Sedimentary architecture of sand bodies in the shallow marine Endalen Member, Firkanten Formation (Paleocene) of the Adventdalen Area, Svalbard

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Abstract

The Firkanten Formation has been the object of many research projects, but due to the economic interests in the lower coal bearing Todalen Member, the upper Endalen Member has received little attention. The Endalen Member is well marked in the mountain sides of the Adventdalen area, representing a succession of shallow marine shoreface sandstones. The close network of valleys cutting through the stratigraphy in this area provide a unique spatial overview of the architectural development of this unit.

From logs, ten lithofacies have been recognized, organized into five facies associations representing deposition ranging from offshore to continental environments. Three types of key surfaces have been found, and an architectural hierarchy of the elements has been established based on their relative apparent extent. With the use of lateral extensive photo-mosaics of outcrops, accompanied by traditional field logs, the spatial development within the Adventdalen area has been investigated.

Four distinct parasequences have been observed, showing a progradational trend and basinward thinning. The internal architecture of these parasequences indicate different coastal morphologies showing a transition from a slightly embayed deltaic coastline to a linear, wave dominated coastline.

This study improves the understanding of the depositional history and morphological evolution of the Endalen Member in the Adventdalen area.

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1. Introduction

1.1. Aim of Study

Even though many investigations of the Firkanten Formation have been carried out due to interests in the coal bearing Todalen Member, the upper Endalen Member has received little attention. From early publications (Kalgraff, 1978; Kellogg, 1975; Steel et al., 1981; Steel and Worsley, 1984; Vonderbank, 1970), the Endalen member has been interpreted as sets of wave-dominated shallow-marine sandstones, an interpretation which still stands. Former investigations have been based upon facies analysis and correlation between sites (Bruhn, 1999; Bruhn and Steel, 2003; Kalgraff, 1978; Steel et al., 1981), but no research has used the modern method of remote photography to create merged photo-models and investigate the architecture and internal geometries within lateral extensive outcrops.

This project aims to re-investigate the Endalen Member with focus on both large scale depositional architecture and the internal architecture of sedimentary bodies to shed more light on the coastal morphology during deposition of the Endalen Member.

In addition to the thin coal seams in the lower part of the Endalen member reported by Vonderbank (1970) and Major and Nagy (1972), new evidence of coal close to the fluvial conglomerates in the upper part of the Endalen Member suggests a late coastal plain development in the north-eastern part of the system. As the sea level fluctuations in this part of the stratigraphy are poorly understood, this study aims to describe and model this development.

1.2. Previous works

The early geological research in Svalbard aimed to map important resources of economic value. Instances of chalk and gold have been found, but no resource has been as successfully exploited in Svalbard as coal. The discovery of large coal-seams initiated large scientific explorations from the mid-19th century to the early 20th century, to investigate the stratigraphy of Svalbard (Arlov, 2003). Due to the economic importance of the coal-bearing Todalen Member, The Firkanten Formation has received a lot of attention in the geological research in Svalbard. Expeditions in the late

19th and early 20th century led to a synthesis by Nathorst in 1910, subdividing the Paleogene succession into six distinct lithological units (Harland et al., 1997). This subdivision was accepted and implemented in research in the years to come.

Early publications on the Paleogene strata concluded a Miocene age for the succession based on terrestrial foraminiferal analysis (Nathorst, 1910), an age determination which was unchallenged until a study of freshwater and marine mollusks of Ravn (1922) suggested a Paleocene to Eocene constraint on the Tertiary sediments. The Paleocene age for the Firkanten formation has later been confirmed by several studies (Blythe and Kleinspehn, 1998; Livshits, 1974; Manum, 1962; Manum and Throndsen, 1986; Vonderbank, 1970).

The lithological investigations of the Firkanten Formation have been many since the description of "The lower light sandstone series" from Nathorst (1910). A current definition of the Formation is described in Major and Nagy (1972), with the recognition of different depositional units within the formation. This sub-division was further addressed by Kalgraff (1978) who named the lower and upper part after their type localities in Todalen and Endalen, respectively. Kalgraff (1978) includes a detailed lithological investigation of the two members, as well as for the Kolthoffberget Member which represents the most distal marine sediments of the Firkanten Formation and is found in southern and western parts of the Central Tertiary Basin. Steel et al. (1981) present the lithostratigraphic evolution of the Tertiary basin, summarizing the work of Kalgraff (1978) and the late 1970s Spitsbergen tertiary project at the University of Bergen.

A detailed analysis of the sequential architecture of the upper Firkanten Formation was carried out by Bruhn (1999), suggesting six separate sequences within the Endalen Member. This work is the latest thorough analysis on the Endalen Member, and the only study of its depositional architecture. Her results led to a peripheral-bulge-controlled depositional model of the Paleogene deposits of the basin (Bruhn and Steel, 2003).

Lüthje (2008) challenges the environmental interpretation of delta plain to prodelta configuration of the Firkanten Formation of Dallmann et al. (1999); Kalgraff (1978); Steel et al. (1981); Steel and Worsley (1984), arguing that lack of fluvial channel deposits suggests a continental plain to shoreface and offshore deposition of the system.

Tectonic controls of sedimentation in the Paleogene succession has been investigated by Kellogg (1975); Steel et al. (1981), Müller and Spielhagen (1990); Steel and Worsley (1984), Bruhn and Steel (2003) and more recently by Piepjohn et al. (2016) and Petersen et al. (2016). Former works have established two well-documented phases of sedimentation relating to the tectonic evolution of the West Spitsbergen fold and thrust belt. Piepjohn et al. (2016) presented a regional study of tectonic deformation in the Arctic, summarizing the deformation of the Svalbard Stratigraphy related to the Eurekan Orogeny. Petersen et al. (2016) is a provenance study of the Paleogene sediments of the Central Tertiary basin, establishing a sub-division of the two-phase sedimentation pattern and correlating the shifts in provenance to the parasequences of Dallmann et al. (1999) and Bruhn and Steel (2003).

This study is part of an ongoing research project on the Paleogene strata at Svalbard and north-east Greenland, aiming to re-investigate some fundamental questions such as the number and age of the basins, the onset of folding and deformation, relation of the basins and basin geometry, depositional environments and paleogeography in these areas.

2. Stratigraphic Framework

2.1. Svalbard Stratigraphy

The rock record on Svalbard is in general a part of the greater Barents Sea Platform, and as such represents an uplifted part of the stratigraphy of the Barents Sea. Sedimentary rocks dominate the stratigraphic record, although both metamorphic and igneous rocks are found. The sediments represent a time span from the latest Devonian to Eocene, with two major non-depositional phases in the late Cretaceous and from the Eocene until present day (Fig. 2.1). The sediments record the northward drift of Svalbard from equatorial latitudes during the Cambrian - Ordovician to the high arctic position it has today, shown by the gradual transition from tropical coals, through both warm-water and cool-water carbonate systems and into a siliciclastic succession with a variety of both marine and terrestrial fossils (Dallmann, 2015; Steel and Worsley, 1984; Worsley, 2008).

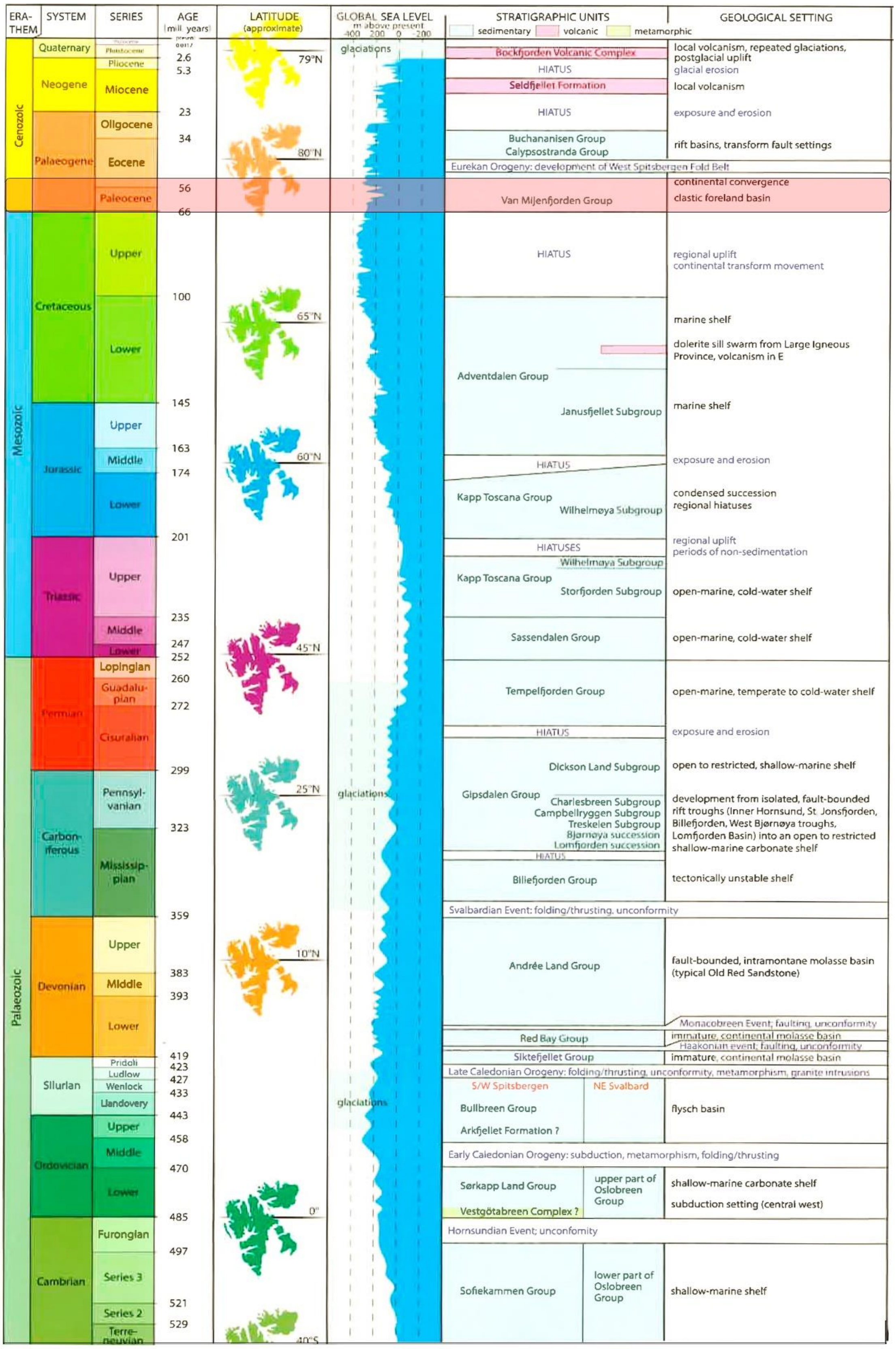

Figure 2.1 - Figure showing the northwards drift of Svalbard, its Stratigraphic units and geological settings from the Cambrian to present day. Red box shows the stratigraphic position of the Firkanten Formation. Slightly modified from Dallmann (2015).

2.2. The Central Tertiary Basin

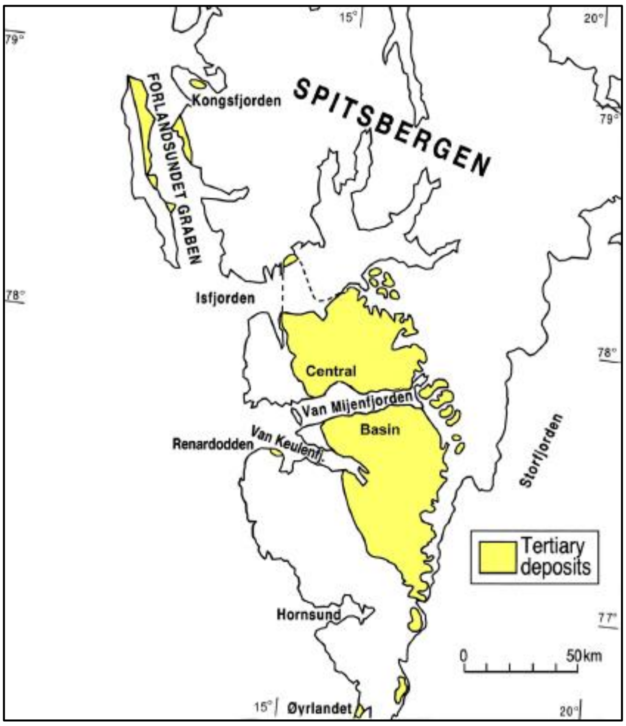

Figure 2.2- Yellow colored map area showing the Spitsbergen Central Tertiary Basin. From Nagy et al. (2013)

The Central Tertiary Basin(CTB) of Spitsbergen is a north-south trending depression bounded by Billefjorden Fault Zone in the east and Spitsbergen fold and thrust belt in the west (Fig. 2.2). The infill of this basin is named the Van Mijenfjorden group after Harland (1969), and is widely recognized as Paleocene to Eocene in age (Dallmann et al., 1999). A tephra layer close to the base of the Van Mijenfjorden group has recently been dated to 61.8 Ma, marking the initial forming of the basin (Jones et al., 2017). The group is approximately 1.5 km thick in the northern part of the basin, thickening to a 2.3 km thick succession in the south (Nagy, 2005; Steel and Worsley, 1984). The stratigraphy dips towards a geometrical center in Colesdalen. Van Mijenfjorden group consists of siliciclastic fine sand- and siltstones, with minor conglomerates and coal-seams close to its base (Dallmann et al., 1999). This base lies unconformably on top of lower cretaceous Carolinefjellet Formation, representing a hiatus of approximately 38 million years (Dallmann et al., 1999; Major and Nagy, 1972; Müller and Spielhagen, 1990). In addition to the Cenozoic strata found on Svalbard today, the compaction and maturation of organics in the deposits show evidence of up to 1000 meters of sediments sitting on top of this strata, removed by erosion (Marshall et al., 2015).

The generalized stratigraphy of the basin shows two phases of basin infill (Bruhn and Steel, 2003; Steel et al., 1981; Steel et al., 1985; Steel and Worsley, 1984) (Fig. 2.3). The first phase includes Firkanten, Basilika and Grumantbyen Formations, and expresses sedimentation from the northern and eastern margin of the basin. The onset of the second phase occur in the marine shales of the Frysjaodden formation, showing a shift in provenance and a progradation of shallow marine and continental deposits of the Hollendardalen, Battfjellet and Aspelintoppen formations from the west (Bruhn and Steel, 2003; Steel et al., 1985).

There are two main models for the origin and development of the Central Tertiary Basin, both relating its formation to the relative plate motion of Greenland and Eurasia. Early interpretations from Steel et al. (1981) suggested a model where extension and transtention caused flooding of a series of small continental basins to a single open marine basin, with a following compressional event creating the West Spitsbergen Orogen and a westerly source for the upper phase of deposition in the Central Basin. Early stages of sedimentation from the rift margins in the east sourced the deposition in the lowermost part of the Van Mijenfjorden Group, whereas uplift of the western margin at some point caused a shift in source area and infill of sediments from prograding deltas (Müller and Spielhagen, 1990; Steel et al., 1985).

A foreland basin model is proposed by Bruhn and Steel (2003), which is widely recognized today. This model presents the Central Tertiary Basin to have formed as a foreland basin related to loading of the crust by the rising West Spitsbergen Orogen. The first phase of sedimentation from the east is suggested to be sourced from gradual flexuring of a peripheral bulge in the basin's eastern margins. This results in a backstepping shoreline and the overall retrogradational distribution of facies in the lowermost formations of the CTB (Bruhn and Steel, 2003). Lüthje (2008) argued that the exposed forebulge east of the basin could not account for the volume of sediment needed to deposit these formations. She suggests the late Cretaceous uplift of Triassic to Cretaceous strata in the northern part of the basin, in combination with longshore drift and storm related re-distribution of these sediments, to source the deposition of the first phase of sedimentation in the Van Mijenfjorden group. A provenance study of the Central Tertiary Basin by Petersen et al. (2016) address this argument, but find their results to be most fitting to the model proposed by Bruhn and Steel (2003).

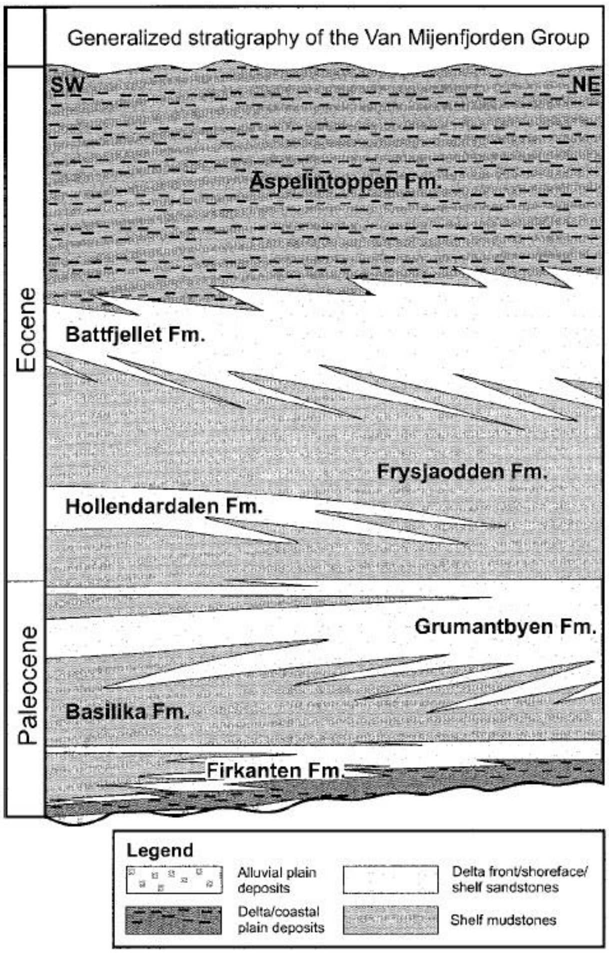

Figure 2.3 - Generalized stratigraphy of the Van Mijenfjorden Group. Firkanten Formation is found in the lowermost part of the group, with an unconformable base to the Cretaceous Carolinefjellet Formation. From Bruhn and Steel (2003).

2.3. The Firkanten Formation

The Firkanten Formation is the lowermost formation of the Van Mijenfjorden Group. This formation represents a transition from continental and marginal marine deposits to shallow marine wedges capped by fluvial conglomerates (Bruhn and Steel, 2003; Dallmann et al., 1999). The thickness of the formation varies from 100 to 170 meters, with approximately 125-meter thickness in the type section in Adventdalen (Dallmann et al., 2001). Firkanten Formation has been subdivided into two members, the Endalen and Todalen Member (Kalgraff, 1978; Steel et al., 1981) (Fig. 2.5), named after the two valleys close to Longyearbyen, which in addition to Longyeardalen are the main study areas of this thesis. The Todalen Member comprise marginal marine and continental deposits of a coastal plain environment protected by barrier islands (Lüthje, 2008). The deposits from this coastal plain include thick, extensive seams of coal of which the mining in Longyearbyen, Sveagruva and Barentsburg are based out of. Endalen Member is defined as the first thick, medium grained, cliff-forming sandstone above the coals and shales of the underlying Todalen and Kolthoffberget members (Dallmann et al., 1999) (Fig. 2.4). The exact boundary between Todalen and Endalen Members is often covered by scree and can be hard to spot due to the naturally weathered expression of the fine-grained, continental deposits of the Todalen Member. However, the Endalen member is composed of extensive sheets of shoreface sandstones, and is therefore expressed as well marked cliff-forming units in otherwise morphological soft rocks (Major and Nagy, 1972). Fission track analysis of grains give an age of 63 ± 2 Ma and 64 ± 2 Ma for the Endalen and Todalen Member respectively (Blythe and Kleinspehn, 1998).

Figure 2.4 – The Firkanten Formation as it can be seen in Longyearbyen. Endalen member expressed as the massive, cliff-forming unit of the upper Firkanten Formation. Beneath lies the non-marine Todalen Member of the same formation. Above Firkanten Formation, the marine shales of Basilika Formation can be seen.

2.3.1. The Endalen Member

The upper part of the Firkanten Formation is expressed as a prominent cliff-forming unit of massive bioturbated and partly stratified sandstones of the Endalen Member. The member is very well marked in the stratigraphy along the margins of the Central Tertiary Basin, outcropping in steep, massive rock-walls of light, reddish grey color (Dallmann et al., 2001; Dallmann et al., 1999). It is approximately 70 meters thick in its type area (Fig 2.5), but varies from 40 (north-east) to 100 (south-west) meters thickness (Dallmann et al., 1999). In the southern part, the Endalen member can be observed interfingering with the distal marine Kolthoffberget Member (Dallmann et al., 1999; Steel et al., 1985). The Endalen member is dominantly composed of large sheets of quartz arenitic sandstones, organized in 4-5 slightly coarsening upwards units of 10 – 30 meters, interbedded with thin conglomerates, clay ironstones and minor shales (Dallmann et al., 1999; Harland et al., 1997; Major and Nagy, 1972; Steel et al., 1981). Thin siltstone beds with plant-remains and a minor coal seam has also been observed in the lower part of the succession north of Adventdalen (Major and Nagy, 1972; Vonderbank, 1970).

