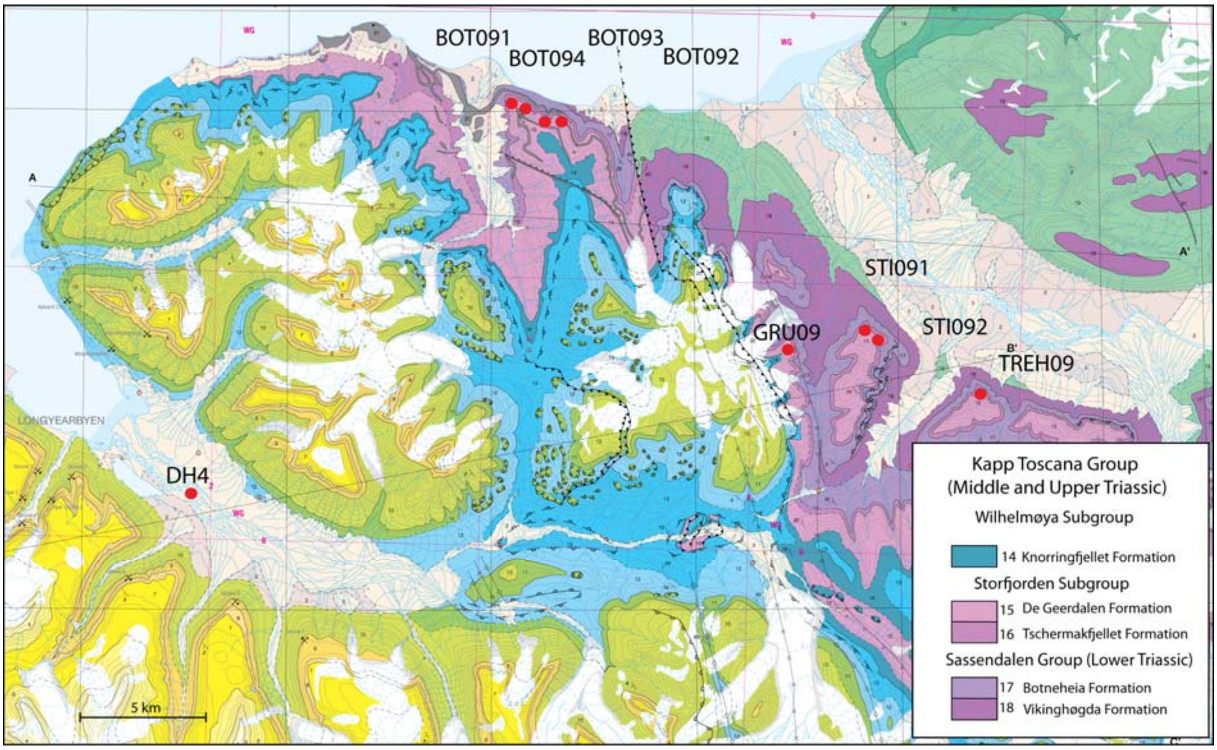


Figure 5: Localities on central Spitsbergen. The sections BOT091-BOT094 are located on Botneheia, the sections STI091, STI092, GRU09 and TRE09 are located in Sassendalen. DH4 represents the well drilled in Adventdalen in 2009. Major, et al 1992: Adventdalen. (revised after Major & Nagy 1964.) Geological map Svalbard 1:100 000, sheet C9G, preliminary edition. Norwegian Polar Institute.

Two sections were studied on Hopen, and five sections were studied on western Edgeøya (Figure 6 and Appendix 8). Some sections are located on the same mountain (e.g. four sections on Botneheia) to give data on lateral extent. Measured sections are given names from the locality, and will often be referred to as shortenings of the mountain name (e.g. KLI equals Klinkhamaren). Sections are digitalized in scale 1:100 and 1:1000, material available for use in the CO_2 –storage project (see Appendix 5 for 1:1000 sections).

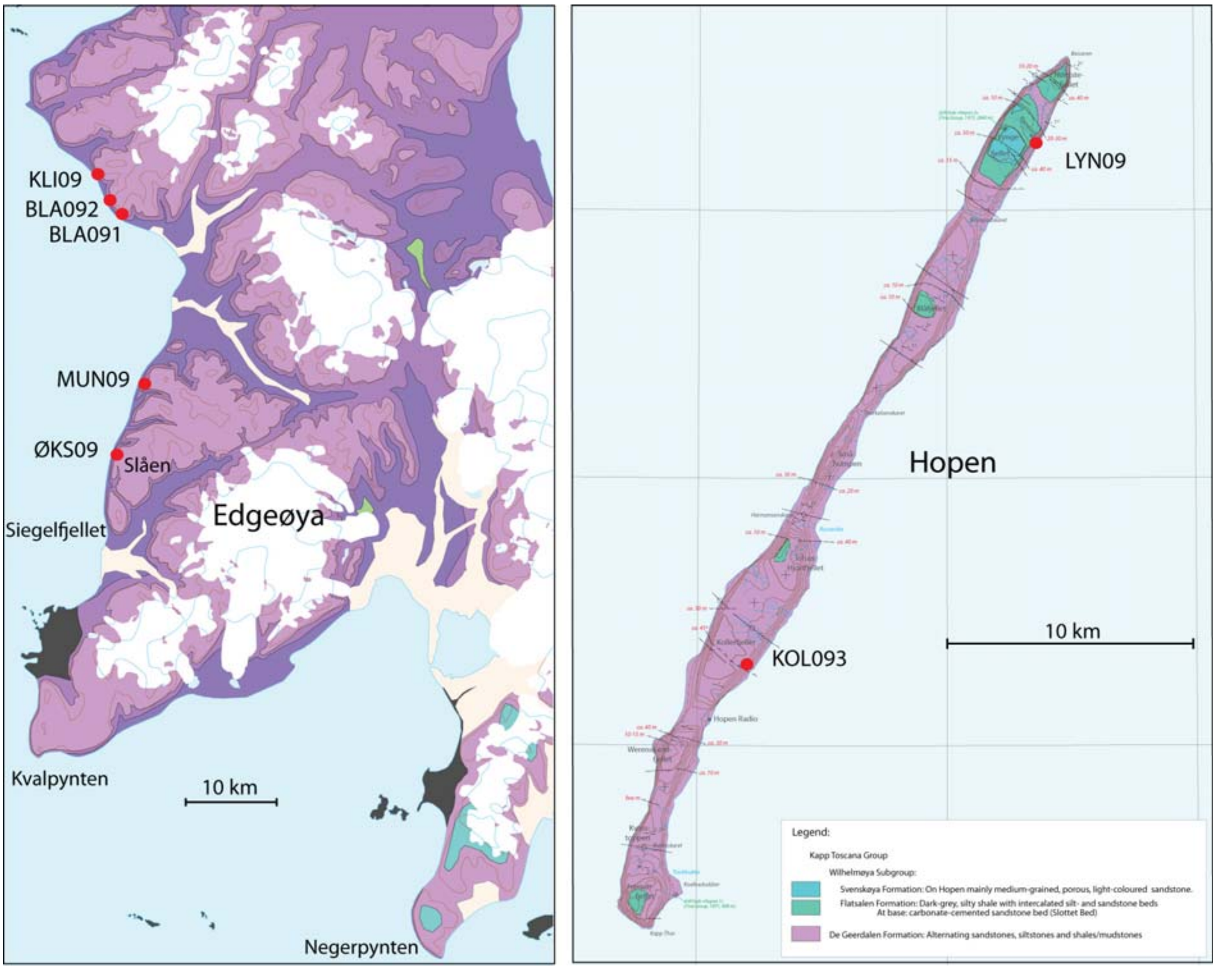


Figure 6: Localities on Edgeøya and Hopen. Mapped by W.K. Dallmann, Norwegian Polar Institute, during cruise with the vessel M/S Kongsøy, organized by the Norwegian Petroleum Directorate, August 2009. Based on a previous map by Smithet al. 1975: Geology of Hopen, Svalbard.

2.2 Core logging

The core materials (well DH4) were collected from Adventdalen in connection with the CO_2-storage project, and were available for study in December 2009. Core logging was carried out in January 2010 (Longyearbyen). Two sections from the total core length of the De Geerdalen Formation were studied, referred to as core interval A and B in this work (Appendix 4). They were chosen based on high sand content in these particular units. The same parameters and legend as used in field were considered during the work (Appendix 1).

2.3 Use of former research

Previous work and research were mentioned in the introduction (Chapter 1), and have been used as additional data basis for this work. Sections measured by Knarud (1980) and data from fieldwork on Edgeøya summer 2008 (organized by the Norwegian Petroleum Directorate) are used to get a better coverage of the studied areas and ease environmental interpretations. The sections from mentioned work are also used to calculate net/gross values in the formation (Appendix 6).

2.4 Sources of error

Possible sources of error are mainly considered to be GPS measurements and covering of sections by scree. The barometer available in the GPS is susceptible to weather changes (pressure) and periodically unstable. To avoid to great variance, relative height of units were taken to limit the time available for the GPS to readjust to new pressure conditions. Covering of areas by scree were a problem in a number of outcrops, in particular in Sassendalen, and will be mentioned in Chapter 4 (Results) regarding the facies mainly affected. There are additionally sources of error regarding net/gross calculations, caused by later erosion of sections and more or less representative sections from different areas. This will be further discussed in Chapter 5.

3. Method

3.1 Facies and Facies Associations

The main tool for interpreting environmental setting during Late Triassic time and deposition of the De Geerdalen Formation has been facies analysis (Figure 7). Facies analysis involves both analysis of sedimentary structures and geometries of outcrops, traditionally the basis for geological models (Mikes and Geel 2006). The focus of this study is analysis of sedimentary structures, while other participants in the CO_2-storage project are working on geometries of the formation, based on LIDAR data (helicopter based scans).

A *facies* is defined as a body of rock with specified characteristics (Reading and Levell 2006). The facies should ideally reflect a particular process, set of conditions or environment (Reading and Levell 2006). They can be defined based on different properties dependent on the characteristics of the particular study area, examples being fossils, composition or sedimentary structures (Reading and Levell 2006). Parameters considered during data collection in this work were grain-size, unit thicknesses and boundary features, sedimentary structures, bioturbation and organic material content. In addition cementation was tested and observed, and divided into calcite- and unspecified cementation. Trace fossils were identified when present in outcrops. The facies are given names from dominating sedimentary structures (e.g. climbing ripples) or other characteristics separating them from other facies (e.g. carbonate rich sandstone), and interpreted to represent a specific process or deposit.

Determination of depositional environment is often difficult to accomplish based on a single facies, because of the tendency for processes to operate in several environments (Reading and Levell 2006). Environmental interpretations often make use of *facies associations*, which is a grouping of facies occurring together in a sequence (Reading and Levell 2006). The facies associations in this work are grouped based on available data. This means that some associations holding detailed data represent specific environments (e.g. mouth bars), while other associations lacking detailed data represent broader environments (e.g. fine-grained deposits in coastal areas).

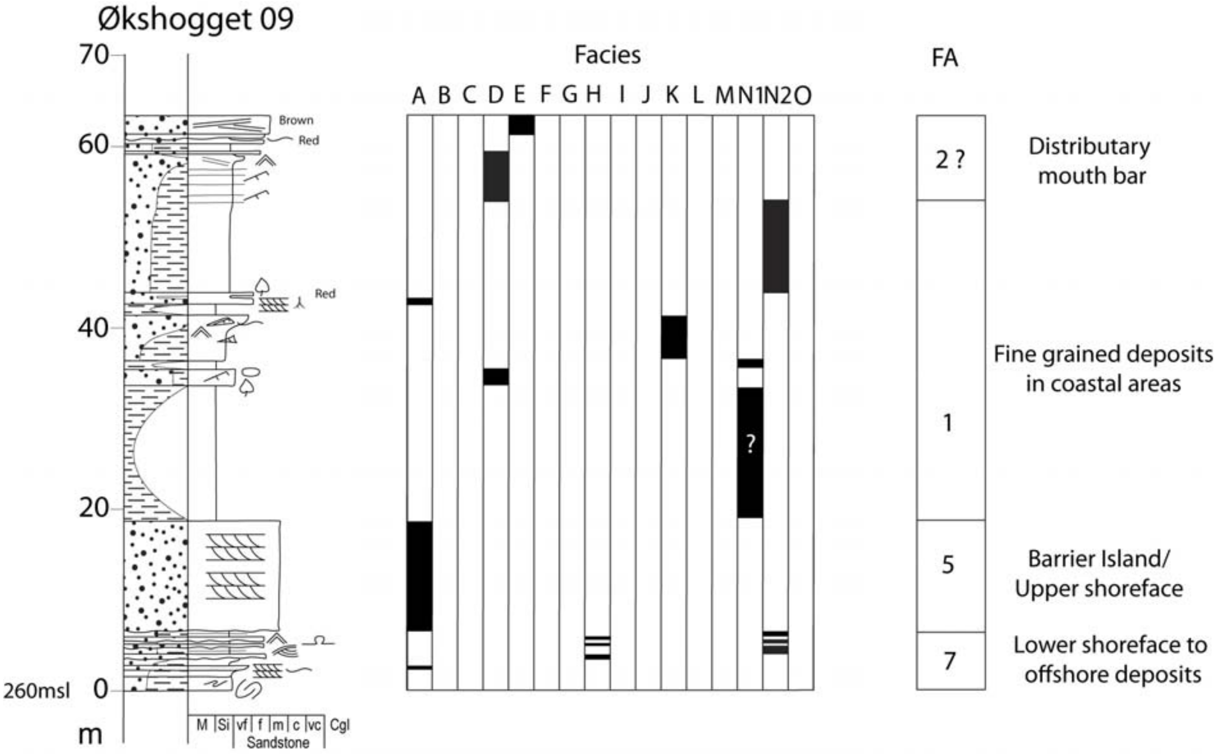


Figure 7: Example on Facies and Facies Association division from Økshogget (Edgeøya). See Appendix 1, 3 and 5 for legend and a complete facies and facies association overview.

3.2 Distribution of sand versus mud

Distribution of sand versus mud can be used to create simple geological reservoir models (Mikes and Geel 2006), and give information on potentially productive parts of a reservoir (Gluyas and Swarbrick 2004). In this work data on distribution of sand versus mud is used to detect distribution trends from eastern Svalbard to central Spitsbergen. The data will be compared with data on facies distribution. Calculation of net/gross values was carried out on measured sections with use of data from previous studies (Knarud 1980) and data collected summer 2008-2009 (see Section 4.3). Net/gross values are expressed as ratio of producible (net) reservoir within the overall (gross) reservoir, in this work representing the De Geerdalen Formation. Additionally the thickest sandstone units and belonging dominating grain-size were measured in each section (see Section 4.3).

4. Results

4.1 Facies

Fifteen facies (A-O) are described and discussed based on parameters mentioned in previously sections (Chapter 3), and an overview of measured sections and associated facies can be found in Appendix 3 and 5. The facies are listed in order of decreasing grain-size.

A. Large scale cross-stratified sandstone
B. Small scale cross-stratified sandstone
C. Climbing ripple cross-laminated sandstone
D. Symmetrical ripple laminated sandstone
E. Low angle cross-stratified sandstone
F. Horizontal bedded sandstone
G. Undulating fractured sandstone
H. Hummocky cross-bedded sandstone (HCS)
I. Mud flake conglomerate
J. Fine-grained rooted sandstone
K. Heterolithic bedding
L. Carbonate rich sandstone
M. Coquina beds
N. Shale (N1: black shale, N2: silty shale)
O. Coal

Facies A Large scale cross-stratified sandstone

Description

This facies occurs in the majority of measured sections, though more frequently on eastern Svalbard (Figure 8). On central Spitsbergen it is observed only in the upper part of the De Geerdalen Formation, while it has been logged close to base of the formation on Edgeøya. It constitutes the upper part of upwards-coarsening sequences, but it is also found directly overlying shale (e.g. KLI09 and TREH09). Associated facies are mainly shale (Facies N), low angle cross-stratified sandstone (Facies E) and small scale cross-stratified sandstone

(Facies B). The facies, often appearing as the most pronounced layers of the De Geerdalen Formation, can not be followed laterally from one mountain to another. It is also hard to detect large scale structures like this facies in core material, but indications are found in both core interval A and B (Appendix 4).

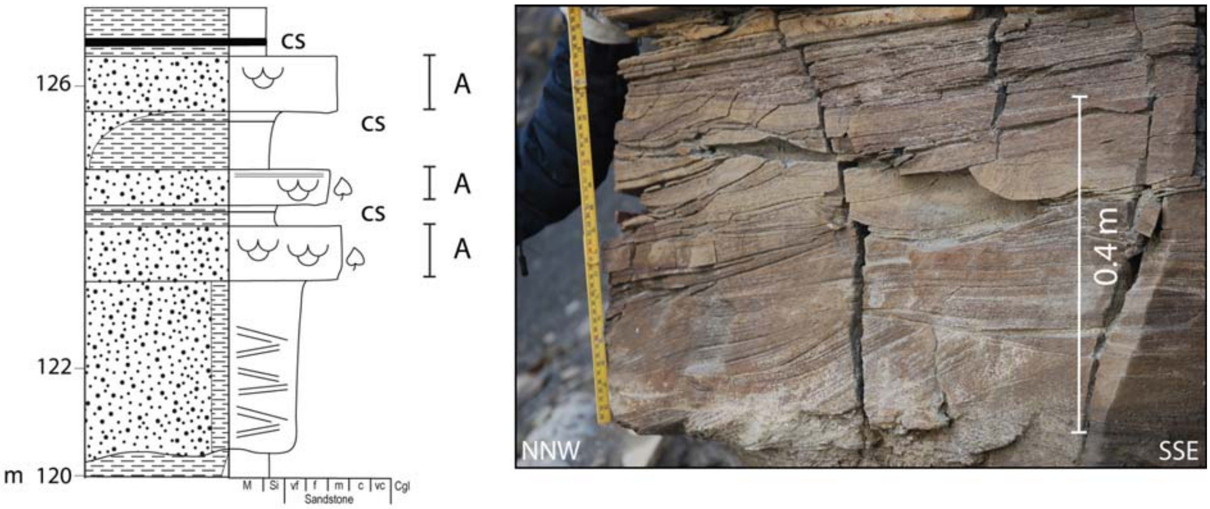


Figure 8: Trough cross-stratification at 123-126 m above base of the De Geerdalen Formation in section BLA091 (Blanknuten) on Edgeøya. The facies is overlying low angle cross-stratification and underlying coal shale and black shale. See Figure 6 for location of section BLA091.

Unit thicknesses typical of this facies are 0.5 to approximately 7 m, and at some localities with an erosive lower boundary. Grain-size is predominantly fine, but locally up to medium-grained sand. Sedimentary structures are mainly large scale cross-stratification, defined as set thicknesses exceeding about 5 cm (Boggs 2006 Chapter 4). Both tabular cross-bedding and trough cross-bedding have been described. The tabular cross-bedding have angular to tangential based foresets and almost parallel boundaries between the sets (Figure 9B).Sets are stacked together as cosets, and at some outcrops they are separated by more horizontal layers with ripple lamination. A unit in section BOT091 shows foresets with systematically changing thickness. Set thicknesses are from 0.1-0.2 m throughout the field area. The foresets are in most cases unidirectional, except from one observation on Blanknuten (Figure 9C). This outcrop shows foresets dipping in two different directions, one being more pronounced than the other.

Trough cross-bedding were more frequently observed in field than tabular cross-bedding (Figure 9A). They have scalloped set boundaries and trough shaped appearance. Set thicknesses are from 0.1-0.4 m. In Sassendalen examples of complex low angle troughs are observed (Figure 9D). The sets and cosets dip in different directions and the bounding surfaces are irregular (as also described in Rubin 1987).

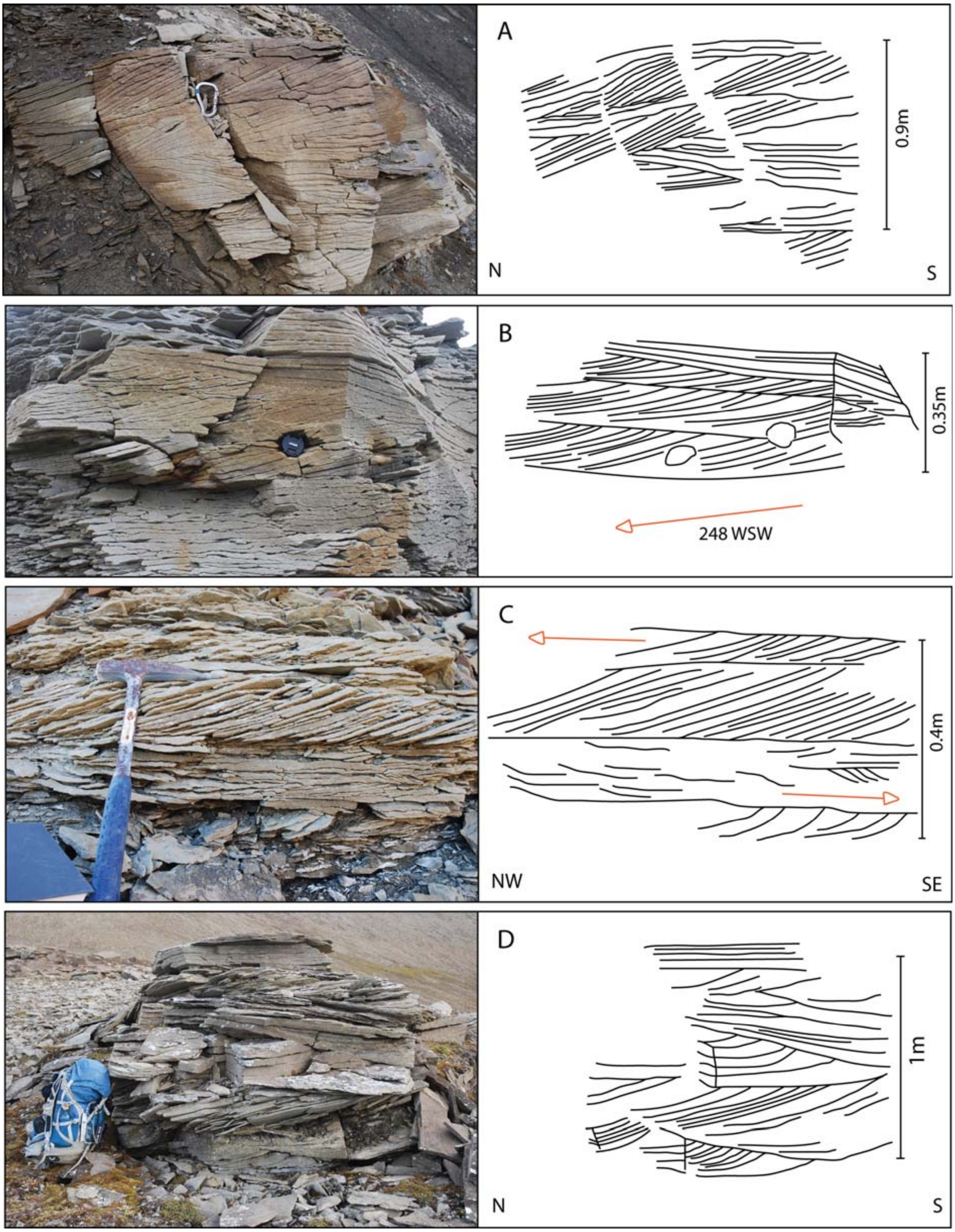


Figure 9: Types of cross-stratification in the De Geerdalen Formation on Svalbard. A) trough cross-stratification at Blanknuten (Edgeøya), B) tabular cross-stratification with tangential foresets at Trehøgdene (Sassendalen), C) Herringbone cross-stratification at Blanknuten (Edgeøya), D) 3D variable cross-stratification on Sticky Keep (Sassendalen).

Small scale structures including climbing ripples and small scale cross-stratification occurs within foresets of some of the larger sets, e.g. on Sticky Keep and Blanknuten. On Sticky Keep the climbing ripple lamination is directed up the slopes of the foresets on a large scale trough cross-stratified unit, defined as counter current cross- lamination (type of superimposed structure) by Collinson et al. (2006).

Transport direction is measured both on tabular and trough cross-stratified units, giving a mean direction 277 degrees WNW/ESE (Figure 10).

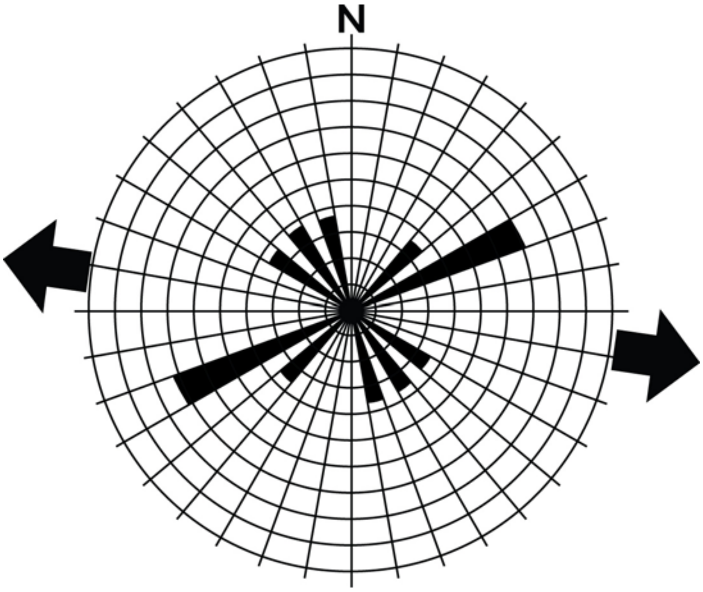


Figure 10: Palaeo-transport directions from central Spitsbergen and Edgeøya. Mean arrow is directed 277 degrees WNW/ESE, based on six measurements. Measurements are taken on both tabular and trough cross-stratified units in sections; TREH09, BOT091, STI091, STI092, MUN09, BLA091 (Appendix 3). Measurements on tabular cross-stratification show a palaeo-transport direction from east towards west (TREH09, Figure 9B).

Organic material in this facies is clearly evident at Edgeøya and Hopen, but also observed in Sassendalen in the upper units. The organic material consists of plant fragments, occurring in between beds normally about 5 cm thick. Plant fragments are normally found at bedding surfaces, and do not appear as clear drapes in outcrops. The fragments are up to a few cm in length (Figure 11). In core material mud drapes of few mm sizes are present in several of the sandstone units, sometimes forming double mud drapes. The drapes appear oblique in the cores and are disturbed by bioturbation and small faults in some units.

Mud flakes are observed in situ at Blanknuten, Hopen and in core material. Extensive amounts also occur on blocks not in situ, close to several outcrops across the field area. They are sub-rounded and up to about 6 cm in diameter.

Figure 11: Mud flakes and plant fragments from respectively Trehøgdene (Sassendalen) and Blanknuten (Edgeøya). Mud flakes are about 6 cm in diameter, and plant fragments are up to a few cm in length. Nikon cover is 6 cm.

The colour within this facies varies from grey to red and brown at weathered surfaces. Reddish cavities of varying size (majority about 3 cm in diameter) are probably mould casts from concretions. The mineralogy is mainly unknown, but some are likely carbonate concretions. In situ concretions are often dark grey and randomly distributed. In Sassendalen concretions with spherical shape and primary layering preserved inside the feature where found (Figure 12). Pyrite concretions up to a few cm were found in the cores. Minor soft sediment deformation structures are observed on Botneheia (BOT093) in the lower part of a sandstone unit, resembling load structures. Calcite cementation in this facies is most evident in Sassendalen, particularly in the uppermost cross-stratified sandstone units. On Edgeøya calcite cementation were proven in the upper part of a few sandstone units (BLA092 and KLI09).

Figure 12: Spherical concretions on Trehøgdene. Primary layering is preserved in concretion to the right (marked by an arrow). Nikon cover is 6 cm.

Discussion and interpretation

Cross-stratification forms by migration of two- and three-dimensional dunes in air or water (Rubin 1987; Boggs 2006 Chapter 4). Aeolian dunes have low preservation potential and often large set thicknesses (Collinson et al. 2006 Chapter 6), favouring water as depositional medium in this facies containing cross-stratification with relatively small set thicknesses.

The shape of foreset lamina varies depending upon the hydrodynamic factors dominating at the time of deposition (Reineck and Singh 1980). Cross-stratification in the De Geerdalen Formation shows a wide range of types related to different flow conditions. The tabular cross-stratification with angular foresets indicates low flow velocities (lower flow regime) with bedload transport and grain-flow dominating on the slipface (Reineck and Singh 1980; Boggs 2006 Chapter 4; Collinson et al. 2006 Chapter 6). The tangentially shaped foresets are formed when the current velocity increases, caused by settling of sediments from suspension as bottomsets and toesets (Reineck and Singh 1980). Tangential shape typically develops in fine sediments and shallow water environment (Reineck and Singh 1980). The often occurring tangentially shaped foresets and fine sand in field can indicate a setting of shallow water in many of the areas. Even though tabular cross-stratification were found both on central and eastern Svalbard, the three-dimensional trough cross-stratification were dominating in most sections, indicative of a possible deeper and stronger current (Collinson et al. 2006 Chapter 6). The more complex cross-stratification found in Sassendalen, quite similar to the three-dimensional variable computer simulated structures described by Rubin (1987), indicate a flow with changing directions or bedform interactions.

The limited current measurements on troughs and tabular cross-stratification suggest a dominating mean palaeo-current directed 277 degrees WNW/ESE, supporting a source area to the east as also indicated by Riis et al. (2008) (Figure 10).

Observations tabular cross-stratification appearing as herringbone structures on Blanknuten indicate tidal influence on this facies, supported by double mud drapes described in well DH4. Mud drapes are deposited during slack-water phases in a tide influenced environment (Eriksson et al. 2006), but can also occur in rivers with seasonal flow (Nichols 1999). Double mud drapes (tidal couplets) are particular indicative of tidal rise and fall, where the two mud drapes forms during the two slack water stages of the cycle (Reading and Collinson 2006).

Herringbone structures are also indicative of tidal environments, and relatively high sedimentation rate to preserve the cross-stratifications (Nichols 1999).

Tidally influenced environments can occur in: upper shoreface of tidally modulated deltaic coasts, mouth bars, different channel types (e.g. estuarine distributary channels, tidal channels in barrier island settings) or (estuarine) tidal sand ridges and deltas (Dashtgard et al. 2009).

The lack of extensive bioturbation in the cross-stratified sand bodies can imply high energy in the depositional environment, and superimposed structures (e.g. counter current structures on STI091) can indicate emergence of large scale bedforms or changing current directions (Collinson et al. 2006 Chapter 6).

Concretions with primary layering preserved in some of the units included in this facies can develop if cementation happened at a early stage of compaction of host rock (Selles-Martinez 1996). The reason why many of the nodules in this facies are weathered out can be because carbonate is more susceptible to weathering than the host rock (see Facies L for description and discussion of concretions) (Collinson et al. 2006 Chapter 9).

Facies B Small scale cross-stratified sandstone

Description

This facies is primarily observed and described on Botneheia (Figure 13), but it also occurs on eastern Svalbard, in Sassendalen and in core material. Like Facies A, small scale cross-stratification is more evident in the upper part of logged sections on Botneheia and Sassendalen, and observed at varying levels in sections to the east on Svalbard. Beds are observed in relation to large scale cross-stratified sandstone (Facies A) and as single units interlayered with shale (Facies N), with gradual or sharp transition between the facies. In core material it is found in both interval A and B (see Appendix 4).

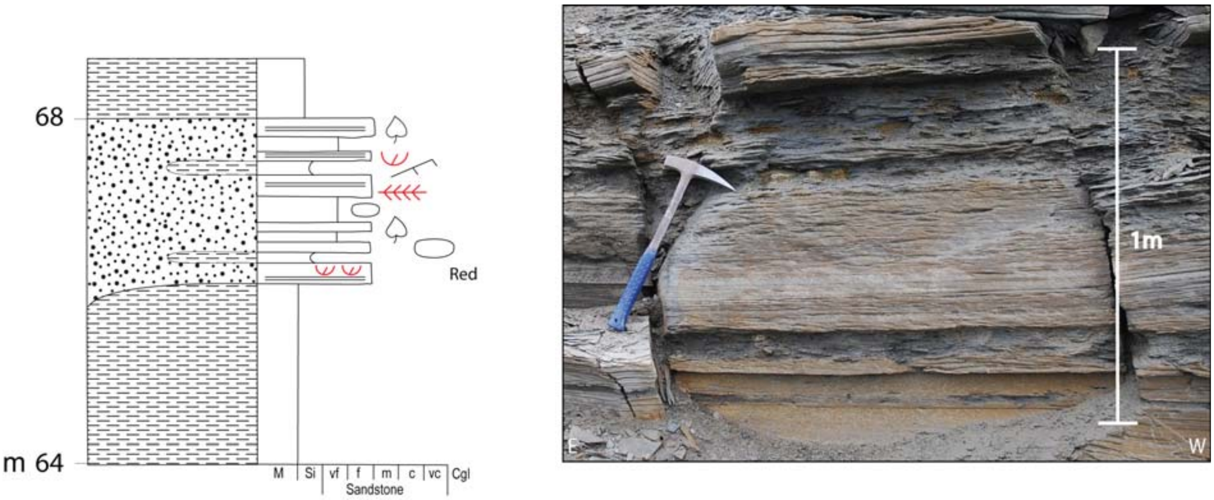


Figure 13: Small scale cross-stratification and herringbone structures in section BOT094 (Botneheia). The sequence is bounded by shale. See Figure 5 for location of section BOT094.

Units are from 0.1-1.5 m, and display grain-sizes from very fine to medium sand. Characteristic sedimentary structures are small scale cross-stratification and herringbone lamination. The ripples are asymmetrical and have foresets dipping in one single direction. Both angular and tangential based foresets are found (Figure 14), tangentially based being most common, and set boundaries are highly variable in appearance. Ripples with tangential foresets often show truncating set boundaries, while ripples with angular foresets show more parallel set boundaries. Some co-sets have plane layers of 1-2 cm separating the individual sets. Set thicknesses are from 0.5-4 cm. In core material the set boundaries are diffuse and set thicknesses seldom exceed 1cm. Double mud drapes on foresets are found in both core interval A and B. The transport directions appear unidirectional and mean transport direction is 255 degrees WSW/ENE (Figure 15).

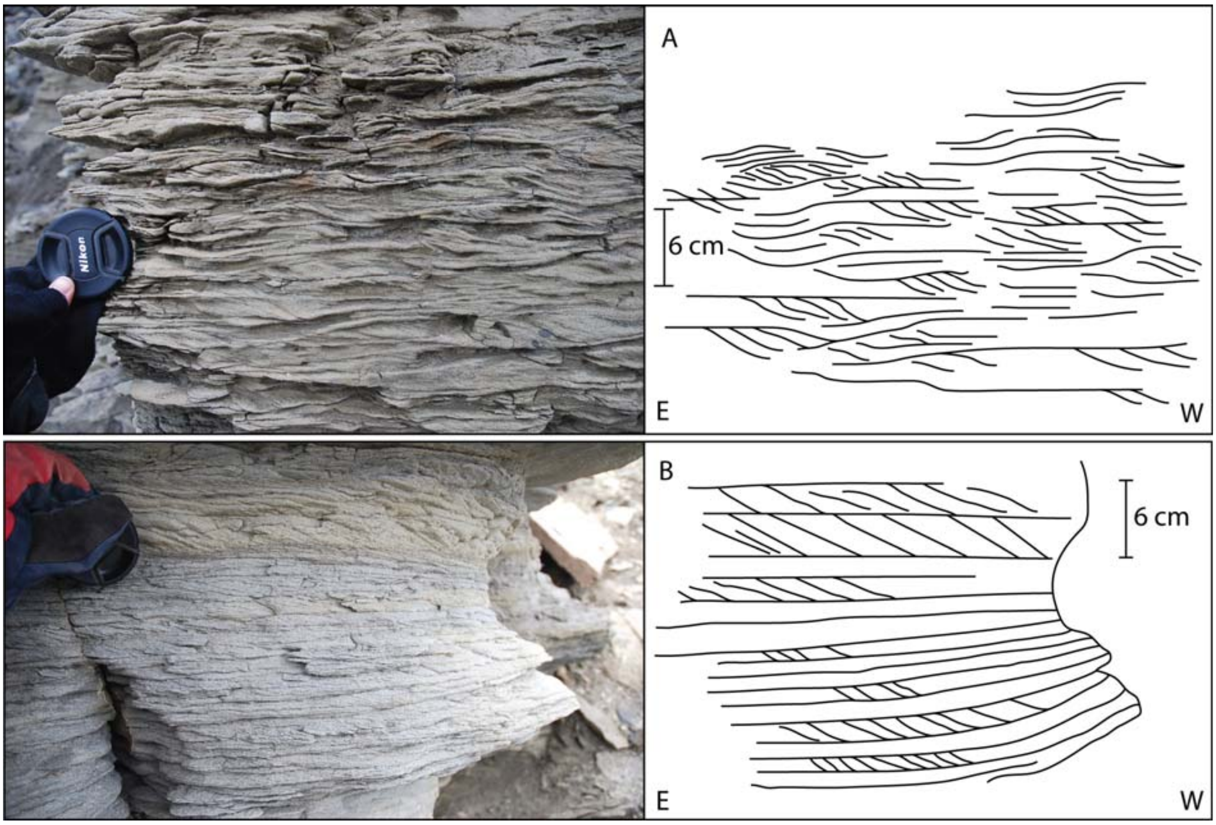


Figure 14: Varieties of small scale cross-stratifications in the De Geerdalen Formation on central Spitsbergen. A) Small scale trough cross-stratification in section BOT093, B) Small scale tabular cross-stratification in section BOT094.

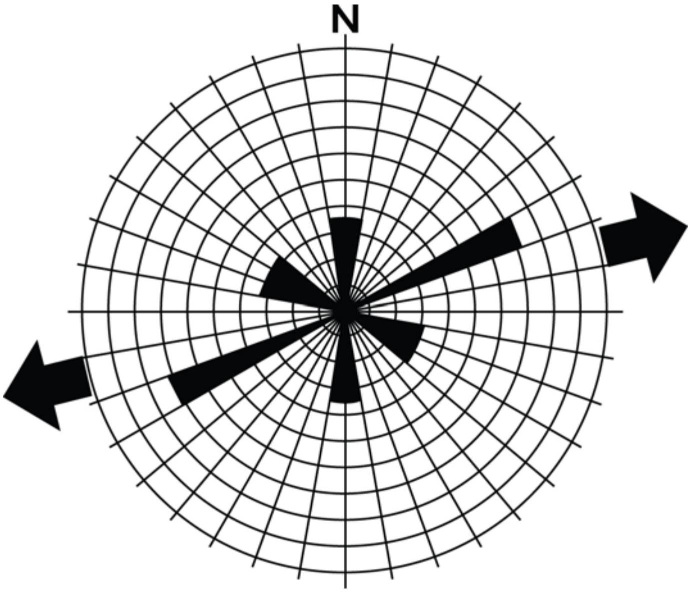


Figure 15: Palaeo-transport directions from central Spitsbergen and eastern Svalbard. Mean arrow is directed 255 degrees WSW/ENE, based on seven measurements. Directions are measured on both asymmetrical ripples and herringbone structures, in sections; BOT093, BLA092, KOL093.

Herringbone lamination is only observed on Botneheia and Sticky Keep (Sassendalen), as part of units also containing unidirectional cross-stratification (Figure 16). Set thicknesses are up to 2 cm, and foresets both angular and tangential based are observed.

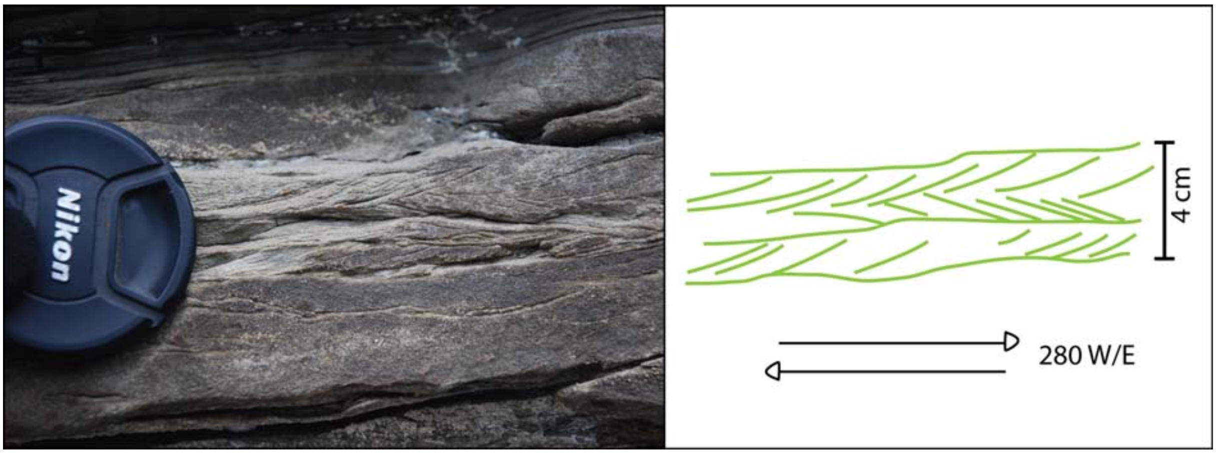


Figure 16: Herringbone cross-stratification in section BOT093 at 65 meter above base of the De Geerdalen Formation on central Spitsbergen. Set thicknesses are about 1cm, and palaeo-transport direction is approximately 280 W/E.

Organic material is found between beds in some units, comprising plant fragments. Colour depends on degree of weathering, and is grey on unweathered surfaces and brown to red on weathered surfaces.

Discussion and interpretation

Ripples form in flowing water by movement of grains, and ripple cross-stratification forms by the migration by current or wave ripples (Reineck and Singh 1980; Collinson et al. 2006 Chapter 6). The small set thickness in this facies is related to decreasing energy from facies A. The asymmetry of the ripples indicates a dominating unidirectional flow, thus it can also be produced by oscillatory or combined flow (Collinson et al. 2006 Chapter 6). The hydrodynamic conditions responsible for tabular and trough cross-stratification have been discussed in Facies A, and also applies to small scale cross-stratification. Herringbone cross-stratification and double mud drapes indicates tidal influence (Nichols 1999), mainly observed on central Spitsbergen.

Asymmetrical ripples can form by current action in different environments, from shallow water to deep marine (deep water currents and turbidity currents) (Collinson et al. 2006

Chapter 6). In shallow marine environments asymmetrical ripples can form because current strength tends to be stronger in the landward direction reaching the surf zone (Reineck and Singh 1980; Reading and Collinson 2006). Asymmetrical wave ripples and current ripples can appear similar, but the internal structure can be helpful in distinguishing them (Reineck and Singh 1980). Slightly asymmetrical ripples with visible internal structures are discussed in Facies D.

Sub environments for development in a fluvial- to marginal marine setting can be; fluvial flood plains, point bars, levees or in different bar deposits (e.g. distributary mouth bars) (Reineck and Singh 1980; Bhattacharya 2006; Boggs 2006 Chapter 9).

Facies C Climbing-ripple cross-laminated sandstone

Description

Climbing ripple lamination is observed in sections on Sticky Keep (STI091) and on Botneheia (BOT094) (Figure 17), and exposed outcrops are only laterally continuous for some meters. The facies is found in association with small- and large scale cross-stratification and shale.

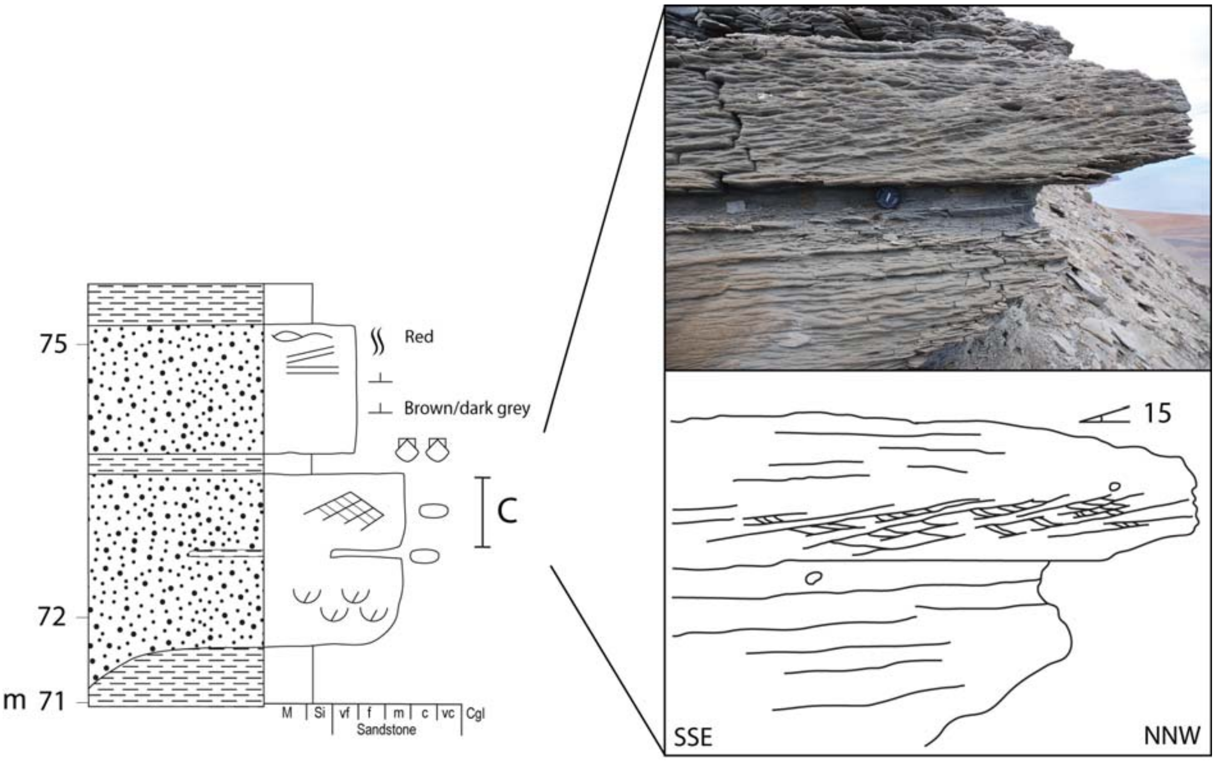


Figure 17: Climbing ripple cross-laminating in section BOT094 (Botneheia) on central Spitsbergen. The angle of climb was measured to about 15 degrees (subcritical climb). See Figure 5 for location of section BOT094.