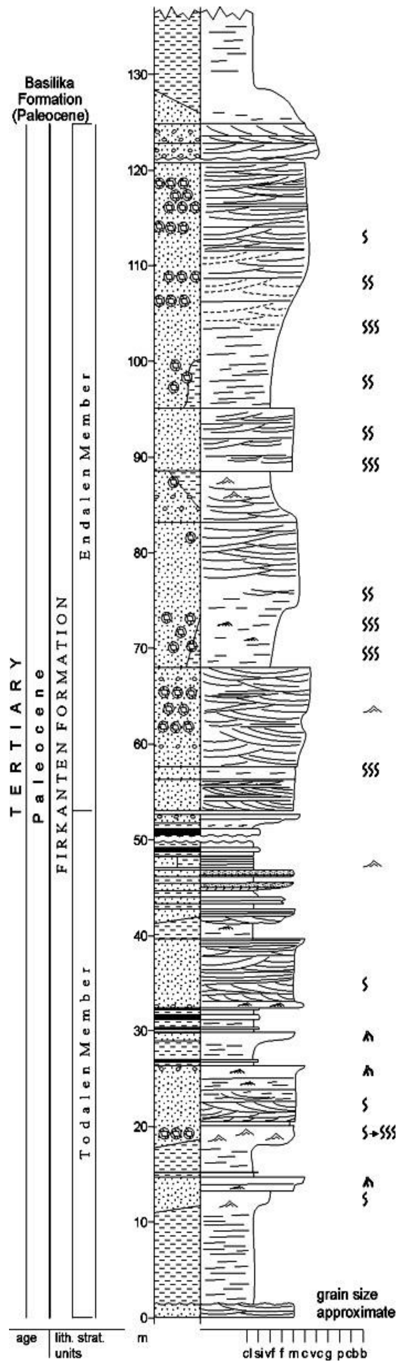

Figure 2.5 - Stratotype of Endalen Member from Karl Bayfjellet. From Steel et al. (1981).

The stacked sandstone sheets is interpreted to represent parasequences prograding into an evolving foreland basin (Bruhn and Steel, 2003). The lower parasequences represent the end of a transgressive phase of sedimentation from delta plain environments of Todalen member to mouth-bar and shoreface sandstones, whereas the upper parasequences represent a regressive phase of shoreface sedimentation and eventually the return to a non-marine alluvial plain. (Bruhn and Steel, 2003; Steel et al., 1981; Steel and Worsley, 1984).

3. Study Area

3.1. Introduction

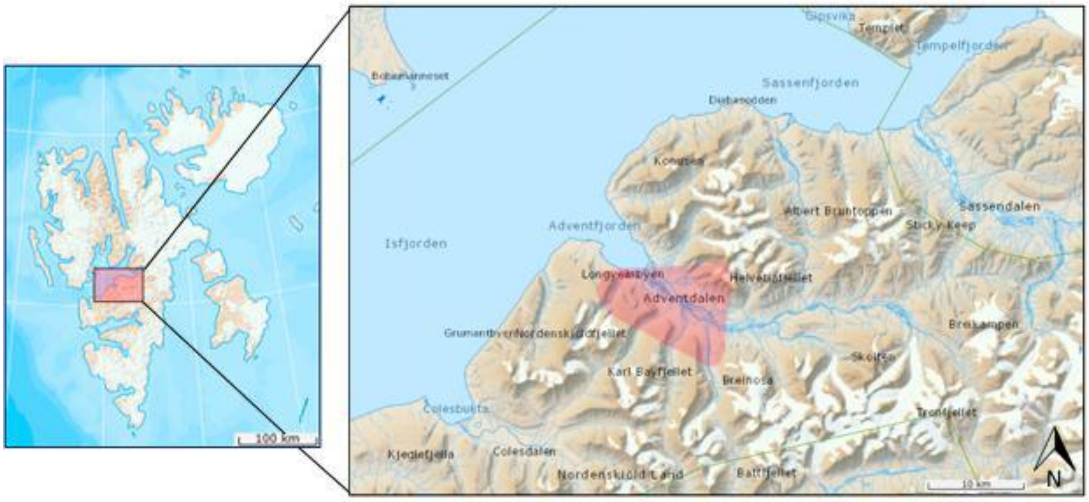

Figure 3.1 - Figure showing Svalbard Archipelago (with exception of Bjørnøya and some minor islands). Right part of the figure show Longyearbyen and its surroundings in the central part of Spitsbergen, and the location of the field area for this study marked in red.

The fieldwork in this study has been carried out in three tributary valleys stretching S(SW) – N(NE) into Adventdalen, close to Longyearbyen (Fig. 3.1, 3.2). These sites are chosen because of their excellent outcrop quality, type sections and closeness to Operafjellet and Breinosa where other recent studies have been carried out. The adjacent valleys cutting through the same stratigraphic succession provides a close grid for 3D investigations of facies and boundary variation. The valleys are all cut into a plateau lying approximately 500 meters above sea level. The plateau-ridge cornices have a lot of eroding force when they break off and avalanche, which generally control the development of free faces of the rock wall, providing better exposure of Endalen Member in west-facing slopes due to the prevailing wind direction (Eckerstorfer et al., 2013). As seen on figure 3.2, four out of five chosen localities for logging are in these slopes facing west-northwestwards. In the Adventdalen area there is a significant stratigraphic dip to the south. The cliffs of Endalen Member, which is found at 600 meters elevation in Hiorthfjellet, lies at only 250 meters above sea level at Sarkofagen in the innermost part of Longyeardalen.

The study area stretches 8.5 kilometers from Longyeardalen to Todalen, and 9.5 kilometers from Todalen to Alten in Operafjellet. The correlations of these localities thus comprise a triangulated field area of approximately 40 square kilometers. Considering models of provenance and coastal orientation from previous studies (Lüthje, 2008; Marshall, 2013), the orientation of localities provide an approximate strike section to the paleocoastline from locality 1 to 4, and a dip-section between localities 4 and 7.

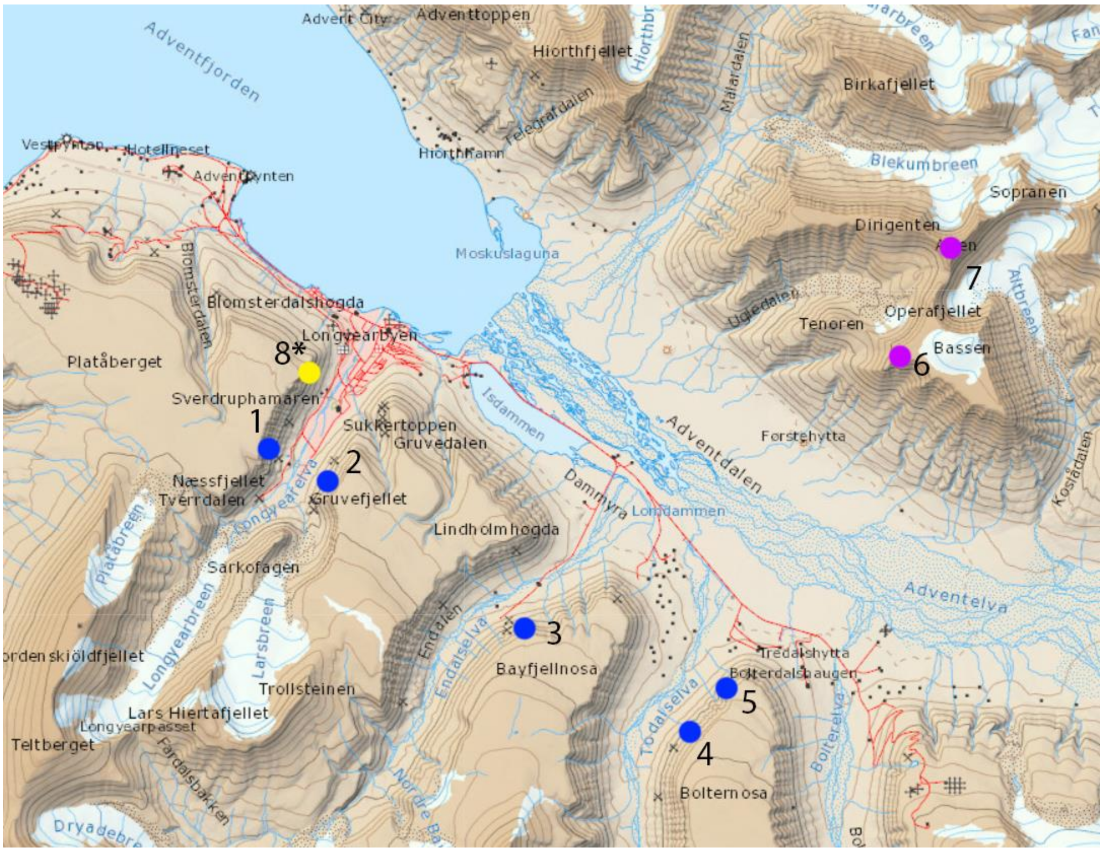

Figure 3.2 – The map shows the field area in Longyeardalen, Endalen and Todalen, the three visited tributary valleys to Adventdalen. Five sections of the Endalen Member were logged at localities marked 1-5, and one locality was investigated and photographed during fieldwork (8). Two additional localities are marked from the two core-drilling locations of SNSK, which has provided pictures of the obtained cores along with lithological logs.*

3.2. Logged localities

Five outcrops have been logged as control points for understanding the facies and boundaries in the photographs.

Locality 1 and 2 is situated in Longyeardalen, in addition to locality 8* which has been investigated and photographed. Locality 2 and 1 is situated above the two old mining villages in the southern part of Longyeardalen, 1100 meters apart (Fig. 3.2). Locality 2 above Nybyen (Fig. 3.3 A), lies east of locality 1 above Sverdrupbyen (Fig. 3.3 B). Both localities have good vertical accessibility and have been logged in one coherent section.

A

B

Figure 3.3 – A) Locality 2, Nybyen. B) Locality 1, Sverdrupbyen

Locality 3 is situated 300 meters above sea level, on the North-West facing slope of Bayfjellnosa, next to abandoned Mine 5. Deeper in this valley, on the western slope of Karl Bayfjellet, lies the stratotype of the Endalen Member (Steel et al., 1981). Most of the rock face has been inaccessible for logging due to oversteepening. As in Todalen, the log is divided in two sections to access good quality outcrops and keep the logging as consistent as possible. The two logged sections are situated approximately 150 meters from each other, and together make up one full length of Endalen Member (Fig 3.4).

Figure 3.4 – Locality 3, Endalen.

Two localities in Todalen is situated approximately 300 meters above sea level in the north-west facing slope of Bolternosa. The two localities have about 600 meters space in between them (Fig. 3.5), locality 5 sitting north-east of locality 4. Some airducts and mine exits from the abandoned mine 6 can be seen in the Todalen Member, situated approximately 20 to 30 meters below the lowermost Endalen Member. The thresholds in the cliffs are covered in scree material, and these gaps in the succession are easy to trace laterally. Thus, in both outcrops, the logs are divided in two parts to access the upper part of the succession.

Figure 3.5 – The North-west facing slope of Bolternosa, showing the logged sections of locality 5 (left) and locality 4 (right).

4. Material and methods

4.1. Introduction

In this study, photography for lateral mapping of sandstone-bodies in combination with vertical logging have been the most important aspects of fieldwork. These techniques supplement each other in a way that logging describes the lithostratigraphy of an outcrop, with photo-modelling documenting the three-dimensional geometries of the different lithostratigraphic units.

The fieldwork for this study has been carried out during one field season, summer of 2017, alongside courses at UNIS. A total of 11 days was spent in the field as day-trips by bike from Longyearbyen together with three different field assistants. Due to snow and ice cover, as well as dark season and polar night, the field season in Svalbard is relatively short (June – September). The field-period was further shortened by days of heavy rain and the following risk of slope failure in the valley sides. These factors presented a challenge when it came to collect enough data for regional correlation. The solution to these challenges has been to supplement the data obtained from fieldwork with logs and core-pictures from two localities in Operafjellet, extending the field area across Adventdalen and providing the possibility of correlation in a north-south direction (Fig. 4.3). A number of lateral extensive high-resolution photographs have been the basis for investigating lateral development of the logged lithostratigraphic units.

All maps are collected from toposvalbard.npolar.no, a digital map service for Svalbard by the Norwegian Polar Institute. Where nothing else is mentioned, all photos in this project are by the author.

4.2. Data acquisition

4.2.1. Photography

The analysis and results of this thesis are largely based on interpretations of photo-material collected during fieldwork. A Nikon D300 camera has been used to capture all the photos of the outcrops. For panorama shots the camera settings are set to match the light, and then kept the same throughout the shots. All photographs are shot in RAW format to enable editing without any significant quality loss. Sets of photos of four different outcrops was taken from a distance greater than 1 kilometer to capture the lateral development of the architecture in Endalen Member (Fig. 4.1). Due to the distance from the outcrop, a 200 mm zoom lens has been used for maximum resolution.

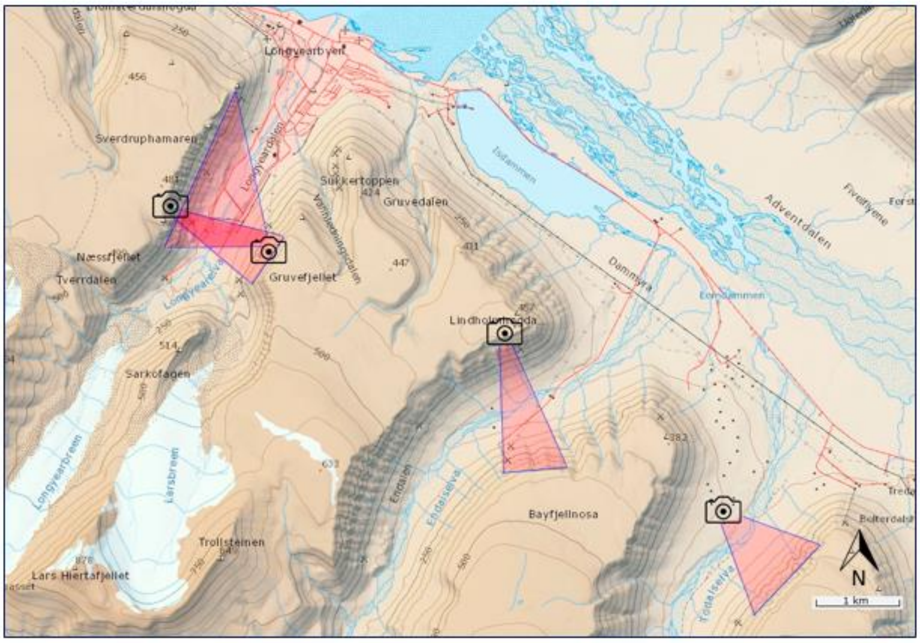

Figure 4.1 – Map showing locations of photography for panorama of outcrops.

4.2.1. Sedimentological logging

Five full length outcrops of the Endalen member has been logged in scale 1:50 with the purpose of showing the vertical development in both architectural elements and lithology. These logs have later been condensed to scale 1:200 for the purpose of lateral correlation (Appendix 1-8).

The main parameters investigated during field logging were:

- **Grain size** estimated based on reference set from W.F. McCollough.

- **Sorting**, with respect to the range of grain sizes within a bed. In this text, this often reflects the relative amount of silt to sand.

- **Primary sedimentary structures**, such as planar parallel stratification and cross stratification of different scale and expressions.

- **Bioturbation and trace fossils.**

- **Bed set and unit thickness**, based on surfaces expressing a significant change of characteristics with respect to one or more of the parameters above.

These parameters were noted directly into pre-made logging sheets. Tools used in the field was a hammer, measuring stick, hand-lens and the grain size reference set.

4.2.2. Store Norske Spitsbergen Kulkompani drill-core data

In addition to the five logs acquired during fieldwork, two logs have been provided from Store Norske Spitsbergen Kulkompani (SNSK) from drilled cores. In this study, pictures of the cores in addition to sedimentary logs made by MSc student Anna Stella Guðmundsdottir, have been used to draw condensed logs to investigate the development of 1st and 2nd order elements in a north-south direction (Fig 4.2, appendix 7-8). The two cores are drilled on Bassen and Alten in Operafjellet north of Adventdalen, and are refered to as locality 6 and 7, respectively (Fig. 4.3). As the definition of the Endalen member do not recognize the massive marine sandstones below the uppermost coal of the Todalen Member, the base of the member is set 25 to 30 meters lower in this study than what has previously been defined. This allows for a chronostratigraphic correlation recognizing a sub-aerial part of the Endalen Member in its north-eastern margins.

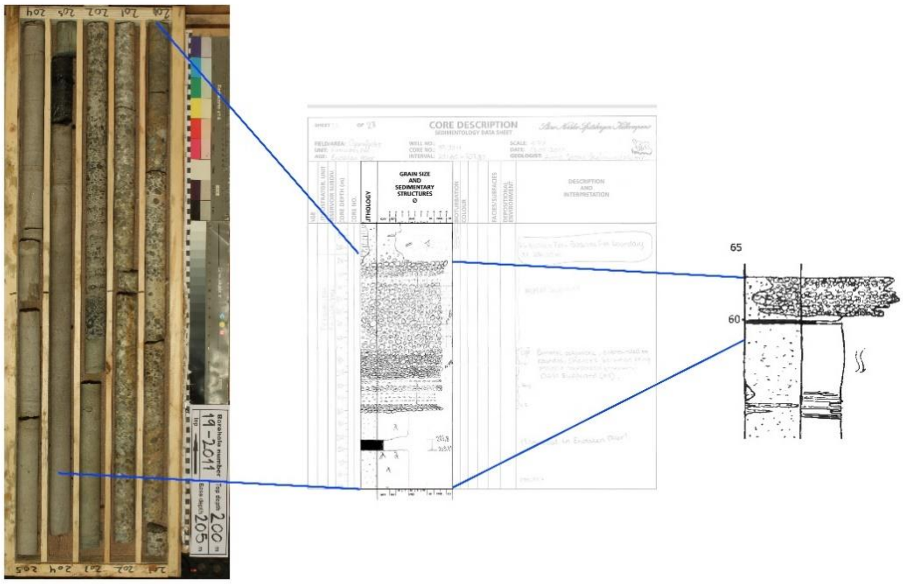

Figure 4.2 – Upper 5 meters of Endalen Member in Core nr. 19, 2001 from SNSK drilled at Alten in Operafjellet. The middle section shows the detailed core log by Anna Stella Guðmundsdottir, while the right log shows the condensed log.

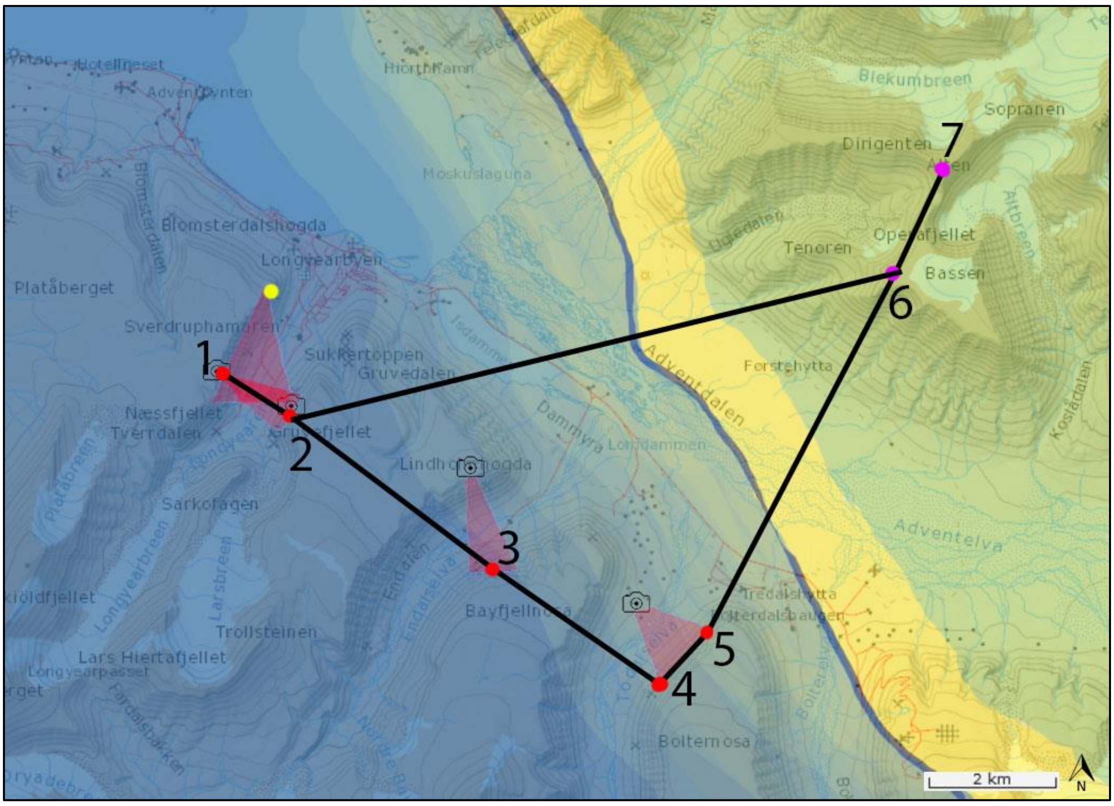

Figure 4.3 – Figures showing localities of lithological logging (Loc. 1-5), localities of drill-core data (Loc. 6 and 7), position of which the panorama photographs were taken and their rock-wall objectives (camera figures and red polygons), as well as correlated log sections (black lines). Yellow dot indicates one locality of close-up photography. The figure also shows a map of the study area, covered with the possible Paleogene study area (interpreted coastline direction from Marshall (2013), Petersen et al. (2016)).