The unit thicknesses are about 0.3-0.5 m, and the grain-size is fine-medium sand. Set boundaries are dipping in the opposite direction of the foresets, and set thicknesses are from 1-3 cm. The upper parts of the ripples are truncated by new ripple sets (stoss side missing). On Botneheia the angle of climb is about 15-20 degrees and on Sticky Keep it is 28-32. This can be classified as subcritical climb based on low angle and truncating boundaries (Reineck and Singh 1980a). Towards the top of the unit on Botneheia the angle of climb decreases. The migration direction of the climbing ripples are according to approximate measurements; SSW (STI091) and NNW (BOT094). The colour of the outcrop on Botneheia is grey, and brown on Sticky Keep caused by weathering. Brown nodules of unidentified mineralogy appear sporadically on Botneheia.

Discussion and interpretation

Climbing ripples are most likely to develop in environments of periodically high sediment accumulation and limited reworking of the sediments (Reineck and Singh 1980). The angle of climb can be an indication of accumulation rate in the current setting; low angle of climb (subcritical climb) corresponding to a higher migration rate than accumulation rate (Collinson et al. 2006 Chapter 6). The low angle of climb on ripples observed on central Spitsbergen probably agrees with these conditions. Truncated set boundaries in the outcrops support this by being evidence of erosion and reduced sediment available in suspension (Reineck and Singh 1980).

Climbing ripples can be present in different subenvironments, for instance in natural levees, on floodplains, in thin bedded levee turbidites or in different type of bar forms (e.g. frictional dominated mouth bars or channel bars) (Reineck and Singh 1980; Bhattacharya 2006; Posamentier and Walker 2006).

Facies D Symmetrical ripple laminated sandstone

Description

This facies is recognized both on Botneheia, Edgeøya and Hopen (Figure 18). The structures are often found in association with hummocky cross-stratified (HCS) sequences (Facies H) and shale (Facies N). In sections on Botneheia the facies is mainly occurring in the lower part of the De Geerdalen Formation, while on eastern Svalbard it is found throughout at many levels in the formation.

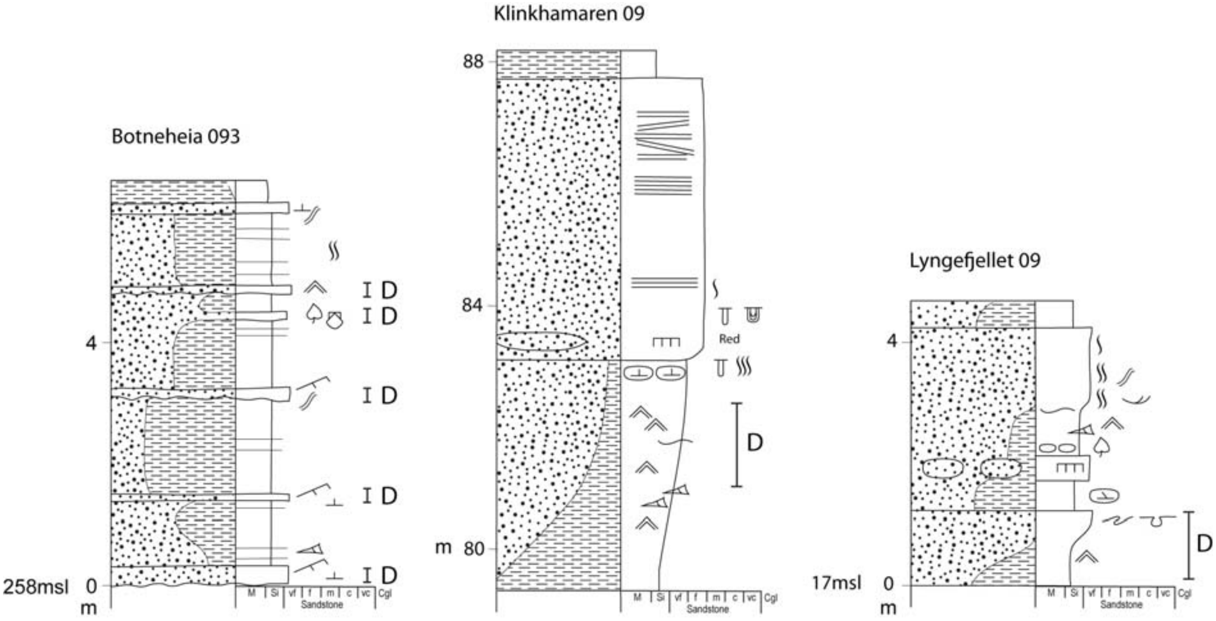


Figure 18: Symmetrical ripple laminated sandstone occurring in different areas on Svalbard, respectively in sections BOT093 (Botneheia), KLI09 (Edgeøya) and LYN09 (Hopen). See Figure 5 and 6 for location of sections.

Units are usually between a few cm up to 0.5 m thick. Very fine sand make up the main portion of the grain-size distribution, though some grades into fine sand. Sedimentary structures found are (symmetrical) ripples, (symmetrical) ripple cross-lamination and plane parallel lamination. Most outcrops are laminated, but bedding > 1 cm also occurs. A trend found is horizontal bedding or massive sand in the lower unit, followed by symmetrical to roughly symmetrical ripples/or ripple cross-lamination in the uppermost unit. Set thickness of the ripples is often 1-3 cm. Different types of symmetrical ripples are found. Examples are wave ripples showing cross-strata off-shoots on Trehøgdene and truncated ripples on Klinkhamaren (Figure 19).

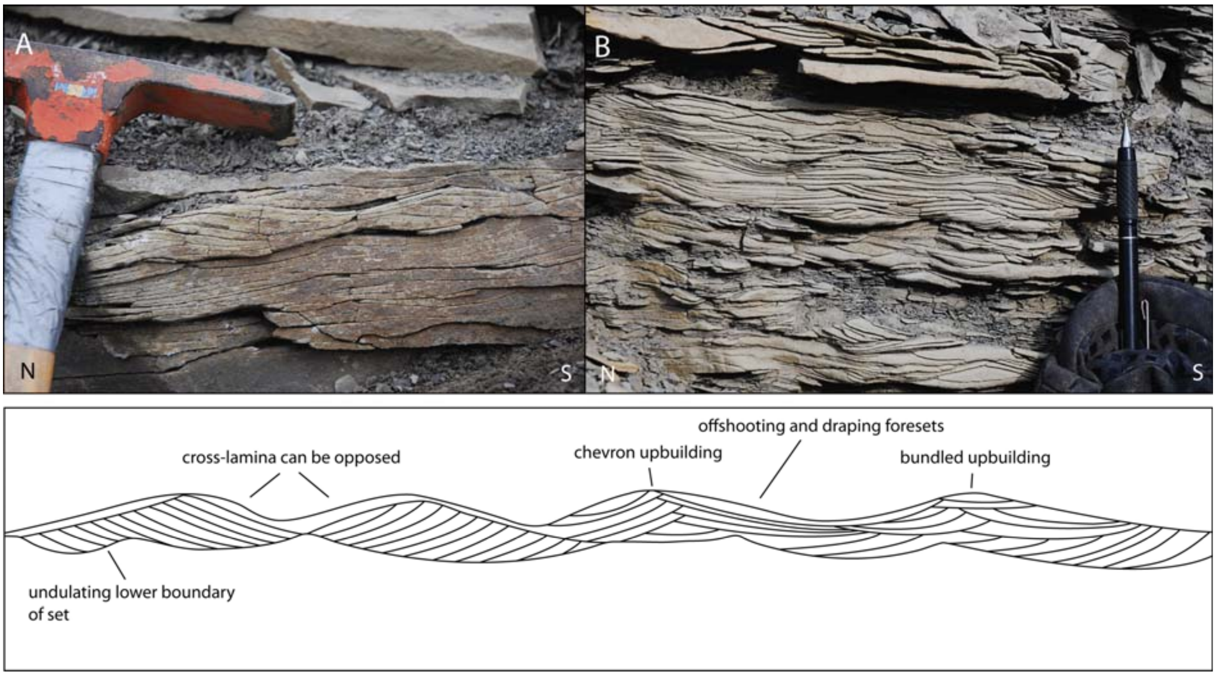


Figure19: Different internal structures in wave ripples. A) Wave ripples in section TREH09 showing irregular lower boundaries (Sassendalen), B) Wave ripples in section KLI (Edgeøya). Figure after Collinson and Thompson (1989).

Some units have erosive lower boundaries, while others show gradational transition to associated facies. Colour varies depending on degree of weathering, appearing red when weathered and dark grey to grey at unweathered surfaces. Organic material (plant fragments) occurs on eastern and central Svalbard. Unidentified bioturbation and *Rhizocorallium* are found on Botneheia. Concretions are rare in this facies, but observed in one section on Botneheia. Calcite cementation is present in some outcrops, sometimes throughout the unit and sometimes just in the uppermost part. Mud flakes are found in sections on Botneheia. Measurements of ripple crestline (6 observations) give a mean SSW/NNE orientation.

Discussion and interpretation

Symmetrical ripples are formed by oscillatory flow produced by wave action, and often displays roughly straight crests (Boggs 2006 Chapter 4). This is frequently observed in field (Figure 20). Irregular lower bounding surfaces are also believed to be a characteristic in wave formed ripples, also found in several field outcrops (Figure 19).

Figure 20: Straight crested, symmetrical ripples on Blanknuten (Edgeøya). Hammer is 30 cm.

Symmetrical ripples are most common in shallow-water environments, e.g. in the lower shoreface zone above wave base (Boggs 2006 Chapter 4). Where on the shoreface and how widespread the structure are depends on the energy regime on the coast/delta (Clifton 2006). A barred coast is more likely to develop ripple lamination in the lower shoreface than an open coast of high- to moderate energy (Clifton 2006). The presence of this facies in many sections in field can indicate barred- or bay systems in the current areas. Occurrence of *Rhizocorallium* can support this being a shallow marine facies (MacEachern et al. 2009). *Rhizocorallium* is often found in Skolithos ichnofacies, indicative of shoreface environment of relative high energy levels (Skolithos ichnofacies described under Facies H) (MacEachern et al. 2009).

Wave ripples can also form in deep water by turbidity currents (Kneller et al. 1997). Kneller et al. (1997) performed flume experiments to model sediment deposition from turbulent currents, and concluded that symmetrical ripples possible could form under these conditions.

Facies E Low angle cross-stratified sandstone

Description

The occurrence of low angle cross-stratified sandstone is widely recognised in the field area, but sometimes difficult to distinguish from hummocky and large scale cross-stratified units

(Facies H and A). On some locations on Botneheia and in Sassendalen the facies is found in the lower units of measured sections of the De Geerdalen Formation, often in association with hummocky cross-stratified sandstone (Facies H) and symmetrical ripple laminated sandstone (Facies D). On Edgeøya low angle cross-stratification is found in upwards-coarsening sequences and on Hopen in close association with cross-stratification (Facies A and B) (Figure 21).

Figure 21: Low angle cross-stratification in section BLA091 (Edgeøya). The structure is present in the lower reaches of an upwards-coarsening sequence, bounded by shale units. Different colours are added to the drawing to easier separate the sets of about 5-15 cm thickness. See Figure 6 for location of section BLA091.

Units are typically from 10s of cm up to 2-3 meters. Grain-sizes found are from very fine to fine sand, very fine sand being the main component in most outcrops. The structure characteristic of this facies is low angle cross-stratification. What distinguish this structure from large scale cross-stratification are nearly planar bounding surfaces and wedge shaped units. The units show lamination to bedding (1-5 cm), and set thicknesses are from approximately 5-15 cm.

Colour of the sandstone is normally light grey to grey, and red/brown when weathered. Units are at some localities sparse bioturbated, and organic material (small plant fragments) is found on Botneheia and on loose blocks close to outcrops on Blanknuten.

Discussion and interpretation

Low angle cross-stratification can form in high- and low energy beach environment, by deposition from suspension created by wave activity (Reineck and Singh 1980).

The structure can develop both in the backshore, foreshore or upper shoreface zone (Reineck and Singh 1980; Boggs 2006 Chapter 9). In the backshore the structure can develop due to infilling of depressions during unusually high water conditions, and in the foreshore as lamina accumulating across the berm and in long-shore bars (Reineck and Singh 1980). Long-shore bars can also be present in the shoreface, especially in high-energy coasts (Reineck and Singh 1980). Fine grain sizes favors low angle of the beach profile, corresponding to very fine to fine sand and low angle of the structures of this facies (Reineck and Singh 1980; Orton and Reading 1993) . This facies is not restricted to form in shoreface environment, but can also constitute bar forms in fluvial environments (Reineck and Singh 1980).

Facies F Horizontally bedded sandstone

Description

The facies occur in association with ripple laminated sands, both symmetrical (Facies D) and asymmetrical (Facies A and B), and low angle cross-bedding (Facies E). It is present both in upwards-coarsening sequences on eastern Svalbard and as compound structure in association with small scale structures on central Spitsbergen (Figure 22). Lateral continuity for more than a few meters was not observed at outcrops.

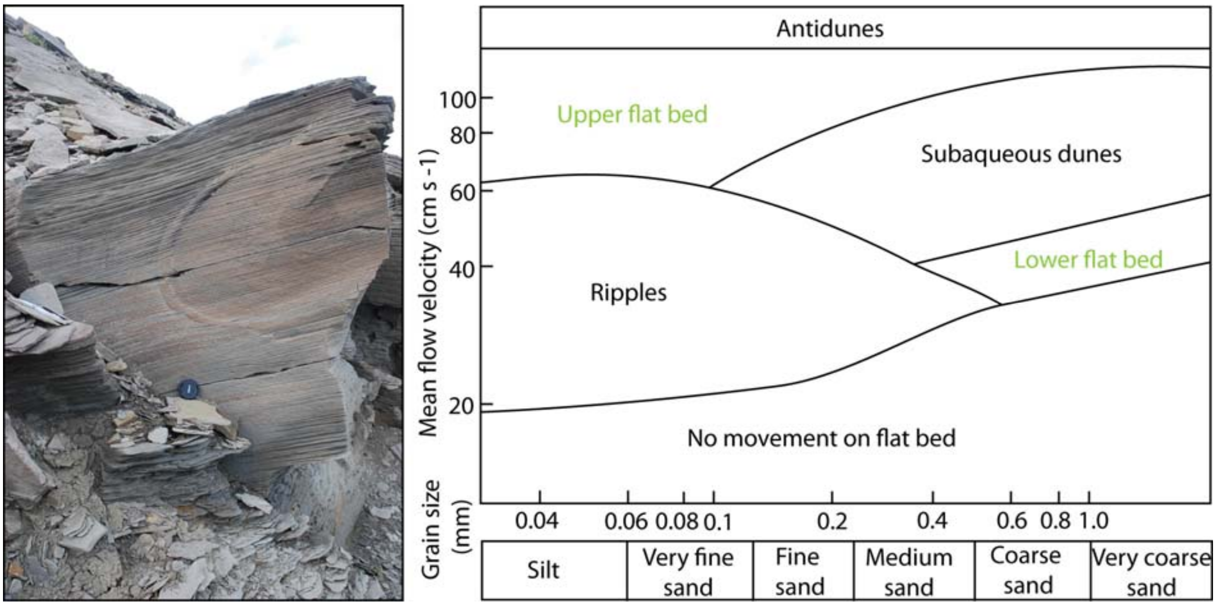


Figure 22: Horizontally bedded sandstone in section BOT094 (Botneheia). Origin of the circle in the picture is unknown. Figure showing structures formed at different flow velocities and grain sizes are after Nichols 1999, Ashley 1990. Nikon in picture cover is 6 cm.

Unit thicknesses are from less than a meter up to a few meters, and the grain-size is fine sand. The structures in this facies show (nearly) parallel bedding surfaces and a roughly horizontal layering. The bed thicknesses are 1-8 cm, but lamination also occurs. Colour of the outcrops is often grey. Bioturbation occurs in one unit on Klinkhamaren and calcite cementation on Trehøgdene. Mud flakes are found on Trehøgdene.

Discussion and interpretation

Flat beds (horizontal bedding) can be produced at high flow velocities (upper flow regime) or from settling of fines under low energy conditions (Boggs 2006 Chapter 4). The dominance of fine sand in outcrops indicates high flow velocities. At lower flow velocities ripples are likely to have formed in fine sand environments. Flat beds can also form in the lower flow regime, but most likely when sediment coarser than about 0.6 mm is in transport (Southard and Bouchwal 1973; Collinson et al. 2006 Chapter 6). This imply that this facies represent upper flow-regime flat beds, normally produced in fine to medium sand under high flow velocities in shallow water (Collinson et al. 2006 Chapter 6). Sparse bioturbation in one sequence on Klinkhamaren tells about reworking by organisms and not rapid enough deposition to ensure complete preservation. Absence of bioturbation at other locations can indicate rapid deposition, or an environment with high fresh water influx (Glørstad-Clark 2009). Presence of mud flakes in one outcrop in Sassendalen (TREH09) support high flow velocities.

Sediment transport is typical unidirectional where flat beds are present, but waves can also lead to their development (Collinson et al. 2006 Chapter 6) Thus this facies can develop in many different environments, and is not a unique indicator of depositional environment (Boggs 2006 Chapter 4).

Facies G Undulating fractured sandstone

Description

This facies mainly occurs on Edgeøya in sections on Klinkhamaren and Blanknuten (Figure 23). It is particularly evident in the lowermost sand units of logged sections, close to base of the De Geerdalen Formation. The facies is laterally continues within some single mountains (e.g. Klinkhamaren). Associated facies are mainly shale (Facies N), low angle cross-stratified sandstone (Facies E) and small scale cross-stratified sandstone (Facies B).

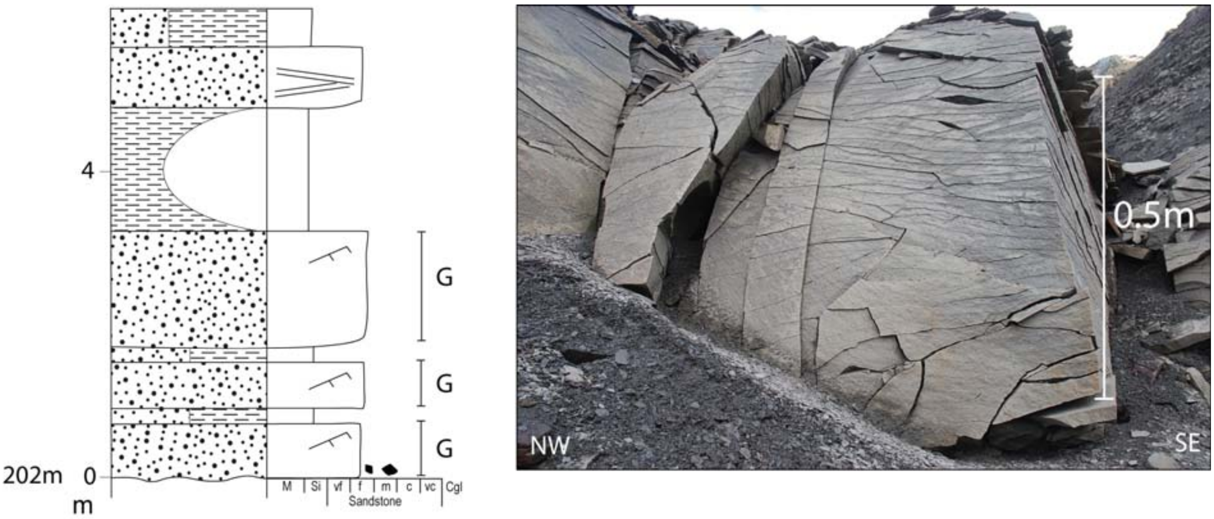


Figure 23: Undulating fractured sandstone at base of the De Geerdalen Formation in section BLA091 (Edgeøya). The unit is erosive based and bounded by shale (Facies N). See Figure 6 for location of the section BLA091.

Units are from 0.1 to 3 m thick, and the grain size is mainly fine sand. Primary sedimentary structures are difficult to detect, but vague symmetrical and unspecified ripples are present in some units. Characteristic of this facies is undulating fracturing. The fracturing separates the units into beds of about 2-10 cm, at some locations forming structures looking like trough cross-bedding or low angle cross-bedding. It is difficult to tell if this is a coincidence, or if actually primary structures are present. Some of the units have erosive lower boundaries, immediately overlaying shale Facies N. Load structures (load casts) are observed in some of the units overlaying laminated clay to very fine sand. Mud flakes and nodules are found in both sections on Edgeøya. The mud flakes are in most cases located at base of units, but they are also found in top of a unit. Colour of exposed outcrops is grey, and red to brown at weathered surfaces.

Discussion and interpretation

Because of lack in diagnostic structures, a number of depositional processes can be responsible for development of this facies. The fracturing is probably secondary in origin, either developed along existing bedding planes or randomly in originally massive units. Load structures can indicate rapid deposition (Collinson et al. 2006 Chapter 9), and mud flakes in association with erosive lower boundaries can imply channel deposits (Dalrymple and Choi 2007).

Facies H Hummocky cross-bedded sandstone (HCS)

Description

Hummocky cross-bedded sandstone was found in most sections (Figure 24), but at different levels above base of the De Geerdalen Formation. It is probably present also in core material (interval A, see Appendix 4), in association with bioturbated sand and silty shale. On central Spitsbergen and in most cases on Edgeøya the facies is found in the lower part of sections. Hopen show HCS in the upper part of the De Geerdalen Formation close to the Slottet bed (in Section LYN09). The facies occurs both as thin units interbedded with shale (Facies N) and as thicker sandstone units, sometimes overlying heterolithic units (Facies K). On central Spitsbergen the facies is lateral continuous for several kilometres, and can probably be correlated between mountains. This is more difficult to accomplish on eastern Svalbard.

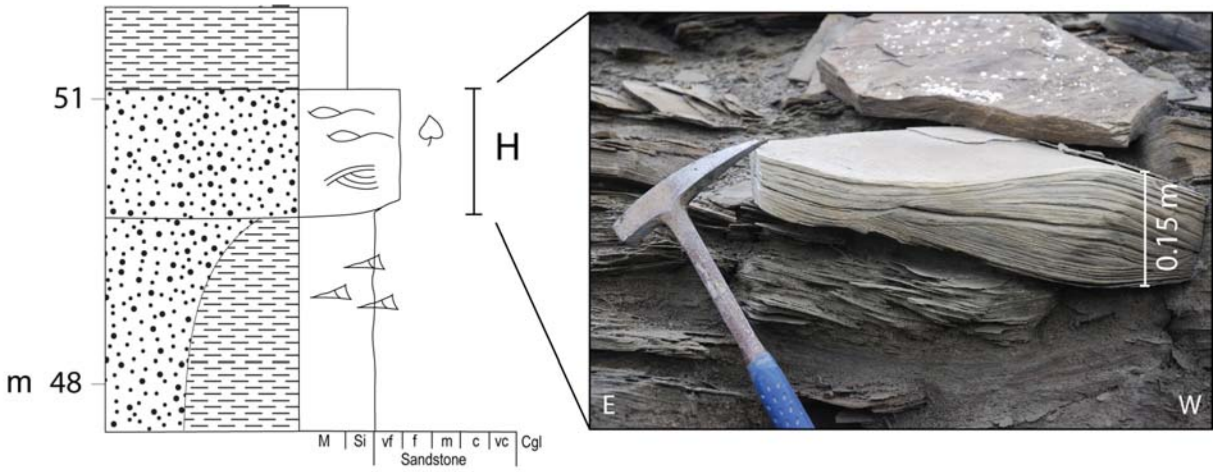


Figure 24: Hummocky cross-bedding at 50 m above base in section BOT094 (Botneheia). The unit is erosive based and bounded by shale (Facies N). See Figure 5 for location of section BOT094.

Most measured units are about 10-50 cm thick, but units from a few cm up to 4 m are found. Grain-sizes are from very fine to fine sand, often being closer to the very fine grained component. The main structure is hummocky cross-bedded sandstone, consisting of hummocks (convex-up) and swales (concave-up) areas (Figure 24). The angle of the dipping lamina is low. Set thicknesses are from 1-20 cm (large scale HCS with set thicknesses exceeding 6-7 cm). In some sections it grades from small to large scale HCS, but usually it alternates unsystematically throughout a section. The structures are bedded (1-2 cm) or laminated, often displaying a continuum from one to the other. The bed thickness has a tendency to decrease upwards in the units. Some units have plane parallel beds on top of the hummocks and swales, and symmetrical ripples or ripple lamination in the uppermost part. Sometimes the ripples are truncated. The lower boundaries of the units are often erosive, and at some outcrops also the upper boundary are abruptly shifting into shale without any gradational transition.

The structures resembling HCS in the core material are low angle, symmetrical and with mud drapes on the lamina. Thicknesses of sets possible to detect are from 1-7 cm. Bioturbated units' separates the HCS sequences.

Trace fossils found in situ and on lose blocks close to outcrops are *Diplocraterion* (Botneheia), *Skolithos* (Botneheia) and *Rizocorallium* (Blanknuten) (Figure 25). Sparse bioturbation were observed on Botneheia in some of the sequences. In core interval A *Teichichnus*, *Ophiomorpha* and *Diplocraterion* are present in association with hummocky cross-stratified sequences. Organic material (plant fragments) is present in small amounts both on Edgeøya and central Spitsbergen. Nodules are on the other hand only observed on Botneheia. Often a mould from the nodule is the only traceable sign, but also in situ nodules are found (clay, pyrite and siderite). The sizes of the nodules are approximately up to 10 cm diameter. Mud flakes are found in a number of outcrops. The colour of units is from grey to brown at weathered surfaces.

Figure 25: The Skolithos ichnofacies. A) *Rhizocorallium* in section BOT093, B) *Diplocraterion* in section BOT091. Figure modified from MacEachern et al. (2009) s.36. Nikon cover is 6 cm and hammer head is 18 cm.

Both minor and heavy deformation are observed (Figure 26), one example being convolute bedding found at Økshogget in the lower part of a HCS sequence. Similar structures and various load structures are also found on other locations at on Eastern Svalbard and in Sassendalen.

Figure 26: Deformation structures (convolute bedding) occurring in Facies H, respectively in section on Økshogget and Blanknuten (Edgeøya).

Discussion and interpretation

The structures are considered to be the product of storm events (Collinson et al. 2006 Chapter 6; Mulder et al. 2008). Storm events can generate currents operating at the same time as high amplitude waves, creating a combined flow regime (Nichols 1999). The current is probably the agent of transporting sand into deeper water in suspension, while the oscillatory motions by the waves creates the typical undulating morphology of HCS structures (Nichols 1999). There have been discussions regarding the role played by the oscillatory and the unidirectional component (Nøttvedt and Kreisa 1987; Mulder et al. 2008). For the low angle cross-stratification to form, a high aggradation rate and a moderate unidirectional flow is needed (Mulder et al. 2008). An increasing current strength can yield structures more asymmetrical and with steeper angles (Kleinhans et al. 2004). Purely oscillatory flow can produce small-scale HCS, which also can occur in turbidite beds as HCS-like structures (Mulder et al. 2008).

To be able to interpret depositional process it is necessary to look at the different elements in an HCS sequence. Modern storm layers can be composed of an: (i) erosive base, (ii) basal lag of mud clasts, shells, plant debris and/or rock fragments, (iii) hummocky cross-stratification, (iv) wave ripple cross-lamination and (v) burrowing interval (Johnson and Baldwin, 2006). Idealized HCS sequences like this have been considered in several publications (Dott and Bourgeois 1982; Nøttvedt and Kreisa 1987; Nichols 1999), and elements from these models are recognized in collected data (Figure 27).

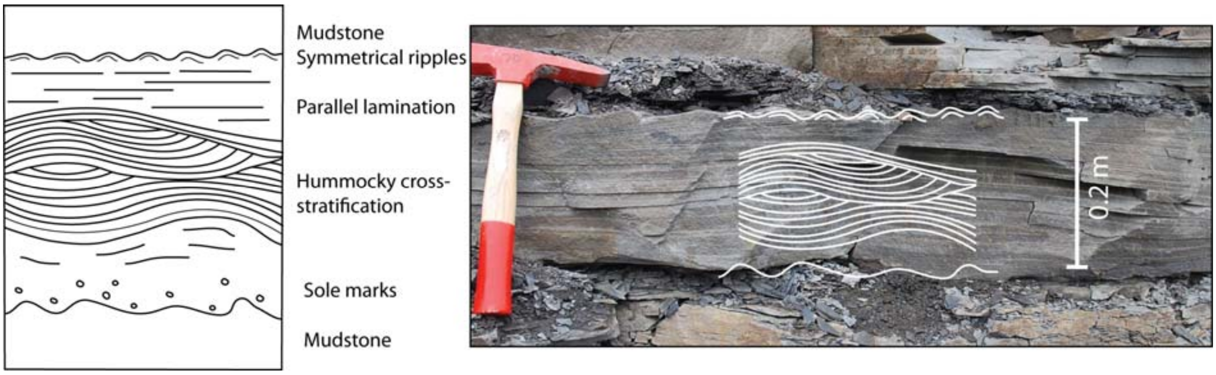


Figure 27: Idealized hummocky cross-stratified sequence (tempestite), figure modified after Nichols 1999, and picture from Økshogget (ØKS09)

Mud drapes observed on HCS structures in core interval A most likely represent reactivation surfaces, indication an episodic migration history (Nøttvedt and Kreisa 1987). Truncated surfaces and missing elements from the idealized HCS sequence in many units throughout the entire field area probably represent unsteady nature of the combined flow currents and new storm events amalgamating older storm beds (Dott and Bourgeois 1982; Nøttvedt and Kreisa 1987; Johnson and Baldwin 2006).

The degree of bioturbation in a HCS sequences reflects the number of burrowing organisms and time between storm events (Johnson and Baldwin 2006). In the observed outcrops degree of bioturbation was difficult to establish, but the presence of trace fossils possible to identify made an interpretation of ichnofacies easier. Findings of *Diplocraterion*, *Ophiomorpha* and *Rhizocorallium* fit in the Skolithos ichnofacies, by being typical ichnogenera (MacEachern et al. 2009). The *Skolithos* ichnofacies is indicative of an environment with high wave and current energy, and tend to develop in muddy to clean marine settings (MacEachern et al.

2009). It is common with abrupt changes in deposition, erosion and physical reworking of sediments in this ichnofacies, conditions possible to find in a wide range of depositional environments; shoreface and foreshore, proximal wave-dominated delta fronts, sandy bars and spits, tidal channels and inlets, flood and ebb tidal deltas, sandy bay margins, low intertidal sand flats, estuary mouth complexes and submarine fans (MacEachern et al. 2009). The high number of *Teichichnus* in core material can correspond to the distal expression of Skolithos ichnofacies (proximal Cruziana ichnofacies), were settings can include: offshore to very distal fringes of the lower shoreface, prodelta to distal delta front, fully marine lagoons and open bays (MacEachern et al. 2009).

Convolute bedding where the easiest recognizable deformation structure in this facies, and its indicative of e.g. turbidite beds, river floodplains and tidal flats (Reineck and Singh 1980; Collinson et al. 2006 Chapter 9). In general convolute bedding is an evidence of possibly liquefaction and rapid deposition (Collinson et al. 2006 Chapter 9), which is also the case in storm deposits.

Because this structure is interpreted as storm beds, they are naturally associated with shelf deposits between fair weather- and storm wave base, respectively at 5-15 and 20-30 meter depth (Nichols 1999; Mulder et al. 2008). Studies show that this facies additionally can occur on the shoreface and in the surfzone (Kleinhans et al. 2004). An example from the North Sea shows that if the wave component is the dominant with a superimposed current, HCS are likely to have formed on the shoreface and inner shelf (Kleinhans et al. 2004). This seems to be the case for most of occurrences in field, because of the low angle and the widespread symmetrical ripple-lamination.

Hummocky and swaley cross-stratification is recognized as an important diagnostic structure in ancient sandstones (Collinson et al. 2006 Chapter 6). These structures are normally only found in fine- to medium grained sand (Nichols 1999), corresponding to the main grain-size being fine sand in outcrops of the De Geerdalen Formation. A study by Doucette (2000) showed that under the same flow conditions low-relief features formed in fine sand and megaripples in medium to coarse sand (Kleinhans et al. 2004), supporting a grain size limitation involved in the process responsible for HCS.

Facies I Mud flake conglomerate

Description

This facies is found in sections on both central Spitsbergen, in core material and on eastern Svalbard (Figure 28). It appears at different levels in the De Geerdalen Formation. What separates this facies from the other occurrence of mud flakes in outcrops (e.g. Facies A and Facies H) is the abundance of mud flakes within a limited area. Associated facies are mainly large scale cross-stratification (Facies A) and shale (Facies N).

Figure 28: Mud flake conglomerate in core interval B (see Appendix 4) and in section BOT093 (see Figure 5) on Botneheia. The mud flakes are from a few mm up to about 6 cm, and some are clearly deformed in the core material.

Units in field are up to 0.5 m and up to about 4 m in core interval B. They are composed of fine sand (matrix) with mud flakes >2 mm, and can be classified as a matrix-supported (oligomict) conglomerate (Boggs 2006 Chapter 5). The mud flakes are from a few mm up to approximately 6 cm diameter, and they are angular to sub-rounded.

Mud flakes observed in core interval B (see Appendix 4) show oblique and sometimes deformed lamination. The size of the mud flakes is similar to field observations, and show a slightly decrease in size from the lower erosive boundary and upwards.

Mud flakes are sometimes preserved in situ also in the field, but can be weathered out leaving red moulds on exposed surfaces. Some outcrops are bedded, with beds from 2-8 cm, and some outcrops are massive. In the bedded sandstone, mud flakes are found in between the beds, making the bed boundaries irregular. The lower boundary of the units is often erosive, and the colour grey to brownish. Calcite- and unspecified cementation is proven in two outcrops on central Spitsbergen, respectively Trehøgdene and Botneheia.

Discussion and interpretation

Conglomerates indicate high energy settings, and can form in many different environments, including; fluvial channels, shorelines (shallow marine), deep water fans (turbidites) and alluvial fans (Collinson et al. 2006 Chapter 7). The content of mud flakes indicate the facies to represent an intraformational conglomerate (Boggs 2006 Chapter 7; Dalrymple and Choi 2007). Clasts in this type of conglomerate can form subaerially by drying out on a tidal flat (intertidal zone) or in other muddy environments (e.g. floodplain), and rip-ups of semiconsolidated mud can take place subaqueous by tidal currents, storm waves or sediment-gravity flows (Boggs 2006 Chapter 7). Dalrymple and Choi (2007) describe mud clasts derived from fluid-mud accumulated in the channel bottom of delta plain channels. They can be separated from mud flakes developed in the intertidal zone by being more rounded and not platy (Dalrymple and Choi 2007).

The fact that the clasts often are angular to sub-rounded indicate short transport of the material (Boggs 2006 Chapter 7). Erosive lower boundaries indicate channel deposits (Dalrymple and Choi 2007), and decreasing size and amount of clasts upwards in a vertically sequences can imply episodic high energy conditions (core interval B, see Appendix 4).

Facies J Fine-grained rooted sandstone

Description

Most of the units occur in the upper part of measured sections at Botneheia, in Sassendalen and on eastern Svalbard (Figure 29). On Hopen it appears at different levels in the two sections. Associated facies are shale (N), coal (O) and sometimes small scale cross-stratification (B).

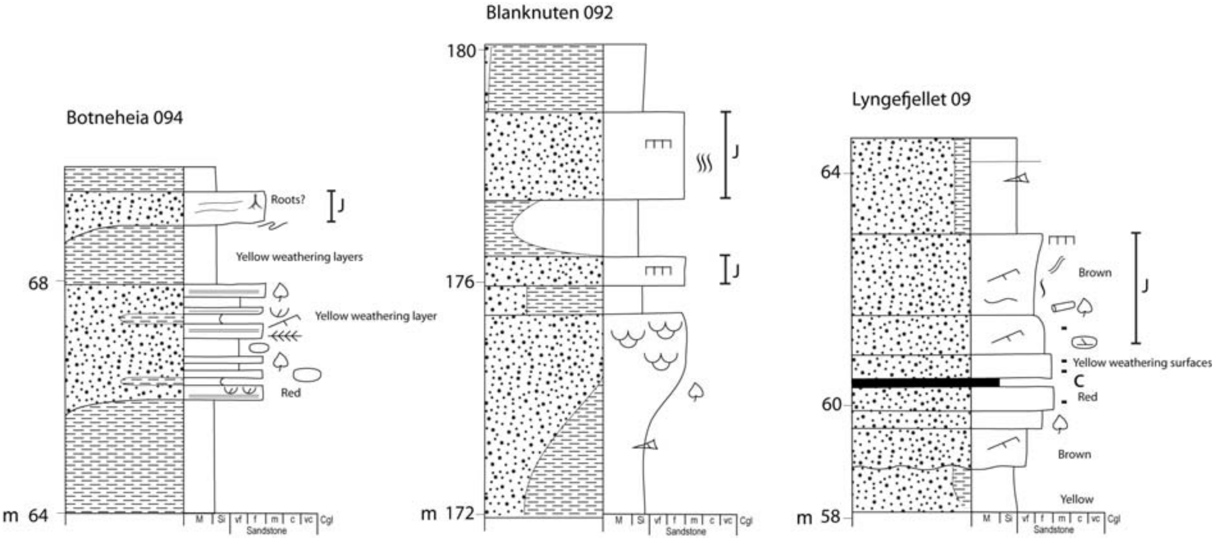


Figure 29: Fine-grained sandstone in sections BOT094, BLA092 and LYN09. Unit on Botneheia shows root tracks and unit on Lyngefjellet have thin coal drapes within the sandstone. Unit on Blanknuten are probably heavy bioturebated. See Figure 5 and 6 for location of sections.

Unit thicknesses are from 0.3 to 1.5 m, and the dominant grain-size is very fine sand. No obvious primary sedimentary structures are observed, but several outcrops are secondary fractured with an undulating appearance like in Facies G and some units are vague ripple laminated. Except from fracturing the exposures are massive and unspecified or calcite cemented. The color is red or brownish. Unit on Edgeøya (BLA092) and Hopen can be heavily bioturbated, and units on Hopen, Botneheia and in Sassendalen show root traces with well preserved plant fossils in some outcrops (Figure 30).

Figure 30: Root tracks in section KOL09 on Kollerfjellet (Hopen) and in section BOT094 on Botneheia (central Spitsbergen). The sandstone is very fine to fine grained, and the units are bounded by shale. Nikon cover is 6 cm.

Discussion and interpretation

Very fine sand can be deposited both under high- and low energy regimes, but lack of characteristic sedimentary structures of higher energy settings (e.g. HCS structures or large scale cross-stratification) makes a low energy environment likely.

The sand fraction can be deposited in several environments, but root tracks and plant material makes it possible to exclude some, for instance fully marine realm. The root tracks from rooted plants can develop when areas get exposed, thus they are indicative of emergence and low flow stage (Bridge 2006). The fine-grain size and root tracks can be indicative of swamp and marsh environment (Martino 1996). In addition root tracked deposits can e.g. be part of crevasse splays and in oxygenated lakes (Bridge 2006).

Facies K Heterolithic bedding

Description

This facies are present on Hopen, Edgeøya, Botneheia and in core material (Figure 31). It often constitutes the lower part of upwards-coarsening successions, and on Edgeøya this is often seen in association with symmetrical ripple-lamination (Facies D). In core interval B it is widespread in the uppermost part, overlying massive sandstone and small upwards-fining sequences.

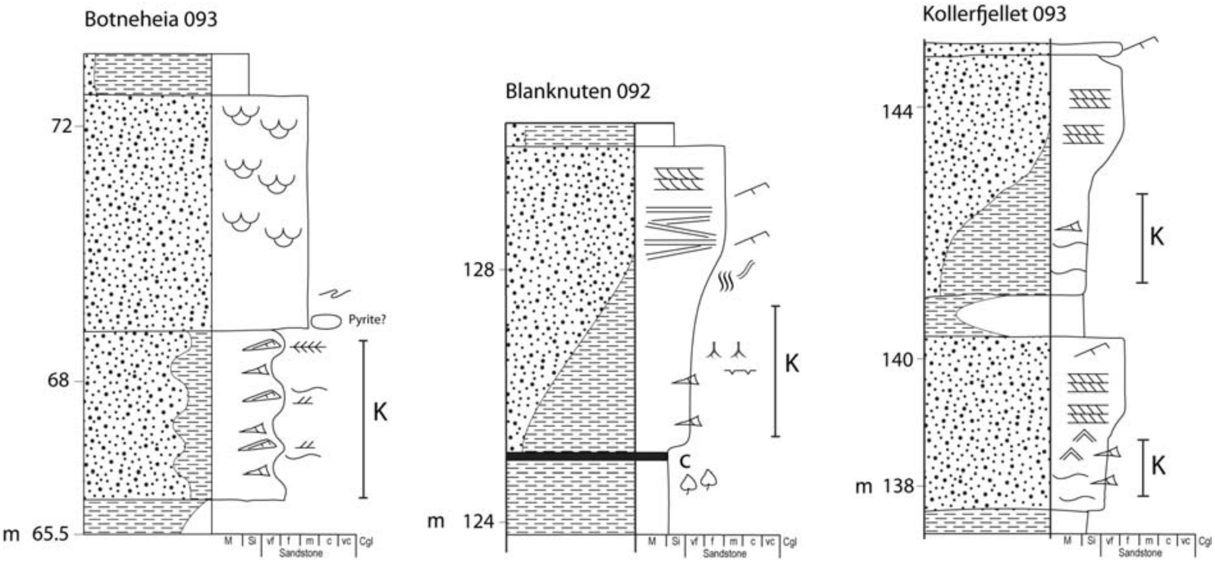


Figure 31: Heterolithic units in sections BOT093, BLA092 and KOL093. All of the units constitute upwards-coarsening units of the De Geerdalen Formation. See Appendix 8 and Figure 5 and 6 for pictures and location of sections.

The unit thicknesses are normally about 1-2 m, but on Blanknuten a unit up to 6 m in thickness was measured. The units have varying content of clay to fine sand. Observed structures are lenticular bedding, wavy bedding and flaser bedding, following classification by Reineck and Singh (1980). A vertical unit on Botneheia shows a gradual change from flaser- to lenticular bedding (Figure 32).

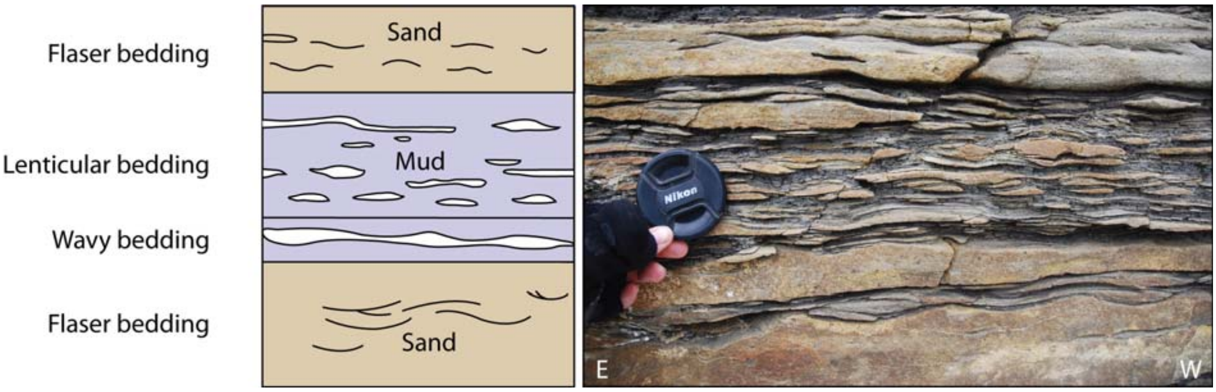


Figure 32: Heterolithic bedding in section BOT093. The ripple shape is slightly asymmetrical, with foresets dipping in a westerly direction (unidirectional). A small normal fault is cutting the deposits. Nikon cover is 6 cm.