4.3. Data processing and analysis

4.3.1. Photo-modelling

The study was intentionally based on interpreting Helicopter-mounted LIDAR data in combination with field-logs. A low degree of exposure of the Endalen Member in the photos, accompanied with snowfall during the data acquisition made the dataset unsuitable for documenting any inter-parasequence architecture. The solution to this challenge has been to use lateral compilations of photos to create panorama models on which interpretations of element boundaries have been drawn.

Photographs and photo-mosaics have been an useful aid in describing and documenting outcrop characteristics, especially after the architectural analysis by Miall (1985) was introduced to clastic sedimentary systems (Miall, 1988). The method has especially proven useful for mapping sand-body architecture in subsurface reservoir analogues (Howell et al., 2014). A description of photography techniques and constraints to this method is presented in Wizevich (1992). Several studies of near-shore marine deposits focusing on depositional architecture have been carried out on a world-wide basis, many of them using photo-mosaics to map sand-body geometries (e.g. Allen and Johnson (2011), Hampson and Storms (2003)).

The photo-compilations of the outcrops were put together in Adobe Photoshop CC 2015 using the "photomerge" tool to create a seamless panorama. Parameters such as brightness, contrast, highlights, shadow and sharpness have been adjusted to fit the purpose of lateral modelling of units (Fig. 4.4). This process has also been proven useful for merging close-up photos of the outcrops, as the photos can be merged vertically as well as horisontally. This gives the possibility of working with pictures of much higher resolution than of one single photo.

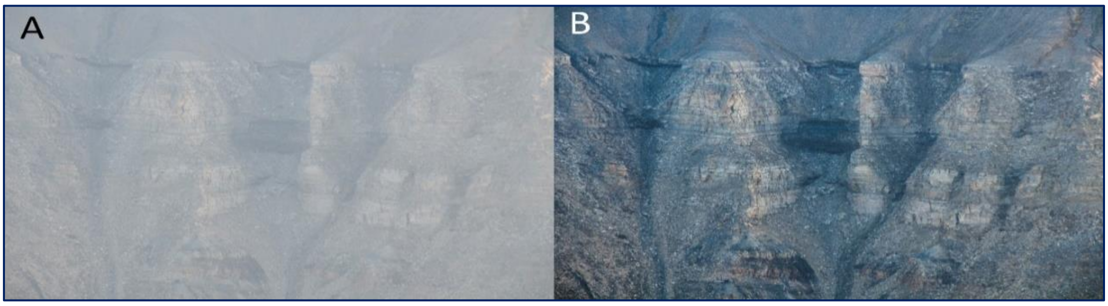

Figure 4.4 – A: Original Photo of the cliff forming units in Endalen, taken towards S(SE) from Lindholmhøgda. A lot of dust in the air combined with a low sun gives a low contrast photo. B: Same photo after adjusting contrast, brightness and sharpness.

Precision of the presented data in this method is limited by a couple of factors. First, panorama models are taken from a single point opposite of the rock face which distorts both scale and dip direction on the object as the pictures are shot. In example, in the Longyeardalen panorama (Fig. 6.1, appendix 9) there is a horizontal distance of 1.1 kilometer from the camera to the cliff objects in the southern part of the panorama, whereas there is 2.0 kilometers to the northern part of the valley. This gives a false impression of northwards thinning. Second, because of the distance from the object cliffs, some elements are too thin to be resolved sharply in the photo-montages. Third, the true thicknesses of the elements are only obtained at the logged localities, and lateral development of the thicknesses are all relative to the thickness at the logged sections.

4.3.2. Digitalization of logs and figures

Both sedimentary logs and handmade figures are scanned and imported to Adobe Photoshop to maintain their original scale. A set of eraser tools have been used to remove the millimeter grid and enhance the drawn lines from the scanned document. This software has also been used to edit and draw interpretations in other figures.

4.3.3. Facies analysis

The logs from the five logged localities, as well as the two core data localities, have been analyzed. “Facies analysis is a fundamental sedimentological method of characterizing bodies of rock with unique lithological, physical and biological attributes relative to all adjacent deposits”(Catuneanu, 2006).

Ten different lithofacies are defined based on the parameters described during logging. In addition to difference in grain size, the different scale and physical expression of sedimentary structures are the most important aspects of this facies analysis as these are a direct response of the energy in the environment of which the sediments were deposited. The energy during deposition can again be related to the depth below sea level for shoreface deposits (Miall, 2016). The ten lithofacies are listed according to the interpreted relative amount of energy during deposition (Fig. 4.5). Facies 9* and

10* have been interpreted from core-photos and logs from SNSK and is placed last in the facies table. (Table 1).

Facies associations consists of several facies in a specific spatial arrangement and is in many cases the key to environmental interpretation (Anderton, 1985). Five different facies associations have been distinguished based on the interaction between facies. These facies associations reflect the environment in which the sediments are deposited and provide the basis for sequence stratigraphic correlation of the logs within the field area.

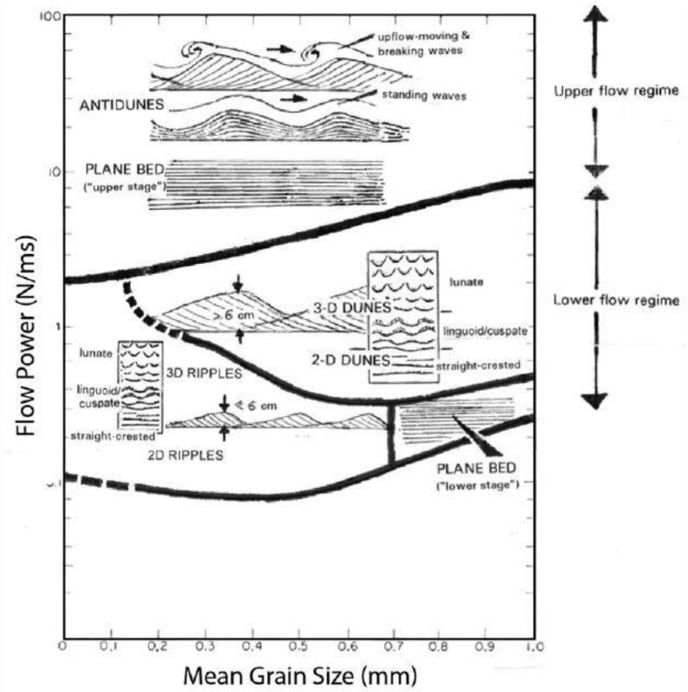

Figure 4.5 – Figure showing the stability of bedforms produced by unidirectional currents. From Allen (1982).

4.3.4. Defining architectural elements

Even though the Endalen Member is defined from the exposure of the member in Endalen, the cliffs above Nybyen (Fig. 4.7) will act as a reference for unit division and hierarchy of elements in this study. This section was chosen because of its great degree of exposure, easy accessibility and because of the possibility of vertical coherent logging.

“Architectural element” is the term used to describe the three-dimensional form of a lithostratigraphic depositional unit, with emphasis on the units bounding surfaces, scale, external shape and internal geometries (Miall, 1988).

To describe the architecture in the Endalen Member, it is necessary to establish a hierarchy of elements and name them according to their relative position to each other. A hierarchy like this is ideally based on the bounding surfaces extent relative to each other in a way where 3rd order surfaces are cut by 2nd order surfaces, which again is cut by 1st order (Fig. 4.6). This works very well in eolian dunes and fluvial systems which is what the method originated from (Miall, 1985), but the study area in this research is too small to capture the entire extent of the elements in a shallow marine setting. Therefore, the surface hierarchy has been decided based on the surfaces apparent extent based on their character within the study area, as well as the relative conformability of the sediments bounded by the surfaces. A surface separating offshore sediments from foreshore sediments marks a larger stratigraphic unconformity than a surface marking transition from alluvial sediments above it to foreshore sediments below. A surface characterization and their sequence stratigraphic importance is presented in chapter 6. This organization of surfaces result in three orders of bounding surfaces, and thus also three orders of architectural elements. First order elements have the greatest thickness, lateral extent, and represent the longest time of sedimentation, followed by second order elements, etc.

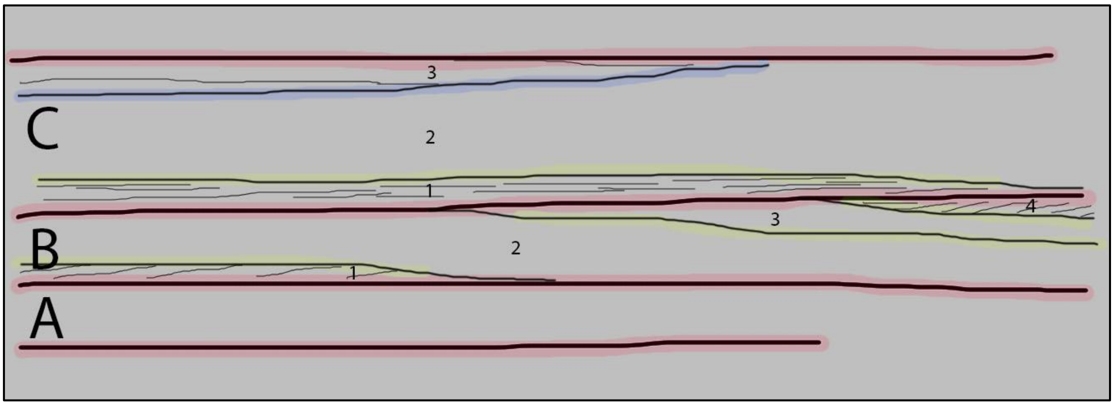

Figure 4.6 – Example figure showing the hierarchy based on the apparent lateral extent of the bounding surfaces and their internal sand bodies.

When specific elements are referred to, first order elements are addressed as capital letters from bottom to top (A, B, C, D). The second order elements are numbered within each of the first order elements (A1, A2, A3, B1…) (Fig. 4.7). 3rd order elements are not numbered as they have relatively short lateral extent, are often disrupted and cannot be correlated from one locality to another. Reference numbers only specifies the elements relative position to each other within a first order unit, and one should not consider elements with similar numbers to have the same lithological or architectural properties. This reference division is based on the outcrop in Locality 2 and applies to all logged sections.

Note that lines are dashed where scree cover the actual boundary of an architectural element. A dashed-line boundary is thus not exact, only meant as a rough indicator based on the lithostratigraphic trends.

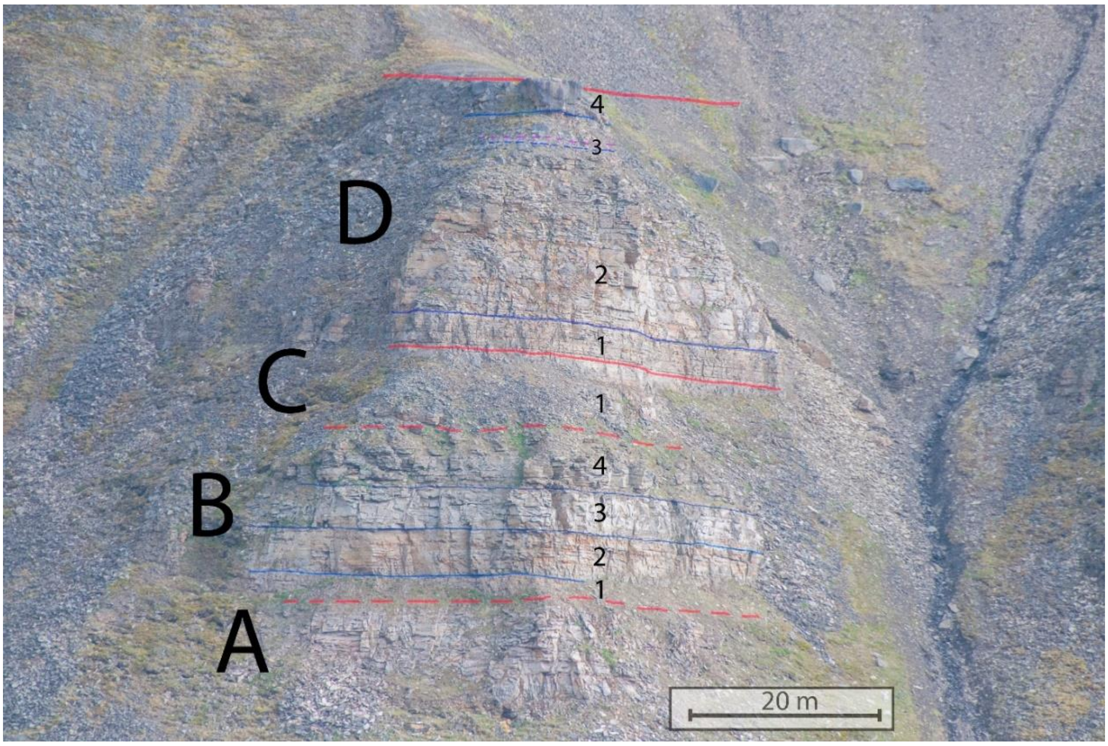

Figure 4.7 – Locality 2, Nybyen. The Picture show how the hierarchy of architectural elements and how they are addressed from oldest to youngest.

5. Lithofacies – Description and interpretation

5.1. Introduction

The following chapter summarize the results and interpretations from the lithological investigation of the five logged localities, as well as the two localities investigated from pre-made logs and core-photos. Ten different facies have been recognized (Table 1).

5.2. Lithofacies

Table 1 – Division of Lithofacies with description of characteristics, depositional process(es) and interpretation of depositional environment(s). Star* marks facies which has not been found in the field. These facies are described from core-logs provided by Store Norske Spitsbergen Kulkompani.

Lithofacies	Description	Depositional process(es)	Interpretation
F1: Claystone	Dark grey claystone	Material settling from suspension in ambient water	Offshore, lagoon
F2: Bioturbated, dark sand- and siltstone	Poorly sorted, very fine sandstone with silt.	Both silt and very fine sand deposited in very low energy conditions and fine sand from slightly higher energy conditions. Mixing and reorganizing due to bioturbation.	Offshore, Offshore transition zone
F3: Ripple cross laminated sandstone	Very fine sand- and siltstone to fine sandstone. Ripples with both bi- and unidirectional current	Oscillatory motion/unidirectional currents	Lower shoreface, shoreface
F4: Massive sandstone	Very fine to fine sandstone	Intermediate energy conditions. Colonization and reworking of sediments by organisms	Shoreface
F5: Plane parallel stratified sandstone	Fine sandstone	Unidirectional flow/Upper flow regime	Shoreface/Foreshore
F6: Hummocky-Swaley cross stratified sandstone	Fine sandstone	Strong oscillatory motion in combination with unidirectional currents	Shoreface storm deposits
F7: Very coarse sandstone	Lenses of granules. Planar cross bedding	Strong unidirectional current	Fluvial channel
F8a – Granule conglomerate	Granules with some very coarse sand	Strong unidirectional current	Fluvial channel
F8b – Pebble and cobble conglomerate	Pebbles and cobbles resting in a matrix of fine sand	Outwash and infill of fine grained sediments.	Marine lag / Fluvial incised channel
F9* – Coal	Coal	Burial of bogs and marshes	Alluvial plain
F10* – Interbedded silt- and fine sandstone	A varying silt/sand ratio with flaser, wavy and lenticular bedding	Rapid and rhythmic pulses of sedimentation in relation with flow and ebb tide.	Marginal marine, Tidal flat

5.2.1. F1 – Claystone

Description

This facies only occur once in the studied localities and is thus the least prominent of the different lithologies found in the Endalen member. It occurs at the boundary of 2nd order elements 3 and 4 within 1st order unit B, as a slightly undulating horizon with a thickness 1 cm – 5 cm, and a lateral extent of 10s of meters. The claystone is easily eroded and forms an apparent gap between the sandstones above and below (Fig. 5.1).

Figure 5.1 – This photo shows the observed horizon of claystone in the Nybyen locality

Interpretation

There are two possible scenarios for the deposition of this clay. The clay of this facies has either been deposited from suspension in very low energy conditions, or as flocculated clay particles as a fluid mud close to the sediment source (Winterwerp and Van Kesteren, 2004). Its position in-between sandy facies may suggest the latter. However, a protected embayment such as a lagoon or back-spit environment could also generate this facies within environments dominated by shoreface sands.

5.2.2. F2 - Bioturbated dark sand- and siltstone

Description

Bioturbated, dark grey-brownish sand and siltstone represent the base of first order architectural elements with a thickness of 300cm to 1200cm, gradually coarsening upwards into facies F3-F6. The sandstone is poorly to moderately sorted, with grains ranging from very fine to fine sand, and with a varying amount of silt. In general, the sandstone has a massive and disturbed expression due to the high amount of bioturbation, but a few sedimentary structures such as ripple lamination and plane parallel lamination are also found in this facies.

In the Northern part of Longyeardalen, above the Longyerbyen church, the facies is well exposed in the lower part of 1st order unit B, showing plane parallel lamination and a few ripple cross laminated horizons. Trace fossils include *chondrites*, *Ophiomorpha*, and *Schaubcylindrichnus* (*Schaubcylindrichnus* is only found in 1st order unit C in this facies) (Fig. 5.2.). In Longyeardalen S, above Nybyen, a 5-centimeter-thick horizon with very high content of organic material can be found in the lower part of unit B1.

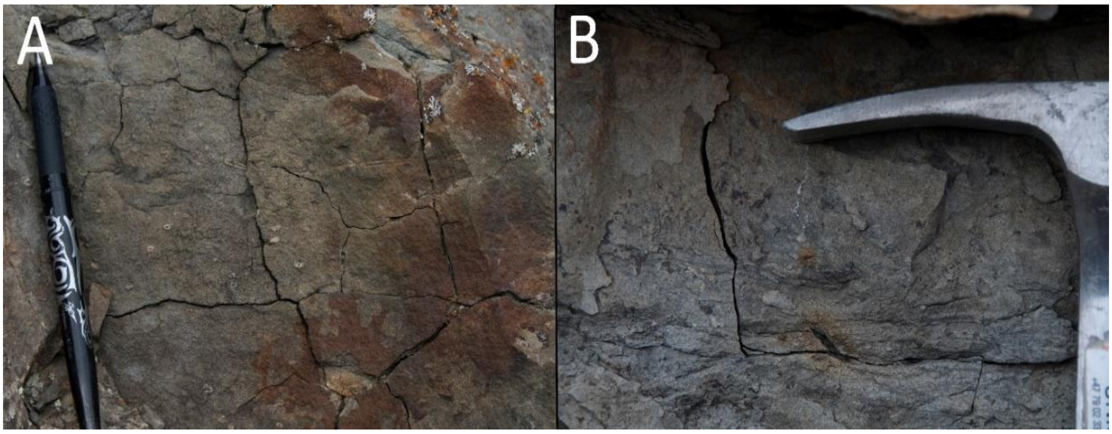

Figure 5.2 – A: The most common expression of this facies in 1st order unit C. White spots in the rock are Schaubcylindrichnus trace fossils. B: Another common expression of the facies with some very weak traces of chondrites in the middle of the photo.

Interpretation

The poor sorting and occurrence of both silt and grains of fine sand suggest a combination of different energy conditions during fall-out and sedimentation. No evidence of waning-waxing flow has been observed, however, this may be due to the heavy bioturbation. The silt and heavy bioturbation suggest longer periods of low energy conditions, whereas the presence of sand indicates some periodic events of slightly higher energy. The presence of the marine trace fossils observed together with the lithological observations points to a depositional environment of lower shoreface and offshore transition zone (Pemberton et al., 2012). The organic rich layer observed in unit B1 can suggest a somewhat more nearshore protected environment for this unit, with more organics in discharge from land, or as a wash-over fan from a vegetated barrier island into a protected marine environment.

5.2.3. F3 – Ripple cross laminated sandstone

Description

This facies represent cross stratification with individual thickness of less than 7 cm in very fine to fine sandstone. This facies mostly occurs in 1st order unit B, but is also found in a few localities within parasequence D. The ripples are usually found in combination within or near boundaries of facies F2, F5 and F6. The total thickness of the facies ranges from 2 cm to 30 cm. Both wave and current ripples are observed, although the most common expression is slightly asymmetric wave ripples with a preferred direction of migration, resulting in lateral accretion of foresets within the wave ripple structure (Fig. 5.3). The ripple cross laminated sandstone varies from a few meters to tens of meters in lateral extent, but the relative position of the facies is continuous for several kilometers.

In unit B2, several lateral extensive horizons of this facies can be seen disrupting bioturbation and dividing the element into architectural elements of 3rd order.

Figure 5.3 - Facies F3 showing wave ripples. Marked section show a preferred direction of migration of the ripple and indicate a component of unidirectional flow as well as oscillatory flow during deposition

.

Interpretation

Formation of the ripples in this facies occur in low to intermediate energy conditions. Wave ripples in fine sandstone results from oscillatory flow motion from waves in the lower flow regime and indicate a shoreface environment of deposition. The asymmetry of the ripples is caused by combined flow conditions of unidirectional- and oscillatory currents. The unidirectional current may relate to river output, longshore currents or rip-currents (Boggs Jr, 2006).

5.2.4. F4 – Massive sandstone

Description

Facies F4 consists of very fine to fine, light grey, generally well sorted sandstone with only very small amounts of other grainsizes such as silt and individual pebbles. This facies is especially common in unit D2, where sections of up to 20 meters have a massive expression with conchoidal breaking patterns and only very thin horizons of siltstone, subdividing the sandstone into 3rd order units. Some areas of oxidized staining reveal a high degree of bioturbation in the sandstone (Fig. 5.4). The most prominent trace fossil in this facies is *chondrites*, but *Macaronichnus* and *Schaubcylindrichnus* is also found within unit D2. Together with Facies F2, this is the most prominent lithology in the Endalen member. The largest sandstone body of this facies is unit D2, which is consistently more than 10 meters thick throughout the study area with only minor instances of facies F3, F5 and F6 disrupting the massive sandstone.

Interpretation

Grainsize and sorting points to deposition in a nearshore environment with relatively steady sediment input and stable energy conditions. The massive expression of the facies is interpreted to be due to heavy bioturbation. The observed trace fossils also indicate deposition in a fully marine environment. *Macaronichnus* trace fossil is indicative for high energy environments, whereas *Schaubcylindrichnus* and *Chondrites* may occur in several different energy regimes (Pemberton et al., 2012). Chondrites may however be related to environments low in oxygen (Bromley and Ekdale, 1984). Thin horizons of siltstone express longer periods of calm weather and low energy during deposition, and the individual pebbles in the massive sandstone is interpreted as drop stones from ice or kelp. This facies is interpreted as shoreface – upper shoreface sandstones.

Figure 5.4 – Facies F4 has a very massive expression. The oxidized spot left of the pen reveal the bioturbation of this facies. Picture from Nybyen

5.2.5. F5 – Plane parallel stratified sandstone

Description

This facies represent well sorted, fine sandstone with plane parallel stratification. The occurrence of this facies is usually in combination or associated with facies F4 and F6, and to the top of 1st order architectural elements (Fig. 5.5). Thickness varies from 10 cm to 300 cm and with a lateral extent of tens to hundreds of meters. The sandstone typically has a sharp lower boundary and an upper boundary fading into either massive or hummocky-swaley cross stratified sandstone. Some instances of a sharp and undulating lower boundary are also found. Horizons of clay-ironstone can be found within the facies acting as inner boundaries between 3rd order elements.

Figure 5.5 – Facies F5 show plane parallel stratification. Picture from Unit B4 in Todalen

Interpretation

Together with associated facies of massive sandstone and hummocky-swaley cross stratification, the combination of fine sand and plane parallel beds suggest that this facies is deposited in upper flow regime conditions (see Fig. 4.5). Because hummocky-swaley cross bedding results from combined flow conditions, the plane beds are most likely to be related to this environment and represent combined flow plane beds. They may also represent foreshore plane beds in the swash zone.

5.2.6. F6 – Hummocky-swaley cross stratified sandstone

Description

Facies F6 is a well sorted, fine sandstone with a light grey to light brownish color and low angled troughs and hummocks terminating one another (Fig. 5.6). Individual bedforms within the facies create internal boundaries within the facies as they terminate each other and are typically 10 to 50 centimeters thick with a lateral extent of less than 200 cm. Total thickness of the facies varies from 10 cm to 400 cm, and typically have a gradual transition to planar parallel stratification or fading into massive sandstone.

Some lower boundaries are sharp and undulating, creating 3rd order element boundaries. Swaley cross stratification is the most common of the two structures as not many antiforms are observed. This facies is common where the silt content is low and is usually found in combination with F4 and F5.

Figure 5.6 – Distinct Hummocky-Swaley cross stratification of facies F6 in locality 2, Nybyen

Interpretation

In general, resulting from oscillatory flow from waves combined with a basinwards directed relaxation current, these bedforms are formed above wave base (Boggs Jr, 2006). Occurrence of these bedforms within very fine sand and siltstone suggest storm related deposits where larger waves lowers the wave base to rework and deposit sediments at a level where usually only fine material is settling out of suspension. The facies usually occurs in combination with plane parallel beds and massive fine sandstone and is therefore interpreted to be deposited within the upper to middle shoreface. A few instances can be found where these bedforms are found within coarse siltstone. These are interpreted to be lower shoreface – offshore transition zone deposits.

5.2.7. F7 – Very coarse sandstone

Description

This facies consists of relatively poor sorted, very coarse sandstone with a varying amount of granule sized fragments. Structures in this facies are planar tabular and planar tangential cross stratification, as well as lens shaped granule horizons.

The facies occur in unit B5, sometimes as two separate beds divided by a conglomerate. The two beds differ somewhat in expression based on the average grain size and scale of cross stratification.

The lowermost facies bed has a thickness of 215 cm in Todalen, thinning to 70cm in Longyeardalen. In Longyeardalen the whole bed is made up of one single set of planar tabular cross bedding, with a dip towards NW. In Todalen, the structures are less visible, but it is likely that the bed comprises of several sets of cross bedding. The external boundaries of this bed are both conglomerate.

The upper bed defines the very top of the Firkanten Formation. and has sets of planar tabular/planar tangential cross stratification with set thickness of 5 – 10 cm, dipping towards west (Fig. 5.7). This bed has a thickness of 280cm in Longyeardalen. At the base of this sandstone there are several brown, vertical traces of 1-3 cm height with a few millimeters thickness (Fig. 5.8). This bed has in average greater grain size than the lower one, as there is a larger portion of granules. Granules cover the foresets in the cross stratified sandstone, and sometimes occur as horizontal to sub-horizontal lens shaped concentrations with a lateral extent of 20 - 100 cm. There is an increase in the amount of pebbles towards east within this bed, to the point that it can be described as a conglomerate in Todalen(F8a). Coal fragments are also found within this facies in Endalen.

Interpretation

As the lower facies bed is composed of 2d dune scale cross bedding, this suggest deposition in the lower flow regime (see Fig. 4.5). The brown, vertical traces found in this bed resemble roots in both shape and color. However, these traces are located at the base of the bed, suggesting either that the top part of a root horizon has been eroded, or that the traces are remaining stems of plants standing up from the surface below. Deposition of the coarse sand in lower flow regime favor the latter interpretation of the plant fragments, as there might not have been enough flow power to erode and cut a sediment horizon bounded by roots.

Figure 5.7 – Planar tabular cross stratification of facies F7 in unit D4 of locality 2, Nybyen.

No clear imbrication of granules, and a lack of completely planar parallel beds suggests that these sands have not been deposited in upper flow regime, but rather as a lower flow regime flat bed. The somewhat coarser upper facies unit is therefore interpreted to be deposited in a lower energy than the lowermost finer dune-scale cross-bedded facies unit (see Fig. 4.5).

Figure 5.8 – Brown, vertical traces within facies F7 in locality Nybyen.

5.2.8. F8 – Conglomerate

Description

F8a – Granule conglomerate

This facies is characterized by matrix supported conglomerate of granules with a matrix of very coarse sand (Fig. 5.9). This facies occurs in the very top of unit D4 in Todalen with a thickness of 150 cm. In Todalen, the facies has a lower, undulating boundary to the very coarse sandstone of facies F7, and an upper boundary to the fully marine Basilika Formation.

F8b – Pebble and cobble conglomerate

This conglomerate differs from F8a in several ways. The clasts consist of pebbles and cobbles with up to 10 cm in diameter. Most clasts rest in contact, which makes this clast supported. The matrix consists of fine to medium sandstone. The conglomerate typically has a thickness of 5 – 15 cm in locality 1-5, with an undulating lower boundary to facies F4 of unit D2. Pictures from drilled cores at locality 6 and 7 show 2.4 meters of this facies with minor beds of F7 and F8a (Fig. 5.10). Clast composition is mainly well-rounded quartz and clay-ironstone. No internal sorting of clasts or imbrication have been observed.

One instance of this facies, unit D3, is only found in Longyeardalen and Endalen, resting between two marine sandstone successions. The conglomerate has undulating upper and lower boundaries to Facies F4. The conglomerate has a maximum measured thickness of 50 cm (Locality 2). In locality 1 and 3, the same conglomerate has reduced to 20 cm in thickness and is partially breaking up and mixing with homogenous sand (Fig 24B).

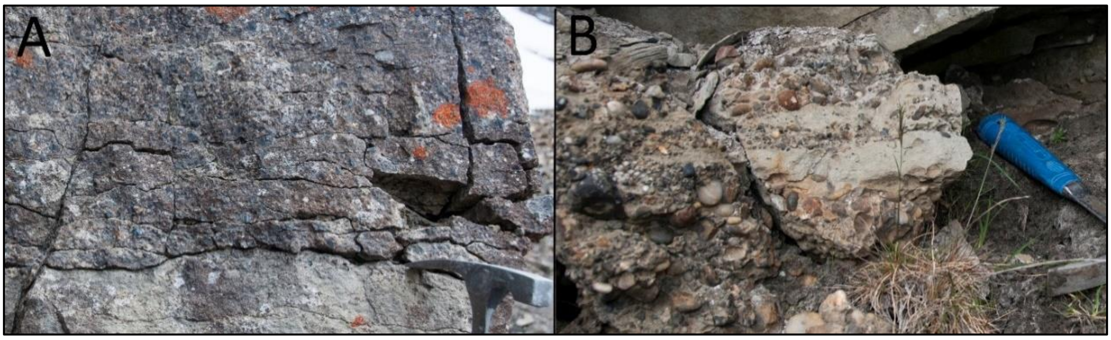

Figure 5.9 – A: Facies F8a with its lower boundary to facies F7 in Todalen. B: Facies F8b in locality 1, Sverdrupbyen, in Longyeardalen.

Interpretation

The size of clasts in this conglomerate can be translated to the capacity of the depositional process. There are two interpretations that fit well with the observations of these facies. Rounded clasts of pebbles and cobbles captured in a matrix of sand, could be the result of either a marine lag and represent a pebbly beach, or it could represent the scour base of a fluvial deposit. Coexisting with facies F7 and with undulating lower boundaries, there is reason to believe the conglomerates of F8a and F8b within unit D2 is of fluvial origin. The distinct coarsening trend of the conglomerate from southern Adventdalen towards Operafjellet to the north-east is a strong indication of source area as the fluvial system is likely to lose capacity seawards (Boggs Jr, 2006).

The local conglomerate of F8b in unit D3 is more uncertain as it is situated within fully marine sandstones. This conglomerate has been described by Bruhn (1999), with a further westwards extent to Bjørndalen and Grumantbyen, and northwards to Adventtoppen and Hiorthfjellet. The clast-supported fabric, sandstone matrix and regional extent in the south-eastern part of the study area point towards this being a marine reworked conglomerate, representing a marine lag from a gentle rise in relative sea level.

5.2.9. F9 – Coal*

Description

Some instances of coal are found in the middle and upper part of the drilled cores from Operafjellet. The coal has sharp upper and lower boundaries, accompanied by root traces from its lower boundary to the facies below. In some parts, thin lenses of very fine sand create an apparent stratification in the coal layer. The coal breaks conchoidally and have a glassy shine in broken up-parts.

One instance of a 13 cm thick coal is found resting within facies F4, 40 cm below F8b conglomerate in Locality 7 (Fig. 5.10). The same coal has reduced thickness to 8 cm in locality 6.

Figure 5.10 – Coal and fluvial coarse sandstones and conglomerates of drill-core 19-2011 at locality 7

Interpretation

Coal is defined by Schopf (1956) as " a readily combustible rock containing more than 50 percent by weight and more than 70 percent by volume of carbonaceous material, formed from compaction or induration of variously altered plant remains similar to those of peaty deposits." Organic matter is best preserved in areas with rapid burial and low degree of oxidation, such as in swampy areas with a high water table (Boggs Jr, 2006). The tertiary coal succession on Svalbard has been thoroughly investigated, lately interpreted to origin from peat mires in a low relief coastal plain environment (Lüthje, 2008).

The interpretation of a coastal plain environment in the upper part of the Endalen member, supports the interpretation of a fluvial origin for the coarse sandstones and conglomerates of unit D4.

5.2.10. F10* – Interbedded silt- and fine sandstone

Description

Facies is recognized by the thin interbedding of mudstone and fine sandstone. Different sedimentary structures vary accordingly to the mud/sand ratio in the rock. Flaser bedding occurs where there is a high amount of sandstone with millimeter thin interbeds of mudstone draping the structures. Lenticular bedding occurs in areas with the opposite trend, where the relative amount of mudstone is higher than the amount of sandstone. In this case, the sandstone occurs in thin lenses of about 0,5 cm in thickness (Fig 5.11). In a few places, vertical layers of mudstone cuts through the otherwise horizontal bedding. Where there is a somewhat equal amount of mud and sand, wavy bedding occurs. Each wavy interbed is commonly less than 0,5 cm thick.

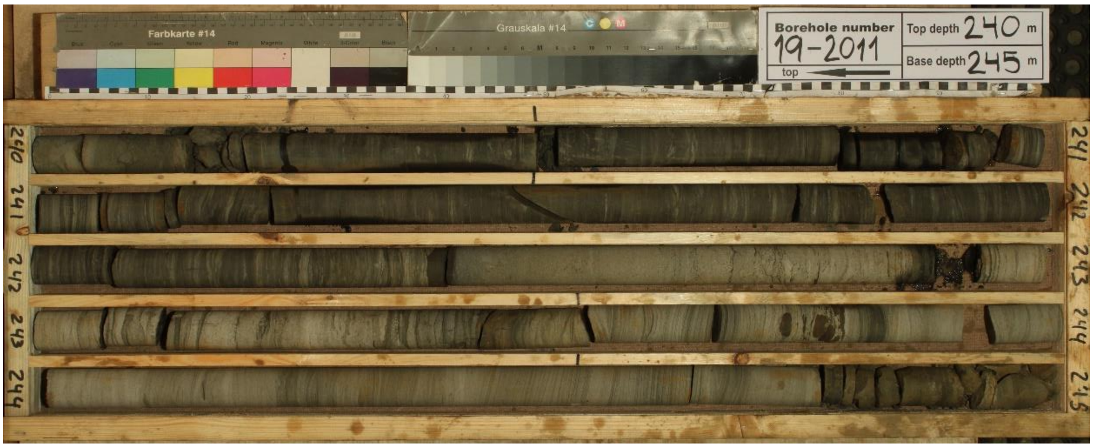

*Figure 5.11 – Core from locality 7 displaying different mud/sand ratio in the thin interbeds of facies F10**

Interpretation

The rapid changes in grainsize suggest that the different structures and mud/sand ratio of this these interbedded silt- and sandstones is due to rapid shift in energy in the depositional environment. The rhythmic interbeds are interpreted as a response to tidal action. Thus, the differences in structures and mud/sand ratio of the rock are due to different energy conditions in the different parts of a tidal flat environment. Flaser-bedded sandstone may represent a sandflat, mudstone with sand-lenses representing a mudflat, whereas the wavy-bedded mud- and sandstone represent a mixed flat (Boggs Jr, 2006).

The vertical mudstone layers occur mostly in the lenticular bedded mudstone, in what is interpreted as a mudflat environment. These layers may be formed by bioturbation, or by exposure and desiccation.

5.3. Depositional Environments

To understand the overall architecture and depositional environment, observing the different facies individually makes little sense as they all represent a building block in a larger puzzle. To understand the depositional story, the facies has been sorted into facies associations. Several different facies can make up one facies association, and one facies may be found in more than one facies association. These Associations are therefore based, not only on the different observed facies, but the interaction and relationship between them, and the overall facies trends. These associations describe the most likely environment of deposition. Color legend for the facies associations can be seen in figure 5.12.

5.3.1. Facies associations

FA1 – Lower shoreface – offshore transition zone

Represented by a lithofacies assemblage dominated by F2, with sporadic ripples of F3 and isolated beds of F6, this facies association is interpreted as the deepest parts of the Endalen Member in the Adventdalen area. Sediments of this association are recognized by fine sand from storms and deposition of mud during quiescent periods. This facies assemblage can be found in second order units B1, B2, C1, D1 and the lowermost part of D2. Of these units, D1 is interpreted to represent the deepest environment with deposition below storm weather wave base. These units either have a massive expression, or internal architectural geometries of parallel to sub-parallel horizontal bedding. The horizontal assemblage of beds is interpreted as event bed surfaces from storms. The massive expressions in the units are interpreted to be caused by heavy bioturbation in the sediments below this wave base. The units of this facies association are all located in the lower parts of the coarsening upwards 1st order parasequences. Due to the presence of sporadic sedimentary structures and the high sand content relative to what can be expected in offshore sediments, the sedimentary environment for these sediments is interpreted as lower shoreface and offshore transition zone.

FA2 – Upper shoreface – foreshore

Facies F3, F4, F5 and F6 are all considered facies deposited under intermediate to high energy marine conditions, and assemblages of these facies represent the lithology of this facies association. These lithofacies occur in combination in units A, B3, B4 and D2. With exception of unit A which has a massive expression, these units show a sub-parallel to wavy horizontal internal architecture. Unit B3 and the top of D2 have a wavy expression which can be related to the troughs and hummocks found in the wave dominated parts of the middle to upper shoreface. The lateral accreting hummocky patterned architecture of facies B4, together with plane beds, troughs and hummocks, this unit is interpreted as the upper shoreface part of a northwards migrating spit or a wave-deflected wandering mouth bar of a delta.

FA3 – Tidal flat

The cyclical and thin interbedding of fine sandstone and mudstone and the presence of wavy, lenticular and flaser bedding in Facies F10* suggest deposition in a much more tidal influenced part of the system than for the other facies. This facies is found in combination of foreshore-upper shoreface facies, and the north-eastern distribution of this facies in the study suggest a depositional environment close to the source area and the palaeo-shoreline.

FA4 – Braided rivers

Facies F7 and F8 are fluvial deposits and represent the non- marine top of the Endalen Member. The sediments consist of conglomerates and very coarse sandstones. The planar cross bedding in these sandstones is indicative of unidirectional currents, and the remains of plant stems at the base of the sandstone are excellent indicators of subaerial exposure. Sheet-like features of granules in the sandstones witness changing flow power in the fluvial system, and in several locations, the general trend is a fining upwards within this non-marine unit. The very coarse sand and the evidence of rapidly changing flow power suggest a braided river system as a more likely depositional environment than a meandering system (Boggs Jr, 2006).

FA5 – Coastal plain

The thin seams of coal of facies F9*, with its associated rooting of sediments below, suggest a sub-aerial, nearshore environment with a high production and storage of organic debris. As for the tidal sediments of FA3, this facies is also only found in the north-eastern part of the study area.

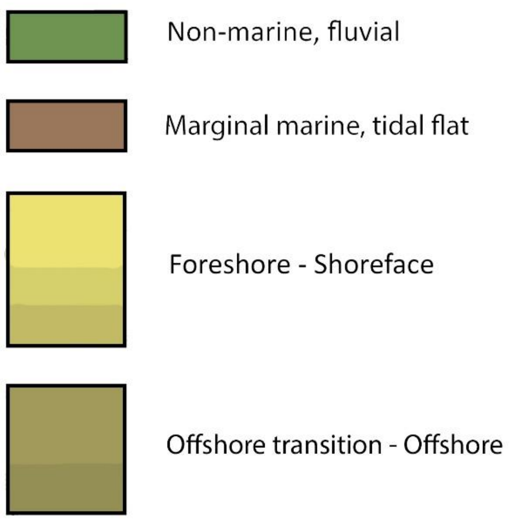

Figure 5.12 – Color legend showing the different facies associations as they are presented in logs, panels and box diagrams. FA5 – Coastal plain is not indicated as this only occur as thin coal-seams which are indicated by black lines in figures.

6. Sand-body architecture

6.1. Introduction

This chapter first describes the characterization of the architectural surfaces and the elements they bound. Then the lateral development of these surfaces and the architectural elements are presented in outcrop scale (< 2 kilometers) from laterally extensive photo-models. These photo models also reveal some characteristic internal architecture of 2nd order elements which are described and interpreted. Last, the surfaces are interpreted in a sequence stratigraphic perspective and presented in a large-scale correlation of the obtained logs, as transects across the study area (< 10 kilometer).