Sand is dominating in the flaser bedded unit, and mud is preserved in the troughs as thin drapes. Some ripples have thin drapes covering them completely, but normally the ripple crest is eroded. Degree of symmetry varies between the different field localities. In lenticular bedded units, mud is the dominant grain size. The vertically and horizontally isolated lenses are often a few cm in length/height, and are asymmetrical to more symmetrical for instance in units on Hopen. In wavy bedded units, the ripple laminated layers are continuous and alternate with mud. In one section on Botneheia (BOT092) the sandstone show structures looking like hummocky cross-stratification, but it is difficult to determine because of incomplete structures. Units in core material are often sparse- to heavy bioturbated, and some small faults are present in top of interval B. Small erosional features are present both in core material (interval B, see Appendix 4) and in units on Kollerfjellet (Figure 33).

Figure 33: Small erosional structures in section KOL093, shown by an arrow (Hopen). These structures can be found in mixed flat environment (Reineck and Singh 1980). Nikon cover is 6 cm.

Most of the outcrops show gradual change between flaser- and lenticular bedding. Weathered surfaces often make it difficult to tell sediment transport directions, but observations on good exposed surfaces often give a unidirectional direction. On Hopen (KOL093) ripples migrating in two directions were observed.

Organic material including roots and plant fragment (e.g. on Blanknuten) is found in connection with these deposits, especially on eastern Svalbard. Colour of units is grey to brown at weathered surfaces.

Discussion and interpretation

The structures classified by Reineck and Singh (flaser-, wavy- and lenticular bedding) are indicative of a setting with both sand and mud available, and alternating energy regime (Reineck and Singh 1980; Martino 1996). The mud fraction is deposited during quiet periods with settling from suspension and ripple lamination during periods of current activity (turbulent water) (Reineck and Singh 1980). Observed erosion on ripple crests in the flaser bedded units imply the beginning of a new period of current activity after still stand, and the dominating sand fraction indicate conditions favouring sand deposition (Reineck and Singh 1980). The contrary situation is prevailing in lenticular bedded units.

This type of conditions can occur in different environments, but are particular indicative of tidal influence and most common on the intertidal- and subtidal flats (Tankard and Hobday 1977; Reineck and Singh 1980). Small- scale erosional structures are also described from mixed flat environment (Reineck and Singh 1980).

In addition to tidal flat setting, the structures can also occur in floodplain environments, as channel fills or on the delta front to prodelta (Martino 1996; Bhattacharya 2006; Dalrymple and Choi 2007).

Desiccation cracks described at Blanknuten suggests alternating periods of submergence (short) and emergence (long) locally at this site (Tankard and Hobday 1977). Roots found in the same unit support a period of emergence.

Facies L Carbonate rich sandstone

Description

This facies occur in the lower part of two sections on Botneheia and on eastern Svalbard at different levels in the formation (Figure 34). It is found in association with shale (Facies N), HCS sequences (Facies H) and heterolithic bedding (Facies K).

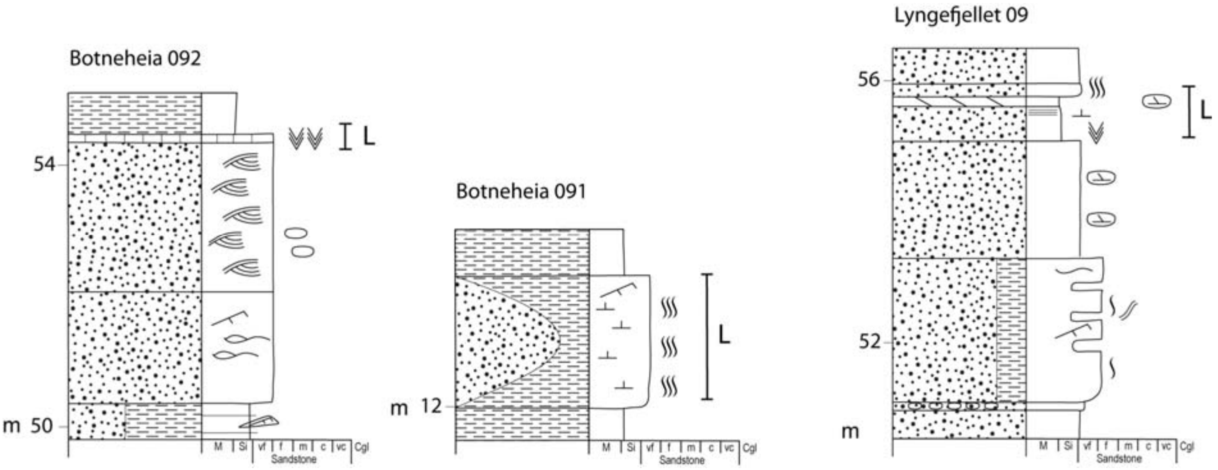


Figure 34: Carbonate cemented units in different areas on Svalbard in the De Geerdalen Formation. Cone in cone structures in section BOT092, carbonate concretions in section BOT091 and siderite layers and concretions in section LYN09 (Hopen). See Figure 5 and 6 for location of sections.

Different occurrences of carbonate rich sandstone are included in this facies; both large carbonate concretions, cone in cone structures and individual siderite layers. Carbonate concretions or lens shaped layers are found on Botneheia and in one section on Blanknuten. Unit thicknesses are from 0.1 to 2 m, and the grain-size is very fine sand. Shale Facies H2 are separating the lenses. On Botneheia this appearance is especially evident (Figure 35). Few primary structures are observed in these lenses, except from vague ripples on top of one outcrop on Botneheia. Secondary undulating fracturing and heavy bioturbation is typical, and the color is often red to brown.

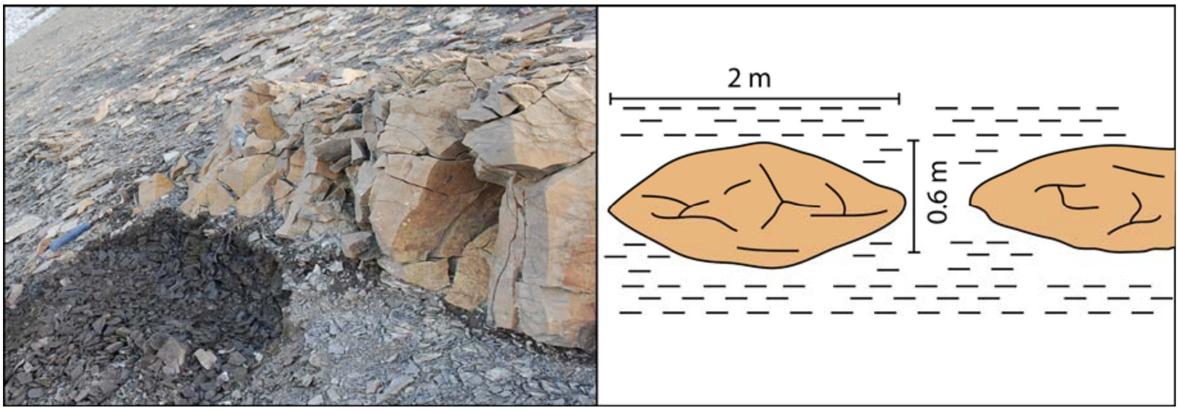


Figure 35: Lens shaped carbonate concretions in section BOT092 (central Spitsbergen), located in the lower reaches of a thick shale sequence. See Figure 5 for location of section BOT092.

Where the carbonate rich layers constitute more continuous layers and not lenses, units containing cone in cone are found, described as stacked conical fracture surfaces in Collinson et al. 2006 (Figure 36 A). On Botneheia (BOT092) a 10 cm thick cone in cone unit are found on top of a HCS sequence, and on Hopen similar structures are found overlying heterolithic and low angle cross-bedded units. A unit on Lyngefjellet showed a compound structure, consisting of cone in cone overlain by laminated calcite rich sandstone and a ball shaped siderite layer. The colour varies between dark grey, brown and red.

Individual siderite layers and concretions are found on Hopen, mainly in the lower part of the sections. They are up to 0.4 m thick and can be made up of concretions, host rock primary being shale (Figure 36 B).

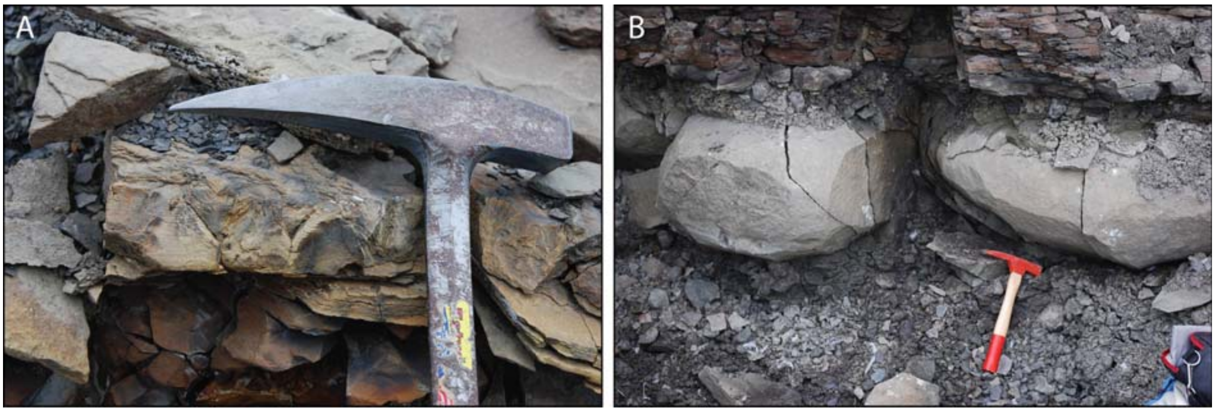


Figure 36: Carbonate rich sandstone in the De Geerdalen Formation. A) Cone in cone structures in section BOT092 (central Spitsbergen), B) Concretions (siderite?) in section LYN09 (Hopen). Red hammer is 30 cm and hammer head in picture A is 18 cm.

Discussion and interpretation

Structures included in this facies are secondary, and formed by diagenetic processes.

Carbonate concretions are the most common type of concretions in sedimentary rocks, and have been discussed in a number of publications (Selles-Martinez 1996; Mozley 1996; Seilacher 2001; Lash and Blood 2004; Raiswell and Fisher 2004).

The lens shaped geometry can reflect compaction of the shale after deposition, and the unsystematic fracturing can have developed along pre-existing discontinuities because of tensile stress (Selles-Martinez 1996; Seilacher 2001). The fracturing can also represent septarian cracks, where the fracture geometries can reflect local stress patterns at the time of origin (Selles-Martinez 1996). Lack of clear calcite in the fractures, common in septarians, can weigh against this theory (Seilacher 2001; Collinson et al. 2006c). Previous sedimentological work done on the De Geerdalen Formation indicates that dissolved bivalve and coquina beds are the carbonate source to these concretions (pers.com. A.Mørk 2010).

Carbonate concretions can either start to grow on the water-sediment interface or under kilometers of sediment overburden in the diagenetic stage, possibly by precipitation from saturated brines (inorganic origin) (Selles-Martinez 1996). They can develop in different environments, from continental shelf or slope, deep basinal environments or non marine settings (Raiswell and Fisher 2004; Wanas 2008). This is difficult to determine without better chemical data, e.g. carbon isotope composition (Raiswell and Fisher 2004).

Siderite concretions commonly occur in mudstone or siltstone, precipitated during reducing conditions (Collinson et al. 2006 Chapter 9). This agrees with field observations, e.g. in the lowermost part of section LYN09 (Figure 36 B). Siderite (FeCO3) generally occurs in freshwater with high Fe content and low sulphate content, but can also develop in reducing Fe-rich shallow marine environment (Boggs 1992 Chapter 9). Knarud (1980) suggest the siderite layers and concretions to be of late diagenetic occurrence, probably transformed from calcite or aragonite.

Cone in cone structures have been given different explanations in the literature, one being crystal growth due to sediment pressure (Seilacher 2001). The structures have been studied more closely on Edgeøya by Marina Tugarova during the cruises with the vessel M/S Kongsøy.

Facies M Coquina beds

Description

Coquina beds are found on Botneheia, on the two southernmost profiles and in core interval B at about 800 m (Figure 37). Knarud (1980) has also reported the facies in several of his sections, both on central and eastern Svalbard. At Botneheia, the facies are located at approximately the same height above base of the De Geerdalen Formation, and both observations occur above small and large scale cross-stratified sand sequences. Facies overlaying the deposits are shale at BOT091 and low angle to HCS sandstone at BOT094. In core interval B (see Appendix 4) it is overlain by mud flake conglomerate.

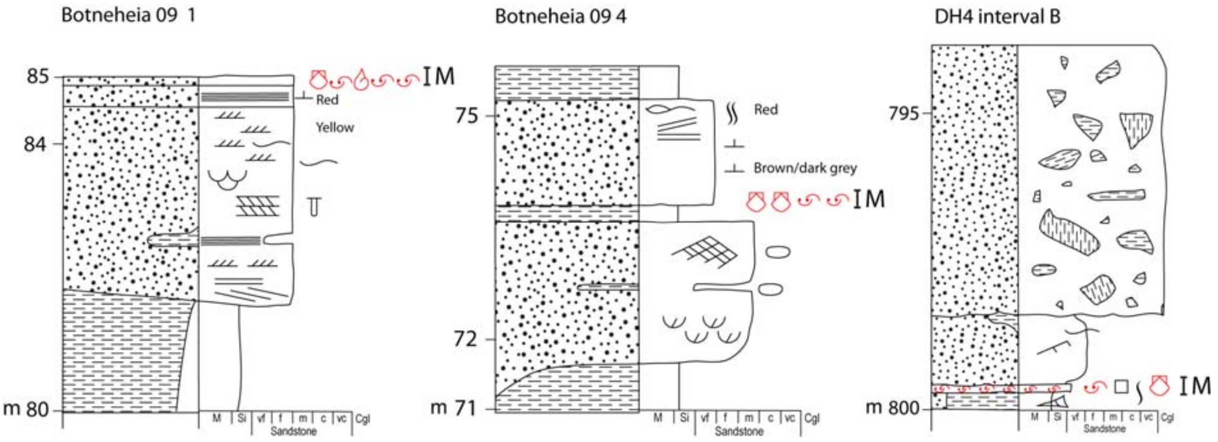


Figure 37: Coquina beds in sections BOT091, BOT094 and core interval B. The coquinas are mostly fragmented and located on top of cross-bedded units, except from the coquina bed in well DH4, underlying a thick mud flake conglomerate unit . It is possible that they represent the Isfjorden member in some areas (see Section 1.5).

Unit thicknesses are about 4 cm, and fossils found are mainly fragmented bivalves (coquina). The deposits can be described as shell bank accumulations. At the southernmost profile phosphate pellets are present. Colour of the outcrops is dark grey to brownish.

Discussion and interpretation

This facies have been described from the De Geerdalen Formation by Knarud (1980) and in Mørk et al. (1982, 1999). Knarud noted the occurrence of this facies in central and easterly areas, mainly in the middle and upper part of his profiles of the De Geerdalen Formation. In this material the accumulations of fossils consisted of a limited selection of intact bivalves, were the preservation grade is interpreted to represent low energy in depositional environment (Knarud 1980). In recently collected data the fossils are fragmented, indicating a higher energy regime.

The location of this facies above cross-bedded sandstone units at Botneheia in our field area agrees with the lower boundary definition of the Isfjorden Member, being at the base of a siltstone bivalve coquina bed occurring above a cross-bedded unit of the De Geerdalen Formation (Mørk et al. 1999). In core interval B (see Appendix 2) the coquina bed does not occur above cross-bedded sandstone, but the location in the upper part of the profile can indicate connection to observations in field. The Isfjorden Member is interpreted to be deposited in shallow marine to locally lagoon environments (Mørk et al. 1999).

Facies N Shale

The focus of this study has been sandstone units, mainly because of better exposed units and the importance regarding the CO_2-storage project. Totally or partially covering on gentle slopes was a problem across the entire field area, making description and interpretation of this facies incomplete. Covering of sections where especially a problem in Sassendalen. Based on sparse observation and associated facies, two sub facies will be described; black shale (N1) and silty shale (N2). In most cases a distinguishing the two was difficult or impossible, and question marks are used in the facies forms (Appendix 5) to emphasise when this is the situation.

N1 Black shale

Description

This facies is found in most of the sections on Botneheia in association with cross-stratified sandstone, mainly in the upper part of logged sections. In core data this facies is found at 856 m in core interval A (see Appendix 4) in association with cross-stratified sandstone and an overlying coal unit. On Edgeøya and Hopen it is most abundant in association with cross-stratified sandstone and in between upwards coarsening sequences (Figure 38).

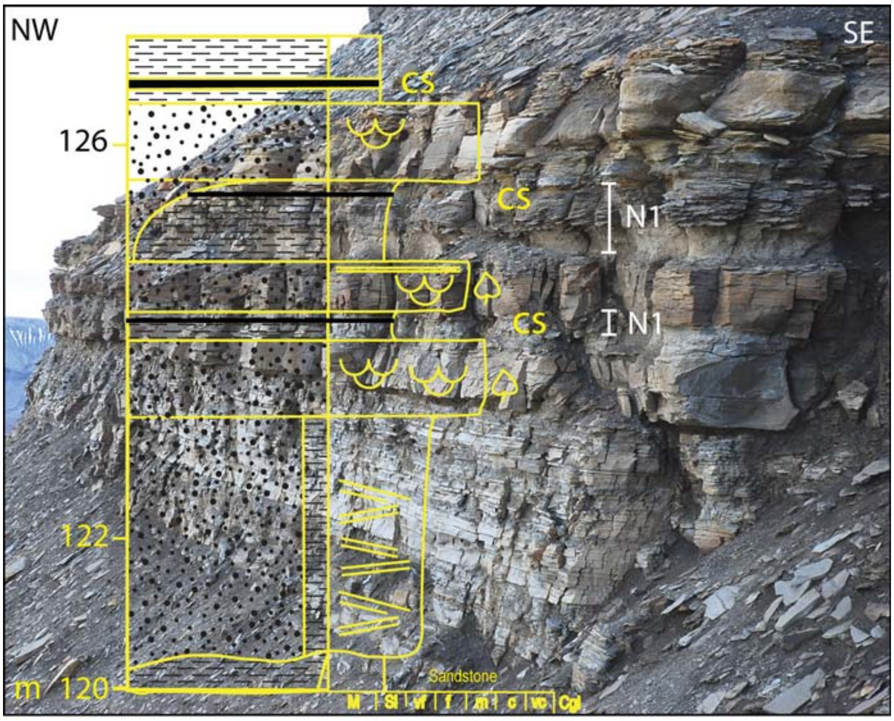


Figure 38: Organic rich shale between cross-stratified sandstone in section BLA091 (Edgeøya). The sequence is interpreted to represent a small delta lobe prograding into a bay (see Chapter 5).

Unit thicknesses are from few cm up to a few 10 s of meters. Grain sizes are clay to silt, and at some localities the facies is laminated with alternating few mm sized coal drapes. Thin yellow layers also appear in this facies, especially evident on Edgeøya. On Botneheia (BOT094) red moulds from nodules were found in some units.

Discussion and interpretation

Shale can form in low energy environments from settling of suspended fine sediments (clay and silt), provided abundant fines (Boggs 2006 Chapter 5).

Black shale can occur on coastal plains (e.g. lagoons, bays and lakes) (Martino 1996; Boggs 2006 Chapter 5) or in deep marine settings (Stow et al. 2001). The thin coal drapes in this facies indicates a coastal setting, and can represent allochthonous coal or coal shale, washed out into lakes within peat swamps as degraded peat (McCabe 1984). The thin yellow layers can indicate influence by marine waters, by being characteristic of sulphur content (McCabe 1984).

N2 Silty shale

Description

Silty shale occurs mainly in association with hummocky cross-bedded sandstone, low angle cross-stratified sandstone and symmetrical ripple laminated sandstone. On Botneheia, Sassendalen and on Edgeøya the facies is most evident in the lower part of the logged sections (Figure 39). Extensive covered areas also occurred in top sections, but they might as well represent black shale. On Hopen the facies is found in the upper part of the De Geerdalen Formation. In core material it is most widespread in core interval A, associated with HCS sequences.

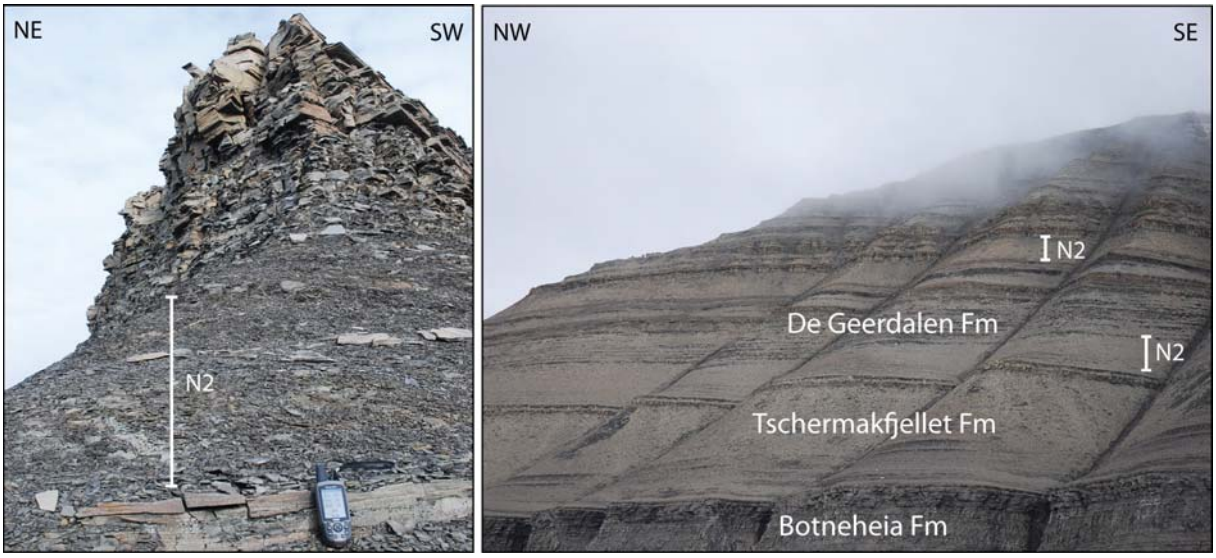


Figure 39: Silty shale in section on Muen and Blanknuten (Edgeøya). See Figure 6 and Appendix 8 for location and panorama pictures of current mountains.

In outcrops and areas not covered, sequences are from a few cm up to about 30 m thick. As this facies also include partly covered intervals with a gentle slope angle, sequences up to 48 m are noted in Sassendalen.

Grain-sizes are from clay to silt, including silt to very fine sand layers of few cm sizes in some of the sequences. The layers are symmetrical- to planar laminated, or structureless in appearance. They are also erosive based and often red to yellow coloured. Sand lenses are observed in thin units close to associated facies like HCS or asymmetrical ripple laminated facies. Because of fracturing and weathering it is difficult to se any lamination in the shale units in field outcrops, but units in core material show evident lamination in this facies. On

Hopen the silty shale often have a particular ball shape appearance, not observed at other locations in the field area (Figure 40).

Trace fossils are only observed in core material in units closely associated with HCS sequences. Weathering- and covering of sequences made this kind of observation difficult in field. The trace fossils are similar to trace fossils observed in Facies H (HCS).

Figure 40: Ball shaped shale in section LYN09 (Hopen). Hammer is 30 cm. See Figure 6 for location of section LYN09.

Discussion and interpretation

Like in facies N1, these deposits are probably deposited by settling of fines in low energy areas. Absence of coal and sparse amounts of plant fragments indicate a more distal depositional environment compared to facies N1. The sandstone layers and absence of storm structures can indicate hemipelagic settling (Wignall and Newton 2001), with supply both from land and deeper marine areas.

Silty and sometimes lenticular sediments observed in this facies are characteristic of delta front environment (Reineck and Singh 1980). The thin interbedded silt- to sandstone units can represent deposits from turbidity currents or gravity flows in the offshore area, supported by the marine fossil assemblage in some areas.

Facies O Coal

Description

This facies is most evident on Edgeøya and Hopen, but is also found in one section on Botneheia (BOT093) and in Sassendalen (GRU09). Associated facies are cross-stratified sandstone (Facies A and B), fine grained deposits (Facies J) and black shale (Facies N1) (Figure 41). Coal shale is also found in core interval A at 855 m, overlying a thick cross-stratified sandstone unit.

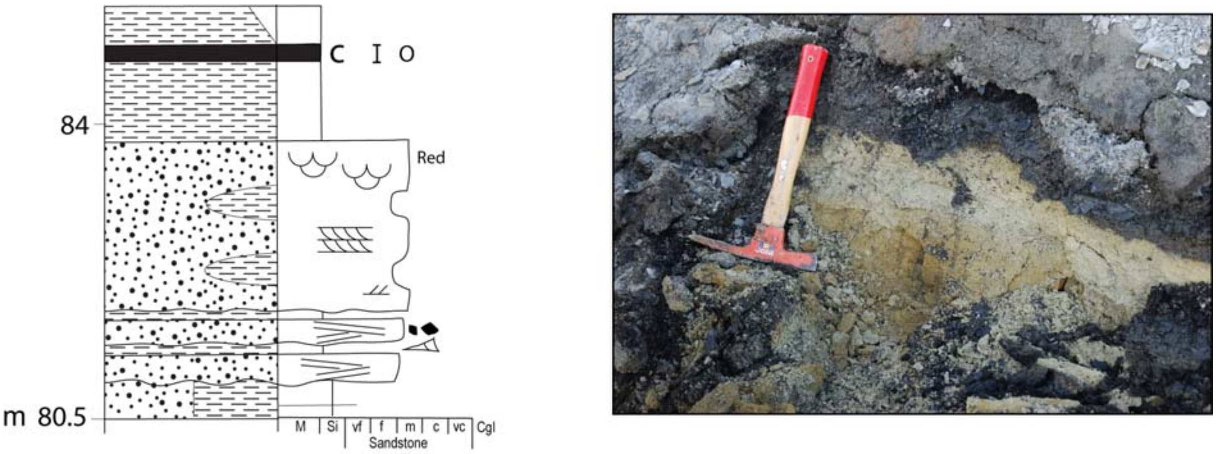


Figure 41: Coal unit in section BLA091. The picture is from fieldwork at Blanknuten summer 2008, further south on Blanknuten. Hammer is 30 cm. See Figure 6 for location of section BLA091.

Units are from 10 to 20 cm thick, and constitute coal or coal shale. At some localities yellow surfaces are found beneath the coal layer. Root horizons are also observed underlying coal units on Blanknuten (pers.com. A.Mørk 2010). Soft sedimentary deformation and partly covering makes it difficult to tell the number of coal layers in some vertical sequences. The coal layers are difficult to trace from one mountain to another, and are only followed for some meters when observed.

Discussion and interpretation

Coal can develop in a number of terrestrial and marginal marine sedimentary settings if favourable conditions are complied, including high water table and abundant vegetation (Collinson 2006). Subenvironments capable of hosting peat accumulation can for instance be braidplains, protected lagoons, abandoned mouth-bar lobes and possibly the landward side of barrier islands (Nemec 1992). In studied outcrops and core material coals are found in association with different facies, indicating the presence of this facies in different subenvironments in the De Geerdalen Formation. Thin coals of lateral limited extent like this are likely to represent an active environment with shortlived overbank settings with autocyclic controls (Collinson 2006).

4.2 Facies Associations (FA)

Seven facies associations (1-7) are described and given names from possible depositional environment. The facies associations are listed in order of proximal to distal position regarding land areas as far as possible, considering that some facies associations can be present both on delta plain and delta front.

1. Fine grained deposits in coastal areas
2. Distributary channels
3. Distributary mouth bars
4. Delta lobe progradations
5. Barrier island/upper shoreface deposits
6. Delta front channel sand
7. Lower shoreface to offshore deposits

Facies Association 1 (FA1): Fine-grained deposits in coastal areas

Description

Structures included in this association are small scale cross-stratification (B), climbing ripples (C), horizontally bedded sandstone (F), heterolithic facies (K), fine grained rooted sandstone (J), coal (O), carbonate rich sandstone (L) and shale facies (N).

The facies association is present both on eastern- and central Svalbard. On Botneheia it is developed in upper section BOT094 and BOT093 (central Botneheia, see Appendix 8 and Figure 5) and sections in Sassendalen contain units indicative of this association in middle/upper part of the De Geerdalen Formation. On Edgeøya it is most evident on Siegelfjellet (2008 data) and on Blanknuten, while sections on Hopen show widespread occurrence of this association throughout the entire section on Kollerfjellet and in lower sequences on Lyngefjellet.

In a number of the sections only a few of the facies of this association is present, and no sections show all of the mentioned facies in a single vertical sequence. Both on Botneheia, in Sassendalen and on Hopen one of the facies combinations occurring together are fine grained rooted sandstone (J), shale (N) and coal (O). The coal layer (10-20 cm thick) is often overlaying a rooted sandstone unit (0.3-1.5 m thick).

On Botneheia the facies small scale cross-stratified sandstone (B), climbing ripple cross-laminated sandstone (C) and horizontal bedded sandstone (F) occur together repeatedly in section BOT094, each sequence separated by shale units. Sequences are from 2-4 m thick, and can only be traced a few meters laterally. Additionally heterolithic and ripple laminated sandstone (B and D) occur together in some sections throughout the field area, and coal also occur in association with other facies.

Discussion and interpretation

This association probably represents different sub-environments (Figure 42), and covering of gentle sloping areas and poor outcrops makes it necessary to create a broad association. There are not many studies on the distinction of sub-environments on the delta plain (e.g. swamps, marshes, tidal flats, lagoons and interdistributary bays) in ancient sediments (Bhattacharya 2006), but several studies discuss deposits from the different sub-environments (Nemec 1992; Bhattacharya 2006).

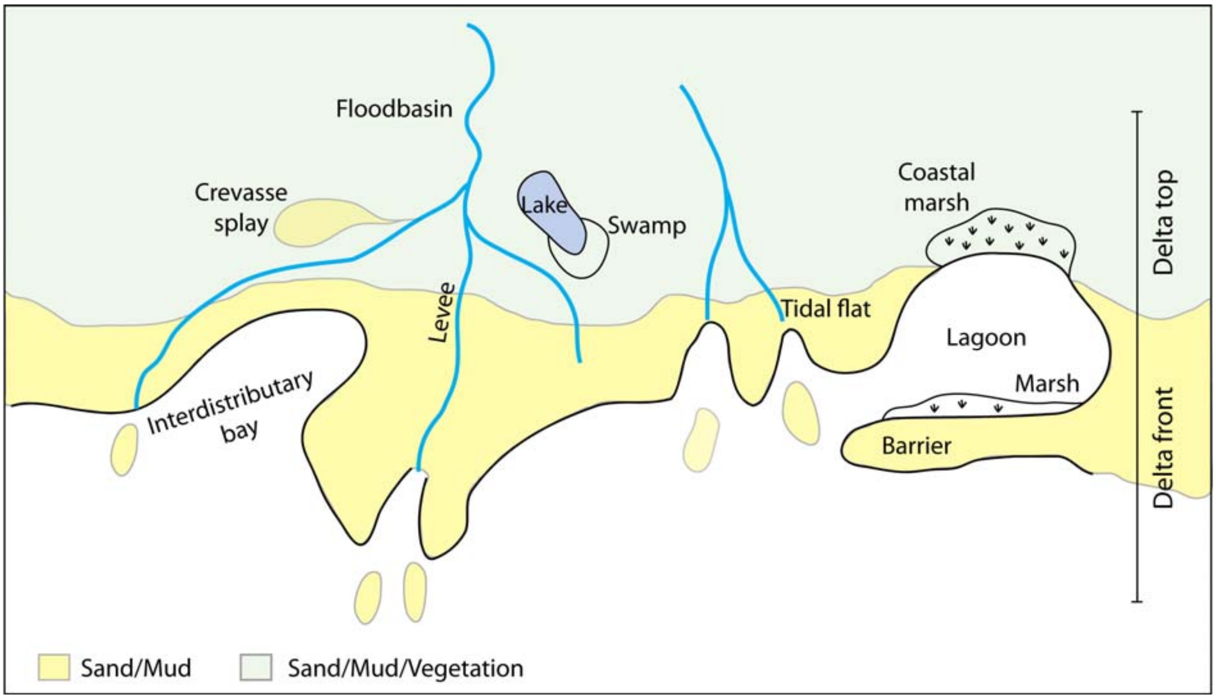


Figure 42: General overview of sub environments on the delta top/plain and delta front. Both features characteristic of wave-, fluvial and tidal influence are included. Facies association 1 contains several of the sub environments drawn in this figure.

Coal occurs in association with different facies, like mention in Section 4.1, and can be basis for discussion of various settings. In some areas on Hopen coal occurs in sequences with fine grained rooted sandstone and shale. This facies combinations is often present in clastic swamp, marsh or lacustrine environments (Martino 1996; Bhattacharya 2006). This deposit is also found in section GRU09 in Sassendalen, but in this area the deposit is not rooted, but contains abundant plant fragments. The deposits are also unspecified cemented and vague ripple laminated. Wave rippled fine grained deposits can indicate lacustrine deposits (Makaske 2001). Individual fine grained units can also be indicative of marsh environment, especially if the deposits are structureless and bioturbated (Makaske 2001). This is e.g. the case in the upper part of section KOL093 and BLA092 (Appendix 5 and Figure 6).

Close to base of measured section KOL093 a coal layer is overlain by a carbonate rich bed with siderite nodules. This type of deposit is interpreted to represent coastal ravinement by Martino (1996). Several meters (50 m) of overlying shale can possibly support this theory of flooding by marine waters (see Appendix 5).

Further up in section KOL093 a coal and fine grained layer is located a few meters above a 4 m thick large scale cross-stratified sandstone unit. This can represent the growth of vegetation on top of a abandoned channel system (Nemec 1992). Nemec (1992) describes this occurrence of coal from a braidplain delta. Coal overlying river deposits is one of the most common settings for their development, especially on flat plains (McCabe 1984). The coal layer is not underlain by rooted sediments, which can indicate floating peat as origin (McCabe 1984). Floating peats, the first step on developing raised swamps of more extensive thicknesses (Robb 2005), are also believed to be thin (McCabe 1984; Robb 2005), corresponding to the observation in this sequence. Thin coal units like the one described and lack of coal in most sections throughout field area, may indicate that this system is not suitable for coal development. McCabe (1984) point out that deltaic environment does not appear to be favorable for coal-forming processes. According to Hazeldine (1989) in Martino (1996) tidal coasts, abandoned coastal plains and inactive alluvial plains are the most common modern peat-forming environments.

Back-barrier/outer lagoon setting (marsh behind barrier) is an example of environment hostile to formation of thick coal successions. This sub environment is probably present both on Edgeøya and in Sassendalen, and the possible barrier deposits will be described in more detail under Facies association 5. In a regressive system a barrier will be overlain by a back-barrier environment, often initiated by a thin coal layer (Boggs 2006 Chapter 9). Lagoonal conditions can be indicated by deposits of fine sand, silt and mud, in addition to peat deposits with plant remains (Boggs 2006 Chapter 9; Reading and Collinson 2006). This is e.g. the case in core interval A in Adventdalen and upper part of GRU09 in Sassensalen (see Appendix 4 and 5). Fine-grained planar cross-bedded sediments are also described from lagoon sequences, interpreted to represent washover-sands from the barrier (Boggs 2006 Chapter 9). This set of characteristics could fit to some vertical sequences observed in field, e.g. in section TREH09 (Figure 5 and Appendix 5). In this section an interval of mainly shale and some thin laminated layers, fine grained deposits (sometimes rooted) and cross-stratified layers occur. The thin laminated layers can represent washover fans, deposited during storms (Reading and Collinson 2006).

Coal also appear on top of and between upward-coarsening sequences north on Blanknuten. The upwards-coarsening sequences are described in more detail under Facies association 4, probably representing a prograding system of bars or lobes on the delta front. In addition to coal layers these black shale areas in between the upwards-coarsening units containing carbonate concretions and bioturbated fine grained deposits. The presence of coal and coal shale indicate that the associated sediments not are fully marine, because peat does not form in siliciclastic marine sediments with large amount of clay (McCabe 1984). Nemec (1992) describes peat growth on abandoned lobes, up to 60 cm in thickness and less than 100 m in lateral extent. This limited lateral extent can agree with the difficulties of correlation coal layers on e.g. Blanknuten.

The black shale units can represent interdistributary areas in between the mentioned abandoned lobes. Martino (1996) interpret dark laminated shale with plant detritus, occurring in the Kanawha Formation (USA), to be deposited in lakes were the organic component represented drowned planar swamps. Swamps can occur on flood plains (Martino 1996). Drowning of peat can only occur if subsidence rate is rapid or if the water level rises due to other factors (McCabe 1984). Influx of saltwater into an abandoned part of a delta can probably slow down peat accumulation, and represent another factor which increases the chance of drowning (McCabe 1984).

Heterolithic bedding occurs rarely as small upwards-coarsening units in outcrops throughout the entire field area, always bounded by shale units. On Økshogget and on Grusryggen rooted fine grained deposits are found in association with heterolithic bedding, a succession interpreted as sub-intertidal sand and mixed flats by Martino (1996). Tidal flats can develop behind barrier islands on high energy coasts or on open coasts with minor wave influence, most likely in meso- to macrotidal environments (Tankard and Hobday 1977). This conditions can be present in the subenvironments; estuary, lagoons or bays (Reineck and Singh 1980). This can correspond to the mentioned back barrier lagoonal setting indicated for other facies in this facies association, closely related to these deposits. Like previously mentioned, heterolithic bedding can also occur on floodplains and other non-tidal settings.

In section BOT094 (Figure 43 and 44) the occurrence of repeated sequences of small scale cross-stratification, horizontal bedded sandstone and climbing ripple lamination can indicate an environment of periodic high sedimentation rate and available sediments (Reineck and Singh 1980).

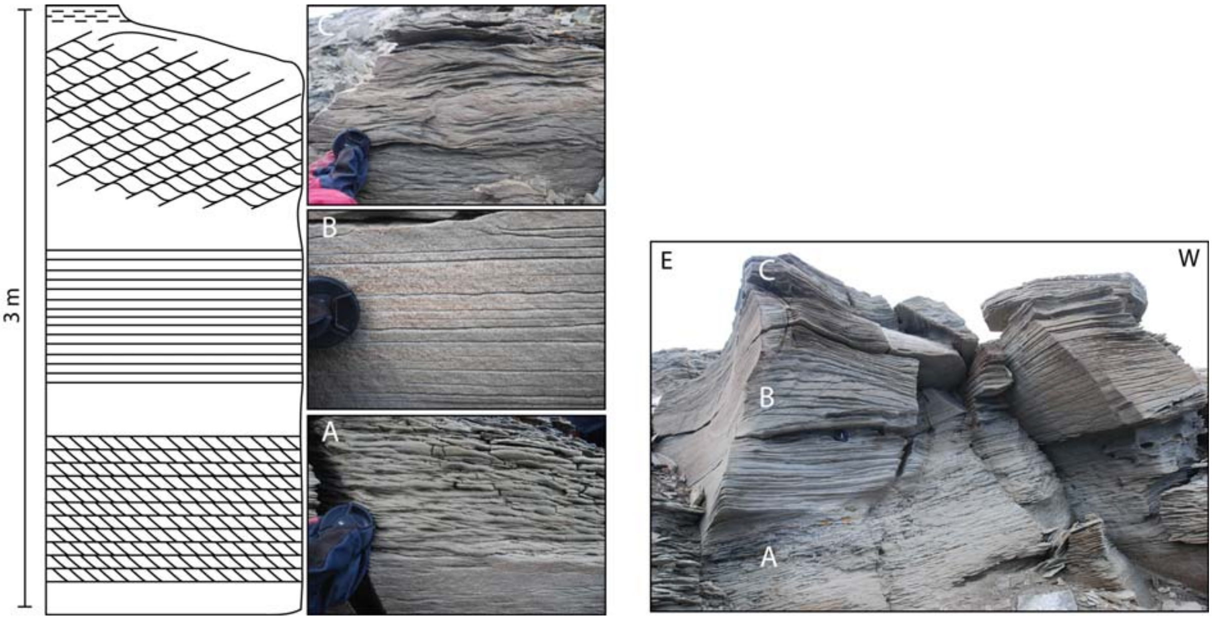


Figure 43: Crevasse splay deposits on Botneheia, 80 m above base of the De Geerdalen Formation (BOT094, central Spitsbergen). See Figure 5 and Appendix 8 for location and picture of locality.

Like mentioned in Section 4.1 this conditions and structures can occur in levees and further out on floodplains. Natural levees are formed by deposition by floodwater from a stream reaching a higher level than normally, and the sandy component is deposited by crevasse splays when high floods (Reineck and Singh 1980). Stringers of crevasse splay deposits can continue out on to the floodplain, and if the system is dynamic, floodplain deposits can contain more sand and be difficult to distinguish from levees and crevasse channels (Reineck and Singh 1980). Lack of large scale cross-stratification underlying these facies probably excludes pointbar or other channel deposits, described in Reineck and Singh (1980). The deposit was not possible to track in sections located only 100s of meters laterally, making the deposits more likely to represents a crevasse channel cut normal to pale current than a larger channel form with higher width numbers (Reynolds 1999). The close association with a coquina bed and hummocky cross-stratification imply a marginal environment open for storm waves, possibly an interdistributary bay environment. Interdistributary bays can contain facies like shale, climbing- and ripple lamination and channel facies (Bhattacharya 2006). Rooted fine grained deposits can indicate the presence of swamp, marsh or lacustrine conditions in the area (Bhattacharya 2006). This pronounced climbing ripple laminated units are also described from Siegelfjellet during field work summer 2008.

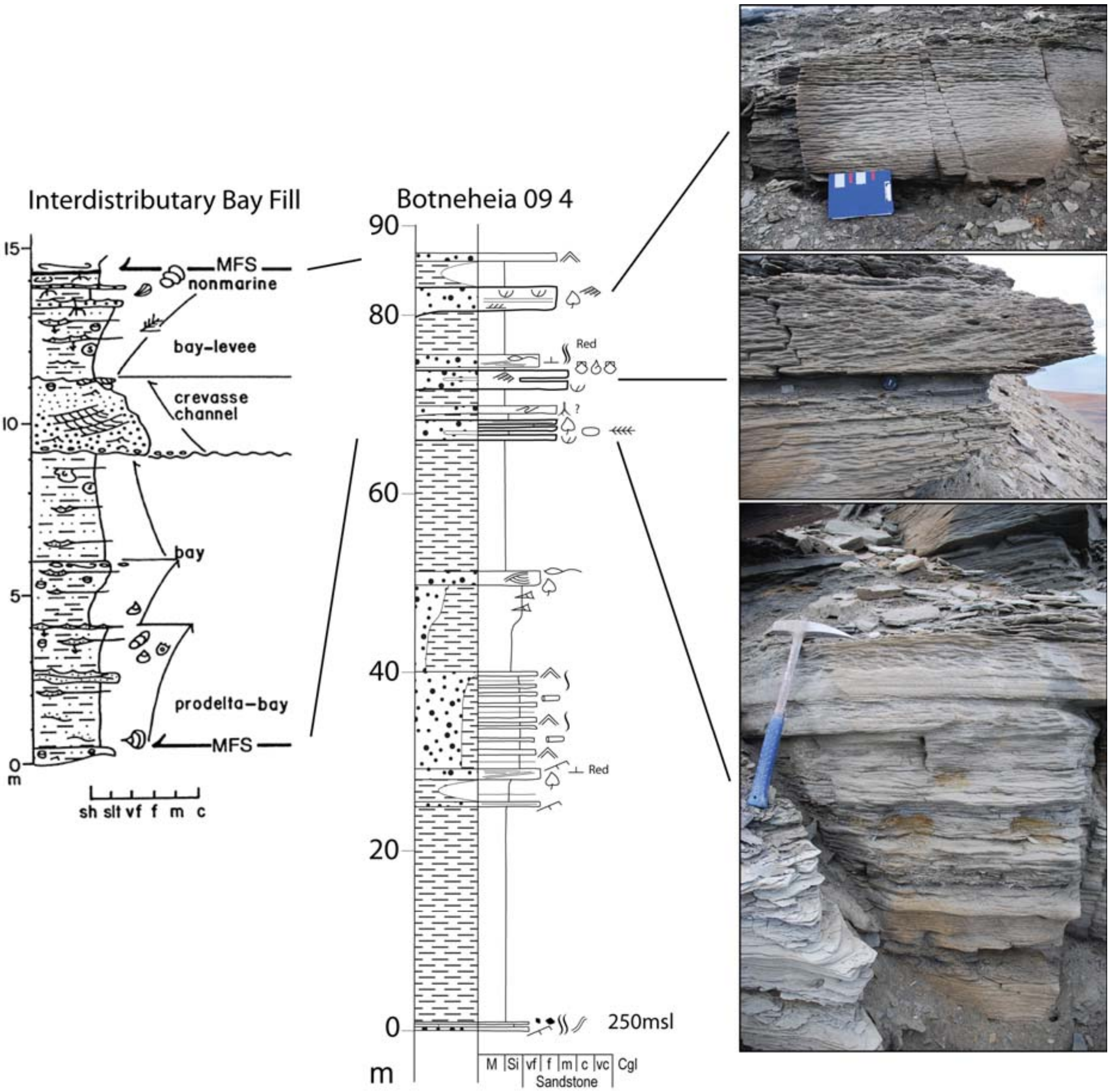


Figure 44: Section of interdistributary bay fill from a river-dominated delta lobe in the Dunvegan Formation (Cretaceous, Alberta, Canada), after Bhattacharya and Walker (1991) in Bhattacharya (2006). Section BOT094 and associated pictures are from Botneheia west (see Appendix 8).