6.2. Characterization of surfaces and elements

Three orders of surfaces have been established with the following characterization seen from photo-models and outcrop:

First order architectural surfaces are laterally extensive boundaries in the photo-models which are traceable for several kilometers, in general across the entire study area, and separate sand body units of the same type of vertical facies variations. As the boundaries all place deeper lithologies on top of the surfaces than what is seen below, the 1st order element boundaries are representing flooding surfaces. 1st order architectural elements are therefore interpreted as parasequences, as these **are** defined as “a relatively conformable succession of genetically related beds or bed-sets bounded by flooding surfaces”(Van Wagoner et al., 1988). The boundaries of the first order elements provide the framework for the sequence stratigraphic analysis of the basin evolution. First order element boundaries are shown as red lines in photo-models.

Analysis of photo-models show some unit boundaries with extensive lateral extents, but shorter than the 1st order element boundaries. Many of these surfaces show thinning of the lithological units they bound and pinch out within the study area. These correspond well to facies association boundaries in the obtained logs. The units bounded by these boundaries are defined as **second order architectural elements.**

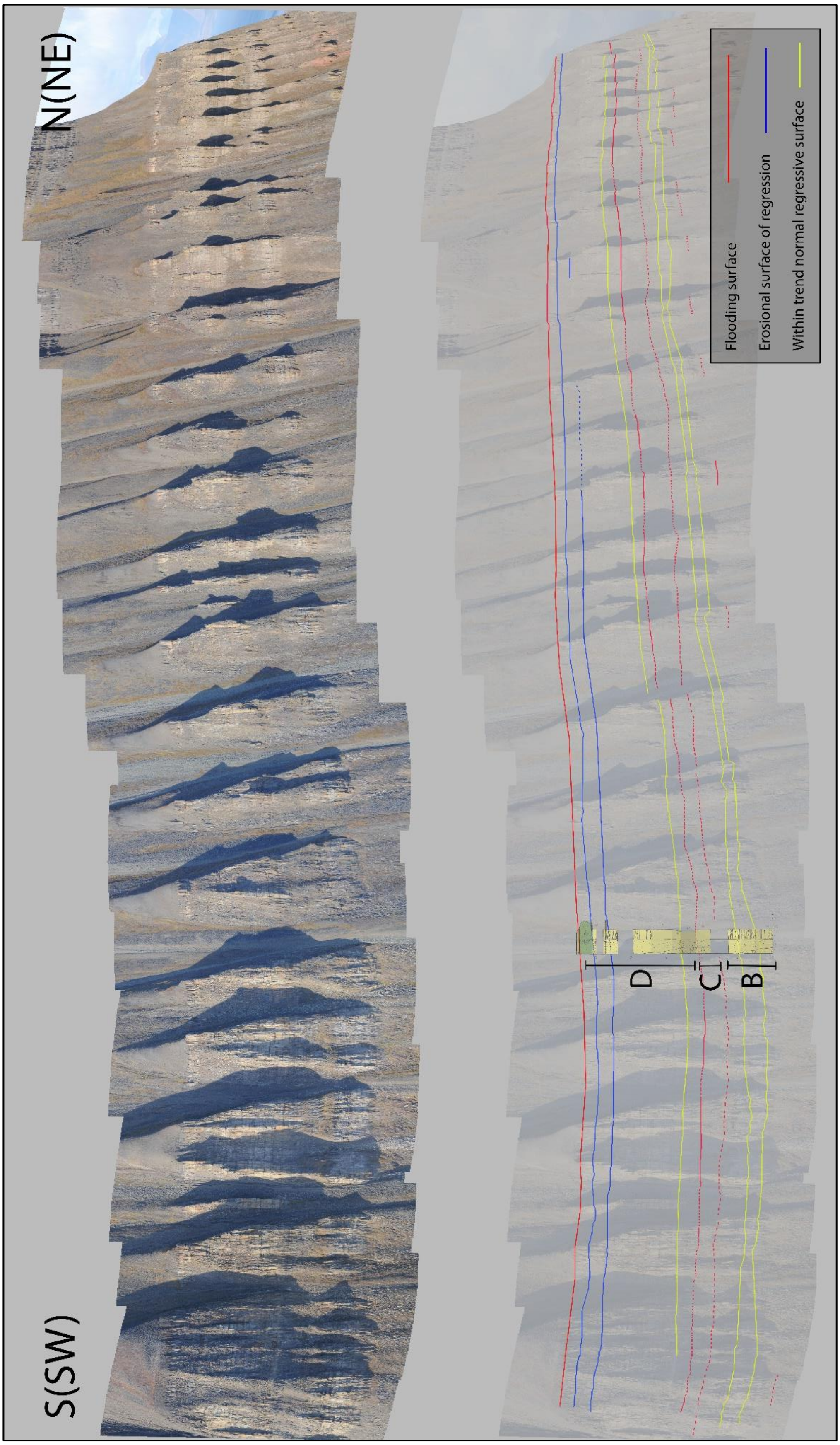

Figure 6.1 - Panorama photo-model of the 2-kilometer-long western valley side of Longyeardalen, showing the architectural configuration of the four regressive depositional parasequences in the most distal part of the study area. The figure is horizontally reduced to 30 percent of original.

Different elements show distinct changes in internal geometry, color and/or weathering patterns in addition to differences in facies assemblage. These are drawn as blue and yellow lines in photo-models, differentiated by their relative importance in a sequence stratigraphic analysis. The differentiation of these boundaries is further described in chapter 6.5.

Within the second order elements, bedding planes reveal individual beds which can be related to depositional geometries. These beds are recognized as architectural elements of third order.

6.3. Depositional units and their lateral development

The architectural surfaces and their elements have been interpreted from panorama photography of the exposures in Longyeardalen (Fig. 6.1, 6.2), Endalen (Fig. 6.3) and Todalen (Fig. 6.4), as well as the logged outcrops. The rock walls in Longyeardalen and Todalen have a north-east to south-west extent and the lateral development seen from photo-models in these valleys all show a dip-oriented cross section of the paleo-shoreline. The Endalen panorama is an oblique oriented model as the logged part of the valley is facing north, exposing the rock-face in a West-East section (Fig 6.3). Vertical displacement of surfaces occurs in these panoramas due to geometric and topographic distortion. Therefore, in sections where the same vertical displacement occurs for all interpreted surfaces, this displacement is not related to the real architectural geometry of the interpreted units.

The organization of lithofacies units and their bounding surfaces show four regressive depositional parasequences with a progradational character and occasional backstepping (Architectural elements A-D). All first order flooding surfaces (red lines) in the photo-models divide two regressive parasequences, implying an intervening transgression.

In general, the flooding surfaces is the only trace of transgression as almost no elements are found to be formed during transgression. Only one possible transgressive unit has been found within parasequence C in locality 4 in Todalen, pinching out northward. This gives the unit a wedge like shape landward (Fig. 6.4). In this locality, parasequence C consist of a two-meter-thick succession with a deepening upwards

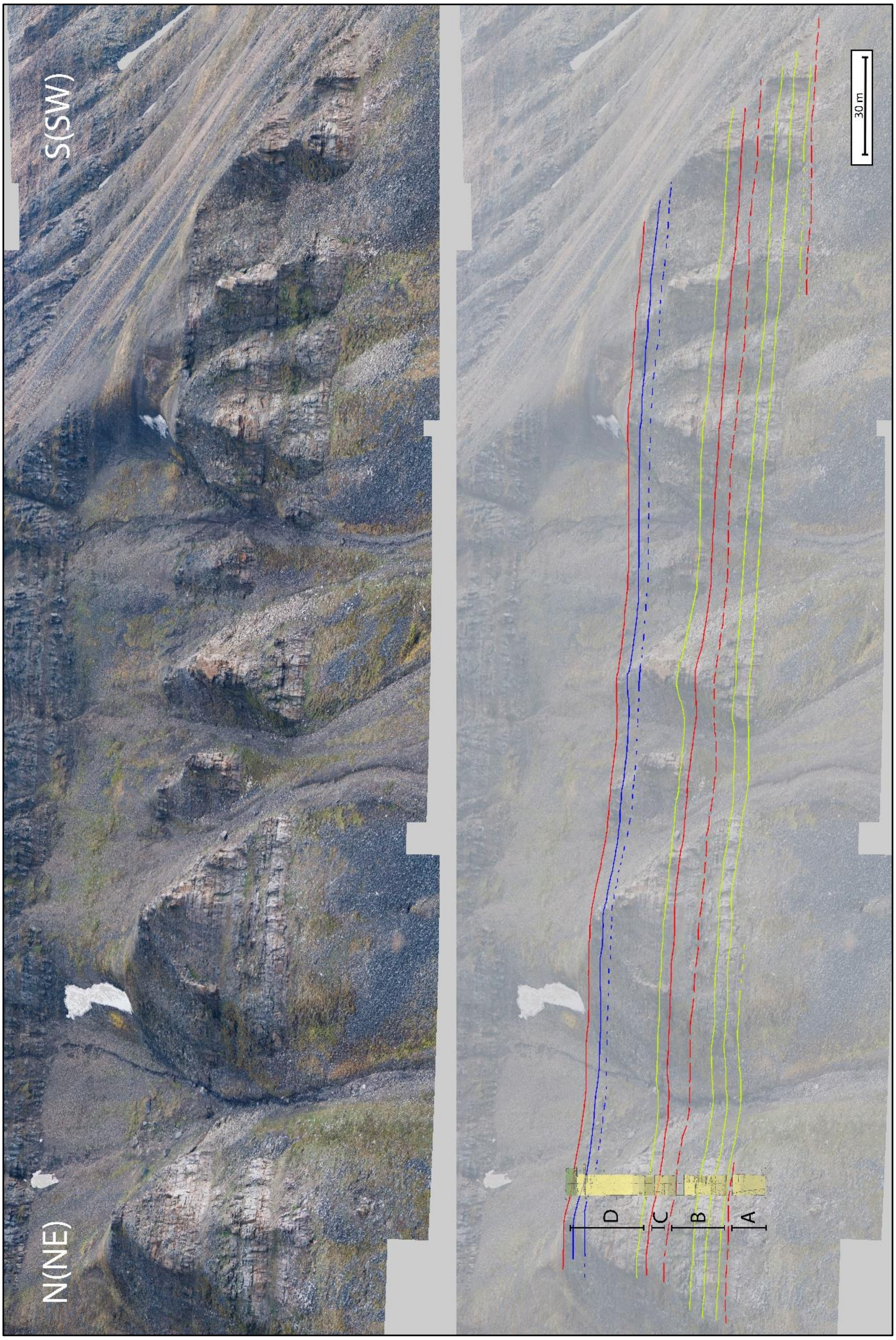

Figure 6.2 – Panorama photo-model of a 530-meter-long section of south-eastern Longyeardalen. The most prominent difference from the western part of Longyeardalen is the occurrence of 2nd order element B1 in the bottom of the second regressive depositional parasequence. Vertical and horizontal distance is to scale.

trend, and a following two meters of shallowing upwards succession. Despite these observations, further investigations are needed to determine a transgressive deposition for this unit.

The architecture of the large scale parasequences show a tabular shape, with some basinward thinning. From figure 6.1, (appendix 9) showing the rock-face of western Longyeardalen, a southward thinning of more than 5 meters can be seen for parasequence C, displaying a southward oriented wedge-shape. In the same photo-model, parasequence D show a dramatic reduction in thickness in the middle of the valley, thickening towards both south and north. This gives the unit a somewhat undulating geometric expression in kilometer-scale.

Of the described parasequences, B shows the most uniform thickness distribution in this southern part of the study area. This unit is however thinning northward where it is interpreted to be interfingering with tidal flat sediments. This same interfingering is seen for parasequence A, which show a dramatic decrease in thickness towards south-west, culminating in isolated exposures up to 10 meters thick.

In the eastern side of Longyeardalen (Fig. 6.2), the same configuration can be seen as for the southern part of the western side photo-model (Fig. 6.1). However, this exposure includes 2nd order element B1, the most distal sediments found in this lower part of the stratigraphy. B2 also shows a somewhat less undulating expression than in the western part of the valley.

In Endalen, the local conglomerate of D3 both reduce its thickness and vertical distance to the fluvial sandstones of D4. As the two units close, the marine sandstone of unit D2 in between them can be seen wedging towards the east (Fig. 6.3).

A slight thinning towards east can also be seen for parasequence B, resulting in the disappearance of B1 and a reduced thickness for unit B2. Unit B4 is not present in Todalen (Fig. 6.4).

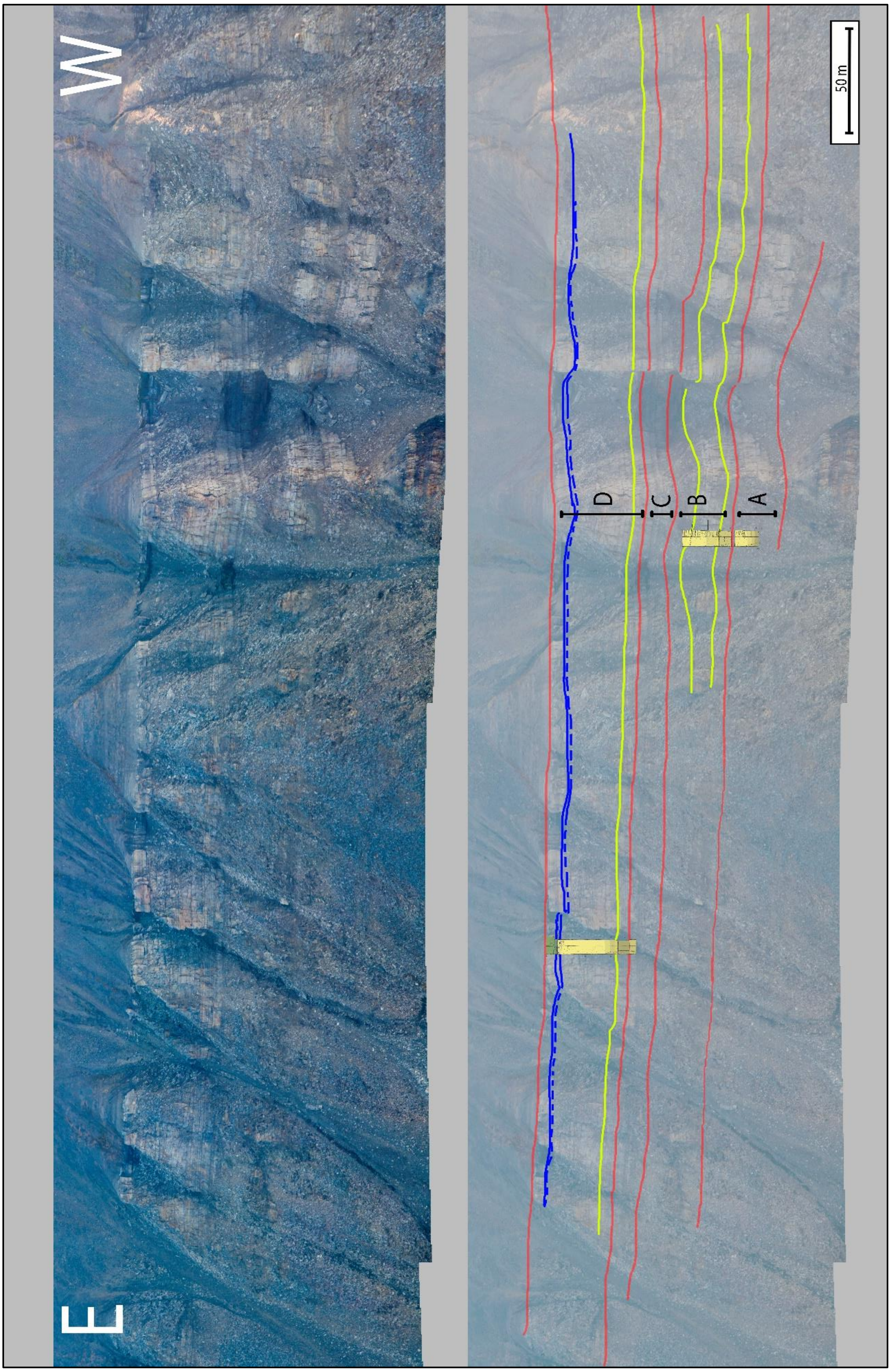

Figure 6.3 - Panorama photo-model by the north-facing rock-face by locality 3 in Endalen.

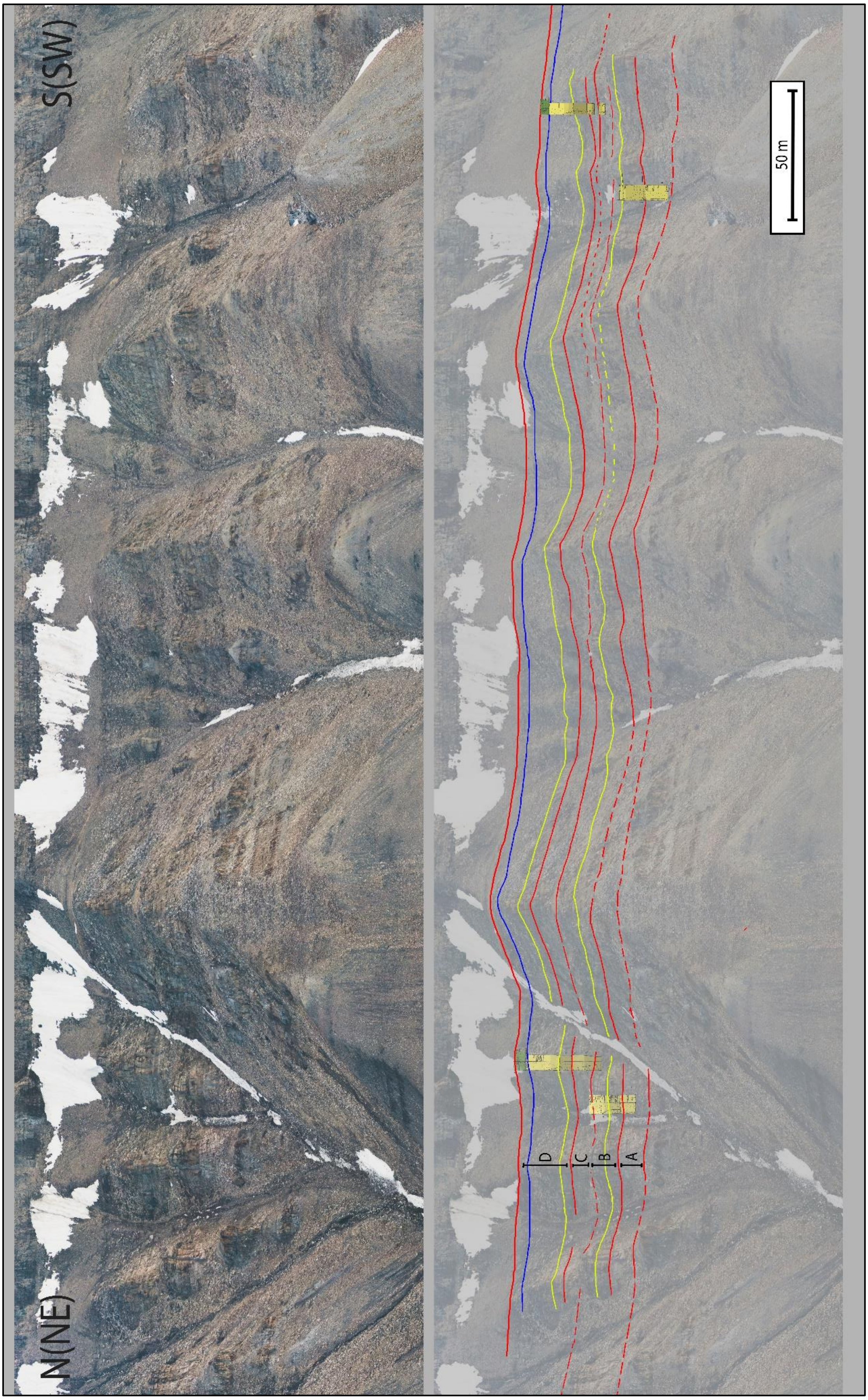

Figure 6.4 – Panorama photo-model of the rock-face by locality 4 and 5 in north eastern Todalen.

6.4. Internal architecture of 2nd order elements

2nd order elements are tabular, extensive lithostratigraphic units displaying differences in color, internal architecture and lithofacies assemblage. The internal boundaries of the 2nd order elements represent the geometric assemblage of 3rd order elements. The orientation, extent and relationship between these geometries are especially interesting as they reveal some characteristics of the depositional system.

In general, 3rd order elements can be traced for tens to hundreds of meters, with thicknesses of single elements varying from a few centimeters to a few meters. The 3rd order elements are interpreted as events of deposition, some likely representing dynamic shifts in the sedimentary system such as a migrating barrier or shifting of a lobe, and others representing storm beds or events of high sedimentation rate. Thus, they are representing a time-span from one storm event to a couple of depositional seasons. Some of the thicker sandstone beds are amalgamated and heavily bioturbated. In these cases, it is possible to distinguish individual beds from each other by the presence of pebble layers or as surfaces with abrupt termination in bioturbation (Fig. 6.5). These are not visible in the panoramic photo-models and are therefore not traceable.