Climbing ripples are also described as characteristic of thin bedded levee turbidites, with associated structures being convolute lamination and ripped-up mud clasts and the grain size often up to medium sand (Posamentier and Walker 2006). The deposits in section BOT094 do probably not represent turbidite levees, because of the lack of convolute lamination and ripped up mud clasts (Walker 2006).

Several depositional environments have now been suggested for the facies combinations in this association: swamp, marsh or lacustrine environments, abandoned channel or lobe systems, lagoon/back barrier environment, levee or floodplain to tidal plain. Some are likely to develop on a coastal or delta plain (e.g. swamps and floodplains), while others is more common on the delta front (e.g. lagoons and bays). Comparing east and central Svalbard the most evident tendency is an earlier development of the proximal part of this facies association on eastern Svalbard.

Facies Association 2 (FA2): Distributary channels

Description

Facies occurring in this association is mud flake conglomerate (I), large scale cross-stratification (A), heterolithic lithology (K) and shale (N). This association is present in Adventdalen, east on Botneheia (BOT092), on Trehøgdene and eastern Svalbard. In central areas of Spitsbergen the association is located in the upper part of the sections. On Edgeøya and Hopen it occurs at different levels in the formation, and more frequently in vertical sections on Hopen than on Edgeøya. Thicknesses of the association in sections at Spitsbergen are between 5 and 35 m, with the thickest occurrences in Adventdalen (35 m) (Figure 45). Lateral extent is insufficient measured, but one sequence on Botneheia is estimated to be 300-400 m in width. Thicknesses on Edgeøya are from 10 to about 40 meters, and sequences on Hopen are up to 10 m in measured sections. Lateral extent has not been studied on Hopen, but on Edgeøya the deposits are possible to track for a few km within single mountains (e.g. Siegelfjellet, Figure 46).

Distributary channels can occur in different areas of a delta and appear as various sediment bodies (Bhattacharya 2006), making it difficult to clearly separate this association from other cross-stratified sandstone sequences. The basis for separating these occurrences from Facies association 3 (distributary mouth bars) is the presence of mud flake conglomerate, lack of superimposed structures and bounding facies associations (often Facies association 1).

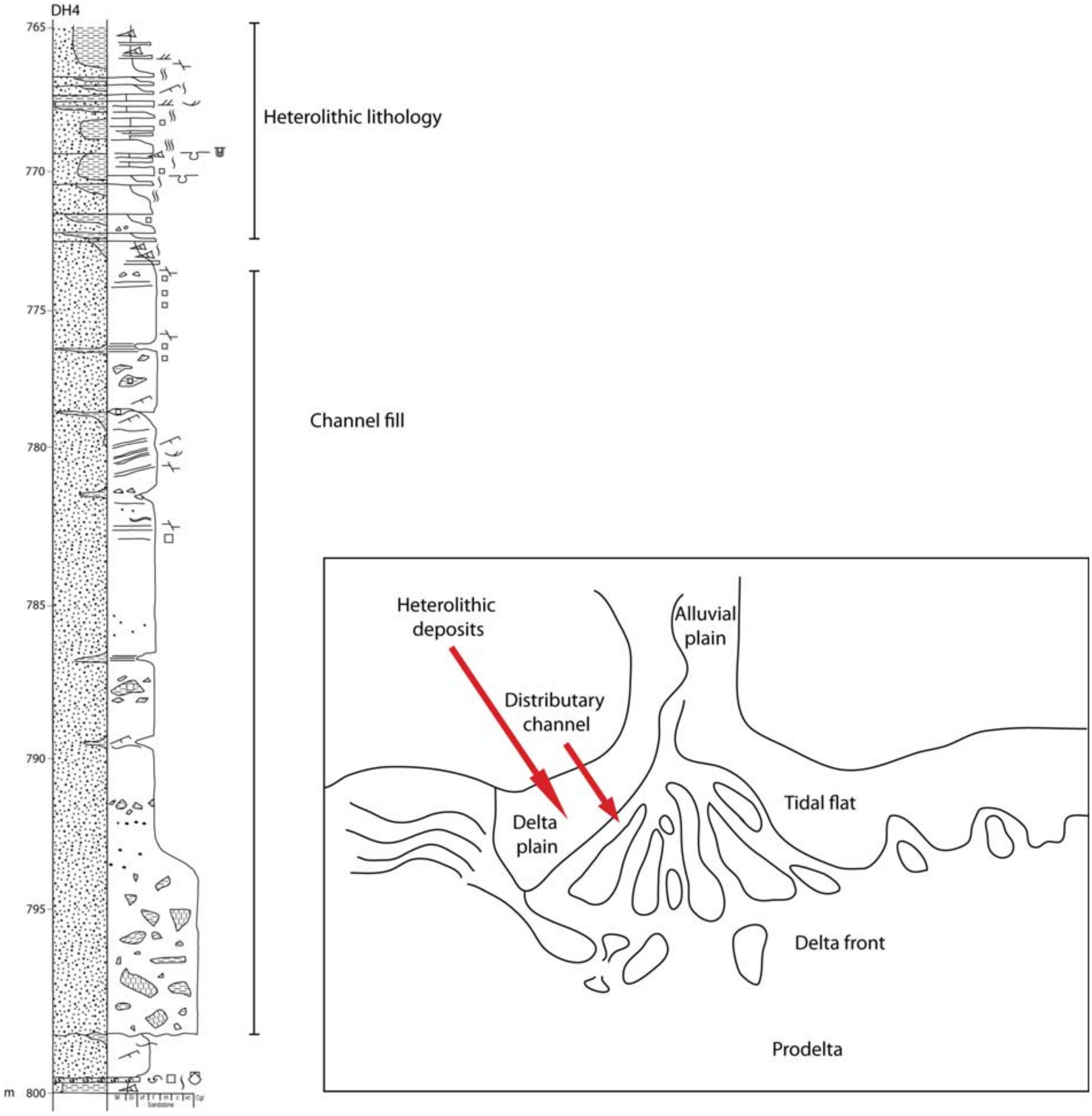


Figure 45: Distributary channel on the delta plain. Figure after Boyd et al. 1992. Section represent core interval B in well DH4 in Adventdalen (see Appendix 4).

Eastern Svalbard: Large scale cross-stratification is the main constituency in the sequences, with both tabular and trough cross-stratification. The lower boundaries are often erosive, and in some sequences the sandstone units are interlayered with thin shale units. On Hopen heterolithic bedding is found as both in the lower and upper reaches of sequences (Figure 47). This is not observed on Edgeøya. Coal layers are present in close association to the cross-stratified sandstone units, more pronounced on Hopen. Some bioturbation, mud flakes and load structures are observed in this association both on Edgeøya and on Hopen. Facies association 1 is bounding the deposits in this association, with higher frequency of coal and rooted deposits than in e.g. the fine grained deposits bounding the deposits of this facies association on central Spitsbergen.

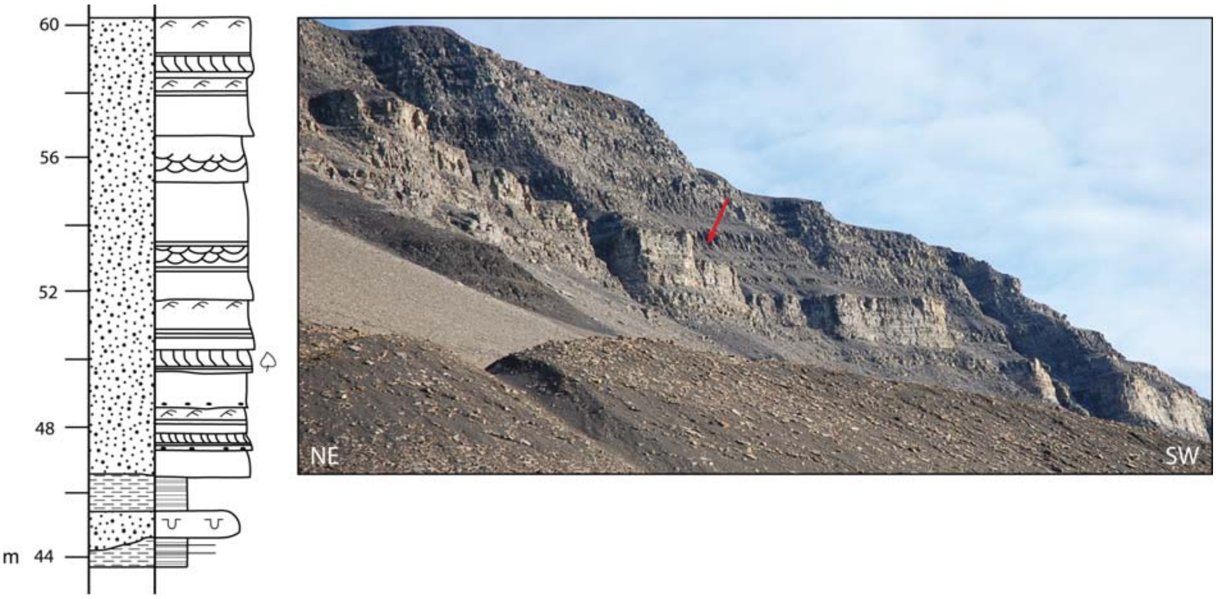


Figure 46: Channels on Siegelfjellet. Lateral continuous for kilometers. Profile measured summer 2008 by Glørstad-Clark. See Appendix 8 for panorama of Siegelfjellet.

Central Spitsbergen: The sequences on central Spitsbergen are erosive based. Mud flake conglomerate are located at base of sequences, but also as repeatedly units upwards in some of the deposits. In core interval B this is especially evident, and the units get thinner upwards in vertical direction. Heterolithic lithology is only observed for certain in core data, and the unit is located on top of the sandy unit. Tidal signatures are represented by double mud drapes and heterolithic lithology and bioturbation is present on Botneheia and in Adventdalen. Some outcrops are cemented and only contains vague structures (e.g. TREH09).

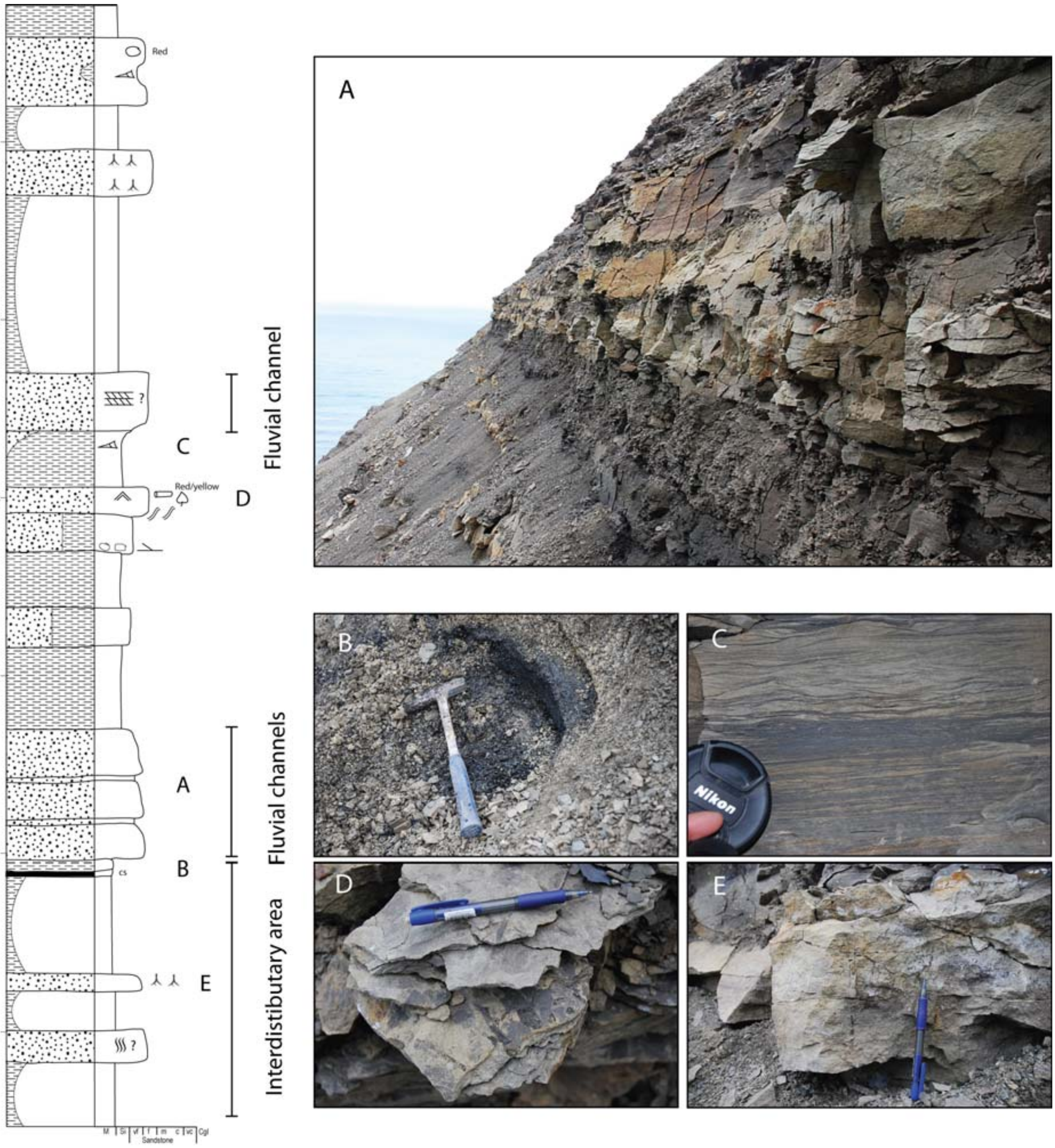


Figure 47: Part of section KOL093 on southern Hopen. Log is drawn by R. S. Rød. Picture A is interpreted as fluvial channel deposit, and pictures B-E as deposits in interdistributary areas (Facies association 1). The facies in the interdistributary areas represent; coal layers (B), heterolithic bedding (C), plant fragments (D) and fine grained rooted sandstone (E). Facies in the channel deposits include large scale cross-stratification and black shale.

Discussion and interpretation

Distributary channels can develop on the delta plain, and extend to the offshore zone as terminal channels (Bhattacharya 2006). They share many of the characteristics of fluvial channels, including an upwards-fining trend from large scale cross-stratification into associated facies (Reading and Collinson 2006). They can be separated from purely fluvial channels by having a lower width to depth ratio and more frequent switching and avulsion due to a prograding system (Reading and Collinson 2006). The few geometric observation obtained in this facies association agrees with the shallow channel characteristic of distributary channels (Figure 48 and 49). Reynolds (1999) found that minimum and maximum thickness and widths of ancient distributary channels where respectively 1 and 40 m, and 20 and 1400 m.

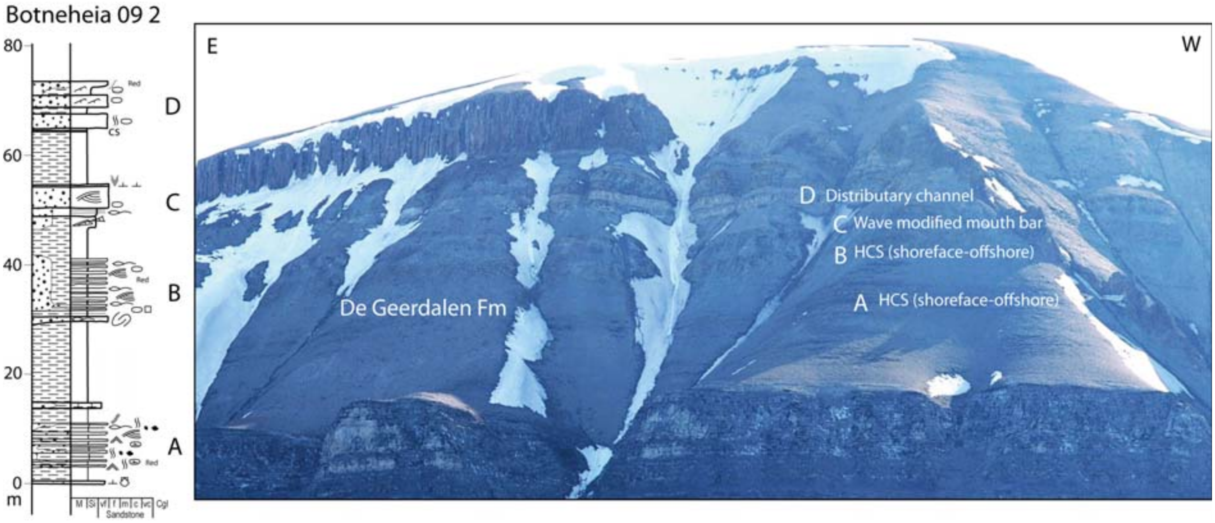


Figure 48: Section BOT092 on Botneheia (central Spitsbergen), showing the development from distal offshore-shoreface associations to channel deposits on the delta top in the upper part. Thickness of distributary channel is about 10-15 m and widths probably exceeding 300-400. See Figure 5 for location of section BOT092.

The prominent mud flake conglomerate at the base of core interval B and in a sequence on Trehøgdene is an indication of channel deposit (lag deposit on the channel floor), a feature reported in several studies (Nakajo 1998; Harris et al. 2004). Riis et al. (2008) describes intraformational conglomerates of upper Ladinian age from the Snadd Formation (see Chapter 1). The deposits are completely lacking bioturbation and contain sandstone- and siltstone clasts with diminishing size upwards in a section, and are interpreted as channels in a deltaic tidal system (Riis et al. 2008). This corresponds to the lower units (in core interval B) of this association on central Spitsbergen with mud flake conglomerate and double mud draped sandstone (Figure 45).

According to Dalrymple and Choi (2007) mud pebbles can be incorporated in channel deposits in the vicinity of the turbidity maximum, often occurring in channels on the delta plain. This is the site of high suspended load, mud drape deposition and periodically strong currents during flood (Dalrymple and Choi 2007). Seen in relation to associated overlying sandy facies and the overall upward-fining trend, the mud flake conglomerate facies probably represent clasts derived from fluid-mud in a channel bottom (described in Facies I). If this is fluid-mud derived clasts, the thinner mud flake events and mud layers upwards in core interval B can be explained by thicker mud deposits in topographically low areas because of more suspended mud in these areas (Dalrymple and Choi 2007). Interbedded sandstone and mudstone in channel fills of distributary channels are also reported by other workers (Nakajo 1998). Mud flakes are not observed in all of the outcrops belonging to this association, either suggesting lack of fluid mud or a lower energy regime.

Mud drapes are only observed in core material (interval B, see Appendix 4) in this facies association. They are in general most commonly developed in active distributary channels because of high suspended load (Dalrymple and Choi 2007). The thickness of mud drapes can be an indication on which type of environment they developed. If this association represented purely fluvial channels, the mud drapes would be thicker (>> 1 mm) and be a result of seasonal changes in river discharge (Dalrymple and Choi 2007). The mud drapes observed in core interval B are mainly a few mm in thickness or less, and occur as double mud drapes. Double mud drapes (mud couplets) develop during a flood-ebb cycle, and is characteristic of the subtidal zone (Nio and Yang 1991). So tidal action can be pronounced in distributary channels, but not present in the fluvial zone (Nakajo 1998; Dalrymple and Choi 2007).

Heterolithic lithology is described by Nakajo (1998) in distributary channels, and interpreted as deposits during intermittent currents and slack water periods. Dalrymple and Choi (2007) explain the fining-upward trend by the transition to tidal-flat successions. Choi and Dalrymple (2004) also did a study on tide-dominated sedimentation in Kyonggi Bay (Korea), where tidal rhythmites occurred in the upper part of upward-fining channel-fill successions. The heterolithic bedding in this facies association is missing obvious evidence of sub aerial exposure (e.g. desiccation cracks), reported from several studies (Tankard and Hobday 1977). This can be due to low preservation potential for some tidal flats (Schwartz 2005). The small-scale erosional features observed in the heterolithic unit in core interval B are on the other hand typical of mixed tidal flat deposits (Reineck and Singh 1980). Mixed tidal flat sedimentation is according to Reineck and Singh (1980) often found on point bars of channels. On Trehøgdene this heterolithic bedding is not observed, this could be due to erosion of the formation down to this level.

Bioturbation is present in both core interval B and in a section east on Botneheia and on eastern Svalbard. On central Spitsbergen it only occurs in heterolithic units. Diversity and occurrence should in general be rare in the setting of active distributary channels (Dalrymple and Choi 2007), but minor bioturbation is reported from some tidal rhythmites on tidal flats (Choi and Dalrymple 2004).

Nakajo (1998) separates upper- and lower distributary channels, based on the relation between fluvial and tidal signatures on the sediments. Lower distributary channels are characterized by thicker sandstone bodies with more tidal influence than upper distributary channels (Nakajo, 1998). It is difficult to use this scheme on sequences observed in field based on collected data, but the sequence in core interval B could agree with characteristics of lower distributary channels (double mud drapes, heterolithic bedding, mud flakes) exceeding out to the delta front. According to Dalrymle and Choi (2007), inclined heterolithic stratification also becomes more abundant in a seaward direction.

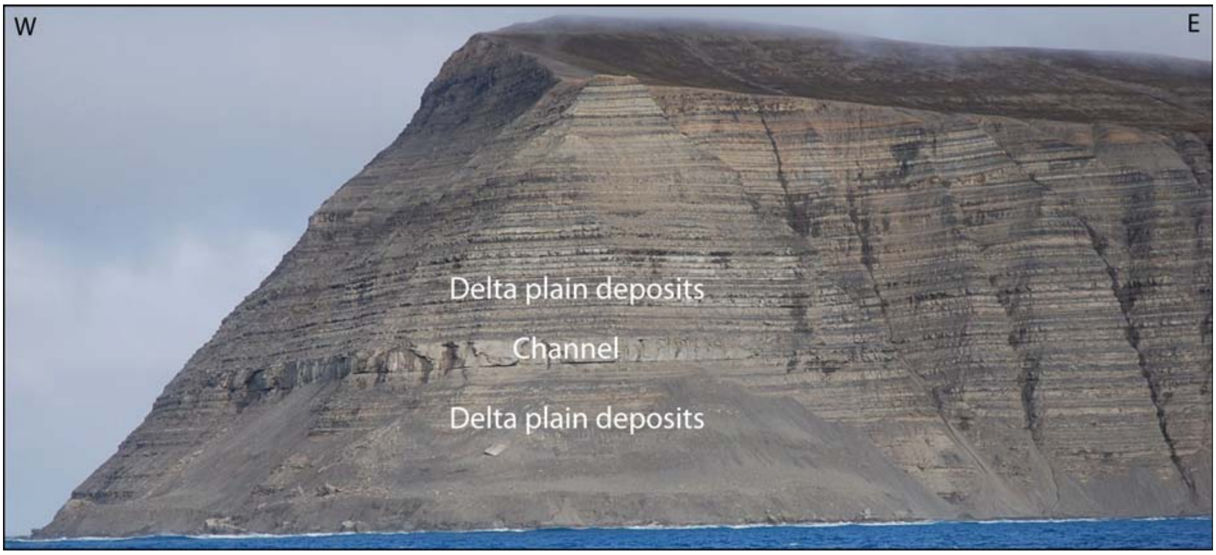


Figure 49: Channel and delta plain deposits on southern Hopen (Kapp Thor). See Figure 6 for location of Kapp Thor. The cliffs were steep and only studied from distance.

The deposits on Hopen have less extensive thicknesses, often shows a slightly upwards-fining trend and lack evident tidal signatures. This can correspond to upper distributary channels, located on the delta plain. The 14 m thick sandstone body on Siegelfjellet can also apply to this scheme. A thick cross-stratified sandstone body (20-40 m) south on Blanknuten can represent distributary channel deposits, but sparse data on this occurrence makes it difficult to separate from inlet channel deposits in Facies association 5.

There are obvious similarities between the channel deposits on central and eastern Svalbard, even though outcrops in Sassendalen and Botneheia only show vague structures due to cementation. The upper and lower distributary channels scheme can only be considered as guiding based on few thicknesses measurements, and uncertainty on the origin of some of the thick sandstone bodies on Edgeøya. But the higher frequency of channels on eastern Svalbard can indicate a more active environment with higher accommodation space in some areas. Lack of extensive mud flake conglomerates in this area can be due to a less muddy environment/substrate, supported by a slightly higher net/gross ratio than on central Spitsbergen (see Section 4.3).

Facies Association 3 (FA3): Distributary mouth bars

Description

Facies included in this association are large scale cross-stratification (A), small scale cross-stratification (B), climbing ripples (C), heterolithic bedding (K), Coquina bed (M) and shale (N). Without more data on the geometry of these deposits it is difficult to tell for certain if they represent bar progradations on the delta front or further inland on the delta plain. The association show similarity with deposits in the Facies association 2 (distributary channels), but are missing the heterolithic lithology and the mud flake conglomerate at base of the sequences.

The association is present on central Spitsbergen (Sassendalen and Botneheia), mainly in the uppermost part of sections on Sticky Keep (Figure 50). Sandstone bodies of similar appearance occur at the same stratigraphic level in the De Geerdalen Formation on this mountain, but the lateral continuity where not possible to map. Sequences at lower stratigraphic level in the formation show similarities, and may be included in this association. Thicknesses of the sequences are from about 2-14 m, with the thickest occurrence on Sticky Keep (STI092).

The sequences are overlaying shale units of extensive thicknesses (up to 30-40 m). They are often calcite cemented and sedimentary structures are difficult to map. The structures possible to detect are low angle complex cross-stratification (see Facies A for description), heterolithic bedding and small scale structures in some outcrops. In section STI091 superimposed structures (climbing ripples) are observed in the uppermost sets of a large scale bedform, and in a sequence at a lower level in the same section herringbone lamination is grading into larger scale cross-stratification. The sequences are erosive based in Sassendalen and does not show a noticeable change in grain size.

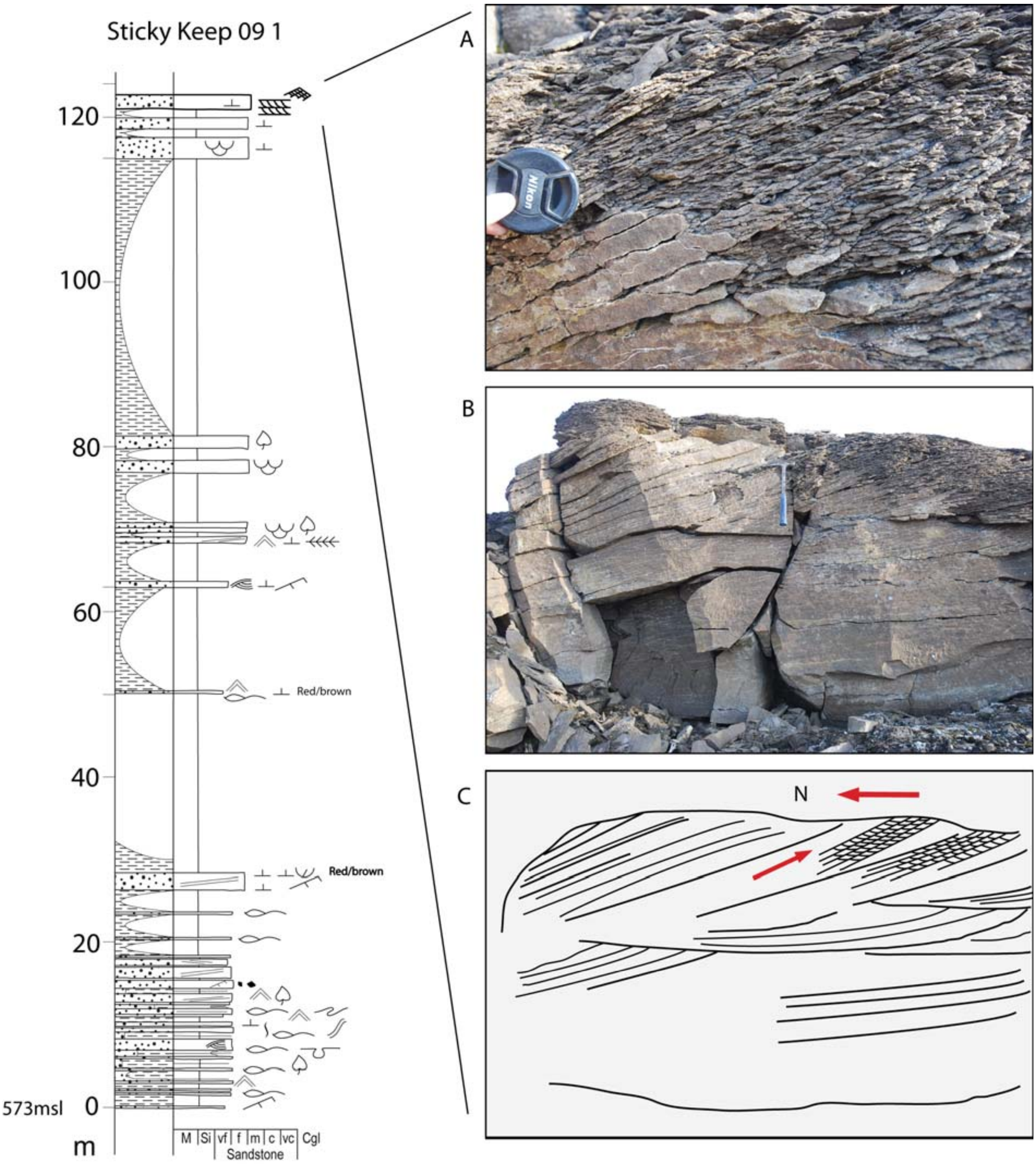


Figure 50: Mouth bar at Sticky Keep at 120 m above base of the De Geerdalen Formation, section STI091. Picture A shows climbing ripples in the upper sets of a larger macro form (mouth bar) shown in picture B. Palaeo-transport direction is shown in drawing C, with the superimposed climbing ripples migrating in the opposite direction.

In section BOT093 large scale cross-stratified sandstone it overlying heterolithic bedding and small scale cross-stratification. A coquina bed and HCS structures overly the deposits at this locality. Mud flakes in this association is only observed in sequence STI092 (100 m above base of the De Geerdalen Fm). The deposits show tidal signs in some outcrops (e.g. herringbone lamination and systematic variations in foreset thicknesses). Bioturbation is not observed in this facies association.

Discussion and interpretation

Distributary mouth bars and distributary channels occur in close connection on the distal delta plain and proximal delta front (Bhattacharya 2006), and produce deposits of similar appearance and possibly as amalgamated deposits. The formation of mouth bars provide that wave processes do not redistribute all of the sediments, and they can either be tidally or/and fluvially influenced (Reading and Collinson 2006). The lack of mud flake conglomerate is not necessary diagnostic, but is in this facies association used to separate the deposits, in addition to influence of basinal processes (tide- and wave influence). Distributary mouth bars are most common on the proximal delta front, and associated sub environments can be barrier- and beach/shoreline systems (Facies association 5 and 7). Mouth bars can develop into barrier islands if the delta front is wave-influenced (see Facies association 5).

Mouth bars are characteristic of prograding conditions (Reynolds 1999). They vary in dimension, but a study of ancient sandstone bodies by Reynolds (1999) show that they on average are twice as long as wide, and have a width from 1.1 to 14 km. Data from a study on modern sandstone bodies by Tye (2004) give widths of mouth bars down to 100 m, indicating that dimensions of ancient bars represent growth of these modern analogs (Bhattacharya 2006). The lack of geometry data makes it difficult to transfer to this facies association, but one can tell that similar sandstone bodies occur at about the same stratigraphic level in the De Geerdalen Formation in Sassendalen and on Botneheia, making a correlation probable. The dimensions depends for instance on flow conditions and the forces acting on the plume (e.g. basinal processes and frictional forces) (Bhattacharya 2006). High wave energy will contribute to an elongation alongshore of the mouth bar, while tides can make the bars elongated normal to the shore (Bhattacharya 2006). High wave energy will in any case be most important in shaping the shoreline and bars, if both tides and waves are acting on the system (Orton and Reading 1993). On Sticky Keep a close association with storm deposits

(HCS) indicates wave influence on this system, and tidal signals in the mouth bar deposits imply a system with combined tide and wave influence.

Cross-stratification and climbing ripples are dominating structures in “frictional dominated” mouth bars (Bhattacharya 2006). These structures are present in this facies association, indicating a shallow basin setting for the development of mouth bars and channels in this system. Dalrymple and Choi (2007) also point out that set thicknesses less than 50 cm is expected in areas with shallow water, and set thicknesses in this association is rarely more than 40 cm. The lack of bidirectional cross-stratification can either indicate a proximal position to the distributary channel (Dalrymple and Choi 2007), or less tidal influence.

Channel bars in different systems, both braided and meandering, can also develop climbing ripples in the upper zone of the bar, often overlying large scale cross-bedding (Reineck and Singh 1980). This tells that deposits in this facies association also can be part of more proximal bar forms.

Mouth bars and channels are often erosive based (Bhattacharya, 2006; Dalrymple and Choi, 2007), corresponding to field observations in the De Geerdalen Formation. This can indicate a location of the bars in a channel, where the erosive base represents lateral-accretion bedding of inter-bar channels (Dalrymple and Choi 2007). On the other hand is covering a possible cause of missing any upwards-coarsening trends, indicating a more distal position to the channels. The lack of noticeable bioturbation can be due to possible brackish water and disturbance by different currents (Dalrymple and Choi 2007).

The mud flake conglomerate, coquina beds and HCS structures overlying a sequence on Botneheia can be explained by transgression and erosion of the delta top (Bhattacharya 2006). Ravinement surfaces form due to marine flooding (transgression), possibly during delta lobe or distributary switching (Reading and Collinson 2006). They are erosive and characterized by landward migration of the shoreface (Reading and Collinson 2006), and surf-winnowed shell fragments and rip-up clasts close to base of the surface are common (Vanderburgh et al. in press 2010). These characteristics agree with field observations in BOT093, and similar ravinement surfaces are present in laterally located sections (BOT091 and BOT094) at about the same stratigraphic level in the formation.

Grain size is difficult to use as environment indicator in this system because of a general uniform grain size throughout the field area. But grain size can explain the nature of the sedimentary structures, respectively fine-medium sand and large scale cross-stratification (dunes) in this association. The occurrence of both two-and three dimensional cross-stratification can be due to variations in water depth and wave-and tidal influence in the system (Dalrymple and Choi 2007).

According to Orton and Reading (1993) grain size is also important regarding development of the delta form and processes. Sandy deltaic coastlines experiencing wave influence, often show a wide shallow inshore profile (dissipative) with bars and ridges (Orton and Reading 1993).

Mouth bars occur more frequently in river-dominated deltas than in wave- and tide influenced deltas (Bhattacharya 2006). Mentioned wave and tidal signs indicate mixed forces acting on the system, and not entirely river-dominated. The heterolithic bedding underlying large scale cross-stratified sandstone on Botneheia (BOT093) can have formed on the delta front or on the delta plain in interdistributary areas.

Facies association 4 (FA4): Delta lobe progradations

Description

This facies association includes the facies heterolithic lithology (K), low angle cross-stratification (E), horizontally bedded sandstone (F), symmetrical ripple-lamination (D), large scale cross-stratification (A), shale (N) and coal (O).

The facies association is present as repeated upwards-coarsening sequences seen in a vertical section on Blanknuten (Figure 51 and 52) and Klinkhamaren. Heterolithic lithology and symmetrical ripples are often found in the lower reaches of the successions, overlain by low angle cross-stratification and trough cross-stratification in the upper part. In section BLA091 one unit show interbedding with shale in the upper part of the sequence. On Blanknuten thin coal units are present in between the sequences, not traceable to Klinkhamaren. Biotubation is observed both on Blanknuten and Klinkhamaren, but only in small occurrence. Facies association 1 separates the repeated upwards-coarsening sequences in most of the sections.

Thicknesses of the sequences are from 5 to 15 m. Data on lateral extent are sparse, but some work was carried out summer 2009 on the lateral extent of one sandstone layer, about 120 m above base of the formation in section BLA091 (see Appendix 5). The layer was followed a few km southwards on Blanknuten, and it is reported to be continuous with the same architecture elements laterally (pers.com. P.T. Osmundsen 2010). Shale sequences (Facies association 1) separating the vertically stacked sandy sequences are from about 1-20 m.

The facies association share many similarities with Facies association 5 (barrier islands) and 3 (mouth bars), but is in most cases missing HCS structures in the lower reaches of sequences like in Facies association 5, and erosive base characteristic of Facies association 3. This does not exclude the possibility that they are closely related, or even represent the same environment.

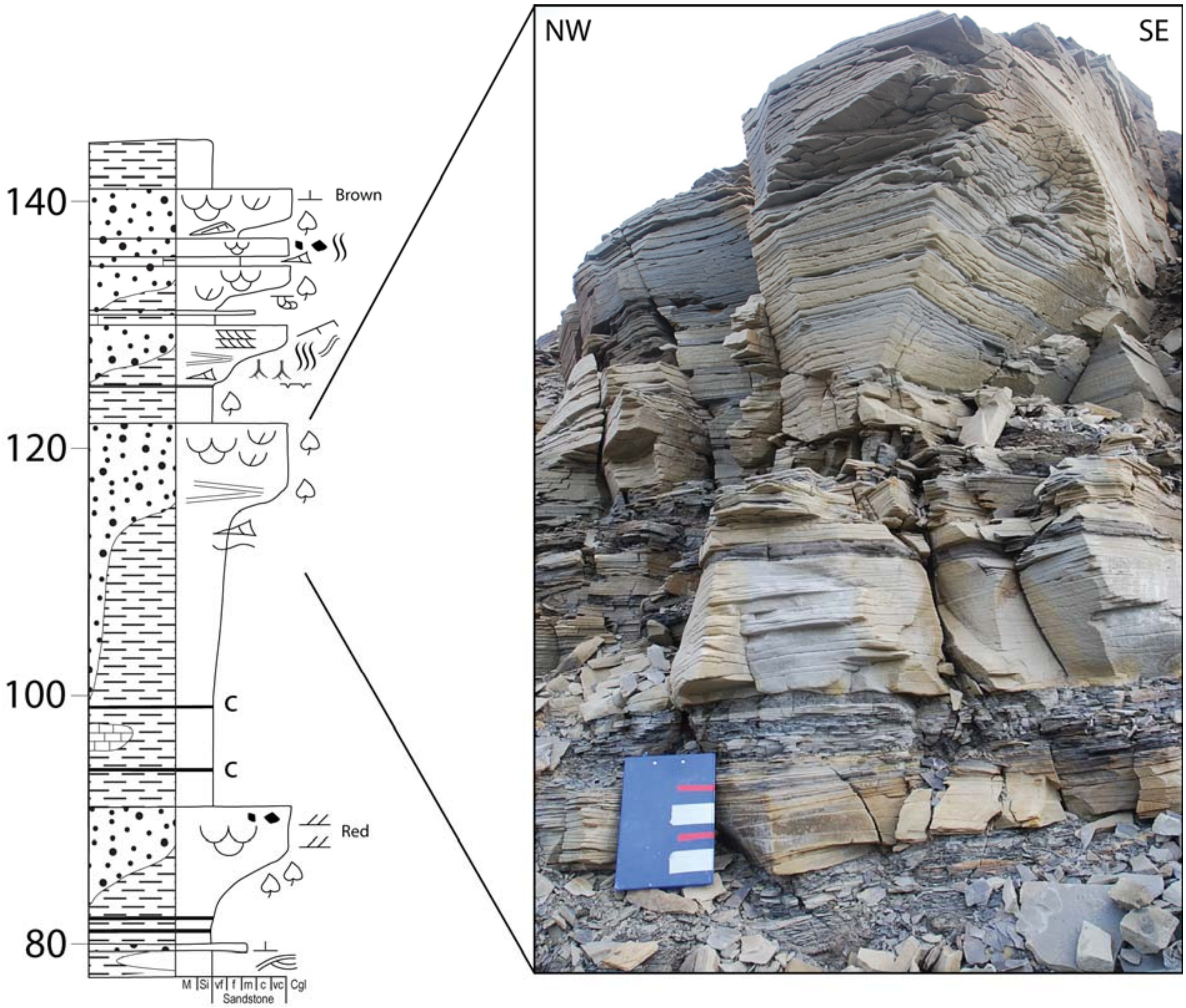


Figure 51: Small delta lobes in section BLA092 (Edgeøya). The section is upwards-coarsening, from ripple laminated to large scale cross-stratification in the upper part. Abundant plant fragments.

This facies association can be separated from mouth bar deposits on central Spitsbergen by the associated coal seams and evident upwards-coarsening trend from symmetrical ripple- to large scale cross-stratification.

Discussion and interpretation

Vertically stacked upwards-coarsening sequences are typical of delta front settings (Hori et al. 2002), and can develop in different environments, e.g. from prograding deltaic lobes or barrier island development in a changing regressive- and transgressive setting (Bhattacharya 2006; Boggs 2006 Chapter 9). Internal structures and associated successions are helpful in distinguishing the different occurrences, with for instance prodelta mud being representative of deltaic progradation sequences (Boggs 2006 Chapter 9). But then again this assumption can be confused by delta lobe or mouth bar progradation into interdistributary bays, sharing similarities with back-barrier environments.

Nemecs (1992) study on the Helvetiafjellet Formation (Svalbard) was mentioned in association with coal and interdistributary bay deposits (Facies association 1). Prograding lobes where also described in this study, and they shear several similarities with this association, supporting this deposits being delta front lobes. The lobes in the Helvetiafjellet Formation are 5-20 m thick and often more than 1 km in width, show marine reworking and are overlain by coal seams. Nemec (1992) interpreted the deposits to represent fluvial fed lobes, prograding into bays on the delta front, periodically affected by storm waves. Thicknesses correspond to these data, and lateral extent is in some cases probably exceeding 1 km on Blanknuten. Marine influences are seen from the abundant symmetrical ripple lamination and the presence of a few marine trace fossils (*Diplocraterion* and *Rhizocorallium*). The heterolithic bedding in the lower part of the successions can develop on the delta front or in interdistributary areas, like mentioned in Section 4.1. Heterolithic sediments are e.g. reported from an ancient tide-influenced delta front deposition (Frontier Formation in Wyoming, USA) in the lower part of an upwards-coarsening sequence (Bhattacharya 2006). According to Dalrymple and Choi (2007) it is not likely to accumulate long successions of rhythmites (few days) on the delta front and prodelta because of disturbance by waves. The associating symmetrical ripples on e.g. Blanknuten can indicate a proximal delta top/delta front setting for these sediments, probably protected to some extent because of associated black shale, rooted sediments and coal layers (see Facies association 1).

Upwards-coarsening subunits often capped by coal beds are also recognized in the upper part of a core in the Barents Sea, representing the Snadd Formation. They are interpreted as deposits in a lower delta plain setting lacking fully continental conditions (Riis et al. 2008). Bioturbation in the lower units are thought to indicate estuarine conditions, agreeing with delta lobe abandonment and subsequent flooding.

Vertically stacked upwards-coarsening sequences (in the Westphalian B succession) are also described by Turner and Tester (2006). The sequences are capped by seatearths and coal seams and overlying interdistributary bay and peat swamp deposits, interpreted to represent a composite crevasse splay delta originating from a distributary channel. Lack of rootlets and other emergent facies are suggested as evidence of subaqueous deposits (Turner and Tester 2006). This model could also be a possible explanation to this association, with wave structures indicative of a connection to a wave influenced environment and continental deposits (coal and roots) indicative of protection from storms and extensive reworking. But it is difficult to tell if the source of the prograding lobes is a crevasse channel or a distributary channel to fluvially braidplaine channel.

Dominance of large scale cross-stratification, minor bioturbation and good preservation are mentioned as indications of high energy traction currents and rapid sediment accumulation by Turner and Tester (2006), characteristics also prevailing in this association. This can be indicative of a friction-dominated delta setting (Turner and Tester 2006). In shallow water, frictional dissipation will restrict the importance of wave action in a landward direction (Dalrymple and Choi 2007), supporting a proximal setting not totally exposed to storm activity.

The interbedded shale and sandstone in section BLA091 (see Facies N1, Section 4.1) probably reflect discharge variations of the fluvial feeder system. According to Bhattacharya (2006) this can produce irregular upwards-coarsening sequences.

Figure 52: Blanknuten on Edgeøya. The thickest sandstone body can represent channel deposits in a barrier setting, but insufficient data makes an interpretation difficult. Overlying sandstone sequences can represent prograding delta lobes. See Appendix 8 for picture of the entire mountain.

It seems that this facies association and Facies association 3 have been deposited in nearly the same setting on the delta front, but they show some different structures mention in the description. This can be due to a change in basin configuration and accommodation space from eastern Svalbard to central Spitsbergen.

Facies Association 5 (FA5): Barrier island/upper shoreface deposits

Description

Facies included in this association are low angle cross-stratification (E), ripple-lamination (B and D), hummocky cross-stratification (H), large scale cross-stratification (A), shale (N) and coal (O) (Figure 53). This association occurs in the lower part of sections in Sassendalen, especially developed on Trehøgdene and ESE on Sticky Keep (STI092). In this area the association is about 20 m thick, and show a transition from hummocky cross-stratified sandstone to low angle cross-stratified sandstone. Thickness of the low angle cross-stratified sandstone is greatest on Trehøgdene (20 m). Further west towards Botneheia the thick low angle cross-stratified sandstone units are missing, and hummocky structures dominate.