This chapter present the most characteristic internal geometries of the different 2nd order architectural elements.

Figure 6.5 - Non-depositional discontinuity surface marked by a distinct increase in bioturbation of the sediments below. This surface represents a common 3rd order element surface within massive amalgamated sandstone beds.

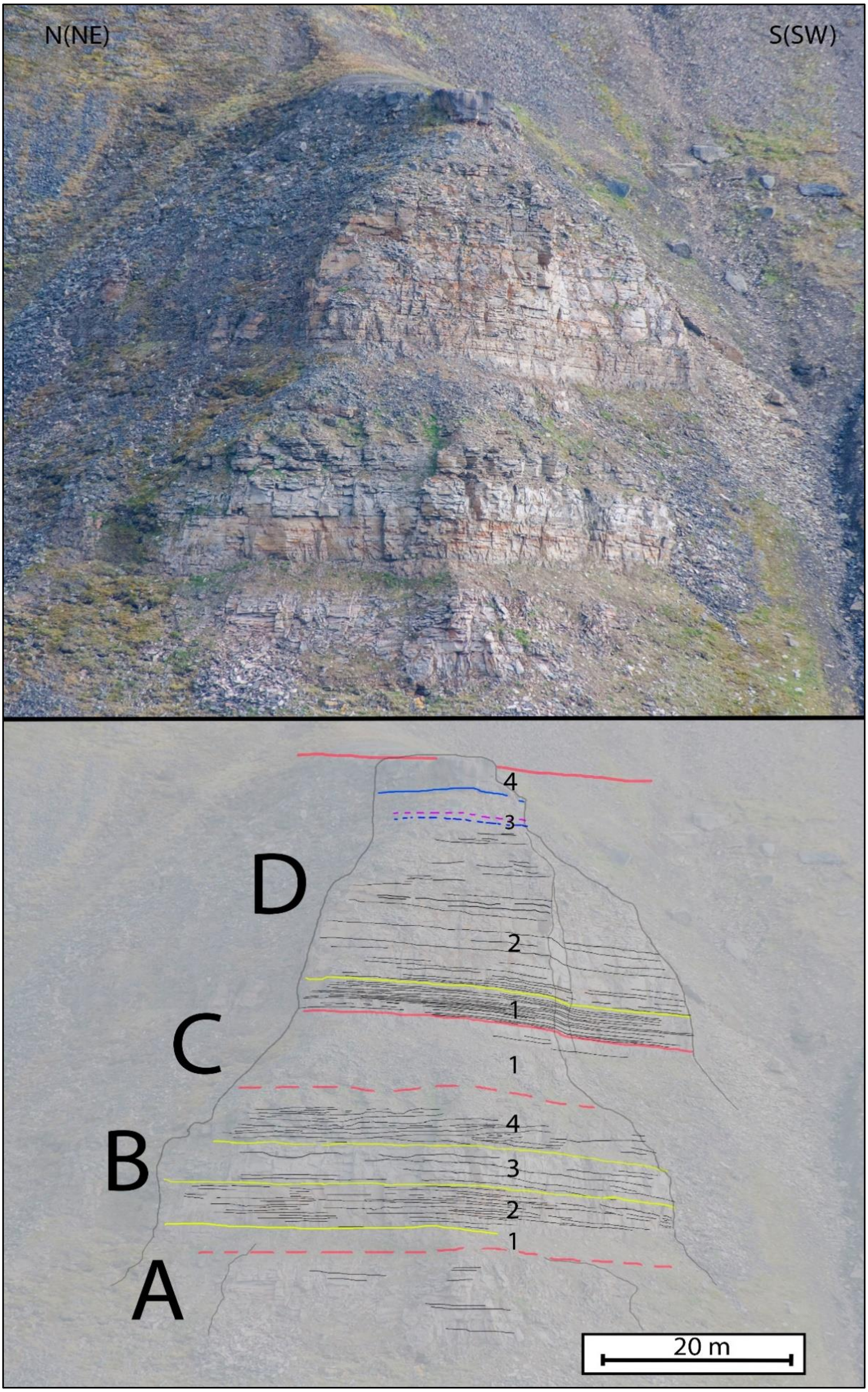

Figure 6.6 – Uninterpreted and interpreted outcrop of locality 2 indicating the different architectural elements and their internal geometries.

6.4.1. Horizontal, sub-parallel event beds

2nd order units B2, D1 and D2 show internal geometries consisting of horizontal parallel to sub – parallel bedding planes. Individual beds are interpreted as event-beds where storms cause near-shore currents, re-suspension and settling of seafloor sediments (Swift and Thorne, 1991; Wiberg, 2000). The beds interpreted from photo-models are not necessarily representing single event-beds as heavy bioturbation alternate the beds after re-deposition. Their surfaces most likely represent storm events of the largest magnitudes, resuspending more sediment than the biogenic processes can alternate before the next storm.

The scale of beds, their frequency and lithological properties are not consistent between the different 2nd order units. A short description of each of these 2nd order units are presented below.

B2

This unit show internal assemblage of horizontal, sub-parallel beds of 3rd order elements (Fig. 6.6, 6.9). The beds are relatively thin (< 50 cm) and are occasionally disrupted. The unit consist of lithofacies F2 to F5, with occasional isolated hummocks of facies F6. Several surfaces can be seen with distinct termination in bioturbation. Without any apparent truncation, each element has an expected lateral extent of 10s to 100s of meters.

D1

Characteristic lateral extensive horizontal parallel thin bedded unit in all logged outcrops (Fig. 6.6, 6.7). The unit is between 3 to 4.5 meters thick comprising of 2-10 cm thick sheet-like beds of facies F2. The upper boundary of this unit is a sharp, erosional boundary to unit D2 above. The internal geometry shows no sign of pinching out, and the lateral extent of these thin sheets are in a scale of >100 meters with occasional disruption of bedding planes from weathering. These sheets are heavily bioturbated, especially towards the top of each bed. The bed contacts are characterized by a gently wavy layer of fines and termination of bioturbation.

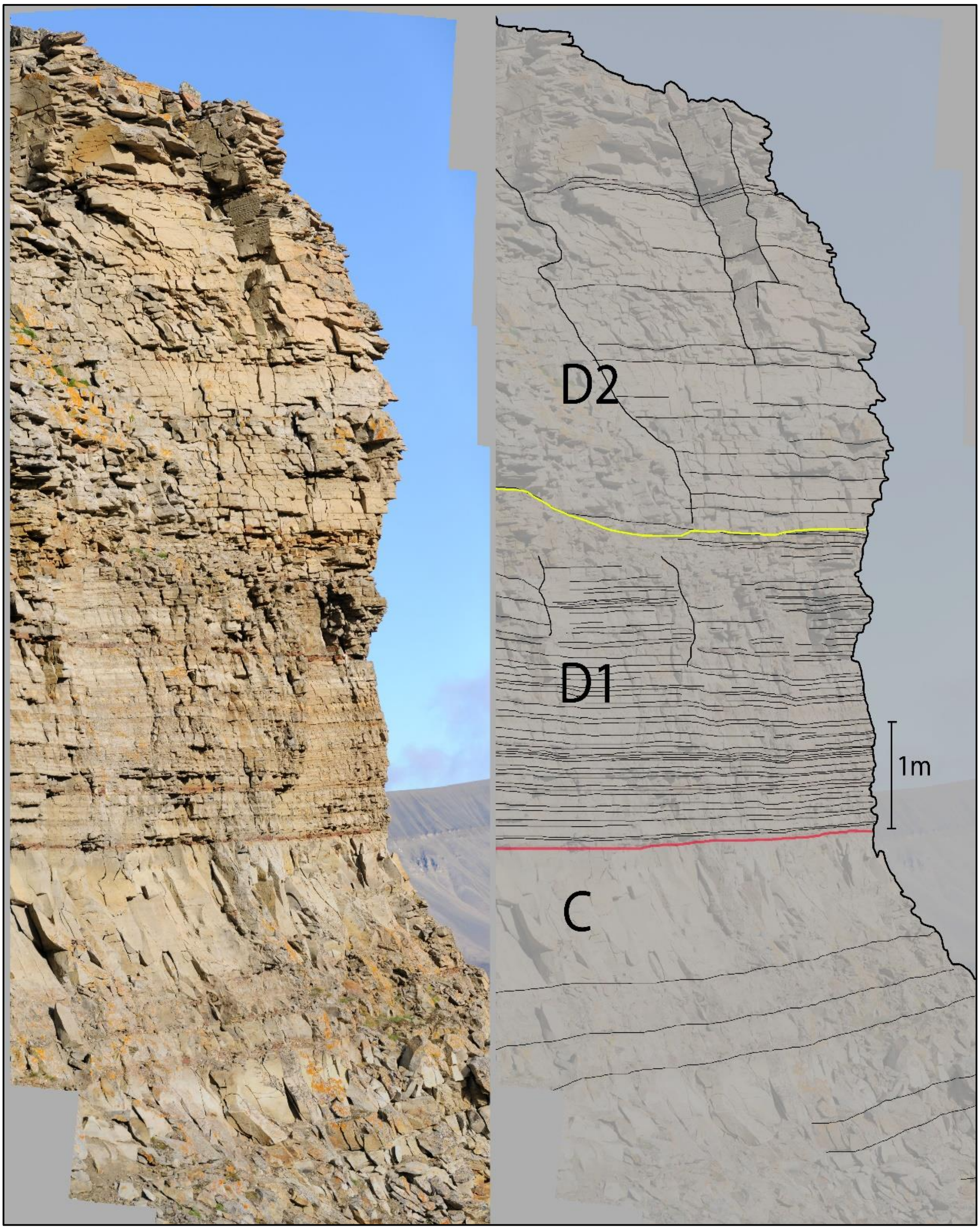

Figure 6.7 - The internal character of units C, D1 and D2 from locality 8 In Longyeardalen. The erosional base of unit D2 is easily recognizable.*

D2

This is the thickest unit of the Endalen Member with an average thickness of 18 meters and a maximum thickness of 23 meters in Endalen. The lower boundary of this unit shows an erosional character to the underlying sheets of D1. The unit shows a coarsening upwards trend in bed-thickness, from < 10cm thin sheets in the lower part to meter thick beds towards the top (Fig. 6.7, 6.10). The general internal architecture consists of horizontal parallel beds with occasional disruptions. The uppermost few meters of this unit show a more sub-parallel to hummocky pattern which corresponds well to the occurrence of lithofacies F6. The top is however, heavily weathered, which makes bedding planes hard to distinguish from weathered cracks in photo-models. The uppermost 50 cm below unit D4 is colored red from iron cementation of the sandstone.

One set of surfaces stands out from the otherwise horizontal trend of the bedding planes within unit D2. The surfaces occur in the middle of Longyeardalen in a relatively thin part of the unit, with a slight dip towards the south-west compared to the other surfaces above and below (Fig. 6.8). These surfaces have not been investigated in the field, and the characteristics of the surface is thus not certain. The dip change is relatively small, and is calculated to be equivalent to 0.03 degrees, to the otherwise 0 – 0.01 degree of dip of other bedding-planes in the same unit. This dip is measured from the photo-model in appendix 9 (Fig. 6.1), and the sources of error related to geometric distortion and 2d imaging of 3d architecture in these models (see chapter 4.3.1) makes the uncertainty of this measurement quite large.

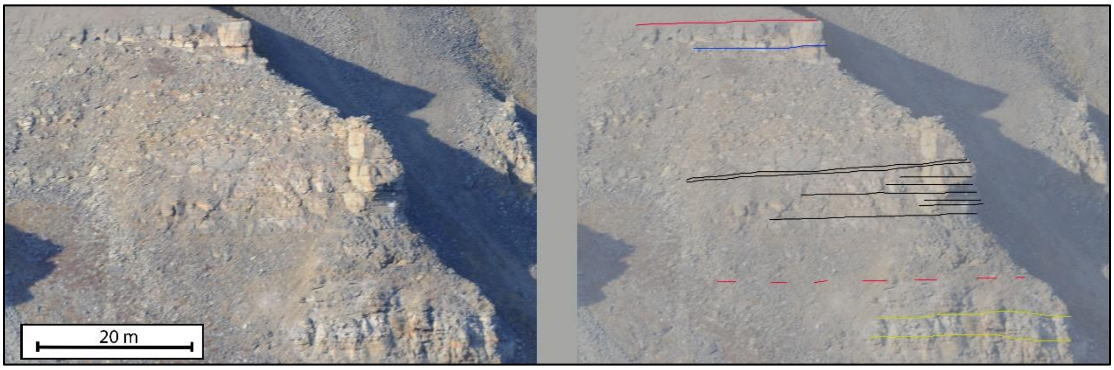

Figure 6.8 – Un-interpreted and interpreted cliff section from the western rock-face of Longyeardalen. One set of bedding planes can be seen with a different dip than the bedding planes beneath it.

Interpretation

Storm generated event-beds are characterized by their large lateral extent, a fine-grained top, and heavy bioturbation at the bed contacts (Storms, 2003; Wiberg, 2000). This internal bed configuration suggests an event-based deposition. Deposition of the re-suspended sediments are not restricted by the wave-base position (Storms and Hampson, 2005).

The most prominent beds are found in unit D1, suggesting an offshore environment of deposition. The erosive contact between units D1 and D2 is interpreted as the storm wave base. This surface has an erosional character due to a lowering of relative sea level and the transition from ambient water to a higher state of energy. Above storm weather wave base, the beds become thicker and more amalgamated, and above fair weather wave base, the event beds become less distinct due to mixing with fair weather sedimentation (Storms, 2003).

Plane parallel beds, individual hummocks and combined flow-character of ripples are all indicative for a high energy environment with both current and oscillatory flow. The high presence of these bedforms indicate a deposition above fair weather wave base, which suggest unit B2 and top of D2 as the shallowest deposits of the described units.

The surfaces of a slightly larger dip within unit D2 are interpreted to represent shoreline clinoforms, representing the dip of the paleo-shoreline. As storms shed of sediments in the upper shoreface and redistribute this in a more distal setting (Hobday and Reading, 1972; Kreisa, 1981; Storms, 2003), the remaining firm sediments may be preserved and stand out as a bedding plane. However, large storms are known to flatten the gradient of the foreshore and upper shoreface (Hobday and Reading, 1972), an observation which does not correspond well to the steeper character of the observed surfaces. The surfaces may therefore reflect a period of more fair-weather deposition, steepening the upper part of the shoreline profile. The measured dip corresponds to deposition in the lower shoreface/inner shelf (Hampson and Storms, 2003).

6.4.2. Wavy-parallel to hummocky geometry

2nd order units B3 and B4 display a set of highly wavy to hummocky patterned internal assemblage of 3rd order elements. The architectural properties in these units reflects the depositional conditions for their internal facies assemblage. The high energy of both oscillatory motion from waves and unidirectional currents forms sets of hummocks, expressed as highly undulating sandstone-bodies of 3rd order. The different characteristics of the units are described below.

B3

This unit lies unconformably on top of unit B2, with a highly undulating erosional surface as its lower boundary. The thickness of the unit is highly variable when tracing the element along a shoreline perpendicular transect (Fig. 6.1).

The internal geometry of this unit shows a wavy-parallel to hummocky pattern (Fig. 6.9, 6.10). The unit dominantly consist of Hummocky-Swaley cross-bedded sandstone of facies F6, but instances of plane parallel stratification and ripple cross lamination are also found in the unit. The internal 3rd order elements often truncate the underlying beds which in some places cause termination of elements. The 3rd order internal elements have an apparent lateral extent of 10s to some 100s of meters.

B4

Distinctive for this unit is an internal assemblage of hummocky-patterned lateral accreting elements (Fig. 6.6, 6.9, 6.10). This unit only has laterally extensive exposures of this geometry in Longyeardalen, where locality 1 and 2 both show an internal configuration of bedding planes with a dip towards north, terminating towards the lower boundary of B4. The sandstone bodies of 3rd order elements separated by these bedding planes vary in extent from a few meters to more than 100 meters, and commonly less than 1-meter thickness. In addition to the lateral accretion pattern in this unit, the bedding planes show in internal wavy to hummocky pattern. Lithologies within the unit is dominantly facies F3, F5 and F6.

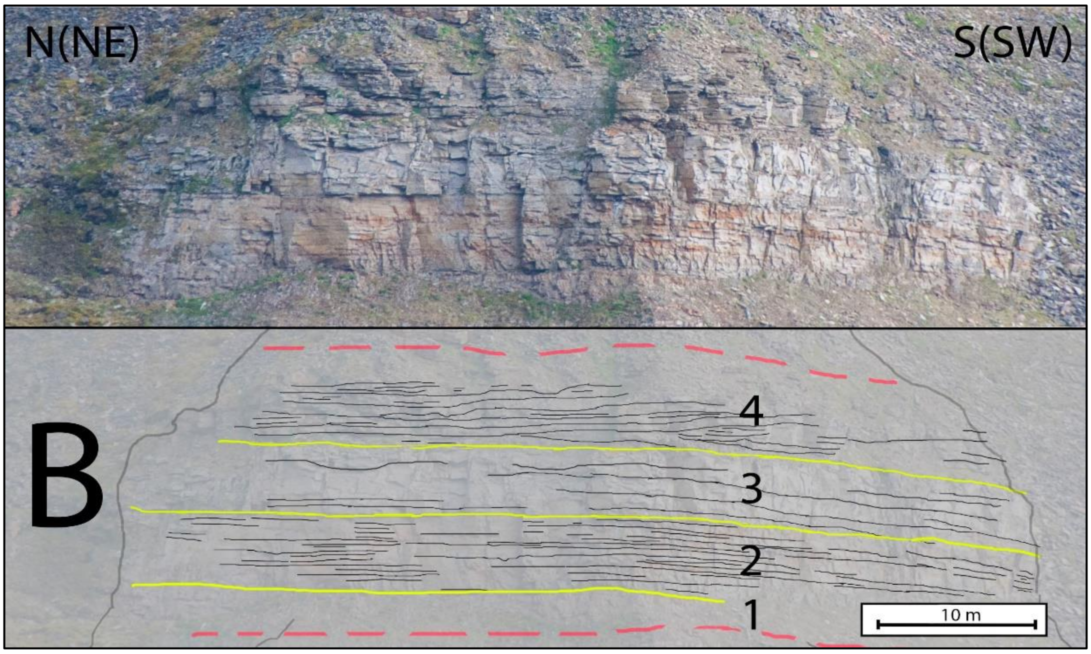

Figure 6.9 - This figure shows 1st order parasequence B and the subdivided 2nd order elements in Locality 2, Nybyen. Bedding planes dividing 3rd order elements are outlined and show distinct geometric features for each 2nd order element.

Interpretation

Both units are representing shoreface deposition above fair weather wave base. The somewhat coarser lithology and larger presence of plane parallel bedding planes suggest a shallower deposition of unit B4 than unit B3.

The scale, extent and orientation of the 3rd order elements within B4 suggest that the unit represents the migration of a distinct bedform and not the progradation of the overall sedimentary system. Considering the northwards migration of the unit, it is most likely representing a bedform controlled by waves and along-shore currents. The north-south trending basin interpreted from previous studies (Bruhn and Steel, 2003; Lüthje, 2008) favors a wind fetch from the south, and a northwards progradation of shoreface bedforms. As no root horizon is found at the top of the unit, the bedform is likely submerged. Wave dominated deltas with one dominating wave direction are found to produce wave-deflected mouth-bars, and these may develop into offshore spits and alongshore sand bars (Nardin and Fagherazzi, 2012). Unit B4 share characteristics to the dune and bar-trough deposits of modern day Skagen spit system (Nielsen and Johannessen, 2009), both in terms of lithology and architecture. The unit may also have been formed by longshore bars.

Figure 6.10 – Uninterpreted and interpreted section of the Endalen Member as it is seen above Sverdrupbyen in the inner part of western Longyeardalen, close to locality 1. Interpretation show the different architectural elements as well as their internal geometrical expression.