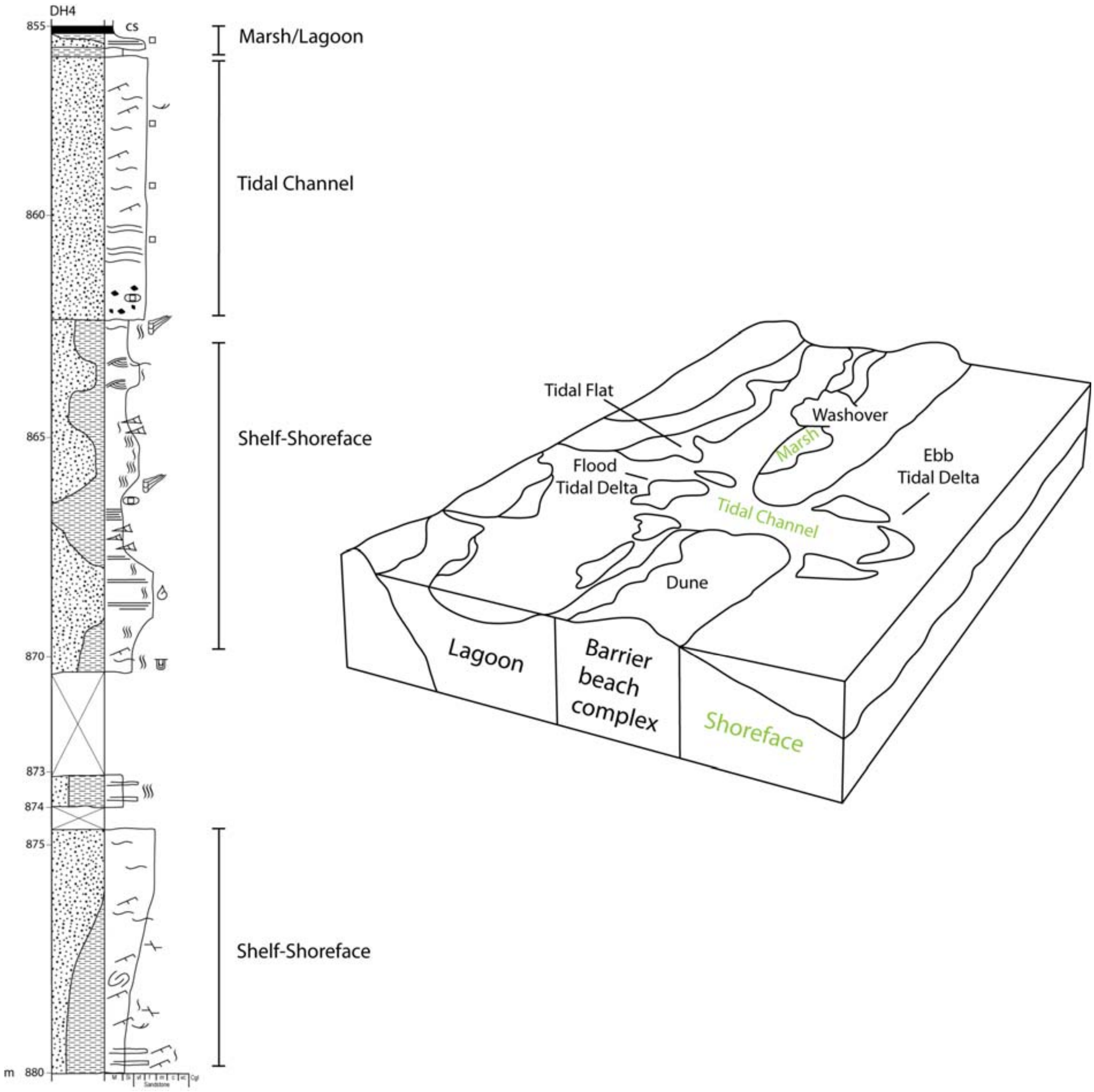


Figure 53: Barrier system illustrated by core interval A in well DH4 in Adventdalen. The sequence is upwards-coarsening from offshore to shoreface deposits to a thick channel sandstone body. Figure after Reinson (1992) in Roger G. Walker, 2006.

In Adventdalen and on Edgeøya (Blanknuten and Økshogget) the hummocky- and ripple laminated sandstone in the lower part of the sections is overlain by large scale cross-stratified sandstone units (2-15 m thick). The thickest cross-stratified sandstone unit is present on Økshogget (15 m). Going northwards to Muen the hummocky structures are overlain by low angle cross-stratified sandstone. All of the sequences are overlain by shale, but in Adventdalen (well DH4) and on Blanknuten (BLA091) also a thin coal layer is present on top of the cross-stratified sandstone.

Discussion and interpretation

Barrier-islands often develop during transgressive conditions and can occur in deltaic systems as well as estuarine (Reading and Collinson 2006). About 12 % of modern open coasts have a barrier island system, where 30 % of these occurrences are deltaic (Maren 2005; Rosati et al. in press). The occurrence of coal and more typical lagoonal deposits overlying shelf and shoreface deposits in some areas indicate a general regressive regime and deltaic conditions (Boggs 2006 Chapter 9). The standard model for barrier development on deltas are derived from the Mississippi Delta complex, and imply that barriers develop from abandoned delta lobes (Maren 2005). A study by Maren (2005) shows that barrier islands also can be part of a prograding delta system. Barriers can be produced from elongated mouth bars in a wave-influenced delta (Bhattacharya 2006), an possible explanation in this setting with abundance of HCS structures.

The different appearance of the vertical successions included in this facies association can be due to cuttings through various elements present in a barrier island system or a different origin. Core interval B and sections on Edgeøya (BLA091 and ØKS09) show large scale cross-stratified sandstone overlying shelf and shoreface deposits. They can represent tidal inlets, described in several publications (Reading 2006; Hobday 1976; Davis et al. 2003), and defined as tidal inlets if they are maintained by tides (Dissanayake et al. 2009). According to Reynolds (1999) the maximum- and minimum thickness of ancient tidal inlet bodies are respectively 7 and 3 m, but thicker barriers have been described from modern analogs (Maren 2005). The measured cross-stratified unit in Økshogget gives a thickness of 15 m. Lack of detailed data from the sandstone unit makes it difficult to tell if it represent a tidal inlet or a different channel form. The erosional contact down to underlying hummocky cross-stratified sandstone units indicates delta front setting. On Blanknuten the cross-stratified unit is about 2 m, overlying low angle cross-stratified sandstone and HCS sequences. The unit contains superimposed sequences, heterolithic bedding and mud flakes above erosional contact, features possible to relate to tidal inlets (Hobday and Horne 1976). The most convincing unit interpreted as tidal inlet is upper part of core interval B (Figure 53). Double mud drapes, probably large scale cross-stratification and overlying coal support the interpretation.

Trough cross-stratification can also be a part of the upper shoreface zone, and are described in tidally modulated settings by Dashtgard et al. (2009). Tidally modulated upper shoreface (USF) sediments are dominated by onshore-directed trough-cross bedding in sandy sediments, and are probably formed in macrotidal- to megatidal settings (Dashtgard et al. 2009). Skolithos ichnofacies is typical for USF, but evidence of this are lacking in field outcrops.

Coals associated with back-barrier/outer lagoon environments, one element in core interval B, are usually thin (few cm) (Nemec 1992). This corresponds to the thin coal layers (10 cm) found overlying beach and channel deposits in this facies association. Nemec (1992) discusses controls on growth in a braidplain delta (Helvetiafjellet Formation, Svalbard), and mention input of clastic sediments, minor rainfall and wave action as important factors in limiting the plant growth in the back-barrier/outer lagoon.

Some sequences lack the large scale cross-stratified element, and consist of upwards-shallowing deposit from HCS storm deposits to low angle beach sequences. These sequences probably represent deposits in between inlets or upper shoreface to beach deposits. Variations in thicknesses of this association among sections in e.g. Sassendalen can either result from different degree of erosion or thickness changes laterally within a barrier-or shoreface system.

Facies Association 6 (FA6): Delta front channel sand

Description

This facies association includes the facies undulating fractured sandstone (G), low angle cross-stratified sandstone (E), horizontally bedded sandstone (F), mud flake conglomerate (I), small scale cross-stratified sandstone (B) and shale facies (N). Structures were often difficult to determine.

The facies association is observed on Edgeøya in sections on Blanknuten and Klinkhamaren (Figure 54 and 55). On Klinkhamaren these sequences were also observed during fieldwork summer 2008 in the lowermost part of two sections. Diffuse large scale cross-stratification was found in some units in these two sections, but generally it was difficult to detect structures in the outcrops.

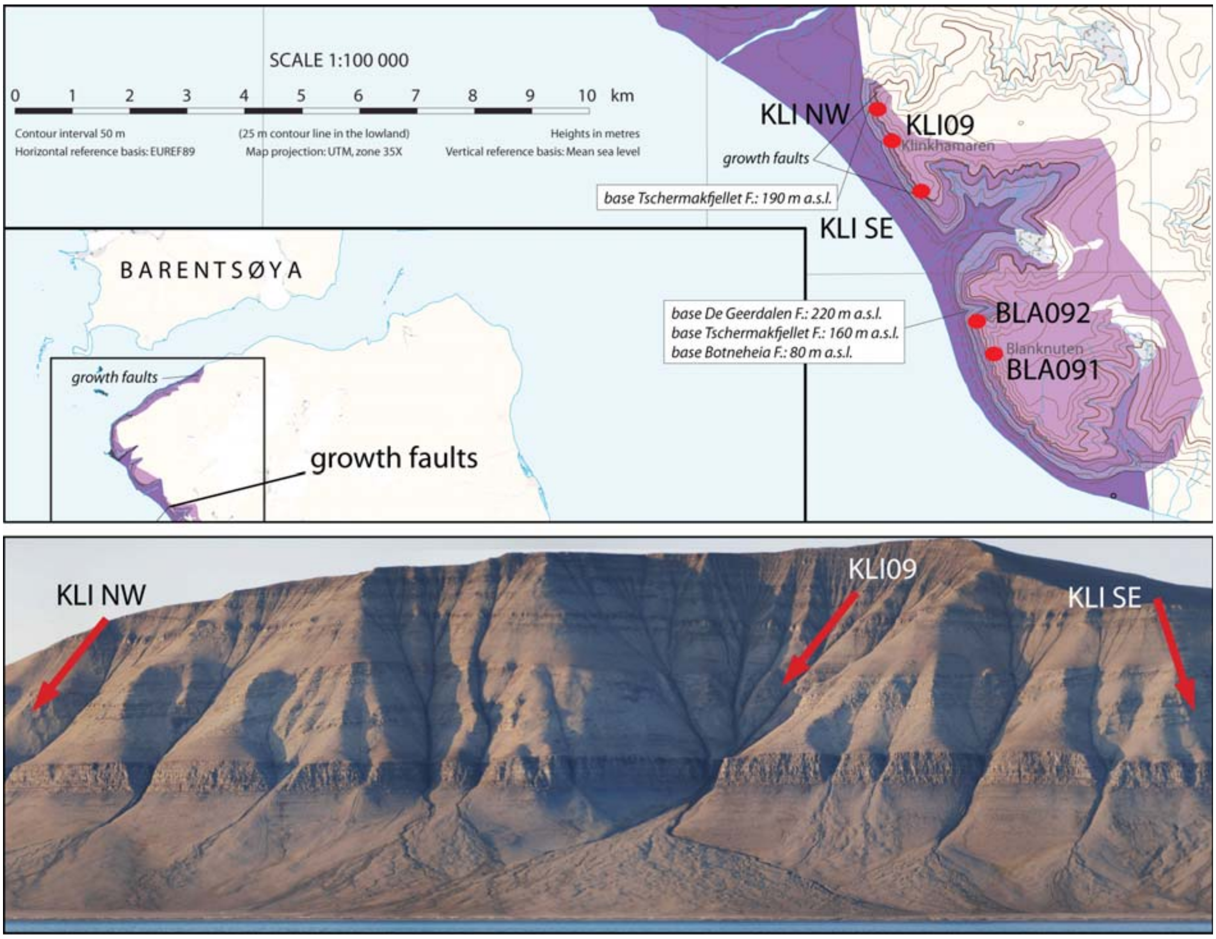


Figure 54: Delta front channel sand on Klinkhamaren. Growth faults can be seen by the dipping layers. Map by W.K. Dallmann, Norwegian Polar Institute, mapped during cruise with the vessel M/S Kongsøy, organized by the Norwegian Petroleum Directorate, August 2009. Location of sections measured during fieldwork summer 2008-2009 is marked with red circles. Picture is from Klinkhamaren, taken by M. S. Woldengen. Red arrows show location of measured sections on Klinkhamaren.

The facies in this association are unsystematically stacked in a vertical sequence, with shale facies separating the sandstone facies. No upwards-coarsening or -fining trends are noted. Load structures and mud flakes are most common in the lower part of sandstone facies, and sandstone units are often erosive based. Observed small scale cross-stratification is mainly unidirectional. Plant fragments are observed in sections measured summer 2008 on Klinkhamaren. The sequences are bounded by thick shale facies, Tschermakfjellet Formation, beneath the deposits and shale in the De Geerdalen Formation above (up to 30 m). The overlying shale succession on Klinkhamaren is covered with lose blocks, making data collection difficult. Also underlying deposits are covered in some areas.

On Klinkhamaren the facies association is present throughout the mountain from SE to NW, a distance of about 2 km. Continuity of the layers are difficult to determine because of disturbance by growth faults in the area (Figure 54). On Blanknuten the facies association is present in section BLA091, but with less extensive thickness than on central Klinkhamaren (respectively 5 and 40 m). The association is not found in other sections on Blanknuten, but seems to be continuous for at least 100 m seen from pictures.

This facies association can represent deposits belonging to for instance Facies association 2 (distributary channels) or even Facies association 7 (lower shoreface to offshore deposits), but is separated as a single facies association based on lack of evident structures like respectively large scale cross-stratification and hummocky cross-stratification in outcrops.

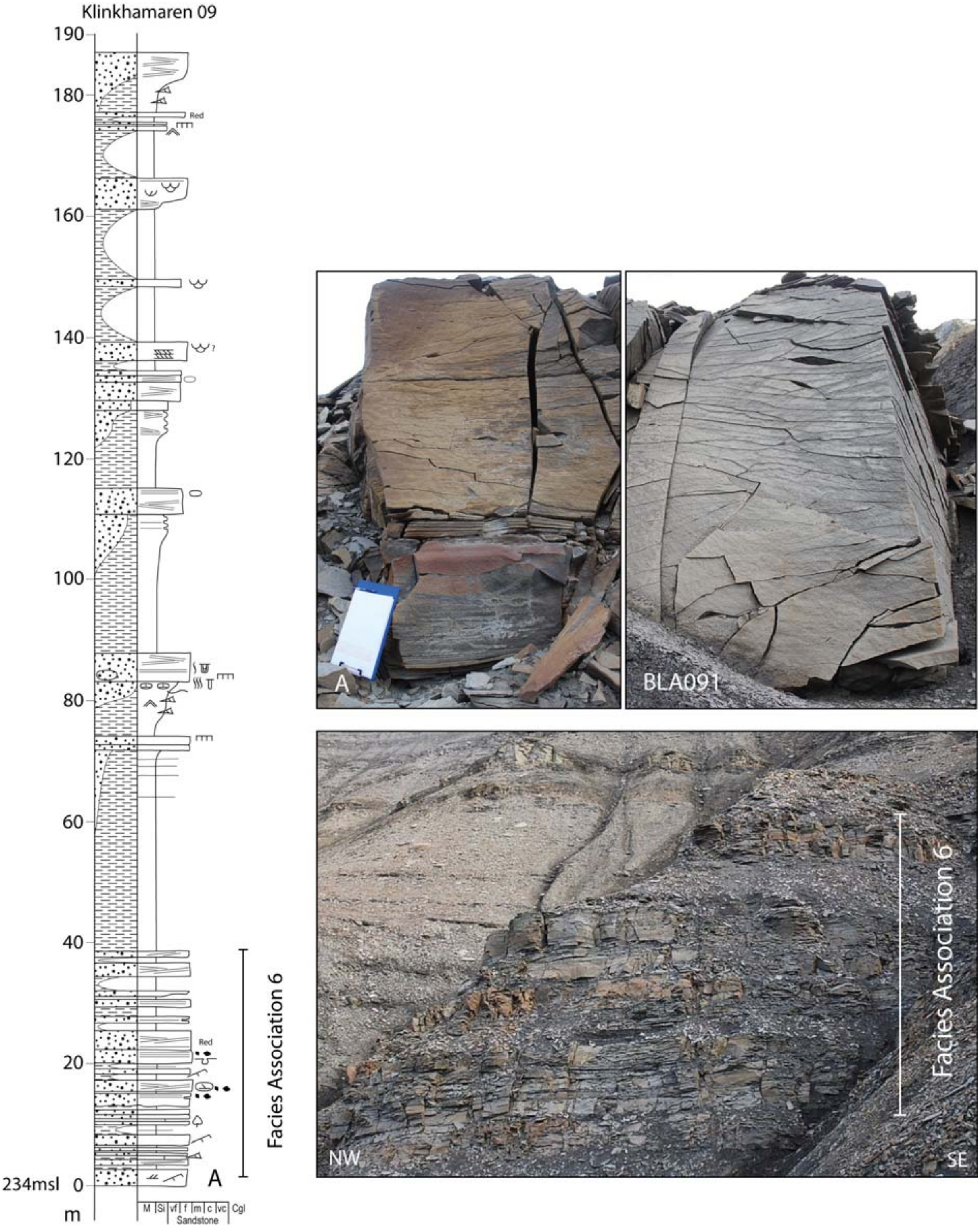


Figure 55: Facies association 6 at Blanknuten and Klinkhamaren. The lowermost picture is from central Klinkhamaren (section KLI09), and shows the package 0-40 meter above base of the De Geerdalen Formation. The picture from BLA091 shows the lowermost unit in the section (Appendix 5).

Discussion and interpretation

The facies association is difficult to interpret because of lack in evident structures, probably caused by secondary modification of outcrops. The evident fracturing in many of the units has been discussed by participants in the Edgeøya fieldwork summer 2008-2009, but there are still uncertainties whether they represent fractures along primary bedding planes or random fracturing.

Even tough the underlying deposits are covered in some areas; it appears as the facies association is directly overlying offshore mud of the Tschermakfjellet Formation with an erosive contact. This can suggest a delta front setting, with fluvially channels prograding out on a shallow shelf. Mud flakes and erosive lower boundaries can support this being channel deposits (Dalrymple and Choi 2007). The load structures observed in some outcrops in addition to lack in burrowing organisms can imply rapid deposition. Rapid deposition can also be an explanation to absence of evident structures. The deposits are previously been interpreted as fluvially delta front deposits based on fieldwork summer 2008 (Glørstad-Clark 2009).

Facies Association 7 (FA7): Lower shoreface to offshore deposits

Description

Facies appearing in this association are heterolithic lithology (K), shale (N), hummocky cross-stratification (H), low angle cross-stratification (E), carbonate rich sandstone (L) and symmetrical ripple-lamination (D). The facies association is most widespread on central Spitsbergen, but is also present in the lower part of the De Geerdalen Formation on Edgeøya and in the upper part of the formation on Lyngefjellet (Hopen). In some areas the Facies E, D and N dominates (e.g. in section BOT094), while hummocky structures dominate in sections only few km laterally (e.g. in BOT093 and BOT091). The carbonate rich facies (L) only occurs in a few sequences included in this association (e.g. BOT091).

The association includes both vertical sequences with dominance of shale (Facies N) and thin ripple- to planar laminated sandstone units (Facies D), and sequences of interbedded hummocky cross-stratified sandstone and shale. Most of the sequences of the latter are between 10 to 15 m, but the full range is from 5 to 40 m, where Edgeøya is the location with greatest differences in sequence thicknesses. Thickness variations are also present between sections on Botneheia and in Sassendalen, but the association is traceable in all of the sections. The sand vs. shale content in the HCS and shale sequences varies from location to location, often being close to 50/50%.

The deposits are found at the same stratigraphic level in the De Geerdalen Formation at both Botneheia and Sassendalen. In both areas the deposits extend laterally for several kilometres. Also on Blanknuten is it possible to correlate the deposits between section BLA091 and BLA092, located less than a km from each other.

In three of the section on Botneheia HCS sequences in the middle to upper part of the sections show an evident upwards-coarsening pattern, with heterolithic and small scale HCS in the lower sequence and large scale HCS in the upper sequence (Figure 56, 50 meter above base profile).The sequence are located at approximately the same stratigraphic level in the formation in these sections. Similar sequences are not found in Sassendalen. The portion of fine sand vs. shale is higher in the upper sequence. On eastern Botneheia the sequence is overlain by carbonate rich sandstone (Facies L). Mud flakes (rip-up clasts) are present in some of the upwards-coarsening HCS sequences (e.g. BOT091).

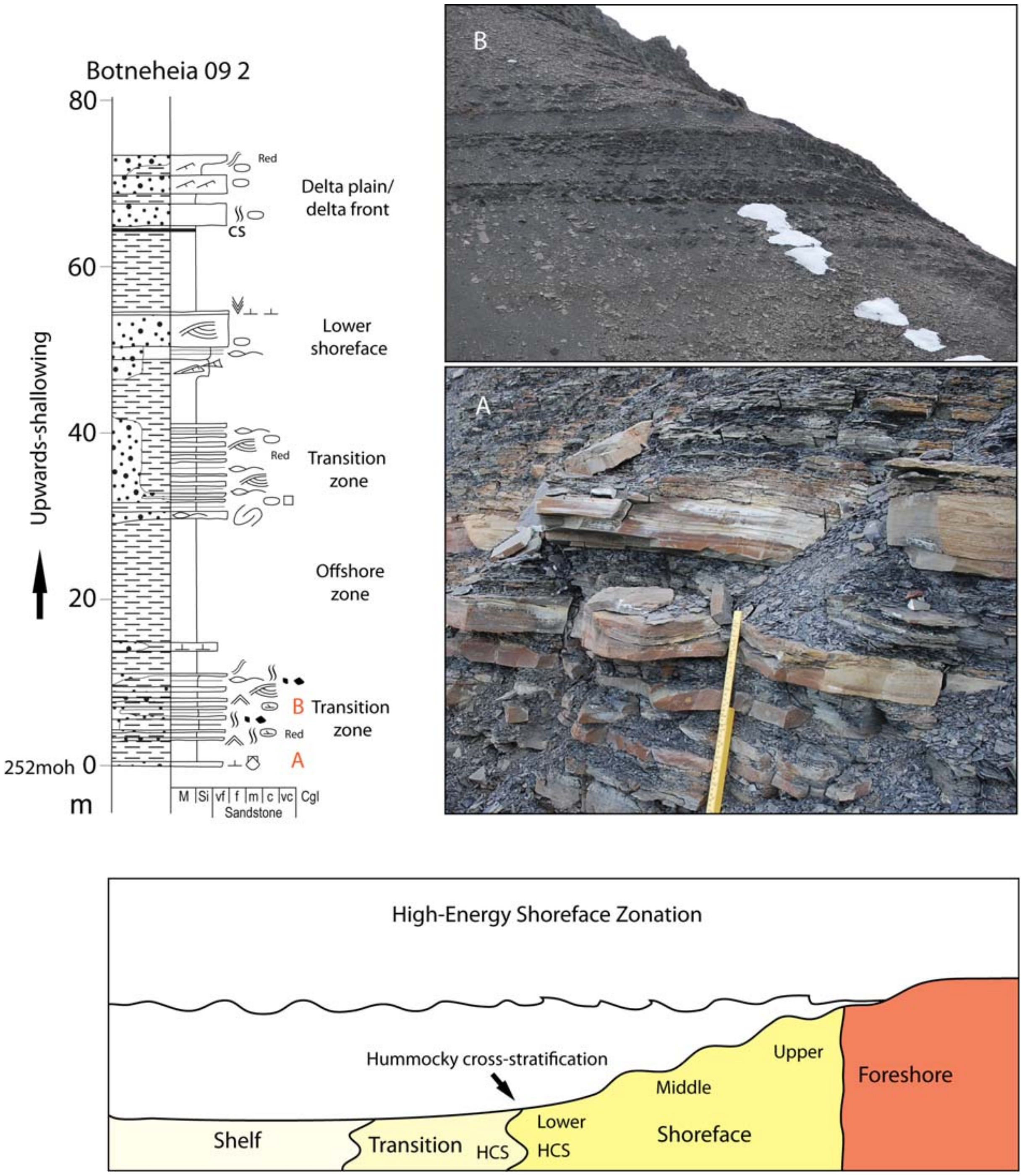


Figure 56: Shelf to lower shoreface deposits on Botneheia (BOT092) in the De Geerdalen Formation. Section BOT092 shows an upwards-shallowing trend. Picture A and B are from the lower reaches of the formation. See Figure 5 for location of section BOT092. Figure after Galloway and Hobday (1996) in Clifton, H.E, 2006.

Discussion and interpretation

Hummocky cross-stratified structures have been discussed in Section 4.1, and there is agreement among several studies on prevailing storm conditions in the zone between fair-weather and storm wave base as explanation for their origin. What can be discussed in this facies association are conditions and delta/coast morphologies responsible for different types of HCS sequences. To discuss morphologies and depths it would clearly be an advantage to have more geometric data on the deposits. The shale dominated units have not been a focus in this study, like previously mentioned, and will only be briefly discussed.

The upwards-coarsening sequences described on Botneheia with higher portion of fine sand vs. shale in the upper sequence can represent mouth bar deposits at the delta front, reworked by wave-action on the shoreface (Bhattacharya 2006). The fact that the deposits can be found at the same level for about 3-4 km does not exclude this possibility, but this lateral extent exceed mean ancient mouth bar width of about 3000 km (Reynolds 1999). It is also possible that the deposits are discontinuous, and represent different bars. Knarud (1980) interpreted similar upwards-coarsening deposits on Botneheia (300-350 msl) as proximal banks. The thicker and amalgamated units upwards in the sequences can also be a result of delta margin progradation (Dott and Bourgeois 1982). Amalgamated HCS sequences are believed to be deposited in the transition to shoreline sands (lower shoreface) (Duke and Prave 1991; Reynolds 1999), agreeing with an upwards-shallowing trend from the more shale dominated sequences and the following individual HCS units. Duke and Prave (1991) mentions rip-up clasts as one characteristic of the amalgamated HCS sequences in their studies, an element also present in this association. Prograding shoreline-shelf sands often shows larger width- and lengths than transgressive sands, but restricted thicknesses (up to 50 m) (Reynolds 1999). Geometric considerations are only speculative because of lack of correlative data.

Willis and Gabel (2001) have described upwards-coarsening sequences (3-6 m) from the tide-dominated delta deposits from the Cretaceous Sego Sandstone Member in Utah, sharing some resemblance with the sequences within this association. They interpret the deposits to represent sand sheets in the offshore area between fair-weather- and storm-wave base. These sand sheets are in this study laterally continuous, corresponding to deposits in this association, but thicknesses are less extensive than in the De Geerdalen Formation. The HCS and shale sequences in this association are not always upwards-coarsening. Duke and Prave (1991) interpreted similar deposits with about 50/50 % sand vs. shale to represent storm deposits well above effective storm wave base in a proximal offshore setting. Dott and Bourgeois (1982) suggests a uniform bottom topography as explanation for areas with laterally extensive and vertically numerous HCS units, as the deposits found in this association.

Willis and Gabel (2001) explains the unbioturbated character of some HCS beds as the result of more complete reworking by waves after switch of sediment supply to a different area. This theory combined with covered and weathered outcrops explain minor or absent bioturbation in several sequences.

Sequences dominated by shale with thin silt- to fine sand layers have been described by Duke and Prave (1991) in the Middle Devonian Mahantango Formation (Pennsylvania). They recognized a facies (1 m to tens of meters) dominated by shale and mudstone, interbedded with thin silt- to very fine grained sandstone. The sand deposits were interpreted as “distal tempestite” sandstone beds in an offshore setting, interbedded with offshore mud (hemipelagic) deposited during calm periods. They base their interpretation on body fossil data. This is difficult to carry out in this facies association because of minor data on fossil assemblage in shale sequences. But based on descriptive aspects their data correlates well with this facies association, and these characteristics from offshore transition/offshore environments are also described by Boggs (2006) and Reineck and Singh (1980).

The carbonate concretions present in some shale dominated sequences are probably developed in a shelf setting (see Facies L for description and interpretation), interpreted from associated HCS sandstone and thick shale sequences. Selles-Martinez (1996) point out how concretions often are situated at the base of their host rock. This agrees with observations from Botneheia and Blanknuten of the lens shaped concretions, where the host rock is silty shale. Why they often are located at a specific location are not easy to explain (Selles-Martinez 1996).

The fine grain size (very fine to fine sand) in this association can imply dissipative conditions on the shoreline, typical of gentle offshore profiles with waves breaking some distance from the shore (Orton and Reading 1993). Diminished shoreface deposits with structures characteristic of fair weather conditions can also support a wide shelf setting (Bhattacharya 2006).

4.3 Distribution of sand versus mud

Earlier studies show that the De Geerdalen Formation contains dominantly shale on central Spitsbergen, and an increasing content of sand towards the SW, E and NE (Mørk et al., 1982). Figure 57 shows calculated net/gross values on sections from collected data on the De Geerdalen Formation, both from Knarud (1980) and newly collected data on eastern Svalbard and central Spitsbergen. The thickest sandstone unit with associated dominating grain size is included (Figure 58) to give a picture of depositional environment.

On central Spitsbergen net/gross values are generally between 0.15 and 0.3, mainly based on recently collected data. A few higher values are noted, e.g. in well DH4 in Adventdalen (0.49). The net/gross calculation did not include the Isfjorden Member in well DH4, possibly resulting in higher values than on Botneheia where this member was hard to detect, and the lower part was probably included. The thickest sandstone units are from 2.5-26 m, with fine sand domination in most of the units.

Net/gross values on western and eastern Spitsbergen are based on data from Knarud (1980), and have values mainly between 0.3 and 0.5. On Festningen a value of 0.62 are calculated, due to a thick sandstone unit of 44 m. It is important to note that the dominating grain size in this unit is very fine sand, compared to fine- and medium sand in other sections with lower net/gross values. The thickest sandstone units are from 12-44 m, generally thicker than on central Spitsbergen.

Net/gross values on eastern Svalbard are slightly higher than central Spitsbergen, but lower than on western and eastern Spitsbergen. For most of the sections the values are between 0.2 and 0.4, except for higher values east of Kvalpynten and on Muen. The thickest sandstone units are between 2-28 m, dominated by the grain size fine sand to medium sand.

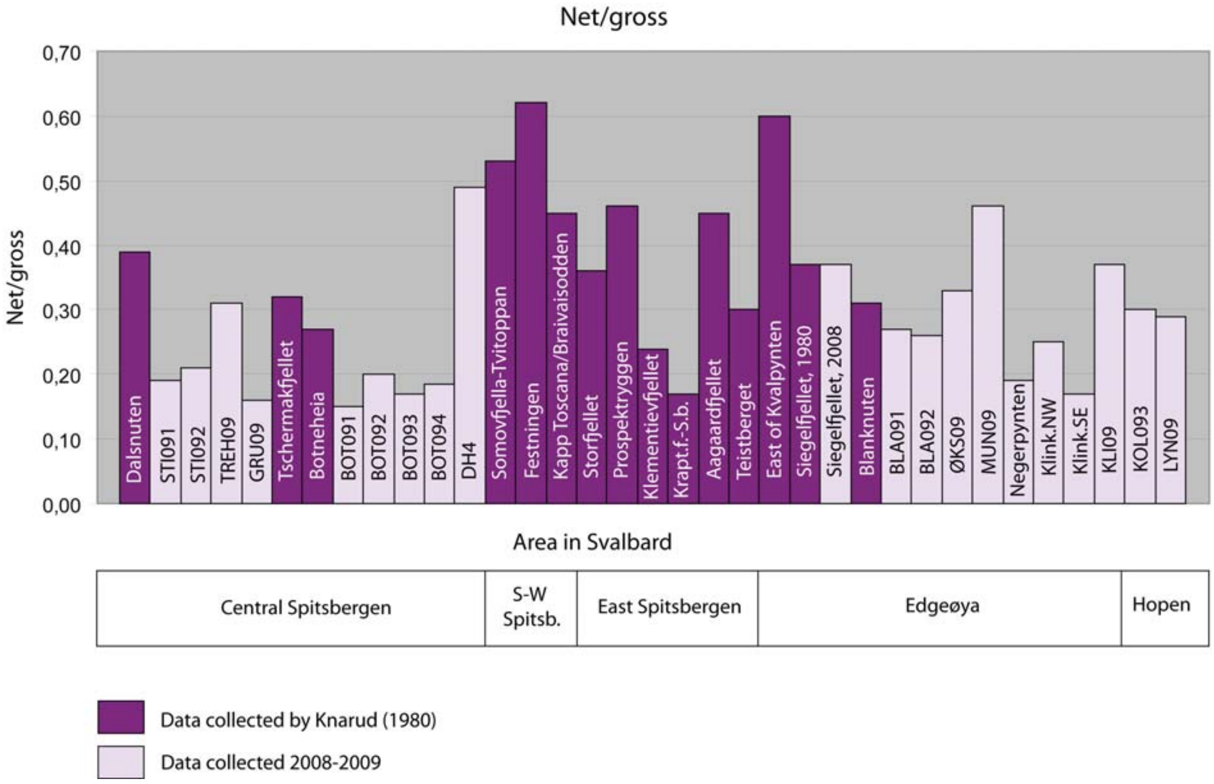


Figure 57: Net/gross values for the De Geerdalen Formation in sections measured by Knarud (1980) and during cruises organized by the Norwegian Petroleum Directorate in summer seasons 2008-2009.

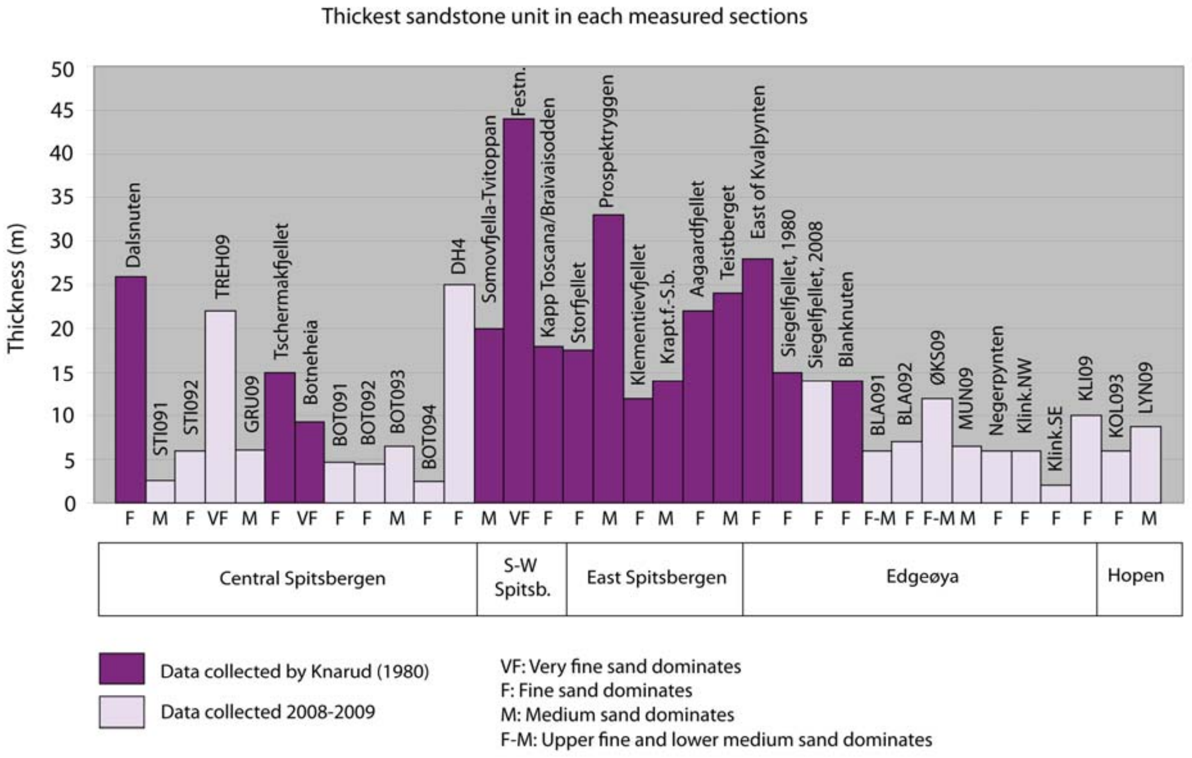


Figure 58: Thickest sandstone unit in sections measured by Knarud (1980) and during cruises organized by the Norwegian Petroleum Directorate in summer seasons 2008-2009. The letters (VF, F, M, F-M) below each column represent dominant grain size in the thickest sst unit.

4.4 Thickness variations of the De Geerdalen Formation

The thickness of exposed part of the De Geerdalen Formation is highly variable within single areas (e.g. Edgeøya), but also from central Spitsbergen and eastwards on the archipelago (Figure 59). On central Spitsbergen thicknesses are from about 65-300 m, while on eastern Svalbard (Edgeøya and Hopen) it varies from 30-230 m. Western and eastern Spitsbergen generally has the greatest thicknesses of the formation.

Erosion of the upper part of the formation is most pronounced on eastern Svalbard, but also evident in some areas in Sassendalen. Botneheia mainly shows complete sections, except the uppermost part of the Isfjorden Member, with exception from BOT092 affected by Cretaceous sills and dykes in the upper succession.

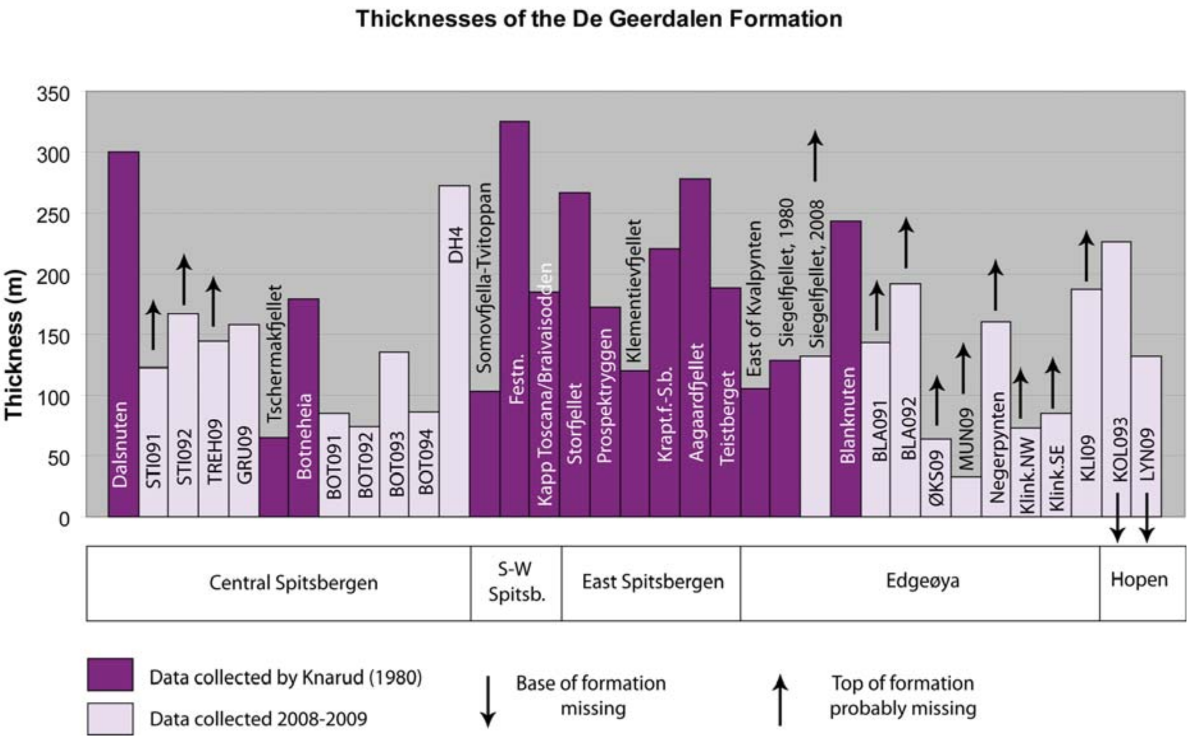


Figure 59: Thicknesses of the De Geerdalen Formation in different areas on Svalbard, based on data collected by Knarud (1980) and during cruises organized by the Norwegian Petroleum Directorate in summer seasons 2008-2009. Black arrows pointing down- or upwards indicate respectively missing base and top of formation, not applied to former data.

5. Discussion

Individual facies and facies associations are discussed in Chapter 4, and will be used as basis for the following interpretation of depositional environment of the De Geerdalen Formation. Eastern Svalbard and central Spitsbergen will be discussed separately before comparing the two areas. Assumptions and problems mentioned in the introduction (Chapter 1) will be discussed in the light of recently collected data, and suggestions to further work will be addressed.

5.1 Depositional environment

The De Geerdalen Formation shows a general regressive development both on eastern Svalbard and central Spitsbergen. Data indicates an earlier development of proximal facies associations (e.g. FA1 and FA2) in eastern areas compared to central Spitsbergen, agreeing with recently drawn palaeogeography for Triassic times in these areas (Riis et al. 2008). An earlier development of proximal facies associations in eastern areas can also be seen from higher sand versus mud ratio on Edgeøya in lower reaches of the formation than on central Spitsbergen (Appendix 7).

Net/gross results will be used in this discussion, but values can only be considered as approximates because of sources of error. The values are dependent both on the exact location, erosion of the formation and on meters section of the total thickness of the formation at the locality. Some sections were not completed because of bad weather or short days during data collection, and some sections involved extinctive scree areas. Fieldwork done in connection to the Knarud (1980) work was helicopter based, making good exposures and localities more available (pers.com. A.Mørk 2010) and probably resulting in higher net/gross values than boat and foot based fieldwork have done in recently work. This can probably be one reason for high net/gross values on eastern Spitsbergen, not addressed further in this discussion.

Thicknesses of the formation are previously described to increase towards eastern areas (Mørk et al. 1999). This is not necessary easy to agree on from measured section (Figure 59), but data from earlier fieldwork (Lock et al. 1978; Mørk et al. 1999), not shown in Figure 59, indicate thicknesses of the De Geerdalen Formation up to 400 m south-east on Edgeøya (Negerpynten) compared to thicknesses rarely exceeding 300 m on western and central

Spitsbergen. Unknown base and top of formation, resulting both from erosion and covering of sections, complicates a conclusion on changing thicknesses of the formation from west towards eastern areas. Erosion down into the De Geerdalen Formation on Edgeøya (Mørk et al. 1982; Mørk et al. 1999) make it possible to assume originally thicker units in this area. This can also be the case on Hopen with base of formation located below sea level (Figure 59). The considerable variations in thickness from one section to another can also be discussed in relation to a possible earlier development of the De Geerdalen Formation in some areas, with synchronous deposition of Tschermakfjellet Formation in bordering areas. Lock et al. (1978) mentions the thickness variations of the Tschermakfjellet Formation and De Geerdalen Formation on Edgeøya as a striking feature, and suggests the lower boundary of the De Geerdalen Formation to be highly transgressive. Knarud (1980) indicated an earlier development of the upwards-coarsening sequences on western Spitsbergen compared to synchronous deposition of Tschermakfjellet shale on central and eastern Spitsbergen. From recently observations of the highly variable deposits at base of the De Geerdalen Formation it seem likely to support a diachronous development of lower boundary of the De Geerdalen Formation, meaning both local and regional thickness variations of the Tschermakfjellet Formation and the De Geerdalen Formation.

The few palaeo-transport direction measurements during this work give a general E to W transport direction and an S-N orientation of the palaeo-coast (Figures 9 and 16 and Facies D), agreeing with recently suggested Ural orogeny to the ESE as main provenance area (Riis et al. 2008). The mentioned possibility of an early western source, resulting in upwards-coarsening sequences in profiles located SW of Isfjorden, are well documented at southern Spitsbergen (Mørk et al. 1982), but there are still uncertainties on source area further north. Lack of new data from this area makes it difficult to discuss.

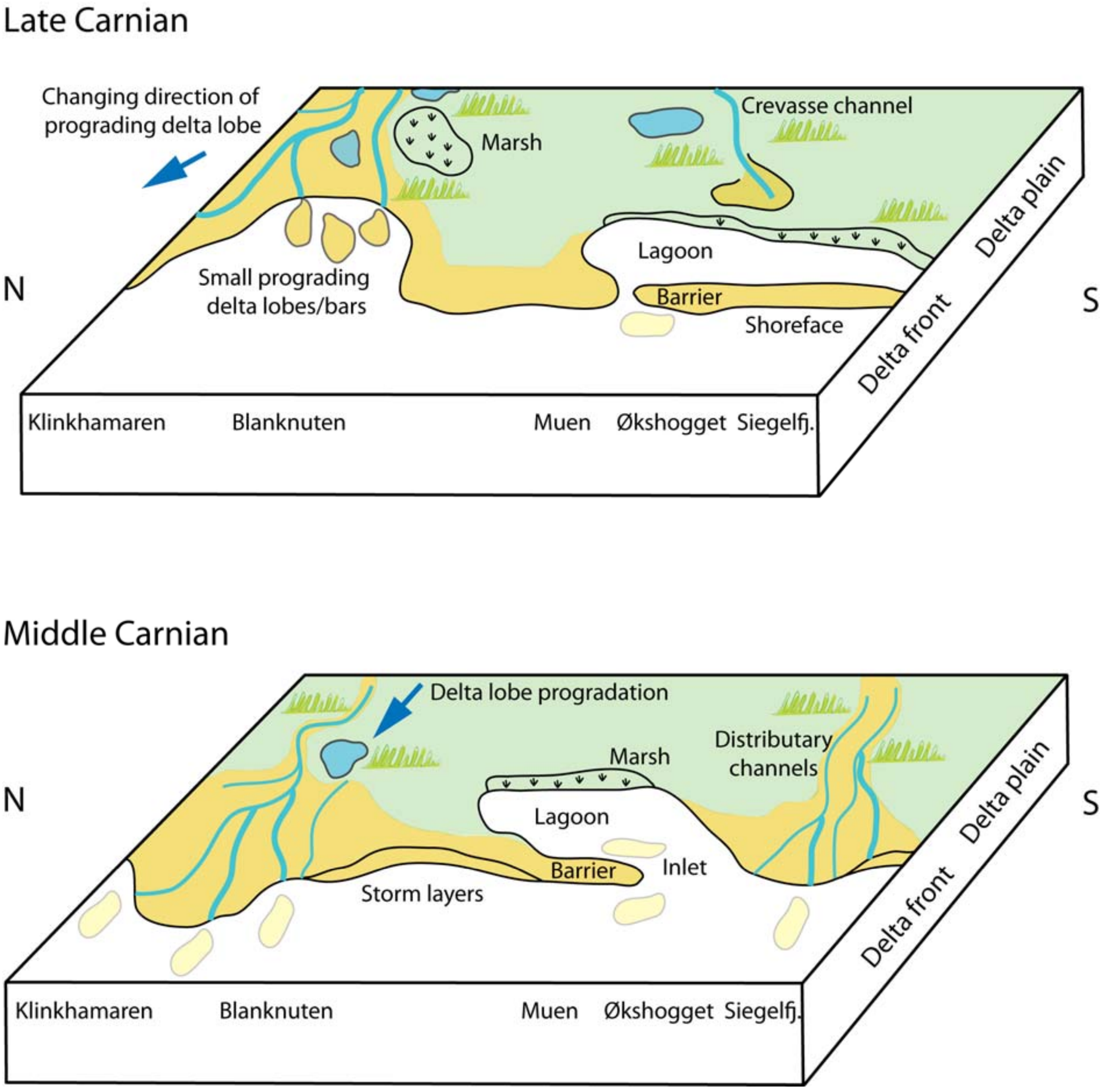
The rapid lateral changes in facies composition in some areas suggest a flat to gently dipping siliciclastic platform setting, with lagoonal to bay and delta lobe systems operating in close association. This also support thickness variations caused by diachronous development of the formation.

Lateral correlations of facies associations is challenging both on eastern Svalbard and central Spitsbergen, both due to covering of several shale units and difficulties regarding exact dating on available material. Used dating methods on Carnian sediments are palynological dating of spore-pollen and marine plankton. The latter are the most reliable dating method, but rarely applied because of few occurrences of marine plankton (pers.com. J.O.Vigran 2010). There are restricted changes in flora during Carnian, making more specific correlations (spore-pollen) between sandstone bodies' difficult (pers.com. J.O.Vigran 2010). Detailed geometric studies (LIDAR-data) are probably the best approach for correlations between measured sections, and such analyses are in progress (NPD-UNIS). Correlation from east towards western areas are particularly challenging caused by the prograding system and diachronous boundaries.

Eastern Svalbard (Edgeøya and Hopen)

Sections from Edgeøya show changing deposits at base of the formation, from delta front channel sand (FA6) on Klinkhamaren to offshore and shoreface deposits (FA7) further south on Muen to Negerpynten, indicating rapid lateral changes in depositional environment. Small variations in sea level can cause considerable effects on hydrodynamic conditions and reworking of sediments on flat platform areas (Glørstad-Clark 2009), supporting a flat delta system to shallow marine sea setting in this area earlier indicated by Knarud (1980). Lack of data on the lower sequences of Hopen sections makes a correlation to this area difficult, but rapid change in depositional environments in the upper part of the De Geerdalen Formation on Hopen indicates a prevailing flat platform setting also in late Triassic times. Only about 20 km laterally the deposits on Hopen changes from distributary channel sand (FA2) and fine grained deposits (FA1) in southern areas to shoreface and offshore sand (FA7) to the north.

Figure 60 demonstrates a possible palaeo-depositional setting from middle- to late Carnian time on Edgeøya, and a correlation panel from Edgeøya and Hopen are shown in Appendix 7. The first occurrence of the formation on Edgeøya in middle Carnian is shown by a marked increase in sand versus mud ratio from the underlying Tschermakfjellet Formation. On central Klinkhamaren a 40 m thick package of undulating fractured sand (FA6) and thin shale layers initiated the prograding delta system. Covering in the lower reaches makes it possible that a more transitional change from prodelta to delta front sand have been missed, but an abrupt transition from prodelta mud to fluvially sandstones are also recognized in ancient deltas, both representing distributary channels and incised valley fill (Bhattacharya 2006). Growth faults in the area, first described by Edwards (1976), make lateral correlations between sections impossible. They are not observed on adjacent mountain Blanknuten, indicating higher sediment supply to Klinkhamaren possibly resulting in faulting. Changing thickness of the base layer on Klinkhamaren can be due to both varying accommodation space and sediment supply. Rapid subsidence and high sedimentation are often explained by fault growth (Garcia-Garcia et al. 2006), possibly also the reason for lack in diagnostic structures in many outcrops in the lower units on Klinkhamaren.


Late Carnian

Middle Carnian

Figure 60: Depositional setting on Edgeøya in middle- to late Carnian, interpreted from several sections in the current area (Appendix 5 and 7).

Whether overlying shale sequence is continental or marine are uncertain, but marine reworking of the following upward-coarsening sandstone sequence imply a marine influence in depositional setting, possibly caused by flooding after delta lobe abandonment. Delta lobe switching and abandonment are described from the Mississippi delta (Bhattacharya 2006), and depends on the balance between oceanographic conditions and sediment supply (Correggiari et al. 2005). Thin occurrence of delta front channels (FA6) north on Blanknuten can be due to less accommodation space or a distal position to the delta lobe assumed to prograde out on Klinkhamaren.

Storm deposits (FA7) overlying the thin occurrence of delta front channel sand (FA6) on Blanknuten can indicate increased wave-influence and decrease in strength from an earlier fluvial source. The thinner sequences of storm layers and offshore mud on Muen and in Økshogget (Slåen) further south can be due to less accommodation space (subsidence/platform geometry and sea level) and a later introduction to the more proximal delta deposits of the formation. It is also possible that several meters of deposits have been missed in the lower reaches because of covering with scree, especially on Muen. The transition to stacked thick packages of low angle- to large scale cross stratified sandstone at these locations indicates upwards-shallowing and shoreface progradation. Rooted fine-grained sandstone and shale sequences overlying the units imply deposition in a protected area, possibly a back barrier setting. The presence of wave structures and heterolithic bedding can indicate a connection to a more marine environment periodically. It is difficult to tell if the same barrier system also were present on Blanknuten because of unanswered questions on the origin of the thick sandstone body south on the mountain (Figure 52), possibly representing an inlet channel or a distributary channel. Knarud (1980) interpreted the upwards-coarsening sequences in his lower section south on Blanknuten to represent a prograding barrier system, based on the elongated form, high plant content and sedimentary structures.

Data from Siegelfjellet (2008) also show upwards-shallowing from storm deposits (FA7) to delta front sand (FA6) or distributary channels (FA2). It appears as a progradation of delta channels has taken place at a later stage than on Klinkhamaren. In the discussion of specific facies association in Chapter 4 it was mentioned a possible common depositional environment for FA6 and FA2, with a suggestion that FA2 are located in a more proximal position than FA6. More data on geometries and lateral correlations in addition to origin of shale sequences can be helpful in the distinction. Ongoing LIDAR studies will hopefully be helpful in improved understanding of this issue, but correlations from one to another mountain can be challenging because of the present wide valleys with removed sediment, scree cover and the mentioned dating problems in Carnian.

Coal horizons observed in the succession on Siegelfjellet were not identified on adjacent mountain Slåen, indicating a limited regional extent. Coal units on Blanknuten were also difficult to correlate between sections, agreeing with correlation problems of coal seems noted by earlier workers (Lock et al. 1978). Coal seems of limited lateral and vertical extent can like previously mentioned be explained by an active and/or hostile depositional environment (Collinson 2006).

Younger sequences show a new depositional pattern, with stacked upwards-coarsening sandstone bodies (FA4) separated by shale units (FA1), lacking signs of storm events. This implies a more proximal location in the delta system, or deposition in a protected area. Only one section on Negerpynten (southern Edgeøya, measured 2008) shows continued storm influence throughout the entire measured section. The upwards-coarsening sequences, especially evident on Klinkhamaren and Blanknuten, show marine reworking in the lower reaches and a few examples on top of units. Coal, fine-grained rooted sandstone and black shale separating the sequences indicate that the progradation of lobes or bars took place in a protected environment. It is possible that an interdistributary bay developed when an earlier delta lobe changed direction (Figure 60). A delta front/delta top and interdistributary bay interpretation corresponds to Knaruds (1980) interpretation of upper deposits on Blanknuten, also displaying upward-coarsening sequences with both marine and continental influence. Tidally influence on the sediments can be argued by the presence of heterolithic bedding in lower reaches of the upwards-coarsening sequences, but like previously mentioned (Section 4.1) this can also develop on mudflats bordering abandoned lobes or under marine conditions. Knarud (1980) mentions lack of herringbone- and exposure structures as indications of rather shallow marine- than tidal plain origin for heterolithic bedding. Lack of bidirectional large scale cross-stratification can support minor tidal influence. Higher net/gross values on central Klinkhamaren than in adjacent sections on Klinkhamaren and Blanknuten can indicate a higher frequency of lobe progradations into this area (Figure 57) (and higher accommodation space).

Central Spitsbergen (Botneheia and Sassendalen)

Central Spitsbergen show a similar stacking pattern of facies association as on eastern Svalbard, with offshore-shoreface and barrier deposits (FA7 and FA5) in lower sections to back barrier (FA1) and distributary channels/bars (FA2 and FA3) in the upper sections.

Figure 61 shows a suggestion to palaeo-depositional setting from middle- to late Carnian time on central Spitsbergen and a correlation panel is shown in Appendix 7. All measured sections in the area displays FA7 at base of the formation, with decreasing thicknesses from the NW part of Botneheia (BOT091) towards Trehøgdene. Like mentioned in Chapter 4 these laterally extensive and numerous HCS units can indicate a uniform bottom topography in the investigated area on central Spitsbergen (Dott and Bourgeois 1982). The upper shoreface deposits in lower sections on Trehøgdene and eastern Sticky Keep can represent parts of a barrier system, interpreted from extensive overlying shale sequences with interbedded fine-grained rooted and cross-stratified sandstone units. Massive covering of scree in many of the sections in the same area, and lack of characteristic coal deposits initiation lagoon successions, makes it difficult to conclude on whether the shale units are continental or partly marine. Findings of a coal layer and following greenish bioturbated fines overlying possible inlet deposits in the lower part of core interval A in Adventdalen support the presence of a barrier system regionally (see Appendix 4).

The thinner occurrence of offshore to lower shoreface deposits in eastern sections in Sassendalen than on Botneheia can be due to an earlier development of a barrier system in this area than on Botneheia, probably developed from a mouth bar or a beach ridges parallel to the coast. Both hummocky structures and barrier development are characteristic of high wave energy coasts with limited tidal influence (Nichols 1999). It is likely the prevailing conditions in these sediments, but tidal influence can not be excluded because of observed double mud drapes in the mentioned inlet sandstone in core interval A. Tidal signatures are also seen in younger deposits of the formation, in the form of small scale herringbone cross-lamination (Figure 15), both in Sassendalen and on Botneheia. Knarud (1980) also describes herringbone cross-bedding from Dalsnuten (Sassendalen), interpreted as structures in a tidal channel.

Figure 61 B shows a possible setting on central Spitsbergen before going up into the uppermost sandy units of the De Geerdalen Formation. Whether fully lagoonal conditions developed on Botneheia are difficult to conclude on from sparse data on shale units and lack of typical barrier sandstone bodies. Alternatively scenarios can be marine transgressions and later progradation of a mouth bar/delta plain system. Short lasting transgressive events when deposition of the upper part of the formation can be seen from ravinement surfaces marked by coquina beds and following HCS structures in sections on central Botneheia.

Lagoonal conditions on central Spitsbergen have not been noted in previous work (Knarud 1980), but rather distal to more proximal bar development in a shallow marine environment. This corresponds to many of the recently studied outcrops on Botneheia and in Sassendalen, but it still seems likely to add the possibility for lagoon environment in Sassendalen and Adventdalen based on collected data.

The upper part of all measured sections contains sandstone bodies of varying appearance, from mud flake rich sandstone units with abundant plant material (FA2) to more difficulty defined units with vague structures (FA3). Geometric data is needed to make a better distinction between the different sandstone bodies, but temporarily the mud flake- and plant fragment rich occurrences are interpreted to be more proximal than their closely associated counter partners (FA3).

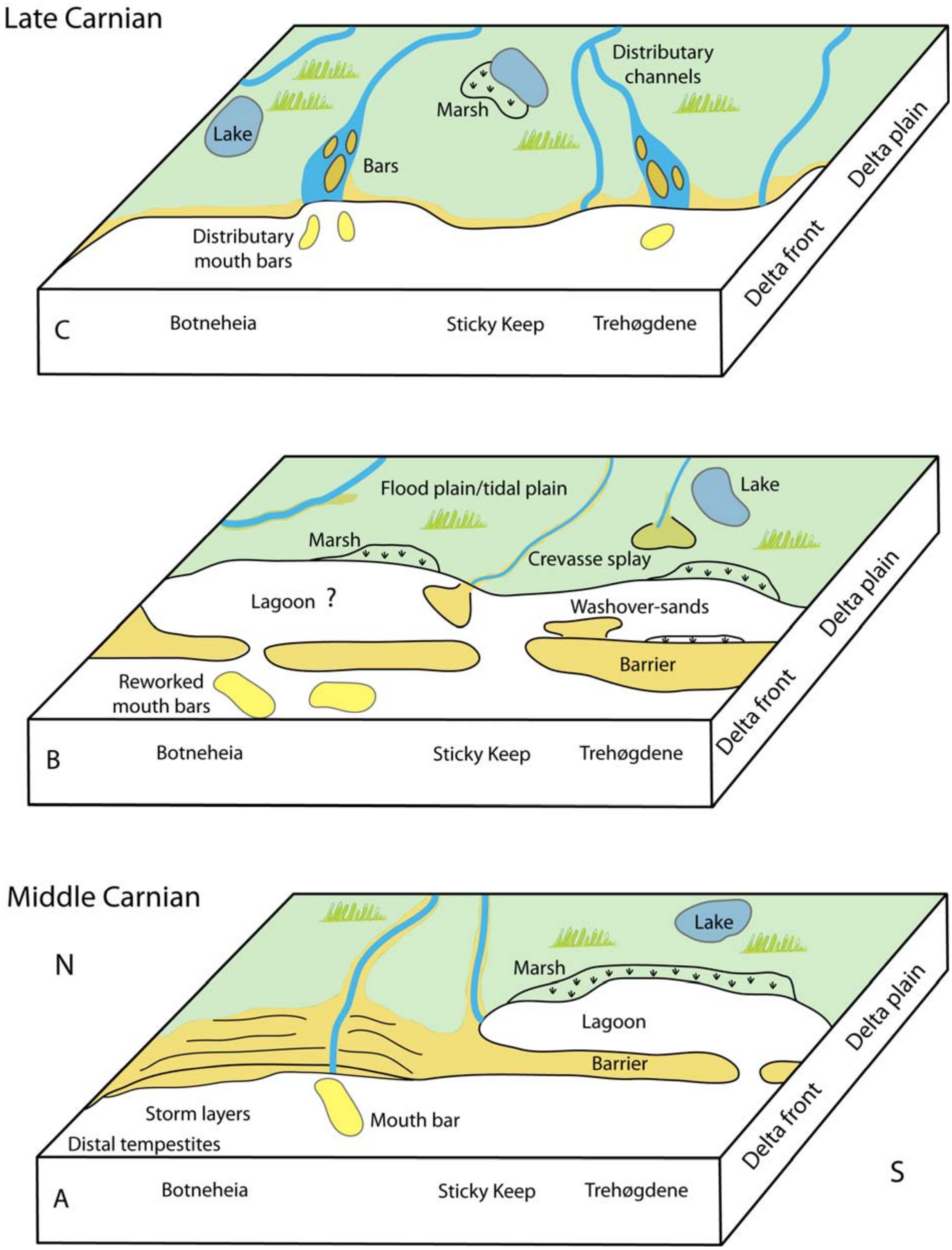


Figure 61: Depositional setting on central Spitsbergen in middle- to late Carnian interpreted from several sections on Botneheia and in Sassendalen (Appendix 5 and 7).

From east to west

Even though the general regressive development of the De Geerdalen Formation can be seen both on eastern Svalbard and central Spitsbergen, is it clearly an earlier appearance and higher frequency of proximal facies association on Eastern Svalbard. Generally higher net/gross values on eastern Svalbard compared to central Spitsbergen can also support this trend. The few higher net/gross values on central Spitsbergen are often due to thick sandstone bodies of very fine to fine sand, not necessary representing proximal facies associations. The occurrence of similar deposits in the Snadd Formation as observed both on Edgeøya (Facies association 4) and on central Spitsbergen (Facies association 2) can support a prograding delta system building out from the ESE.

The previously discussed (Facies association 2) differences between distributary channels on central Spitsbergen and Edgeøya can be due to a changing basin configuration from the first appearance of the formation in eastern areas to later (diachronous) appearance on central Spitsbergen. Infilling from the prograding delta system can have caused decreased accommodation space and the sediment supply can also have changed throughout Carnian.

Tidal signatures are more common on central Spitsbergen than on Edgeøya and Hopen, but still only rarely observed. Mud drapes, herringbone cross-stratification and heterolithic bedding are the present structures indicative of tidal influence, occurring in sequences interpreted as barrier systems and interdistributary areas. It is possible that sedimentary structures have been overlooked or missed caused by covering by scree or bad quality outcrops, making an east-west comparison difficult. Earlier studies have interpreted the formation to be deposited under microtidal influence (Knarud 1980), and to be mainly wave- and river dominated (Lock et al. 1978; Knarud 1980). Heterolithic bedding occurring on tidal flats are mainly described from macrotidal settings, but can also develop in protected areas in microtidal settings (Reading and Collinson 2006; Yamashita et al. 2009), the latter probably being representative during deposition of this formation. The widespread occurrence of storm deposits in FA7 support a microtidal setting, because tidal signatures can have a tendency to mask the effects of waves in meso- to macrotidal environments (Bhattacharya 2006).

The presence of the Isfjorden Member on Botneheia and in Adventdalen (well DH4) underlies the sediment of Wilhelmøya Subgroup on central Spitsbergen, deposited during transgressive conditions in early Norian (Riis et al. 2008). The Wilhelmøya Subgroup is initiated by the Slottet Bed (Mørk et al. 1999), only observed on Hopen (Lyngefjellet) during this work, but occurs at several localities across the Svalbard archipelago (Section 1.5).

5.2 Further investigations

A returning problem during the interpretation of different facies associations was the lack of geometric and correlative data on sandstone bodies. Analyses of LIDAR-data are like mentioned in progress (NPD-UNIS), and will be interesting to follow up on. It would also be interesting to do further field investigations of the formation on Spitsbergen, both on western and eastern areas, to get a better understanding of the discussed source areas to the west and possibly N/NE. Further investigations could also include more detailed study of shale sequences as correlative data, including sampling and dating.

6. Conclusion

This study aiming to develop a depositional environment model of the De Geerdalen Formation shows that the sedimentation pattern changes from eastern to central areas on Svalbard. The collected data material is not sufficient to conclude on the origin of most of the sandstone bodies or to discuss source areas earlier indicated to the NW. However, knowledge from this work can indicate:

- A regressive facies development from storm dominated deposits to channel/bar and interdistributary deposits in the upper successions in most areas.
- More proximal facies associations on Edgeøya than on central Spitsbergen during early times of deposition.
- Relatively higher sediment supply to areas displaying growth faults on Edgeøya than on adjacent mountains, suggesting delta lobe progradation into these areas (e.g. Klinkhamaren).
- A rapid lateral change in facies associations, especially evident on eastern Svalbard, implying a shallow siliciclastic platform setting with changing relative sea level, sediment supply and sediment reworking during deposition of the formation.
- A changing basin configuration from early to late time of deposition, demonstrated by changing sandstone bodies from eastern to central areas, probably the result of infilling of a shallow marine shelf and decreasing accommodation space.
- A common provenance area for the Snadd Formation in the southern Barents Sea and the later developing De Geerdalen Formation on Svalbard. They probably represent a continuous depositional system with a diachronous lower boundary. Thickness variations of the De Geerdalen Formation can be caused by this diachronous development of the formation and varying erosion during post-Triassic times.
- Agreement with the recently suggested main provenance area located to ESE (the Uralian orogeny). Sparse data from this work can not contribute to any conclusions, but apply as supportive data to recently seismic and sedimentological studies.
- Microtidal setting during deposition of the formation, with tidally signatures in barrier and interdistributary area deposits.

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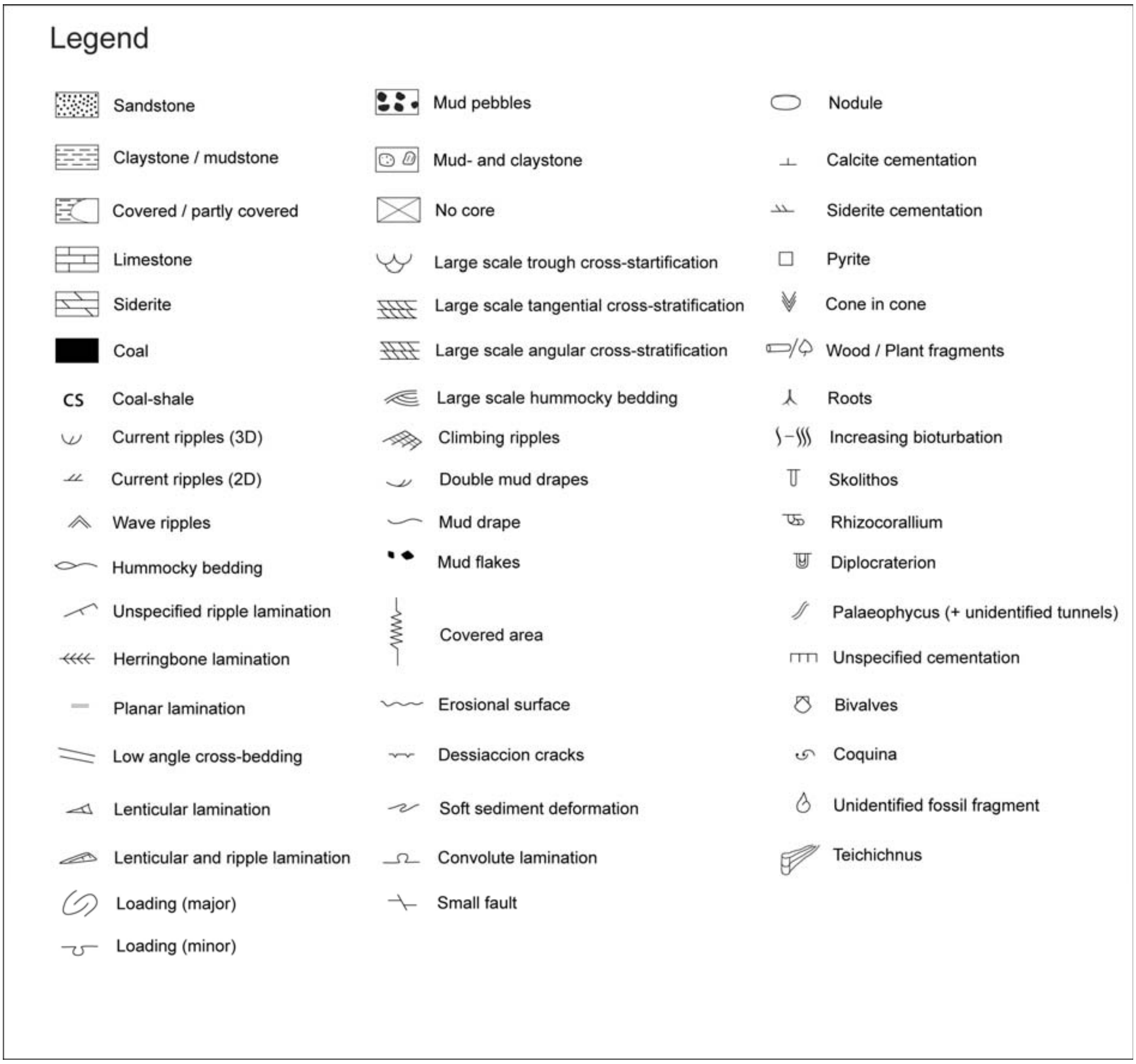
Appendix

Appendix 1 Legend to measured sections



Appendix 2 Field localities and sections

Location	Section	Measured (date)	Weather	Coordinates
Central Spitsbergen: Botneheia				
Botneheia (west)	BOT091	10-11.06.09	Cloudy, 2-4 derees, windy	8 msl N 78 20.552 E 16 21.036
Botneheia	BOT094	03.09.09	Cloudy, windy, cold	Base De Geer.Fm. N 78 20.239 E 016 22.756
Botneheia (central)	BOT093	01.09.09	Cloudy, fog, no wind	Base De Geer.Fm. N 78 19.901 E 016 24.958
Botneheia (east)	BOT092	12-13.06.09	Sun, 2-4 degrees, windy	Base De Geer.Fm. N 78 19.956 E 016 26.636
Central Spitsbergen: Sassendalen				
Grusryggen	GRU09	29.08.09	Sun, no wind	Base De Geer.Fm. N 78 15.086 E 016 49.619
Sticky Keep	STI091	24.08.09	Sun, about 10 degrees, no wind	Base De Geer.Fm. N 78 15.697 E 016 56.764
Sticky Keep	STI092	25.08.09	Cloudy-sun, about 7 degrees, no wind	Base De Geer.Fm. N 78 15.437 E 016 58.254
Trehøgdene	TREH09	27.08.09	Sun, no wind	Base De Geer.Fm. N 78 14.305 E 017 08.042
Eastern Svalbard: Edgeøya				
Klinkhamaren (central)	KLI09	17.08.09	Strong wind, cold, some snow	Base De Geer.Fm. N 78 01.254 E 021 08.530
Blanknuten (north)	BLA092	20.08.09	Cloudy, some fog, some wind	Norht ridge
Blanknuten	BLA091	19.08.09	Cloudy, some wind	Base De Geer.Fm. N 77 59.242 E 021 12.581
Muen	MUN09	16.08.09	Sun, some wind from north	South ridge
Økshogget (on Slåen north)	ØKS09	15.08.09	Cloudy, no wind	Base Tschermak.Fm. N 77 44.980 E 021 14.397
Eastern Svalbard: Hopen				
Lyngefjellet (Hopen north)	LYN09	12-13.08.09	Cloudy, some fog, about 6 degrees	Base of section N 76 41.361 E 025 27.701
Kollerfjellet (Hopen south)	KOL093	13-14.08.09	Cloudy, some snow, cold, windy	South western gully

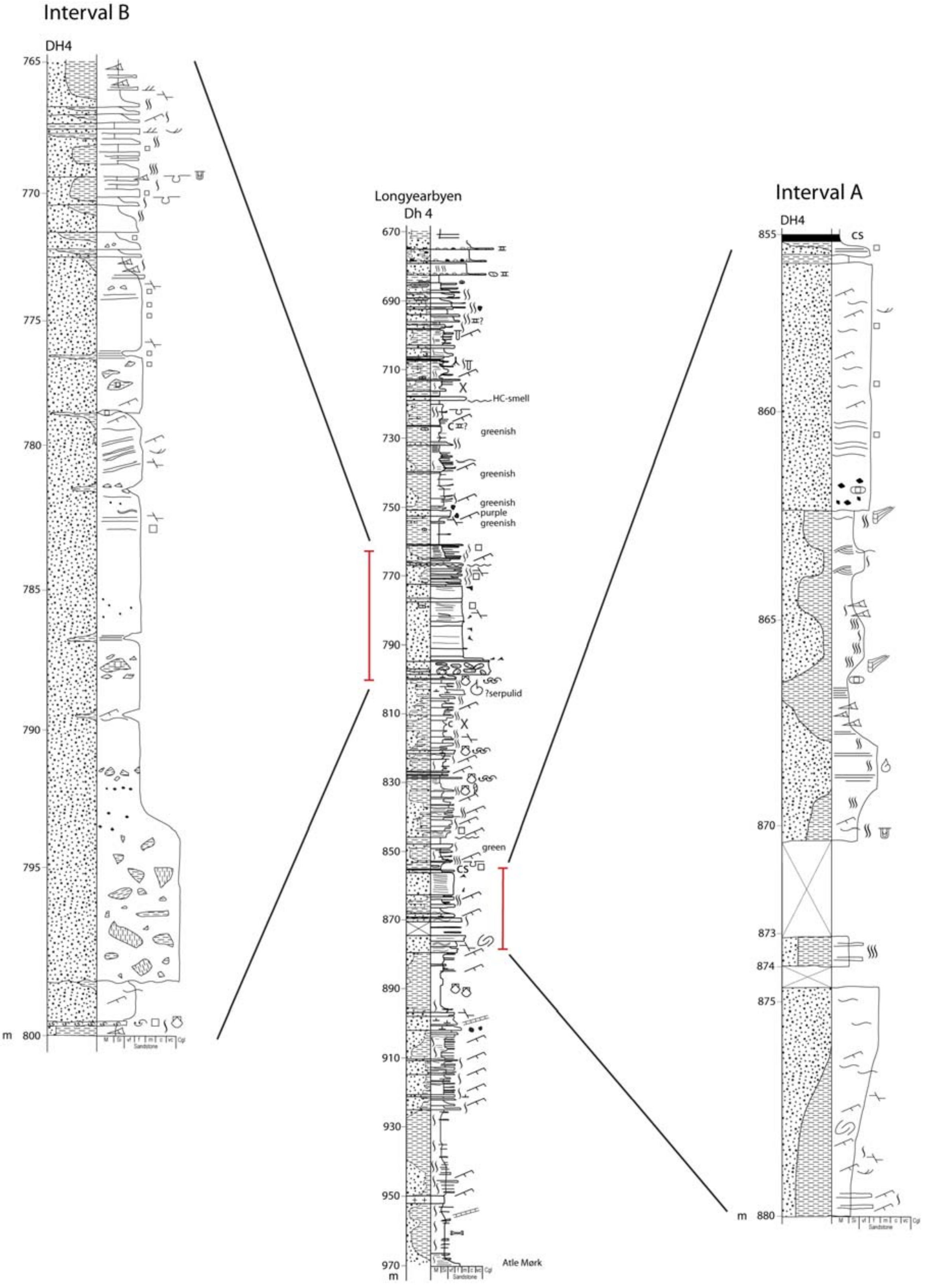
See Figure 5 and 6 for map with sections marked. Coordinates are missing for BLA092, MUN09 and KOL093, but their positions relative to sections close by with exact coordinates can be seen at maps in Chapter 2. Core data (Well DH4) is not included in this table (see Appendix 4).

Appendix 3 Description of facies

Code	Facies	Lithology	Structures	Thickness	Contacts	Geometry	Bioturbation	Mud flakes	Organic material	Cementation	Colour	Associated facies	Occurence
A	Large scale cross-stratified sandstone	F-m sand	Trough and tabular cross-stratification	0.5-7 m	Often erosive base	Some lensoid	Rarely observed in core material	In situ on Blanknuten, Hopen and in well DH4	Plant fragments	Somtimes calcite or unspecified	Grey, red, brown	N, B, E, O, I, K	Upper part on central Spitsbergen, varying on eastern Sv.
B	Small scale cross-stratified sandstone	Vf-m sand	Trough and tabular cross-stratification (small scale), herringbone	0.1-1.5 m	Gradual or sharp	Short lateral extent	None observed	None observed	Plant fragments	None proved	Grey, red, brown	N, A	Upper part on central Spitsbergen, varying on eastern Sv.
C	Climbing ripple cross-laminated sandstone	F-m sand	Climbing ripple lamination	0.3-0.5 m	Sharp	Short lateral extent	None observed	None observed	None observed	None proved	Grey, brown	A, B, N	Upper part of STI091 ans BOT094
D	Symmetrical ripple laminated sandstone	Vf-f sand	Symmetrical ripple lamination	Few cm-0.5 m	Erosive or gradual		*Rhizocorallium* and unspecified bioturbation	On Botneheia	Plant fragments	Calcite in some outcrops	Grey, red	H, E, N	Lower part on central Spitsbergen, varying on eastern Sv.
E	Low angle cross-stratified sandstone	Vf-f sand	Low angle corss stratification	About 0.5-3 m	Often gradual	Some lensoid?	Sparse bioturbation	None observed	Plant fragmnets on scree material close to outcrops	None proved	Grey, red, brown	H, A, B, N, D	Lower part on central Spitsbergen, varying on eastern Sv.
F	Horizontal bedded sandstone	F sand	Horizontal bedding	< 1 m- few m	Sharp		Observed on Klinkhamaren	Observed on Trehøgdene	Not observed	Calcite cementation on Trehøgdene	Grey	B, C, D, A, E	Different levels
G	Undulating fractured sandstone	F sand	Undulating fracturing	0.1-3 m	Erosive based	Limited lateral extent	None observed	Often close to base of units	Not observed	None proved	Grey, red, brown	N, E, B	Lower part on Klinkhamaren and Blanknuten
H	Hummocky cross-bedded sandstone	Vf-f sand	HCS, symmetrical ripples	0.1-4 m	Often erosive base	Often lateral extensive sequences	*Diplocraterion, Skolithos, Rizocorallium, Teichichnus, Ophiomorpha*	Widespread	Seldom	None proved	Grey, brown	N, D, K,	Lower part on central Spitsbergen and Edgeøya, upper part in LYN09
I	Mud flake conglomerate	> 2m-6 cm, f sand matrix	None	0.5-4 m	Erosive based		None observed	Widespread within limited areas	Not observed	Calcite and unspecified on Botneheia and Trehøgdene	Gre, brown	A, N	Different levels
J	Fine-grained rooted sandstone	Vf sand	Vague ripple lamination, fracturing	0.3-1.5 m	Sharp		None to heavily	None observed	Plant fragments and roots	Often unspecified	Red, brown	N, O, (B)	Different levels
K	Heterolithic bedding	Clay-f sand	Heterolithic bedding	1-6 m	Shap to gradual		Sparse to heavy	None observed	Plant fragments and roots on Blanknuten	None proved	Brown, grey	N, H, A, B	Different levels
L	Carbonated rich sandstone	Vf sand	Cone in cone, fractureing, vague ripples	0.1-2 m		Short lateral extent, some lense shaped	None to heavy	None observed	Not observed	Calcite	Grey, brown, red	H, N, J	Different levels
M	Coquina beds	Shell banks		About 4 cm	Sharp	Limited lateral extent		None	None		Dark grey, brown	A, H, N, B	Upper part on central Spitsbergen
N1	Black shale	Clay to silt	Laminated clay	Few cm-10 s m	Sharp or gradual	Often lateral extensive sequences	None observed	None	Coal drapes	None	Dark grey	A, O, J, K	Different levels
N2	Silty shale	Clay to silt	Symmetrical- to planar lamination	Few cm-30 m	Sharp or gradual	Often lateral extensive sequences		None		None	Grey	H, E, N, D	Most evedent in lower parts
O	Coal	Coal, some shale	None	10-20 cm	Sharp or gradual from shale	Limited lateral extent	None observed	None	Coal	None	Dark grey, black	N, A, J	Most evident on Edgeøya and Hopen in middle-upper parts

Vf sand = very fine sand, F sand = fine sand, M sand = medium sand
Sv. = Svalbard

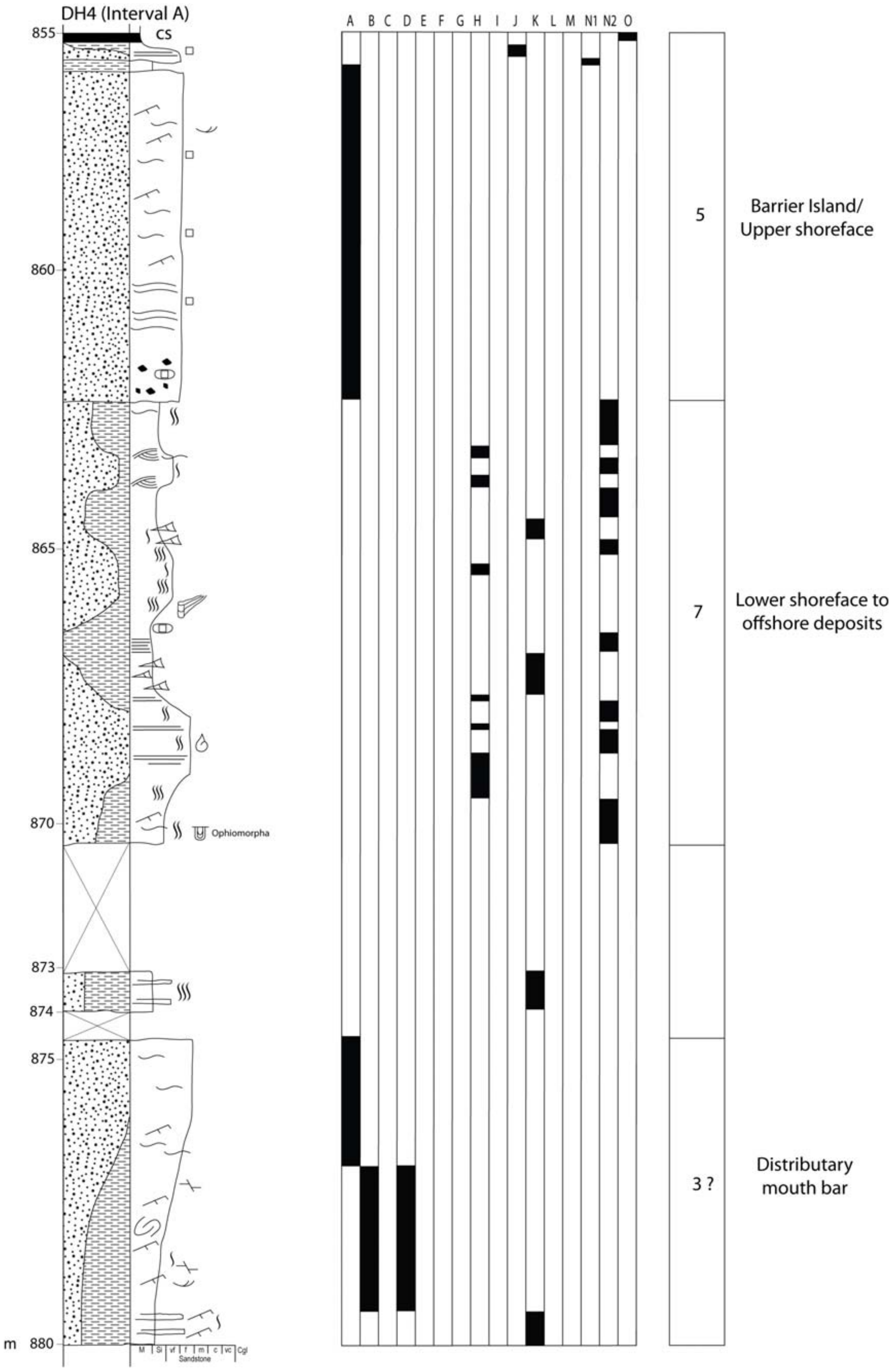
Appendix 4 Well DH4

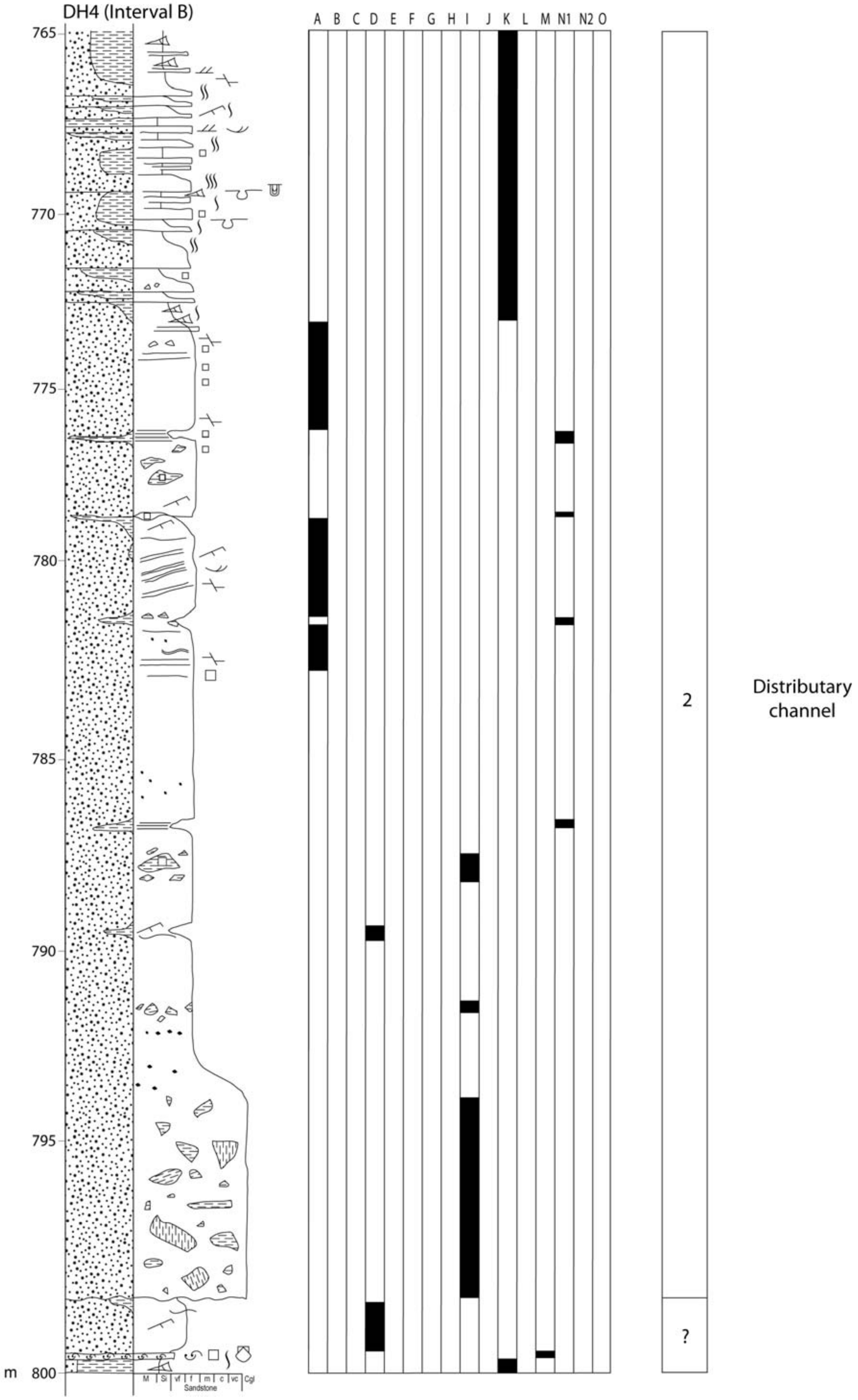


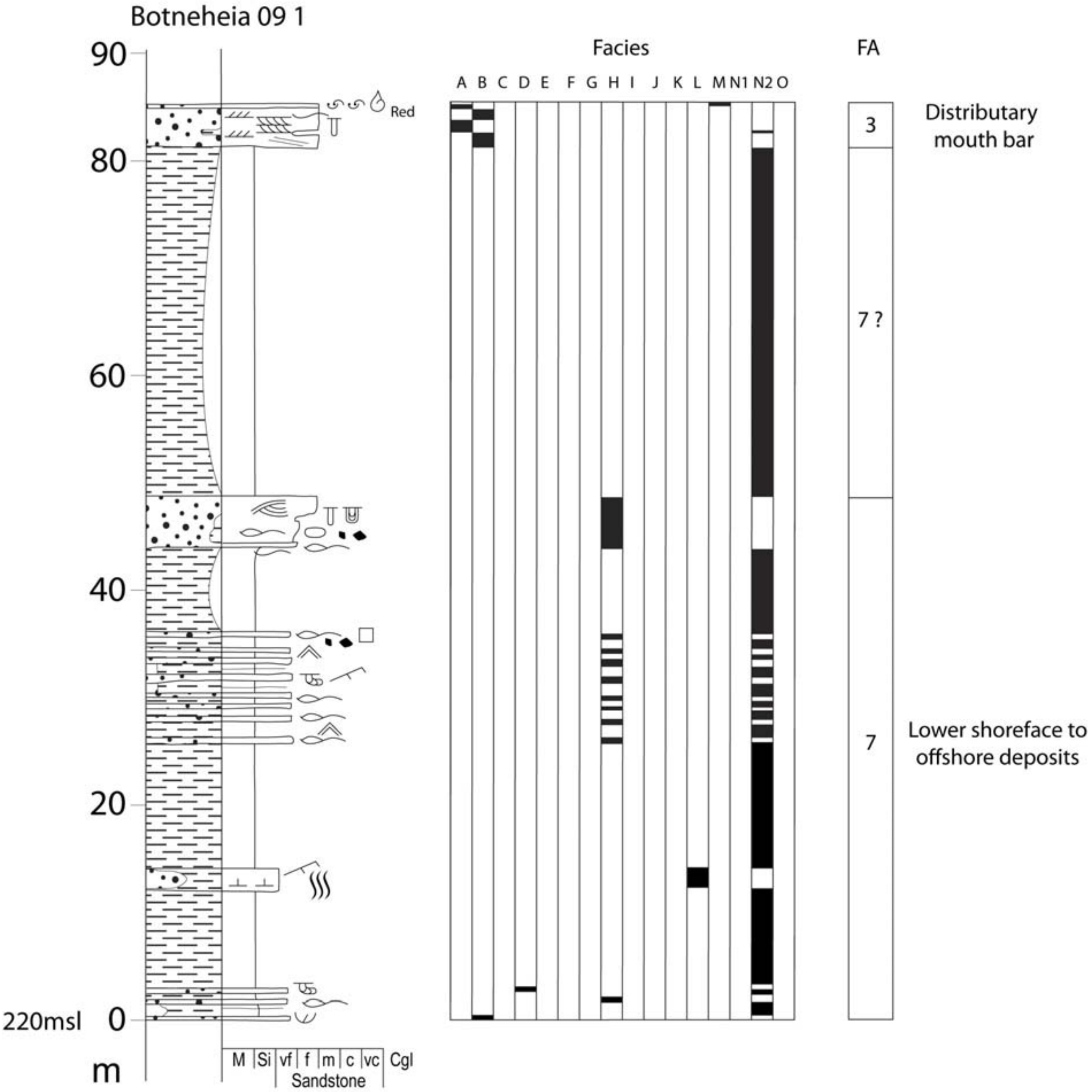
Well DH4 is located in Adventdalen, central Spitsbergen. The De Geerdalen Formation is interpreted to be from depth 970 to about 698 m, included the Isfjorden Member. Above the Isfjorden Member (at 765-689 m depth) is the Wilhelmøya Subgroup (see Section 1.5). Core interval A and B represent sand rich units in the formation and displays different depositional environments.