6.5. Sequence stratigraphic analysis

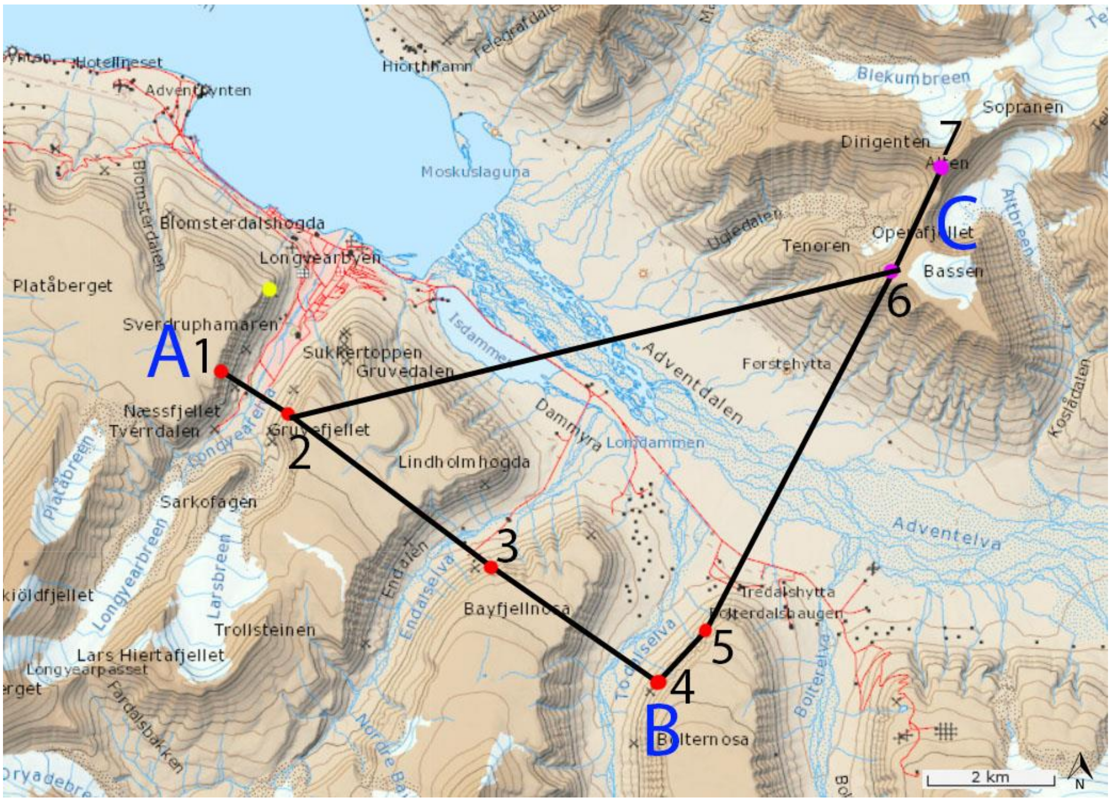

Figure 6.11 - Map showing the studied localities, as well as the three transects used for sequence stratigraphic analysis.

To further investigate the large scale depositional patterns between the different outcrops in the study area, a sequence stratigraphic analysis has been carried out. Sequence stratigraphy is defined by Van Wagoner et al. (1988) as "The study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities".

6.5.1. Key sequence stratigraphic surfaces

Three types of sequence stratigraphic surfaces have been recognized in field and interpreted from photo-models (Fig 6.12).

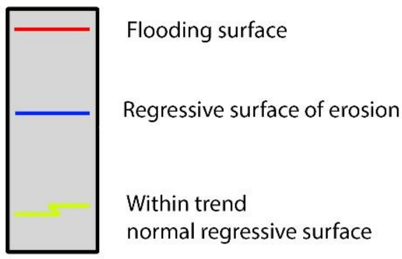

Figure 6.12 – Legend for the three key figures as shown in figures.

Flooding surface

The first and most important surface type place deeper facies on top of shallower facies (Fig. 6.14 A). All 1st order element boundaries are represented by this type of surface. The transition from proximal to distal lithologies in the logged sections at these boundaries suggest a rise of relative sea level, resulting in a flooding surface. As flooding happens in a relatively short time span, very small changes in relative sea level may cause extensive flooding (Kamola and Van Wagoner, 1995). Thus, these flooding surfaces act as chronostratigraphic markers when correlating localities across the study area (Catuneanu, 2006). Some flooding surfaces are of smaller extent and are interpreted as less prominent changes in relative sea level. This is especially observed in the northern part of the study area, where several small scale floodings place shoreface and foreshore sediments on top of tidal flat deposits. The surface produced by these small-scale flooding events are not recognized as first order boundaries as they have a relatively small lateral exten. In addition to the small-scale flooding surfaces in the northern part of the study area, there is one local flooding of the marine reworked conglomerate of parasequence D3 in the south-western part of the study area. This event is only captured in localities 1, 2 and 3.

Regressive surface of erosion

This type of surface occurs when the relative sea level drops, forcing a seaward shift in shoreline and fluvial incision of the sediments below (Bhattacharya and Walker, 1991). Two instances of this boundary type are seen within the Endalen Member, both in the uppermost part of the succession (Fig 6.13, 6.14 C). The surfaces are seen as the lower boundary of the conglomerates and coarse sandstones of unit D3 and D4. Unit D3 is interpreted to represent the same type of fluvial material which is found in unit D4, but has experienced an intense marine reworking during a local flooding. The undulating lower boundary of this conglomerate suggest an erosive contact to the marine sandstones of unit D2 below. Unit D4 has an erosive lower boundary in the entire study area, an unconformity which may be linked to a further basinward forced regression of the system.

Figure 6.13 – Regressive surface of erosion separating unit D4 from D2 in locality 2.

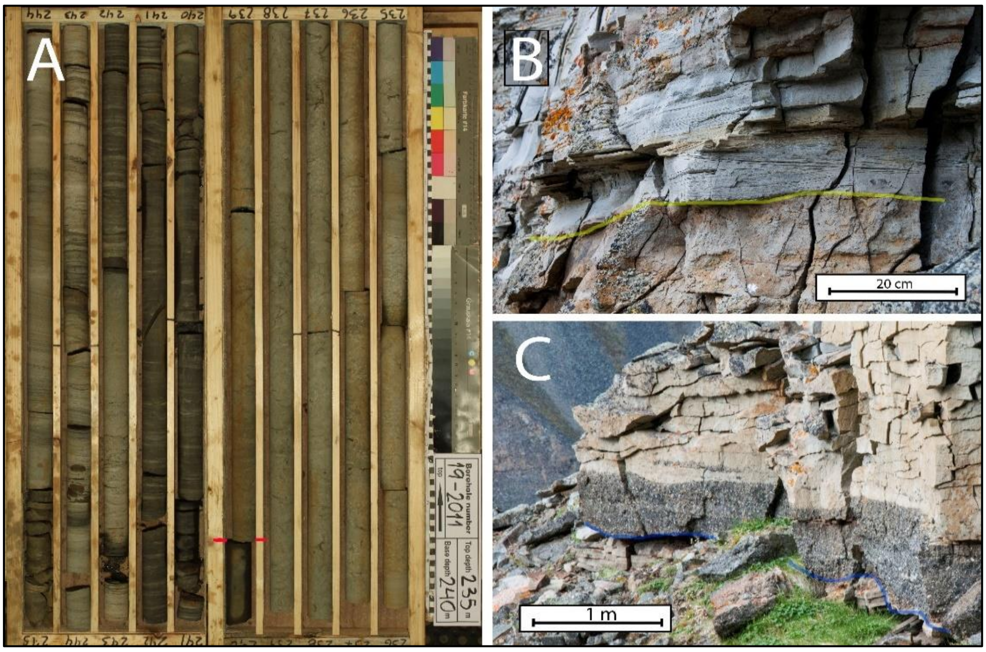

Figure 6.14 – Figure showing the three most common surfaces within the Endalen member. A) Pictures from cores drilled by SNSK at Alten, Operafjellet. Flooding surface placing lower shoreface sediments on the right, on top of tidal flat sediments on the left. Red mark indicates the flooding surface. The sediments are younger upwards and to the right. B) Within trend normal regressive surface of an erosional character separating unit B2 and B3 in locality 2. C) Regressive surface of erosion, placing the local conglomerate of unit D3 within upper shoreface sandstones of unit D2.

Within-trend normal regressive surface

Most of the boundaries dividing the 2nd order architectural elements represent this type of surface (Fig. 6.14 B). This type of surface is a lithological discontinuity within a normal regressive parasequence, with a strong physical expression in outcrop (Catuneanu, 2002). Catuneanu describes the surface as a “contact that develops during normal regressions on top of prominent shoreline sands." Although the surface represents a lithological discontinuity, the surface is conformable and must be correlated with diachronous lines as the surface prograde along with the shoreline. In this study, this boundary divides all lithological units within parasequence B, as well as the boundary between unit D1 and D2. The boundary separating unit B2 and B3 shows an erosional character, but this is interpreted to be only locally time-quivalent unconformities as unit B3 have a slightly higher energy regime and facies of more erosive character.

6.5.2. Sequence stratigraphic development

Log-panels for three different transects have been correlated and interpreted (Fig 6.15, 6.17, 6.18). Diachronous within facies trend boundaries are represented by shazam lines in the transects. These lines tie together similar lithologies existing in different times, and therefore show the progradational and retrogradational nature of the sedimentary system.

Observations

In general, the parasequences are sheet-like, basin scale units, with a general coarsening upwards trend. There are four distinct parasequences, displaying lateral continuous cliffs in the mountain-sides in the study area. The parasequences have relatively consistent thicknesses through the study area and approximately extents for 10s to 100 kilometers.

Parasequence A is only present as isolated cliffs in Longyeardalen, with a more continuous extent towards north and east. It holds a facies assemblage of F4 and F5, which also gives the internal architecture of the parasequence a massive expression. Parasequence A is 11 meters thick in locality 2, with somewhat thinning towards the east. Interpreted correlation to the logs presented from Operafjellet, it is thickening significantly in northern direction where it interfingers with lithostratigraphic units of tidal flat deposits and coal. A larger number of facies shifts is seen in parasequences A and B in locality 6 and 7, bounded by several small-scale flooding surfaces (Fig 6.17,

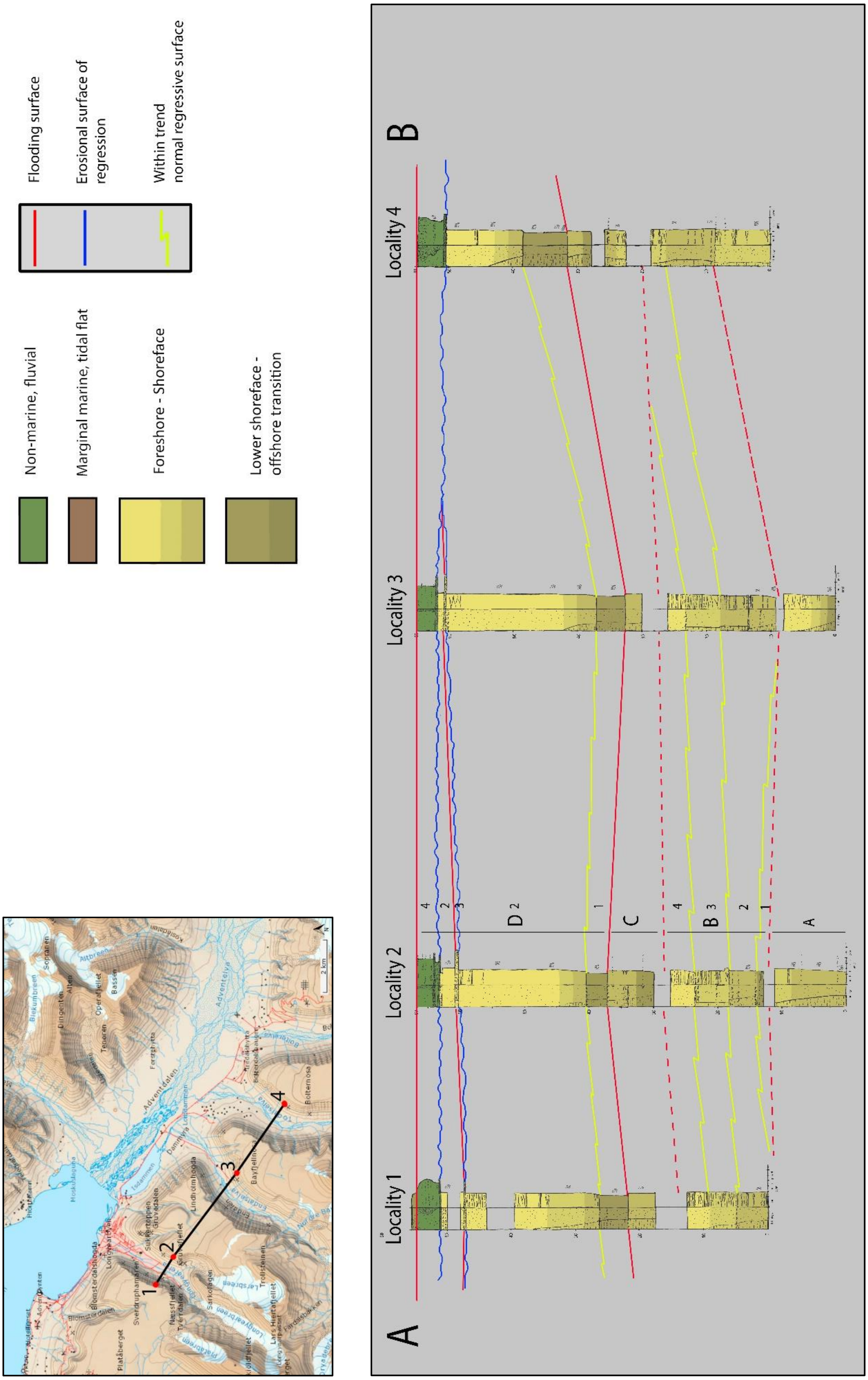

Figure 6.15 – Transect of logged sections in the 8.5-kilometer NW- SE direction from locality 1 to locality 4.

6.18). These flooding surfaces cannot be seen south of Adventdalen. The flooding surfaces representing 1st order parasequence boundaries are correlated to the flooding surfaces in localities 6 and 7 which show the largest displacement of facies.

In these transects the architectural nature of parasequence C is better displayed than in the outcrop-scale panorama models. This parasequence is recognized as a massive, dark unit of three to eight meters thickness south of Adventdalen. With a larger range

of facies and a greater thickness in locality 6 and 7, the parasequence has an overall wedge-like external shape, pinching out towards south-west. The parasequence is 13 meters thick in locality 6, thinning to approximately 6 meters in locality 1 (Fig. 6.18).

Unit D3 is only present in the south-western part of the study area, with a maximum thickness of 50 cm in locality 2 (Fig 6.15, 6.16, 6.18). The unit is an instance of marine reworked conglomerate of facies F8b and occurs as a thin bed within unit D2. The unit has a sharp and somewhat undulating erosive lower boundary and a transitional upper boundary to unit D2. D3 has an upper boundary representing a flooding surface which is interpreted to be time-equivalent in locality 1, 2 and 3.

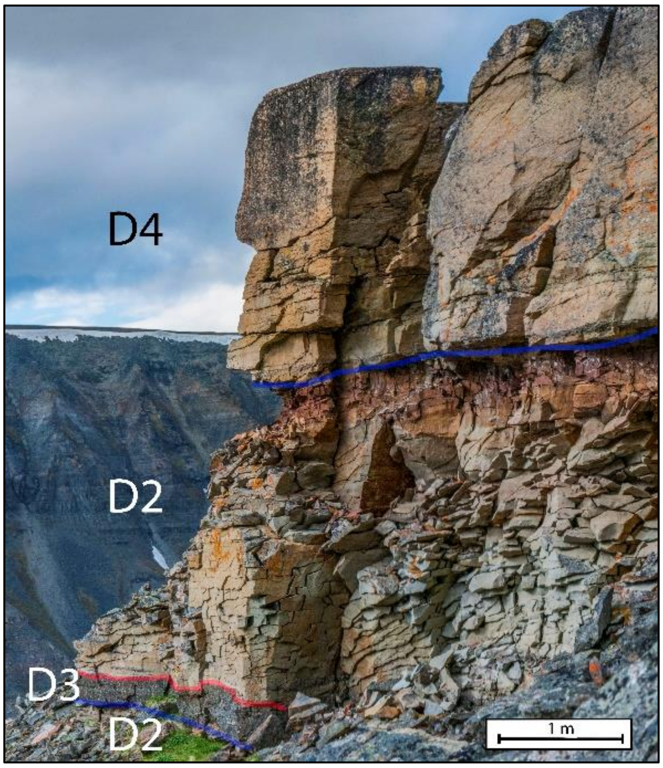

Figure 6.16 - The configuration of elements in the upper part of 1st order parasequence D in locality 2.

Element D4 represents the fluvial top sandstones and conglomerates in the succession (Fig. 6.16). This unit is well marked in outcrops as a distinct hard-profile cliff-unit of 2 – 3 meters thickness. This thickness has little variability within the study area. However, the internal composition changes as a distinct increase in pebble sized clasts towards the north. The unit has an undulating erosional boundary, and a non-depositional flooding surface to the fully marine shales of Basilika Formation above. The fluvial sandstones and conglomerate in unit D4 is found

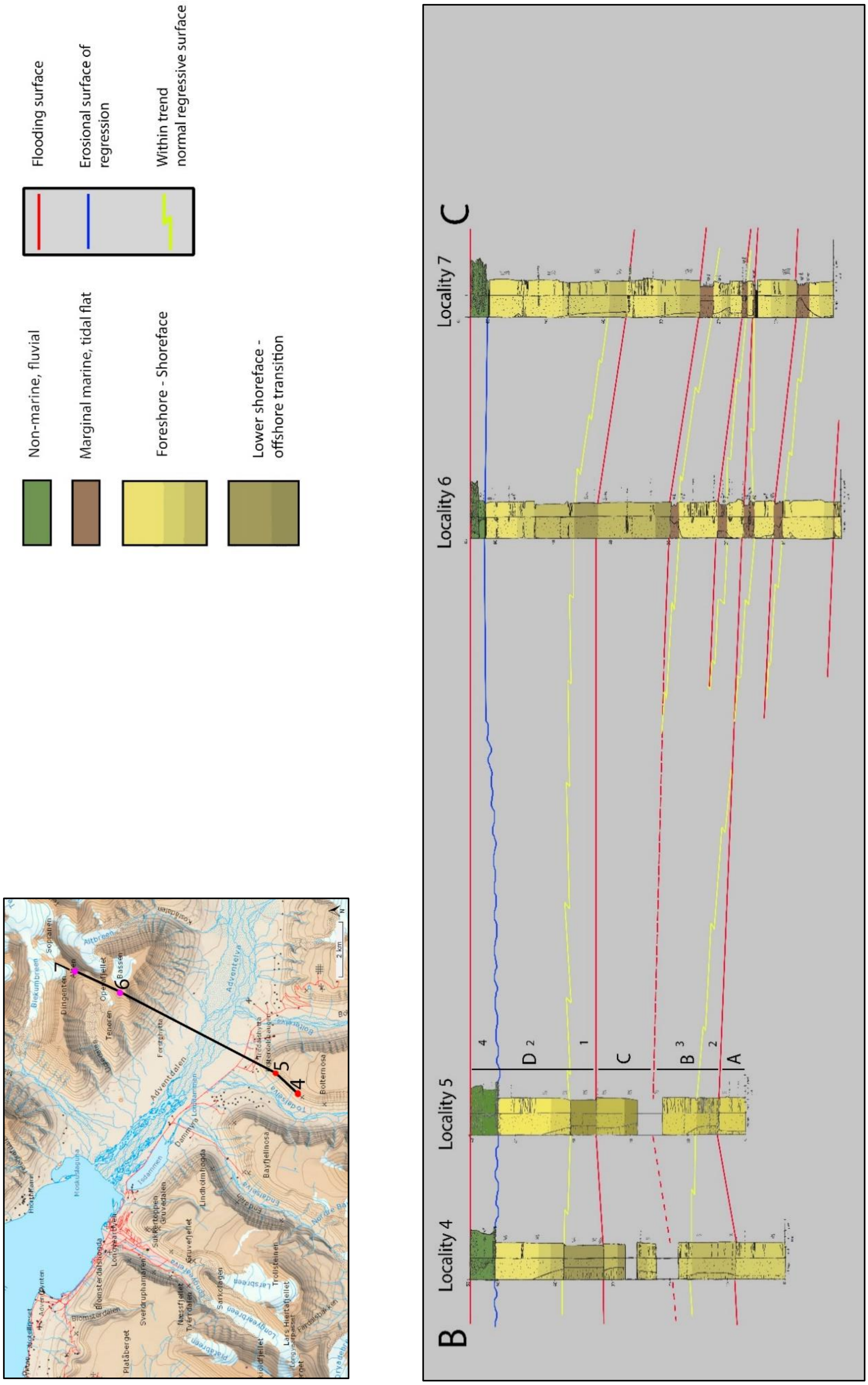

Figure 6.17 - Transect of logged sections in the 9.5-kilometer S(SW) - N(NE) direction from locality 4 to locality 7.

above a thin layer of coal in Operafjellet, which indicate a relatively low degree of incision in the north. Further south, the coal-seam is not present, and unit D4 show a more pronounced erosional lower boundary.

From the displacement of facies stacking pattern in the parasequences, the relative magnitude of the different intervening flooding events can be determined. Maximum flooding surface in this part of the stratigraphy is the one terminating Endalen member, placing offshore shales of the Basilika Formation on top of the fluvial sandstones in the Endalen Member. Within the member, the largest landward shift of the shoreline is the flooding of parasequence B, which place lower shoreface sand- and siltstones on top of foreshore and tidal flat sediments (Fig. 6.17, 6.18).