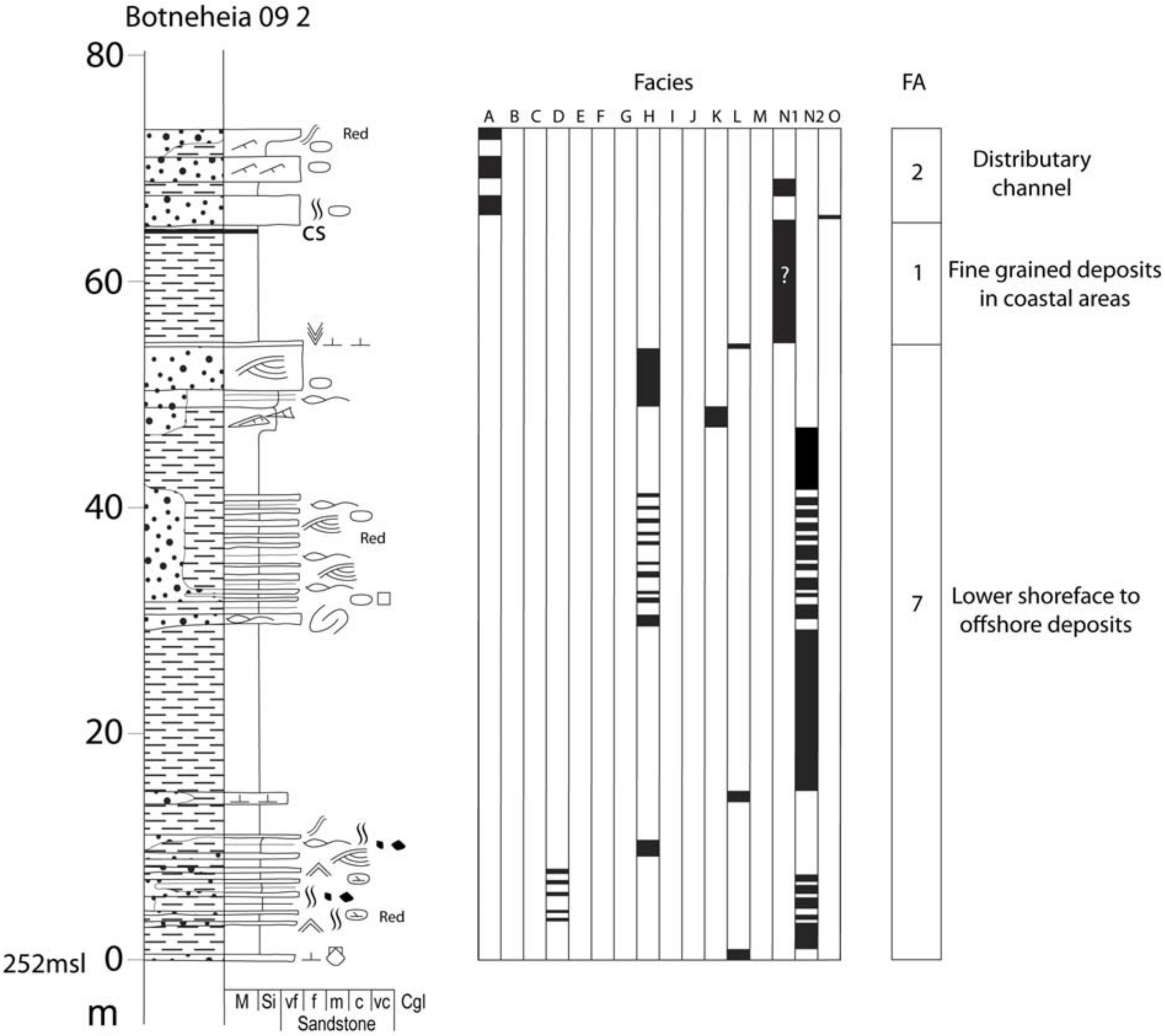
Appendix 5 Facies and facies associations

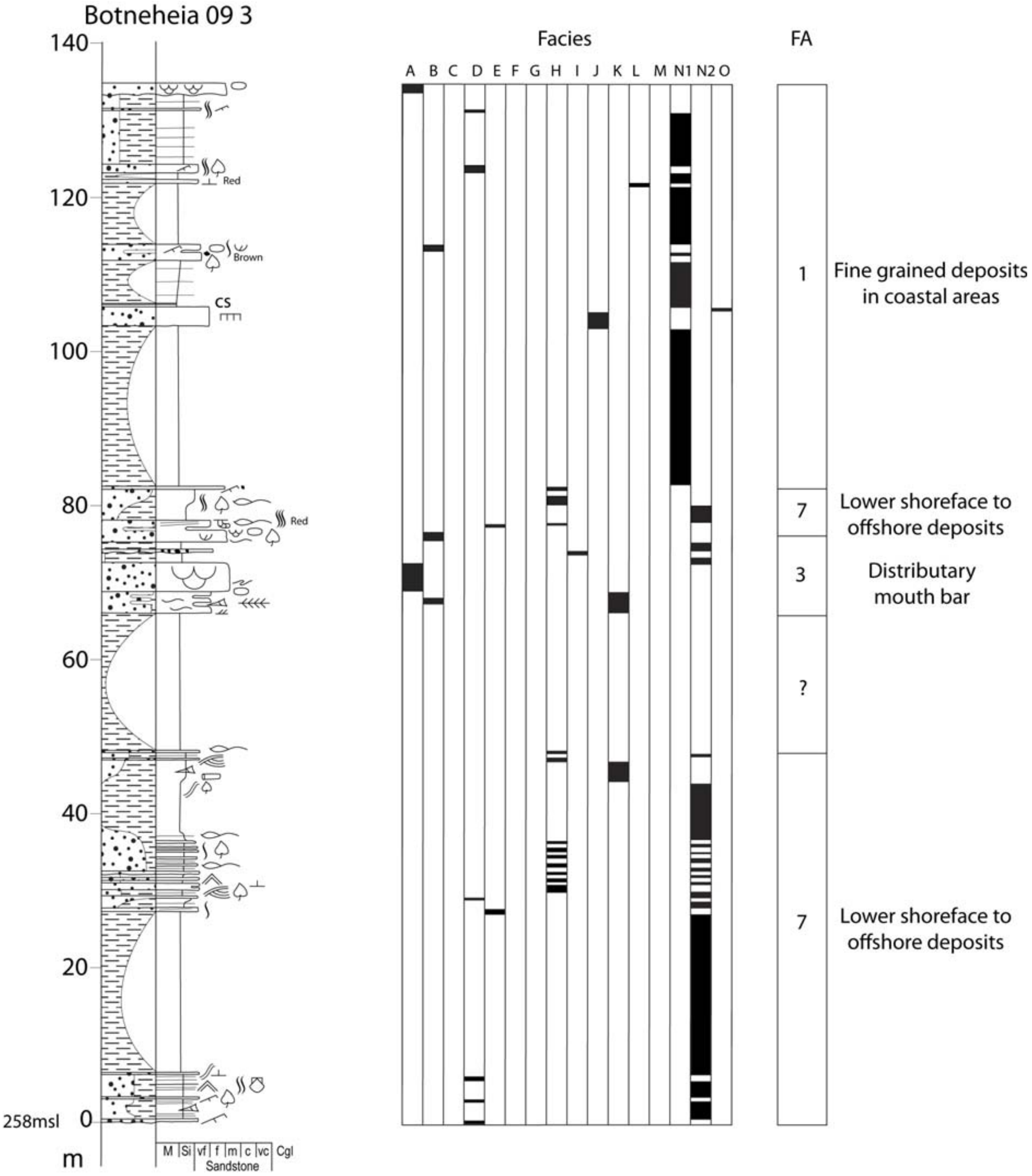
Sections with Facies (A-O) and Facies associations (1-7) from core data (Well DH4) and field sections on central Spitsbergen and eastern Svalbard (Edgeøya and Hopen).

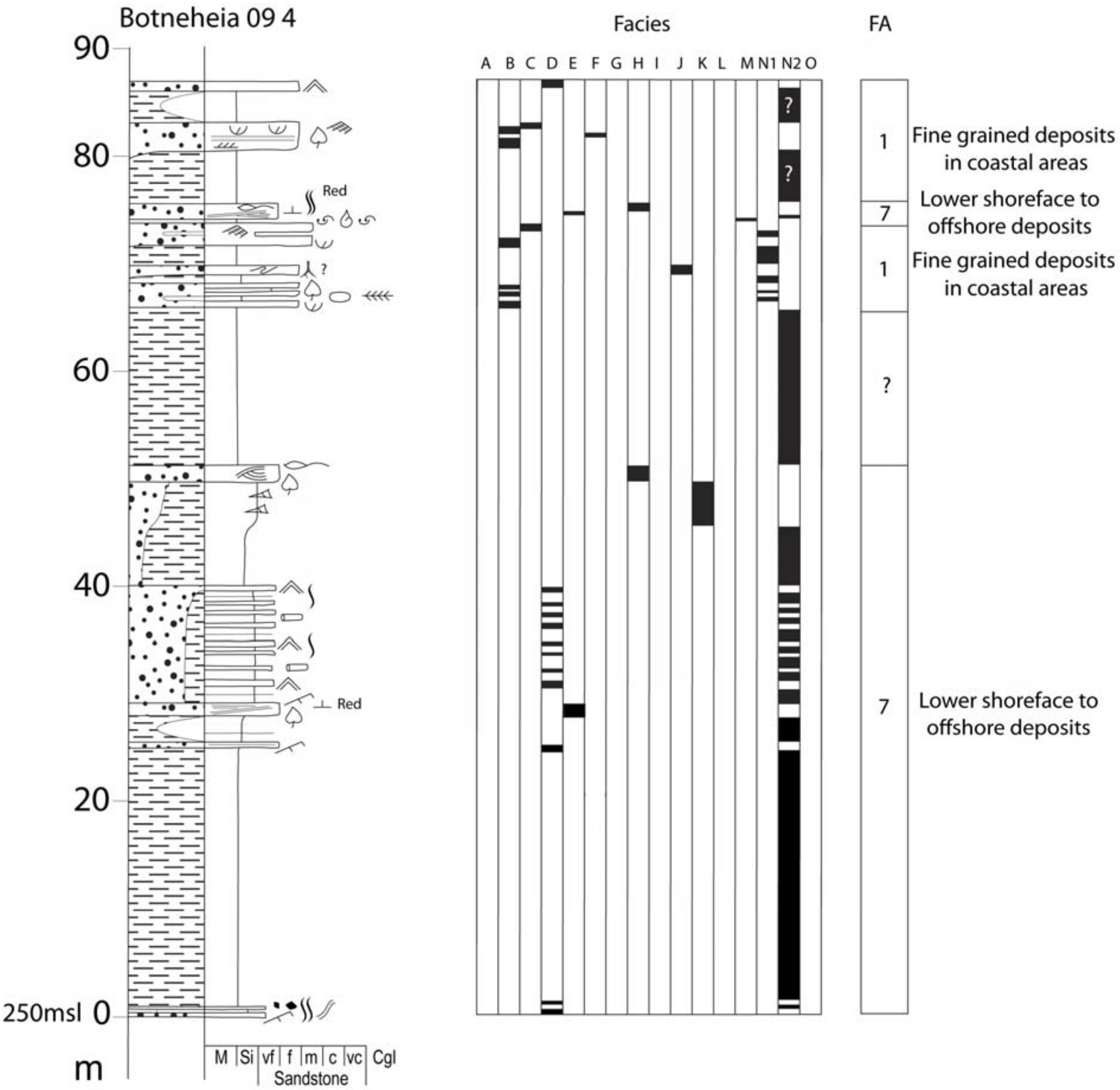


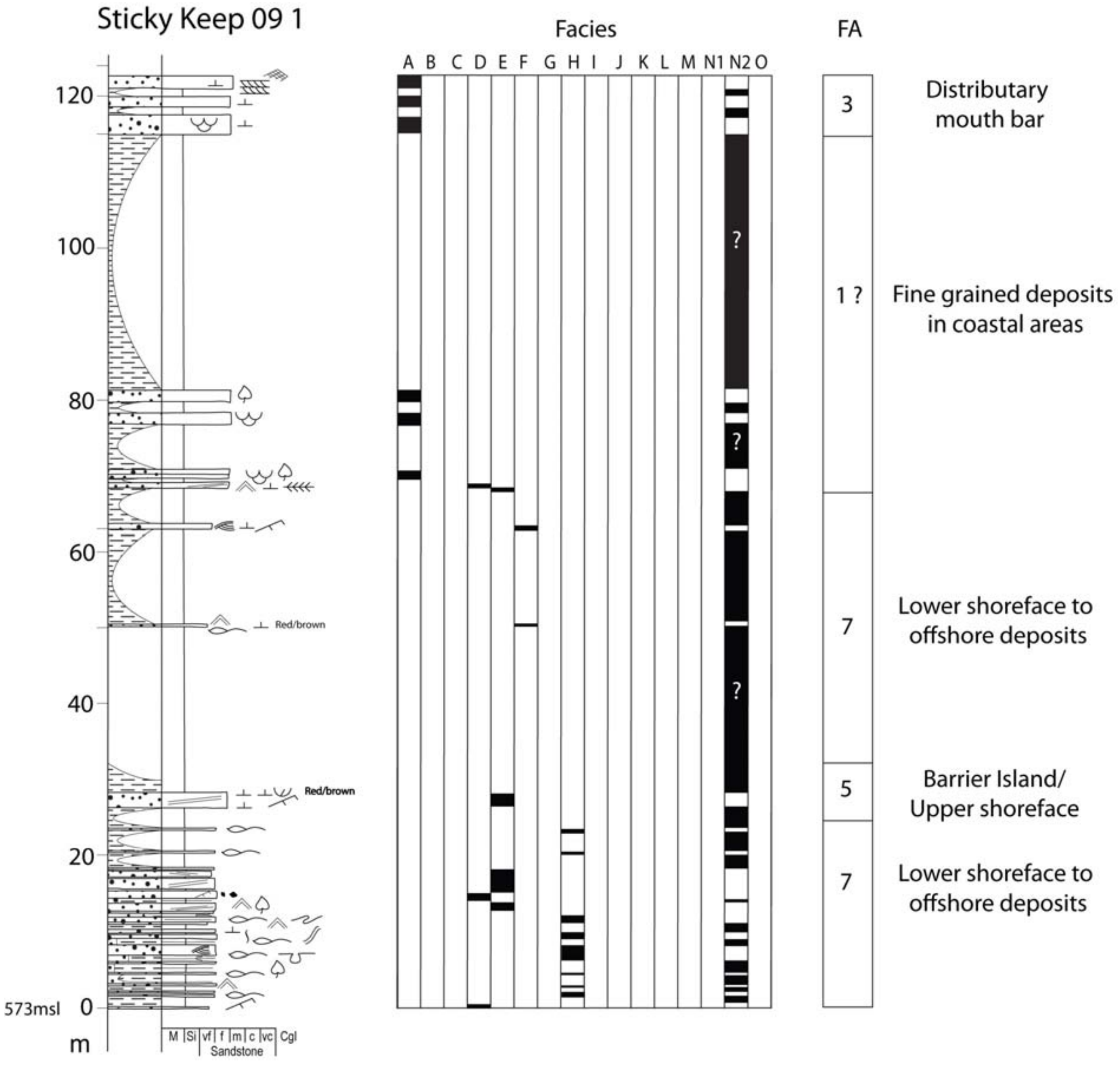

DH4 (Interval B)
765
770
775
780
785
790
795
m 800
M
Si
vf
f
m
c
vc
Cgl
Sandstone
A B C D E F G H I J K L M N1 N2 O
2
?
Distributary channel

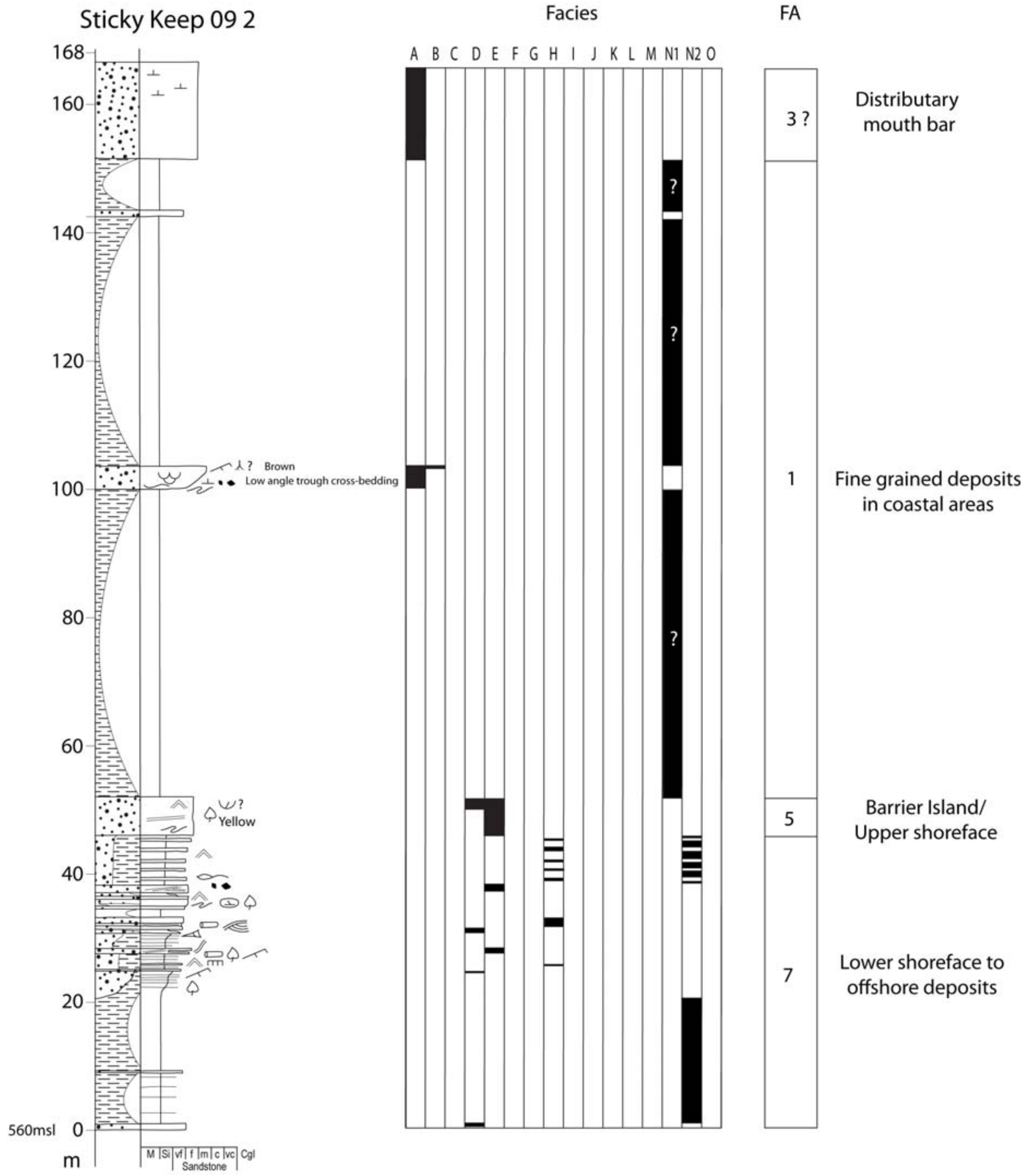

Botneheia 09 1
90
80
60
40
20
0
220msl
m
Red
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Facies
A B C D E F G H I J K L M N1 N2 O
FA
3
7 ?
7
Distributary mouth bar
Lower shoreface to offshore deposits

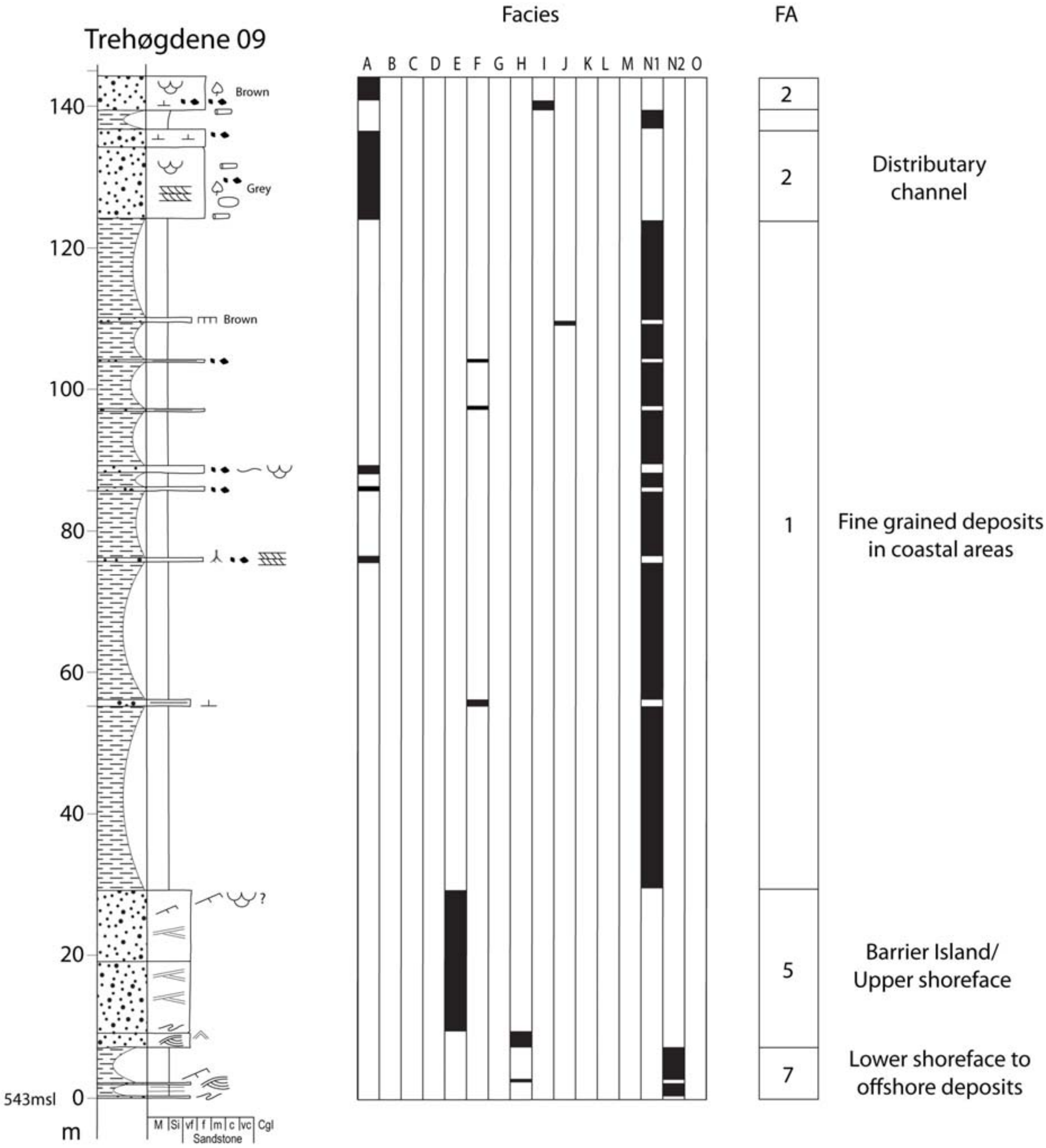

Botneheia 09 2
80
60
40
20
0
252msl
m
CS
Red
Red
Red
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Facies
A
B
C
D
E
F
G
H
I
J
K
L
M
N1
N2
O
?
FA
2
Distributary channel
1
Fine grained deposits in coastal areas
7
Lower shoreface to offshore deposits

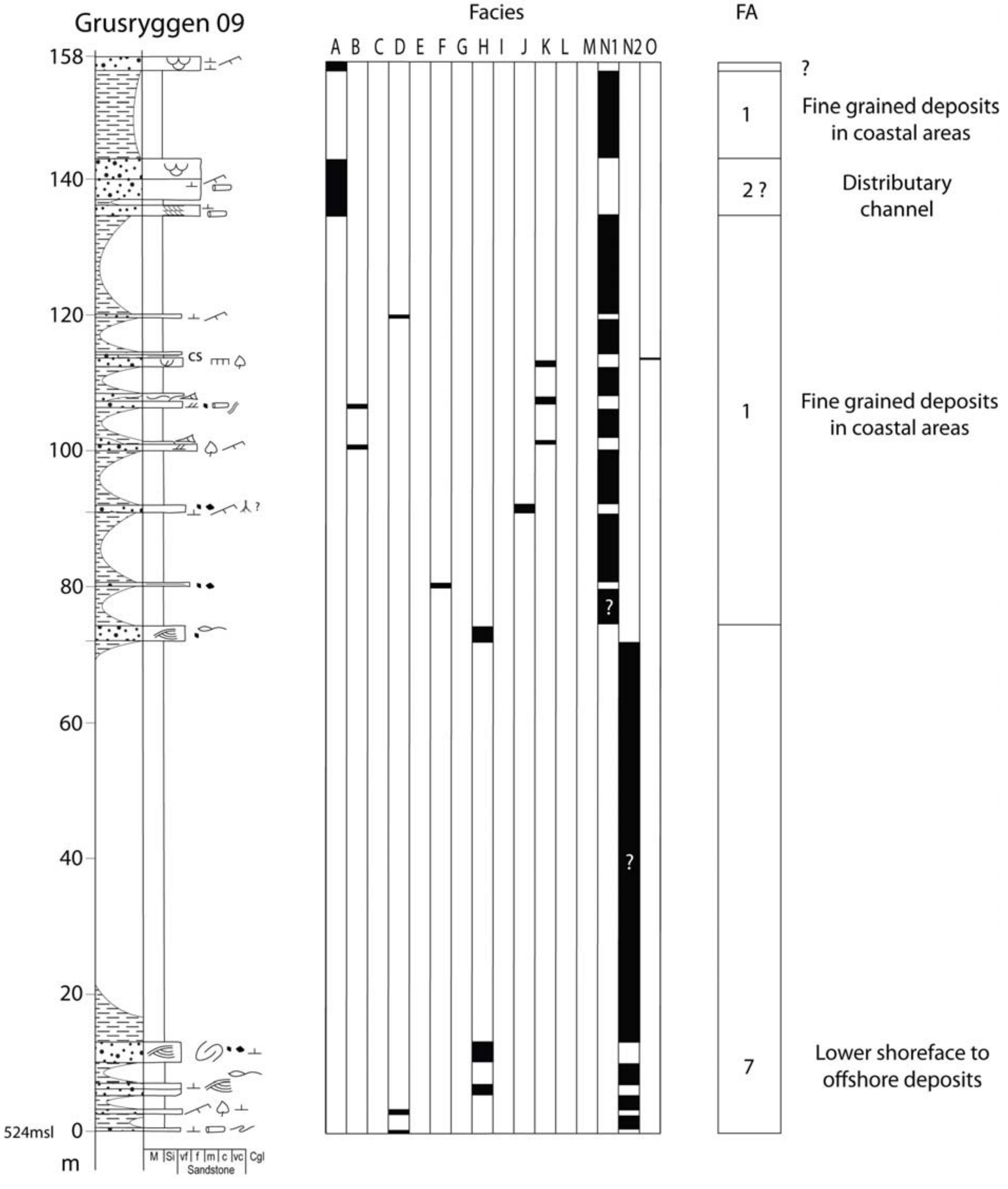

Botneheia 09 3
140
120
100
80
60
40
20
0
258msl
m
CS
Red
Brown
Red
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Facies
A
B
C
D
E
F
G
H
I
J
K
L
M
N1
N2
O
FA
1
Fine grained deposits in coastal areas
7
Lower shoreface to offshore deposits
3
Distributary mouth bar
?
7
Lower shoreface to offshore deposits

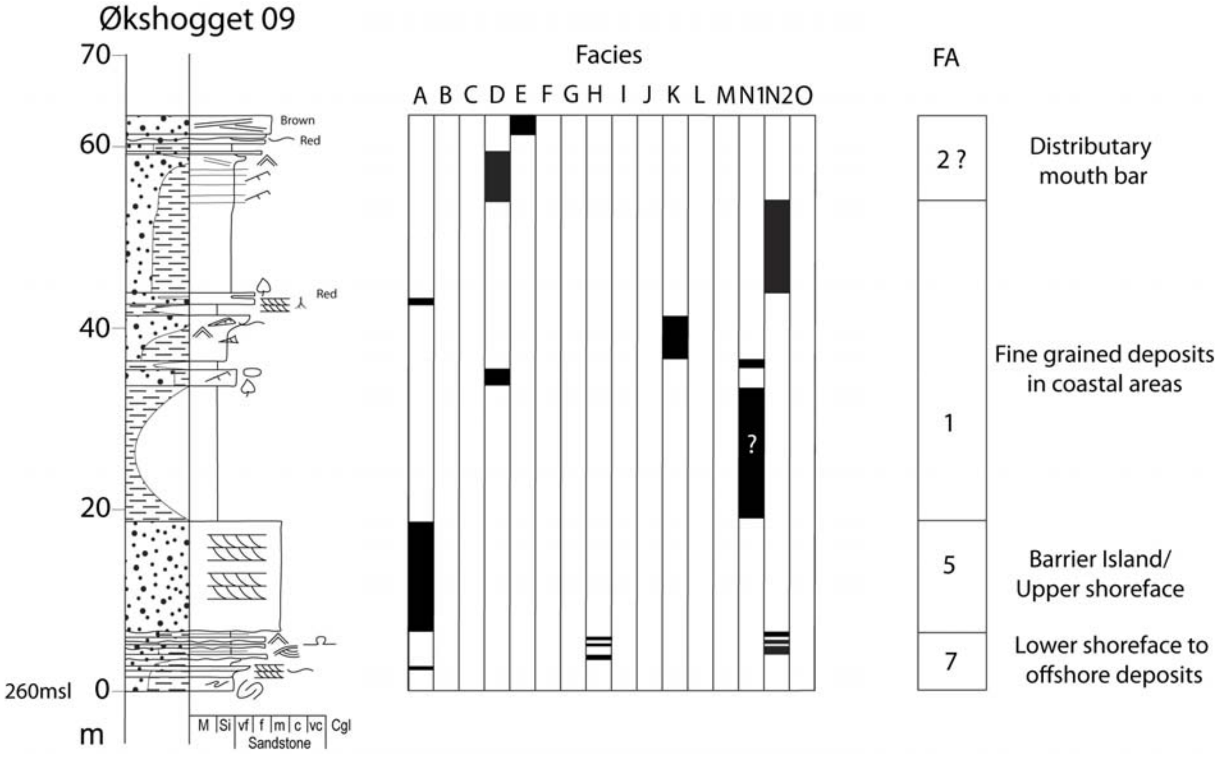

Botneheia 09 4
90
80
60
40
20
250msl 0
m
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Red
?
Red
Facies
A B C D E F G H I J K L M N1 N2 O
?
?
FA
1
Fine grained deposits in coastal areas
7
Lower shoreface to offshore deposits
1
Fine grained deposits in coastal areas
?
7
Lower shoreface to offshore deposits

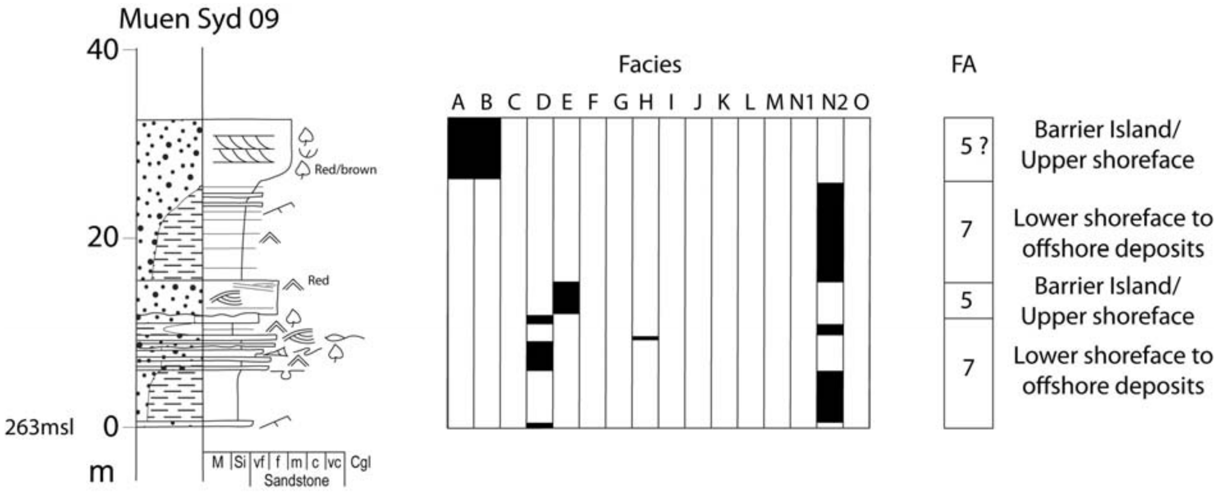

Sticky Keep 09 1
120
100
80
60
40
20
573msl 0
m
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Red/brown
Red/brown
Facies
A B C D E F G H I J K L M N1 N2 O
?
?
?
FA
3
1 ?
7
5
7
Distributary mouth bar
Fine grained deposits in coastal areas
Lower shoreface to offshore deposits
Barrier Island/ Upper shoreface
Lower shoreface to offshore deposits

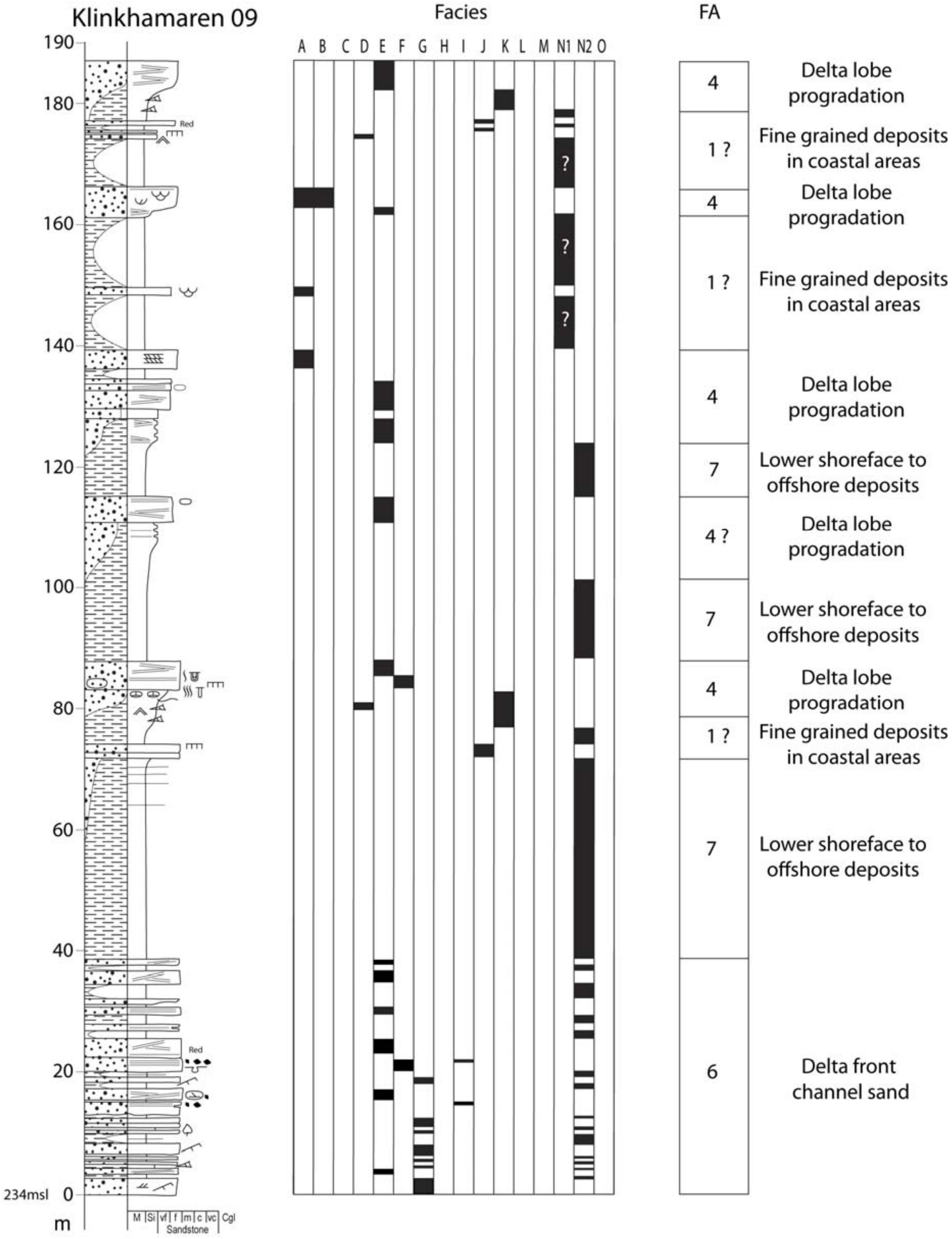

Sticky Keep 09 2
168
160
140
120
100
80
60
40
20
560msl 0
m
M Si vf f m c vc Cgl
Sandstone
? Brown
Low angle trough cross-bedding
? Yellow
Facies
A B C D E F G H I J K L M N1 N2 O
?
?
?
FA
3 ?
Distributary mouth bar
1
Fine grained deposits in coastal areas
5
Barrier Island/ Upper shoreface
7
Lower shoreface to offshore deposits

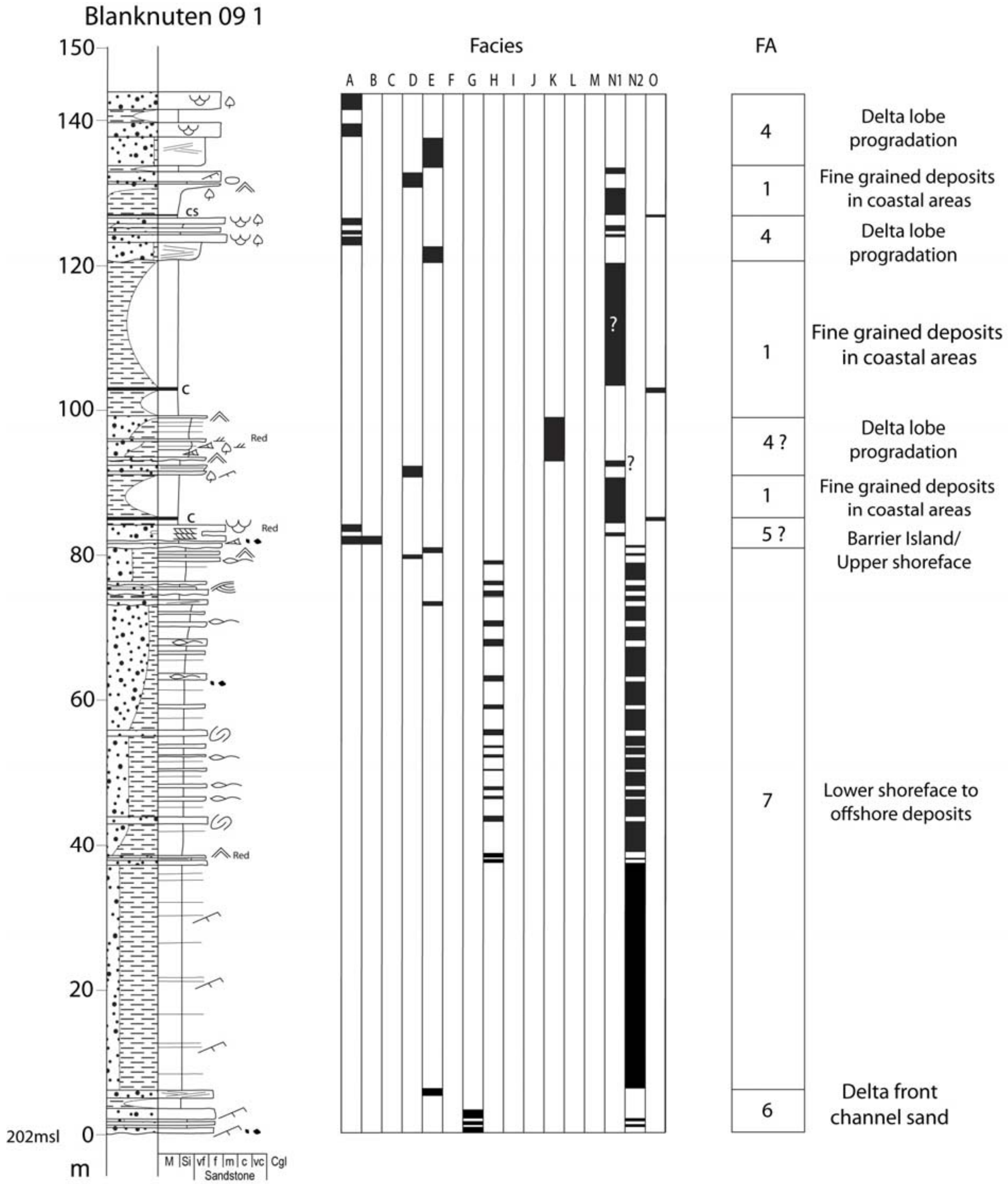

Trehøgdene 09
Facies
FA
A B C D E F G H I J K L M N1 N2 O
Brown
Grey
Brown
?
140
120
100
80
60
40
20
543msl 0
m
M Si vf f m c vc Cgl
Sandstone
2
2
1
5
7
Distributary channel
Fine grained deposits in coastal areas
Barrier Island/ Upper shoreface
Lower shoreface to offshore deposits

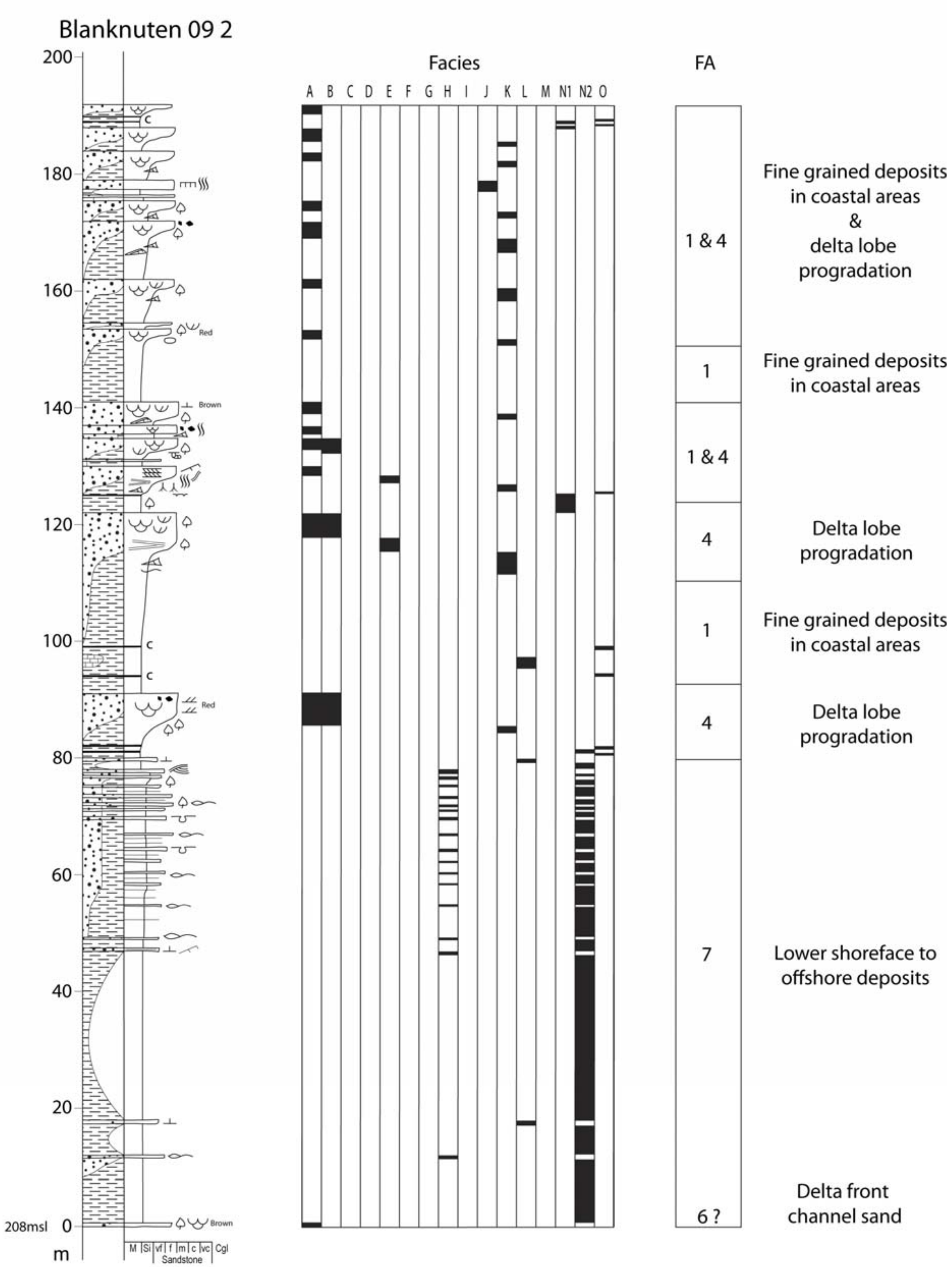

Grusryggen 09
Facies
FA
A B C D E F G H I J K L M N1 N2 O
158
140
120
100
80
60
40
20
524msl 0
m
M Si vf f m c vc Cgl
Sandstone
cs
?
1
Fine grained deposits in coastal areas
2 ?
Distributary channel
1
Fine grained deposits in coastal areas
7
Lower shoreface to offshore deposits

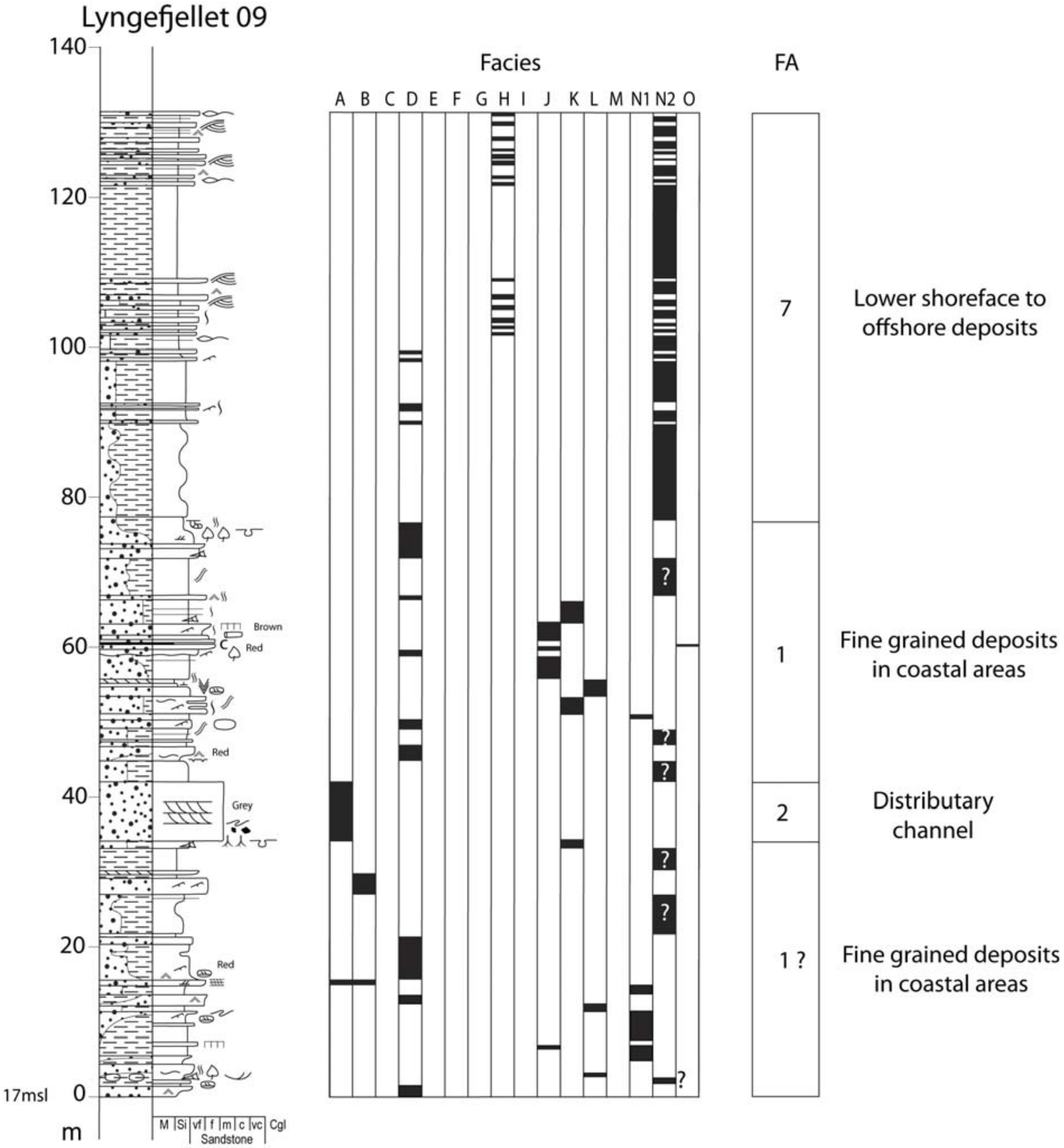

Økshogget 09
70
60
40
20
260msl 0
m
Brown
Red
Red
M Si vf f m c vc Cgl
Sandstone
Facies
A B C D E F G H I J K L M N1 N2 O
?
FA
2 ?
Distributary mouth bar
1
Fine grained deposits in coastal areas
5
Barrier Island/ Upper shoreface
7
Lower shoreface to offshore deposits

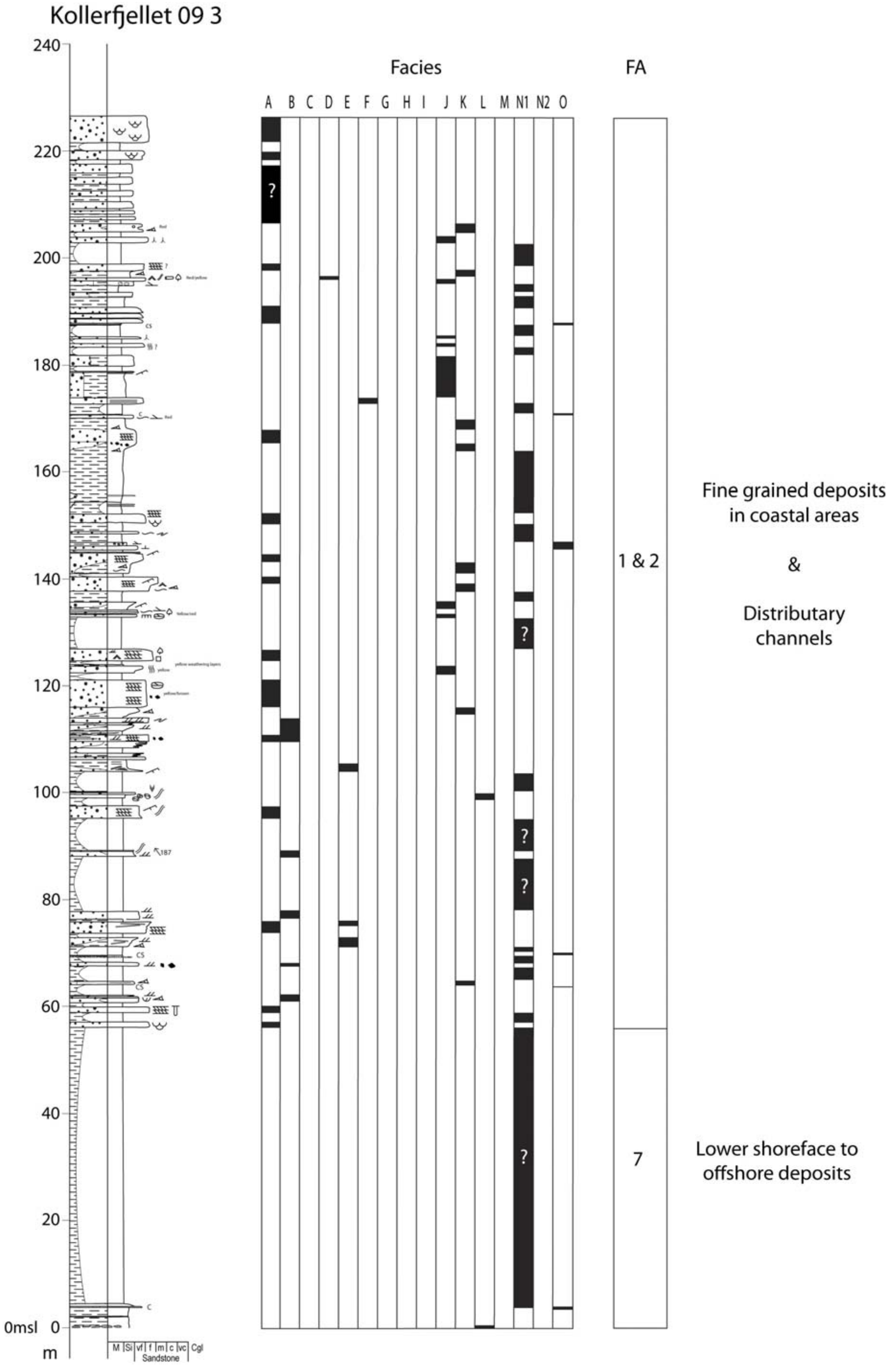

Muen Syd 09
40
20
263msl 0
m
Red/brown
Red
M Si vf f m c vc Cgl
Sandstone
Facies
A B C D E F G H I J K L M N1 N2 O
FA
5 ?
Barrier Island/ Upper shoreface
7
Lower shoreface to offshore deposits
5
Barrier Island/ Upper shoreface
7
Lower shoreface to offshore deposits


Klinkhamaren 09
190
180
160
140
120
100
80
60
40
20
234msl 0
m
Red
Red
M Si vf f m c vc Cgl
Sandstone
Facies
A B C D E F G H I J K L M N1 N2 O
?
?
?
FA
4
Delta lobe progradation
1 ?
Fine grained deposits in coastal areas
4
Delta lobe progradation
1 ?
Fine grained deposits in coastal areas
4
Delta lobe progradation
7
Lower shoreface to offshore deposits
4 ?
Delta lobe progradation
7
Lower shoreface to offshore deposits
4
Delta lobe progradation
1 ?
Fine grained deposits in coastal areas
7
Lower shoreface to offshore deposits
6
Delta front channel sand


Blanknuten 09 1
150
140
120
100
80
60
40
20
0
202msl
m
cs
c
c
Red
Red
Red
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Facies
A
B
C
D
E
F
G
H
I
J
K
L
M
N1
N2
O
?
?
FA
4
Delta lobe progradation
1
Fine grained deposits in coastal areas
4
Delta lobe progradation
1
Fine grained deposits in coastal areas
4 ?
Delta lobe progradation
1
Fine grained deposits in coastal areas
5 ?
Barrier Island/ Upper shoreface
7
Lower shoreface to offshore deposits
6
Delta front channel sand

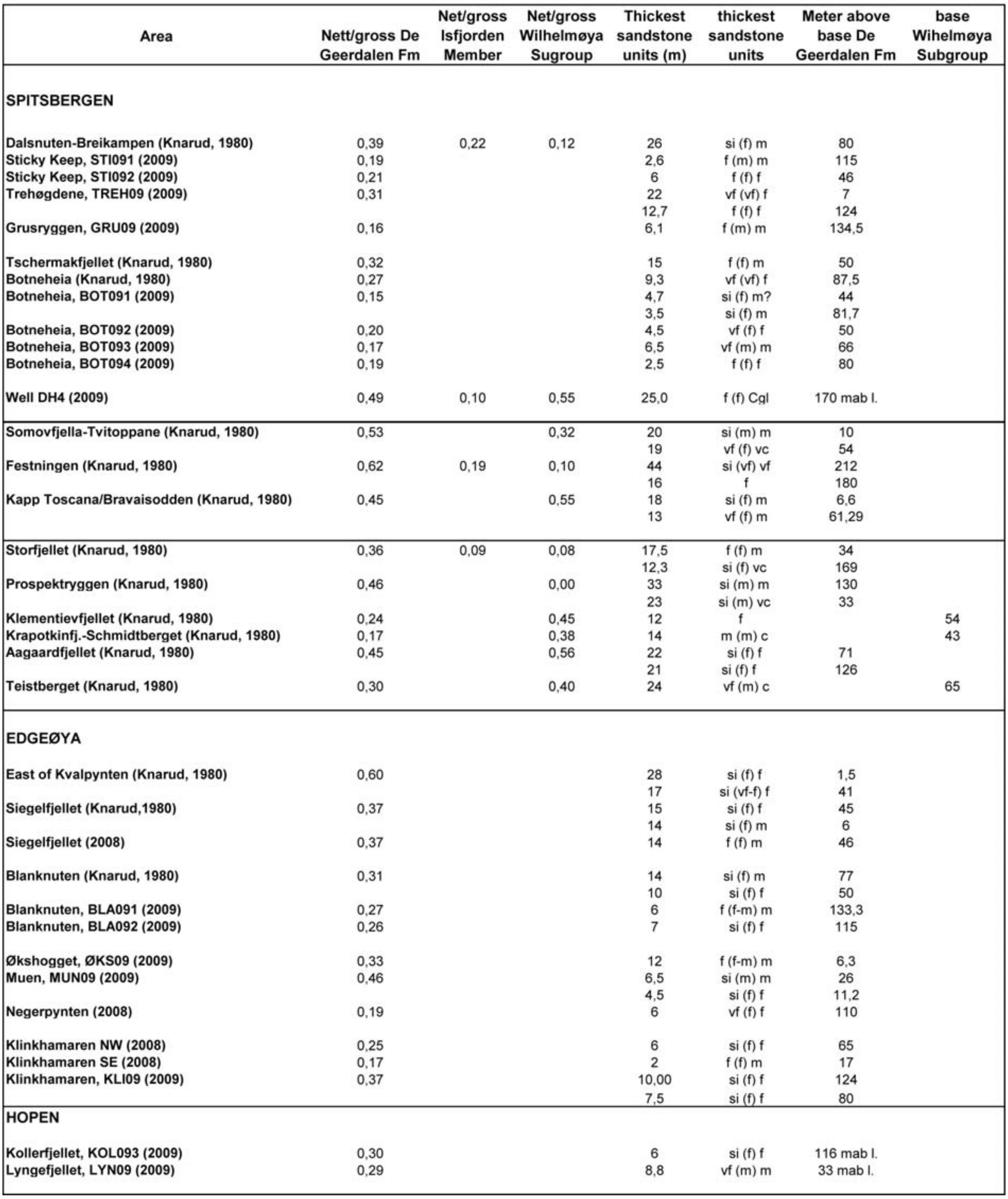

Blanknuten 09 2
200
180
160
140
120
100
80
60
40
20
208msl 0
m
c
Red
Brown
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Facies
A
B
C
D
E
F
G
H
I
J
K
L
M
N1
N2
O
FA
1 & 4
Fine grained deposits in coastal areas & delta lobe progradation
1
Fine grained deposits in coastal areas
1 & 4
4
Delta lobe progradation
1
Fine grained deposits in coastal areas
4
Delta lobe progradation
7
Lower shoreface to offshore deposits
6 ?
Delta front channel sand


Lyngefjellet 09
140
120
100
80
60
40
20
0
17msl
m
M
Si
vf
f
m
c
vc
Cgl
Sandstone
Brown
Red
Red
Grey
Red
C
Facies
A
B
C
D
E
F
G
H
I
J
K
L
M
N1
N2
O
?
?
?
?
?
?
FA
7
Lower shoreface to offshore deposits
1
Fine grained deposits in coastal areas
2
Distributary channel
1 ?
Fine grained deposits in coastal areas


Kollerfjellet 09 3
240
220
200
180
160
140
120
100
80
60
40
20
0msl 0
m
M Si vf f m c vc Cgl
Sandstone
cs
c
187
Facies
A B C D E F G H I J K L M N1 N2 O
?
FA
1 & 2
7
Fine grained deposits in coastal areas
&
Distributary channels
Lower shoreface to offshore deposits

Appendix 6 Net/gross values in the De Geerdalen Formation

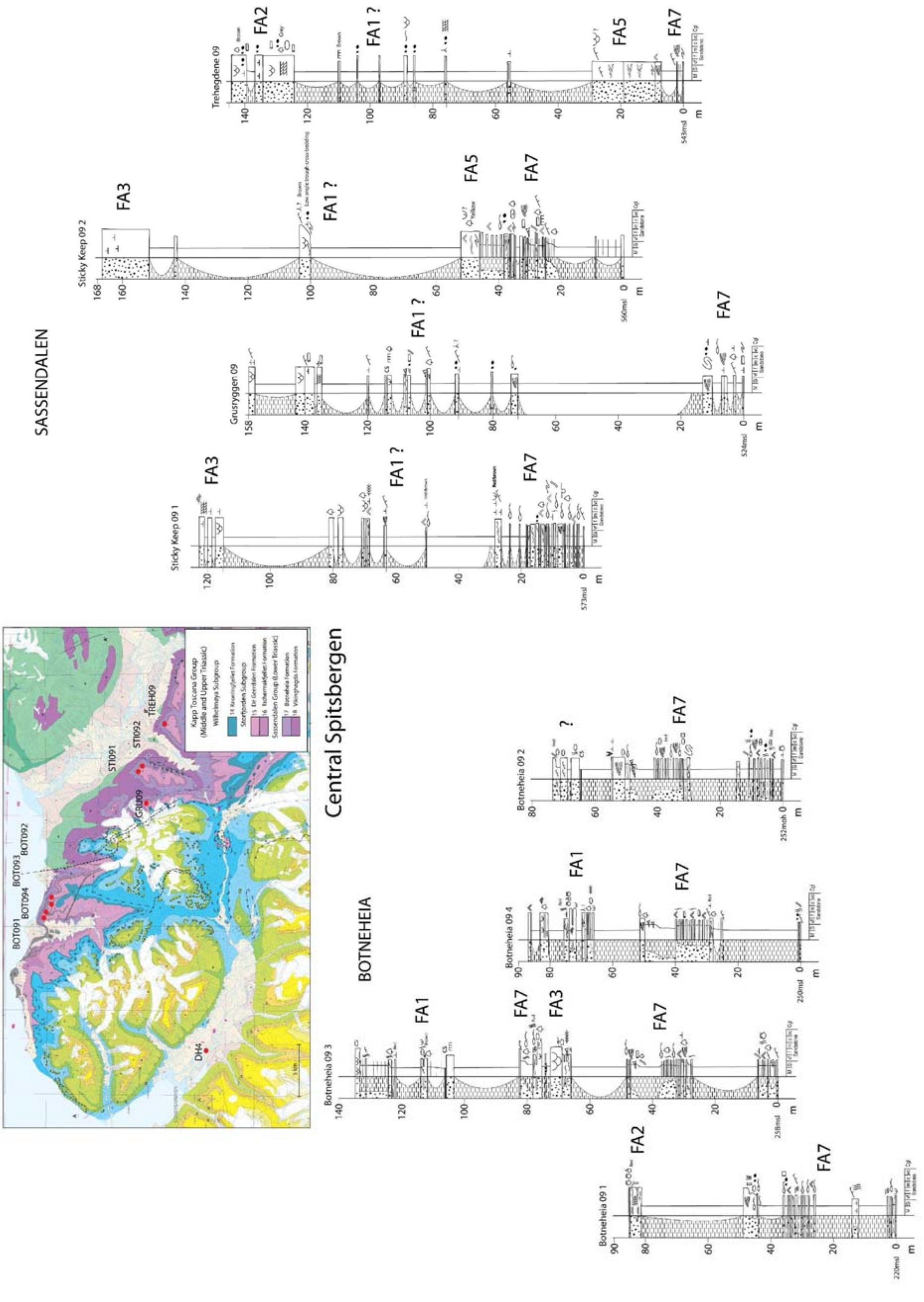
Net/gross values based on data from Knarud (1980), and fieldwork summer 2008 and 2009 (organized by the Norwegian Petroleum Directorate).



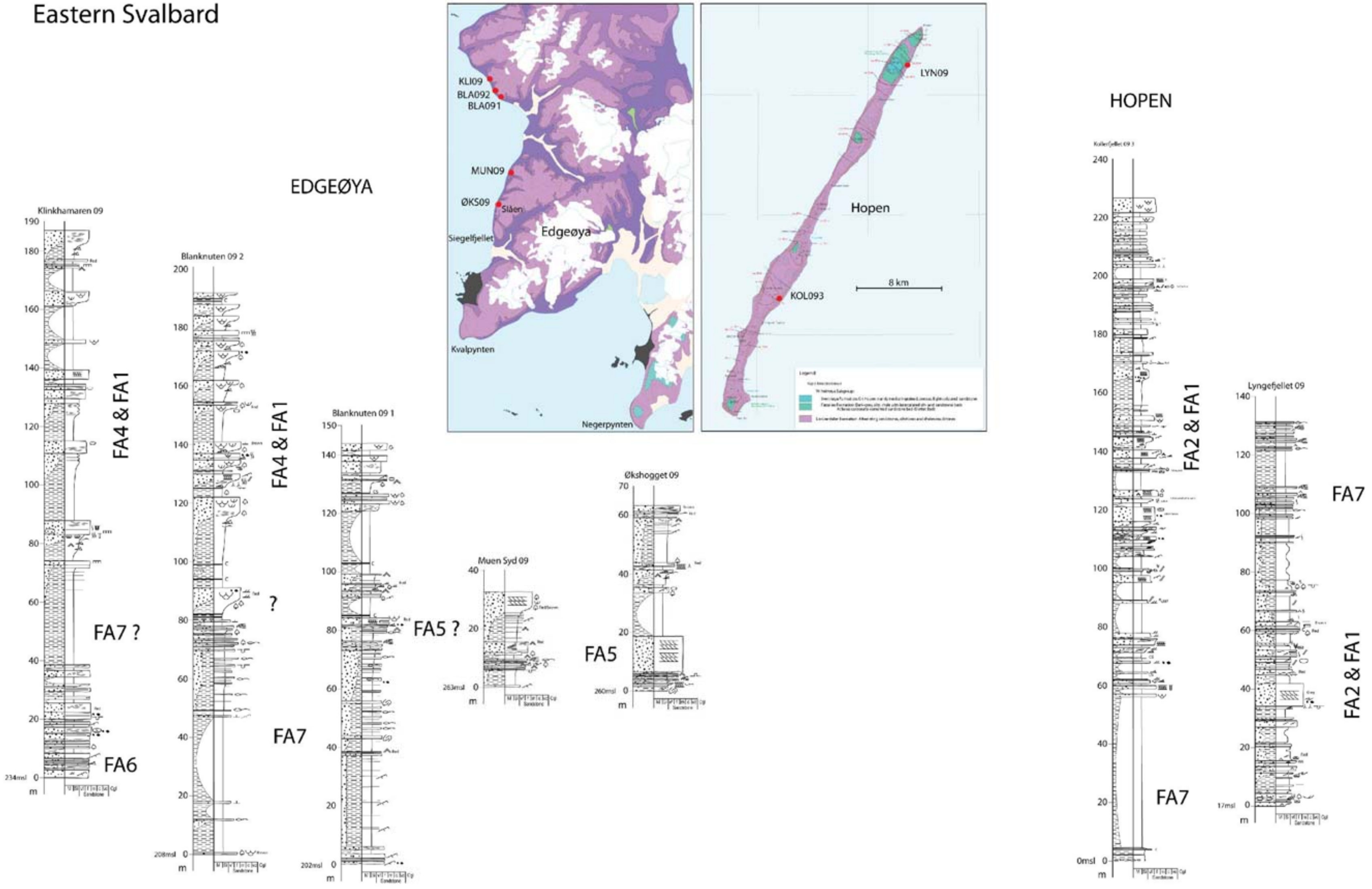
Area	Nett/gross De Geerdalen Fm	Net/gross Isfjorden Member	Net/gross Wilhelmøya Sugroup	Thickest sandstone units (m)	thickest sandstone units	Meter above base De Geerdalen Fm	base Wihelmøya Subgroup
SPITSBERGEN							
Dalsnuten-Breikampen (Knarud, 1980)	0,39	0,22	0,12	26	si (f) m	80	
Sticky Keep, STI091 (2009)	0,19			2,6	f (m) m	115	
Sticky Keep, STI092 (2009)	0,21			6	f (f) f	46	
Trehøgdene, TREH09 (2009)	0,31			22	vf (vf) f	7	
				12,7	f (f) f	124	
Grusryggen, GRU09 (2009)	0,16			6,1	f (m) m	134,5	
Tschermakfjellet (Knarud, 1980)	0,32			15	f (f) m	50	
Botneheia (Knarud, 1980)	0,27			9,3	vf (vf) f	87,5	
Botneheia, BOT091 (2009)	0,15			4,7	si (f) m?	44	
				3,5	si (f) m	81,7	
Botneheia, BOT092 (2009)	0,20			4,5	vf (f) f	50	
Botneheia, BOT093 (2009)	0,17			6,5	vf (m) m	66	
Botneheia, BOT094 (2009)	0,19			2,5	f (f) f	80	
Well DH4 (2009)	0,49	0,10	0,55	25,0	f (f) Cgl	170 mab l.	
Somovfjella-Tvitoppane (Knarud, 1980)	0,53		0,32	20	si (m) m	10	
				19	vf (f) vc	54	
Festningen (Knarud, 1980)	0,62	0,19	0,10	44	si (vf) vf	212	
				16	f	180	
Kapp Toscana/Bravaisodden (Knarud, 1980)	0,45		0,55	18	si (f) m	6,6	
				13	vf (f) m	61,29	
Storfjellet (Knarud, 1980)	0,36	0,09	0,08	17,5	f (f) m	34	
				12,3	si (f) vc	169	
Prospektryggen (Knarud, 1980)	0,46		0,00	33	si (m) m	130	
				23	si (m) vc	33	
Klementievfjellet (Knarud, 1980)	0,24		0,45	12	f		54
Krapotkinfj.-Schmidtberget (Knarud, 1980)	0,17		0,38	14	m (m) c		43
Aagaardfjellet (Knarud, 1980)	0,45		0,56	22	si (f) f	71	
				21	si (f) f	126	
Teistberget (Knarud, 1980)	0,30		0,40	24	vf (m) c		65
EDGEØYA							
East of Kvalpynten (Knarud, 1980)	0,60			28	si (f) f	1,5	
				17	si (vf-f) f	41	
Siegelfjellet (Knarud,1980)	0,37			15	si (f) f	45	
				14	si (f) m	6	
Siegelfjellet (2008)	0,37			14	f (f) m	46	
Blanknuten (Knarud, 1980)	0,31			14	si (f) m	77	
				10	si (f) f	50	
Blanknuten, BLA091 (2009)	0,27			6	f (f-m) m	133,3	
Blanknuten, BLA092 (2009)	0,26			7	si (f) f	115	
Økshogget, ØKS09 (2009)	0,33			12	f (f-m) m	6,3	
Muen, MUN09 (2009)	0,46			6,5	si (m) m	26	
				4,5	si (f) f	11,2	
Negerpynten (2008)	0,19			6	vf (f) f	110	
Klinkhamaren NW (2008)	0,25			6	si (f) f	65	
Klinkhamaren SE (2008)	0,17			2	f (f) m	17	
Klinkhamaren, KLI09 (2009)	0,37			10,00	si (f) f	124	
				7,5	si (f) f	80	
HOPEN							
Kollerfjellet, KOL093 (2009)	0,30			6	si (f) f	116 mab l.	
Lyngefjellet, LYN09 (2009)	0,29			8,8	vf (m) m	33 mab l.	

Mab l. = meter above base logg
Si = silt, vf = very fine, f = fine, m = medium

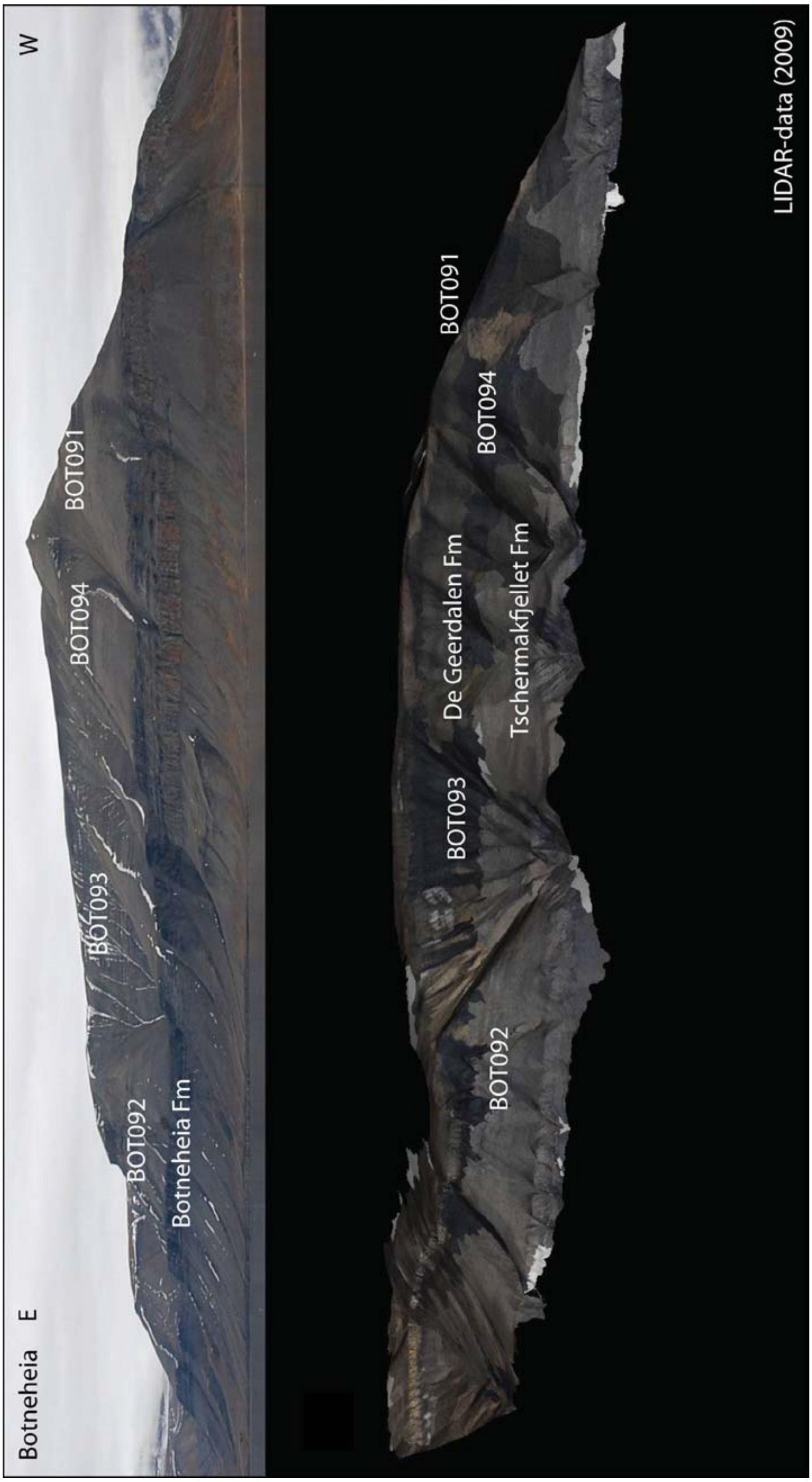
Appendix 7 Correlations panels from central Spitsbergen and eastern Svalbard



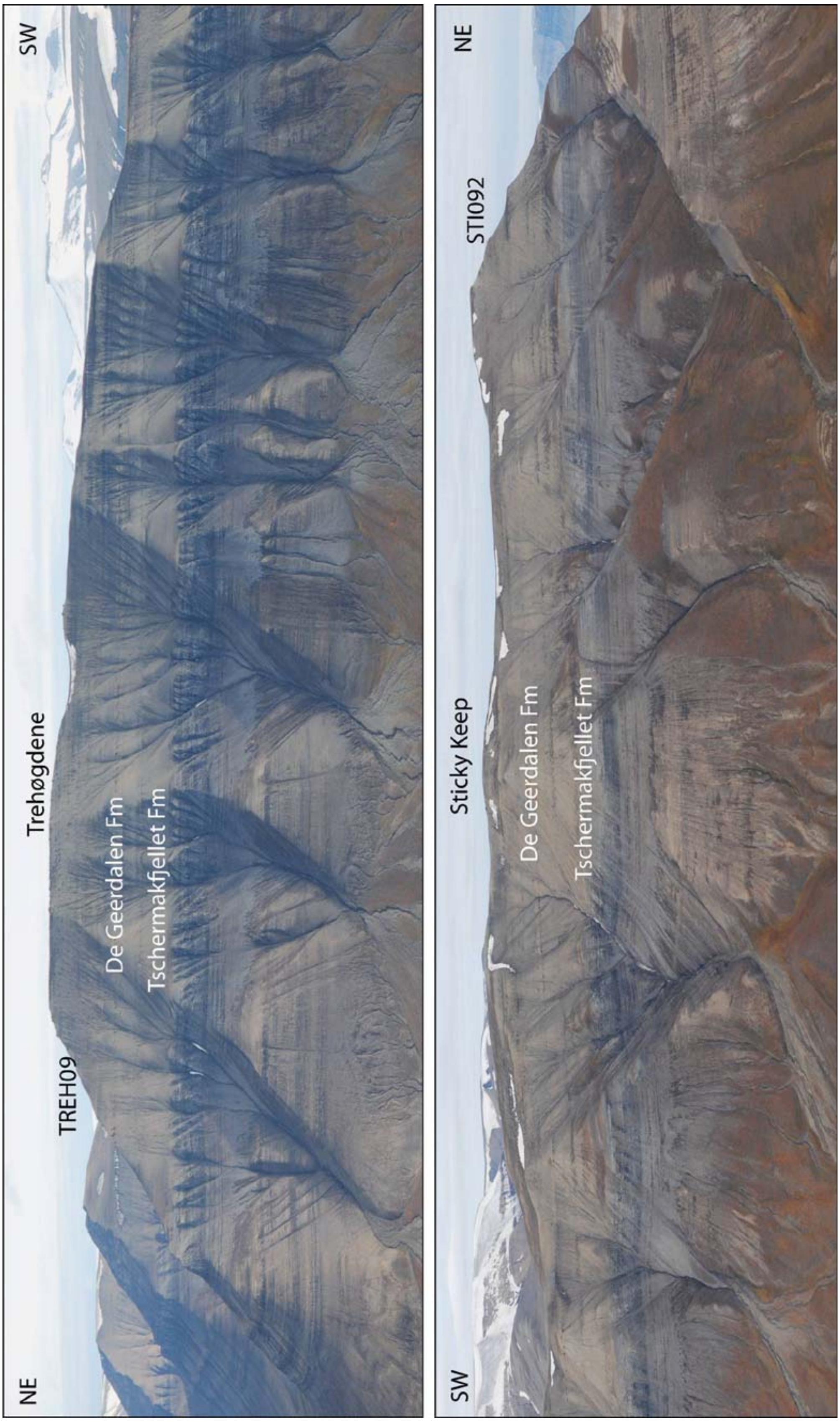
Eastern Svalbard



Appendix 8 Panorama pictures



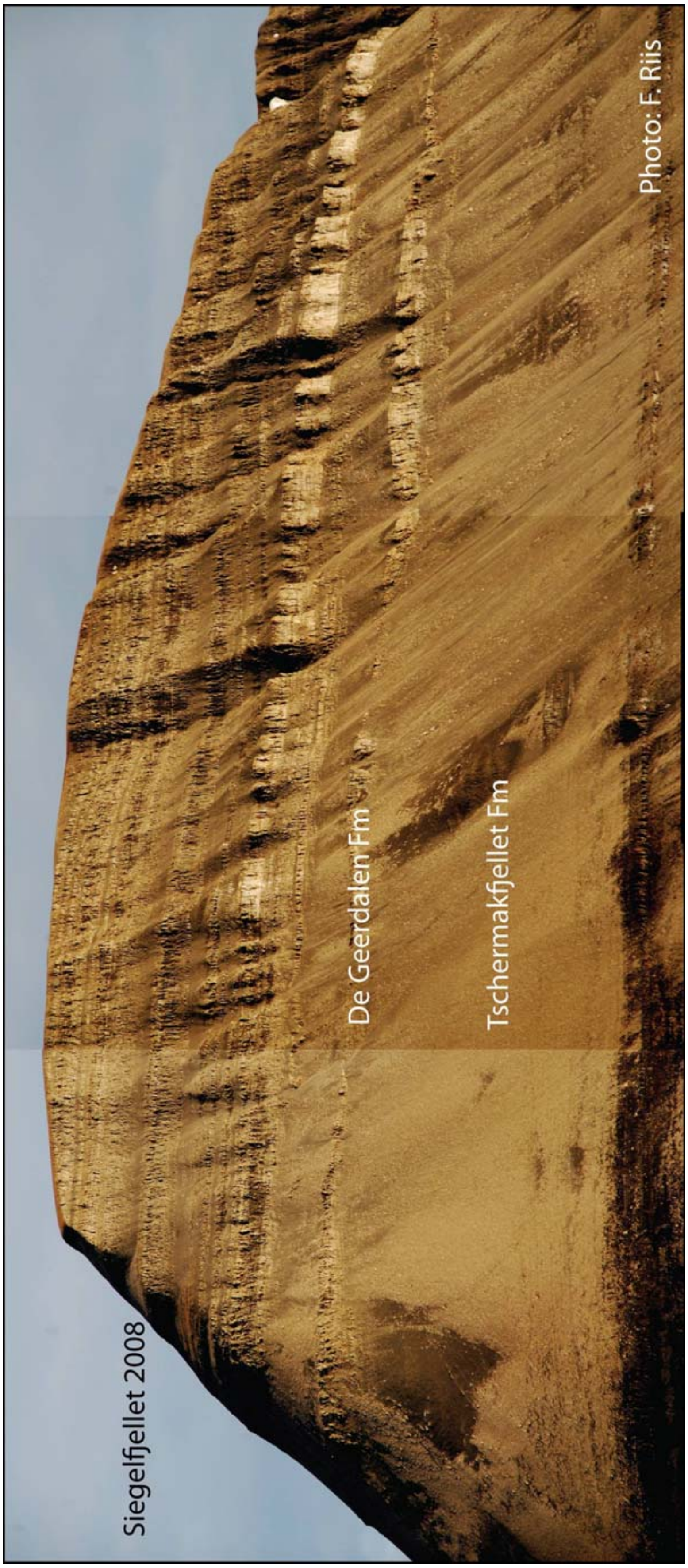
Picture of Botneheia with the four sections marked at the logging localities. The LIDAR-figure is a model based on helicopter scans taken summer 2009, data collected for the CO_2-project in Longyearbyen.



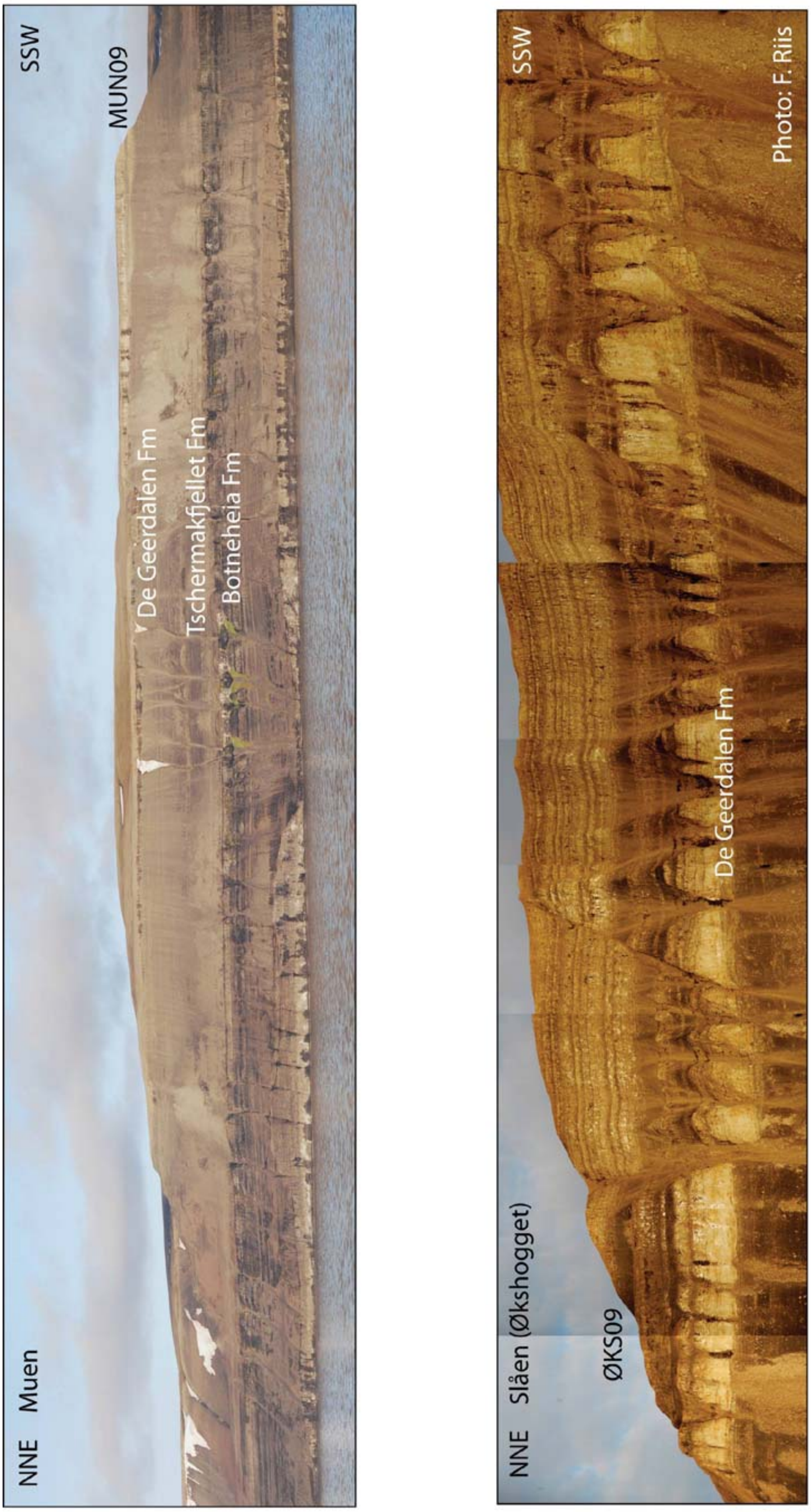
Panorama pictures of Trehøgdene and Sticky Keep in Sassendalen (central Spitsbergen). One section was measured on Trehøgdene NE, marked TREH09 in the picture. Two sections were measured on Sticky Keep, only location of STI092 shown in this picture NE on the mountain. STI091 is located west of STI092.

Photo: M. S. Woldengen

Panorama pictures of Blanknuten and Klinkhamaren (Edgeøya). Two sections were measured on Blanknuten NW, marked BLA091 and BLA092 in the picture. One section was measured on Klinkhamaren in 2009, marked KLI09. Localities marked KLI08 represent logging localities summer 2008 (fieldwork organized by the Norwegian Petroleum Directorate).



Panorama picture of Siegelfjellet. Section Siegelfjellet 2008 were measured during fieldwork summer 2008 (organized by the Norwegian Petroleum Directorate).



Panorama pictures of Muen and Økshogget on Slåen (Edgeøya). One section was measured on Muen and one in Økshogget, marked MUN09 and ØKS09.

Panorama picture of Hopen south west (Kollerfjellet). The section on Kollerfjellet is marked KOL093. Base of the De Geerdalen Formation is located below sea level.