The maximum flooding surface divides the stratigraphy into two parts with different architectural properties. Parasequences A and B show a larger range of facies, with a somewhat steeper dip in shazam lines than in parasequences C and D. The occurrence of tidal flat sediments also disappears in the two upper parasequences. This results in lateral extensive wedge architecture of the 2nd order elements within parasequence B. The two upper parasequences show a more undulating, tabular geometry across the study area. Parasequence D show the greatest thickness throughout the area, suggesting the largest basin depth of this parasequence.

A thinning of 10 meters of the total thickness of the Endalen Member is documented in an eastern direction from Endalen to Todalen, with the most dramatic reduction of unit D2, from 23 to 11 meters (Fig. 6.15).

Interpretations

A general trend in the 2nd order elements is a thinning of the more distal lithofacies towards north and east, and in some cases pinching out onlapping a flooding surface. The proximal facies have the opposite trend, thinning towards south-west and culminating in a top-lapping flooding surface. This suggests a south-east to north-west trending shoreline, prograding and back-stepping according to the relative sea level.

As parasequence A occurs as a continuous sheet in the eastern and northern part of the study area, and only as a few isolated cliffs in Longyeardalen, the depositional system is interpreted to have a lobate shape at its shoreline. The isolated cliff units in the west

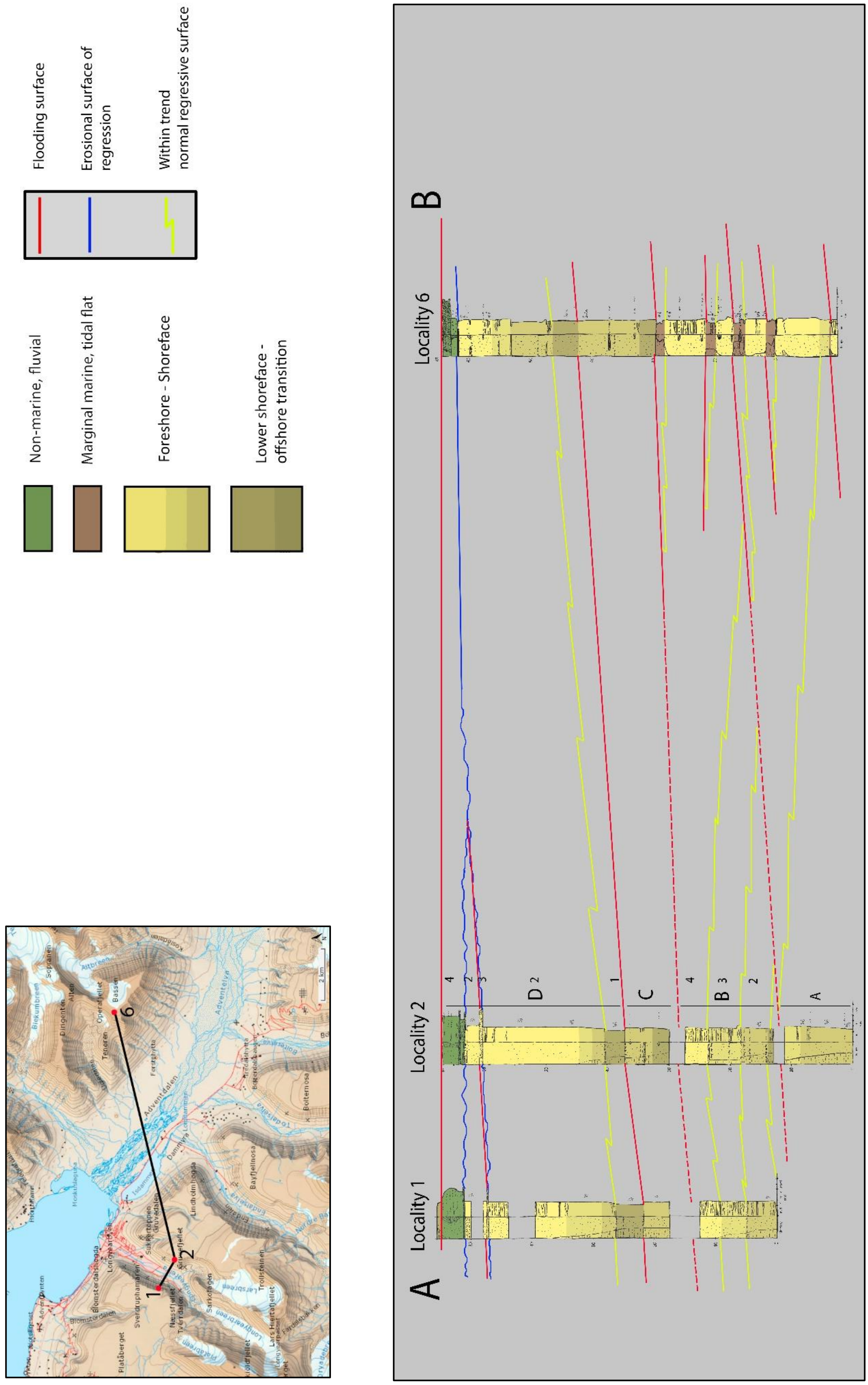

Figure 6.18 - Transect of logged sections in the 11-kilometer W(SW) – E(NE) direction from locality 1 to locality 4.

is interpreted as mouth bars of a delta system (Boggs Jr, 2006), and reflect a fluvial sourced deposition in the first phase of the Endalen Member. The sheet like extent of unit D4 together with the interbeds of conglomerate and cross stratified sandstones, are all evidence of an extensive braided river system (Boggs Jr, 2006) covering the coastal plain in the north-east and the marginal marine sandstones towards the south-west. As both this unit and the local unit D3 have erosional characteristics in basin-direction, they may have prograded as a response to forced regression.

7. Discussion

7.1. Sedimentary architecture of shallow marine shoreface successions

The Endalen Member is the first thick cliff-forming sandstones in the Central Tertiary Basin, marking the flooding of the continental deposits of Todalen Member and the transition to a sand dominated coast (Bruhn and Steel, 2003; Dallmann et al., 1999; Marshall, 2013). In Adventdalen, the Member consist of four distinct units showing an upwards coarsening trend in lithofacies, each one terminated by a flooding surface overlain by a deeper facies association. The units are interpreted as parasequences, each one showing a basinward progradation and significant landward displacement of the coastline during flooding events. This cyclic sedimentation gives the parasequences a tabular architectural expression within most exposures, but lateral correlation of bounding surfaces in photo mosaics, as well as correlation between logged sections show a general thinning of proximal facies and thickening of distal facies, resulting in a large-scale wedge shape of parasequences. This expression has previously been described by Bruhn (1999), Bruhn and Steel (2003) and Steel et al. (1981), but never documented from laterally extensive photo mosaics. Similar large-scale architecture is commonly described for wave dominated deltaic shorelines, for example in the Blackhawk Formation of the Book Cliffs in Utah, USA (Hampson and Howell, 2005).

One distinct architectural feature in the lower part of the succession is the hummocky patterned lateral accreting elements of unit B4. This unit is interpreted as a northwards migrating bedform controlled by waves, likely to represent a deflected mouth bar, a spit or longshore bars. These bedforms are closely linked, and generally origin from irregularities along the coastline in combination with waves and currents (Guillén and Palanques, 1993; Nardin and Fagherazzi, 2012; Nielsen and Johannessen, 2009). As parasequence A is interpreted as mouth bars due to its irregular occurrence in the western part of the study area, it is not unlikely that the next parasequence also relate to the same delta.

Parasequence B show a range of facies from shoreface to the lower shoreface – offshore transition zone, within a 12 meter thick succession, whereas parasequence D show the same range in associations in a 24 meter thick succession. The occurrence of tidal flat sediments which are found north of Adventdalen in parasequence A and B are not present in the two upper parasequences.

The other characteristic feature, especially in parasequence D, is the laterally extensive horizontal parallel beds formed by storm events. Considering approximately the same magnitude of sediment compaction and rate of syn-depositional subsidence, the vertical distance from a unit to a subaerial environment above, gives an approximate depth below sea level during deposition of the unit (Helland-Hansen, 2010; Klein, 1974). As the conglomeratic unit D3 is interpreted to be deposited at sea level, a distance from the shoreline of about 670 to 820 meters can be calculated for unit D1 in locality 1, occurring at 20 meters depth. As this is interpreted to represent the SWWB, this is in good accordance with the depth of other wave-dominated shorelines (Boggs Jr, 2006). The succession of parasequence D in this study show a good resemblance to the succession of storm generated beds in the K4 parasequence of Blackhawk formation (Hampson and Storms, 2003; Storms and Hampson, 2005). In general, this succession shows a very fine grained, thinly bedded unit below SWWB, with non-depositional discontinuities and heavy bioturbation, with an abrupt transition to a fine sand dominated unit marked by several erosional discontinuities. This resembles the transition from unit D1 to D2 in this study.

Storms (2003) show how the number of event-beds per vertical meter reduces upwards from close to 45 beds at 30 – 35 meters to approximately five at 10-15 meters depth. The results are based on computed models and do not account for bioturbation mixing the sediments at lower depths, factors which may have altered the beds to a slightly thicker and more amalgamated expression in parasequence D. Storm beds in shallow water are thick, amalgamated and show evidence of high energy such as hummocky stratification. In deeper environments the beds are thin, contain more matrix and show evidence of deposition by more gentle currents (Kreisa, 1981). With a thicker succession of single facies associations and storms as the main depositional agent, the shoreline in the upper two parasequences of this study is likely to be more linear and further away from river outlets.

The different observations for the lower and upper part of the stratigraphy suggest a change in coastal morphology after the flooding of parasequence B.

A gently embayed coast with wave dominated delta progradation, associated landward tidal flats and a relatively steep-dipping shoreface profile of parasequence A and B is flooded and overlain by the prograding, gently dipping, linear and wave-dominated shoreline represented by parasequences C and D (Fig. 7.1). The thin coal seam in the north-eastern part of the study area suggest a coastal plain environment in the proximal parts of the latter shoreline configuration, abruptly transitioning into an alluvial plain.

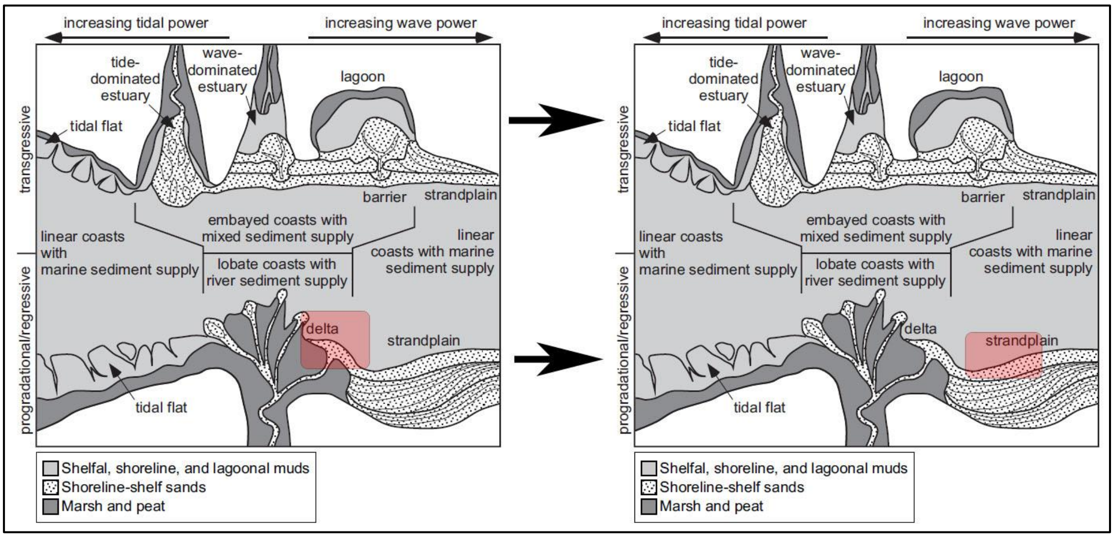

Figure 7.1 – Plan view showing idealized shoreline morphologies in transgressive and regressive systems, indicating the relationship of tidal and wave power in different depositional environments. Red marking indicates the transition from a wave-dominated delta of parasequence A and B to a linear wave-dominated coast in parasequence C and D.

7.2. Regional sedimentary development of the Endalen Member

The lithofacies presented in this study are in good accordance with previous studies (Bruhn, 1999; Kalgraff, 1978; Lüthje, 2008), except for the coal-seams found in locality 6 and 7 in the MSc project of Anna Stella Guðmundsdottir. In addition to these facies, the architectural expressions of the sand-bodies are implemented in the interpretation of facies associations and depositional environments.

Bruhn and Steel (2003) show a sequence stratigraphic analysis of the Firkanten Formation with 8 small scale sequences stacking up to form an overall transgressive-regressive cycle. The maximum flooding of this cycle occurs at the lower part of small scale sequence 6, matching the maximum lateral displacement of facies associations found at the boundary of parasequence B and C in this study. This surface also correspond to a slight change in provenance according the study of (Petersen et al., 2016).

Jochmann et al. in prep. and Jones et al. (2017) show a correlation of bentonite layers along the eastern margin of the CTB in N – S direction, implying a continuous extent of the coastal plain environment and the shallow peat-accumulating intrabasins of the Todalen Member in the Longyearbyen – Svea area. This discards previous interpretation by Lüthje (2008) on the general co-existing of the Todalen and Endalen Members, and suggest instead a major flooding and change of the system during its transition to shoreface sedimentation of the Endalen member. This major change is also addressed by Marshall (2013), presenting a flooding of the low-lying wetlands and switching to a clastic dominated shoreline with peat accumulation only continuing in the Bassen area at Operafjellet mountain. The presence of a coastal plain environment in this area is well documented in the sequence stratigraphic analysis of this study, with a further north-eastwards migration of these sediments after the maximum flooding of parasequence B. Evidence for the repeated progradation of this environment can be found towards the top of parasequence D where a thin coal seam is found.

As the provenance of the sandstones of the Endalen member is interpreted as uplifted strata in the Edgeøya area approximately 120-150 kilometers east of the study area (Petersen et al., 2016), the sand is likely to have been brought westwards by fluvial transport. The lack of fluvial deposits in Todalen Member reported by Lüthje (2008) led to the conclusion that the Endalen Member could not be a delta, as she interpreted the Endalen Member to be the shoreline of the adjacent time equivalent Todalen Member. However, as this model is discarded, the allogenic forcing mechanisms causing the flooding of the Todalen Member may also have initiated fluvial transport from the east.

The following figures (Fig. 7.2 – 7.9) show the development of the sedimentary environment throughout the deposition of the Endalen Member. This development is based on the combined lithological and architectural investigations of this study, as well as published research on both wave-dominated shorelines and regional studies of the Firkanten Formation.

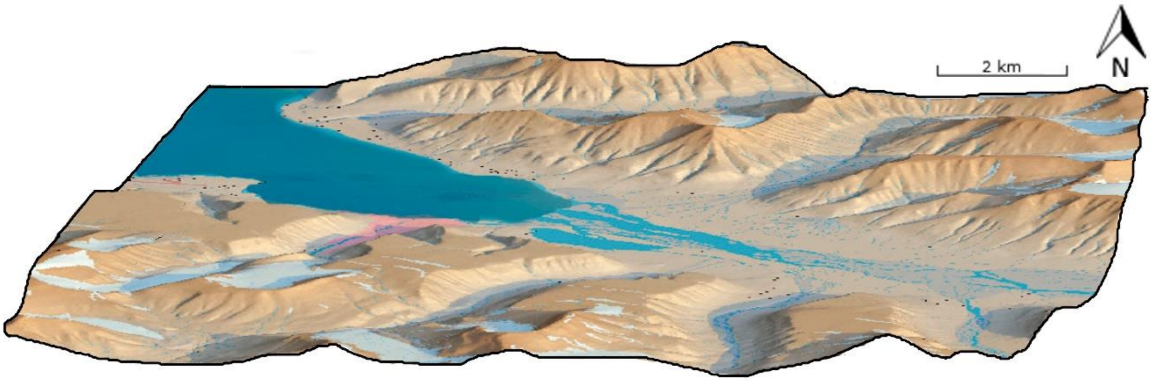

Figure 7.2 - Present time shoreline morphology and topography within the study area. Scale is only correct for left-right direction in the map. The following figures represent this part of the study area. Surface layer from toposvalbard.

Figure 7.3 - Palaeogeographic reconstruction of the study area and conditions present after the termination of the Todalen Member. Flooding of previous continental flats and rapid expansion of shoreface sediments with peat accumulation continuing only in the Bassen area. Inspired by palaeogeographic reconstruction by Marshall (2013). Surface layer from Google Earth

Figure 7.4 - Maximum extent of the parasequence A with an un-even shoreline configuration and only local bars in the western part of the study area. Surface layer from Google Earth.

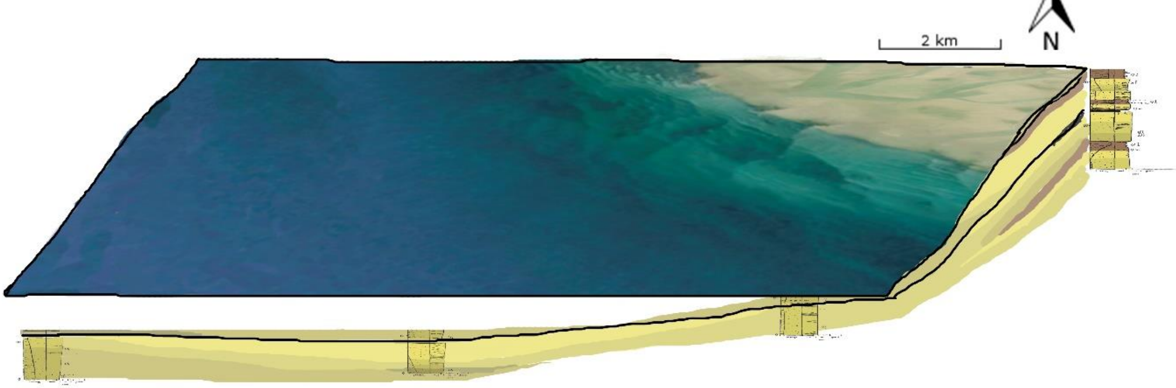

Figure 7.5 - Flooding of parasequence A followed by the progradation of an undulating sand-dominated coast. Sand-dunes can be seen prograding northwards along the coast, producing the hummocky-patterned lateral accretion elements of unit B4. The north-eastern part of the system shows a tidal flat prograding and backstepping in response to small changes in relative sea level. Surface layer from Google Earth.

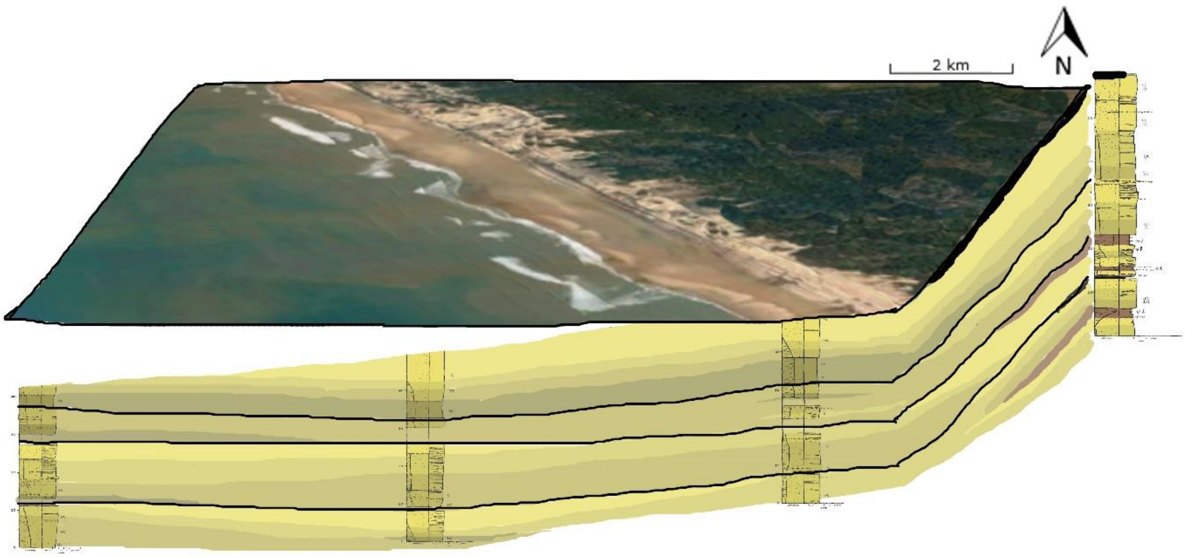

Figure 7.6 - Maximum flooding within the Endalen Member results in a change in shoreline morphology as the Parasequence C and D represent a straight and open shoreline. The shoreline of Parasequence C is interpreted to lie north-east of the study area with re-deposition of shoreface sediments in a basinward direction due to storm activity. This parasequence is flooded and overlain by the heavily storm influenced shoreface sands of parasequence D. This progradation brings the continental plain back into the north-eastern part of the study area. Surface layer from Google Earth.

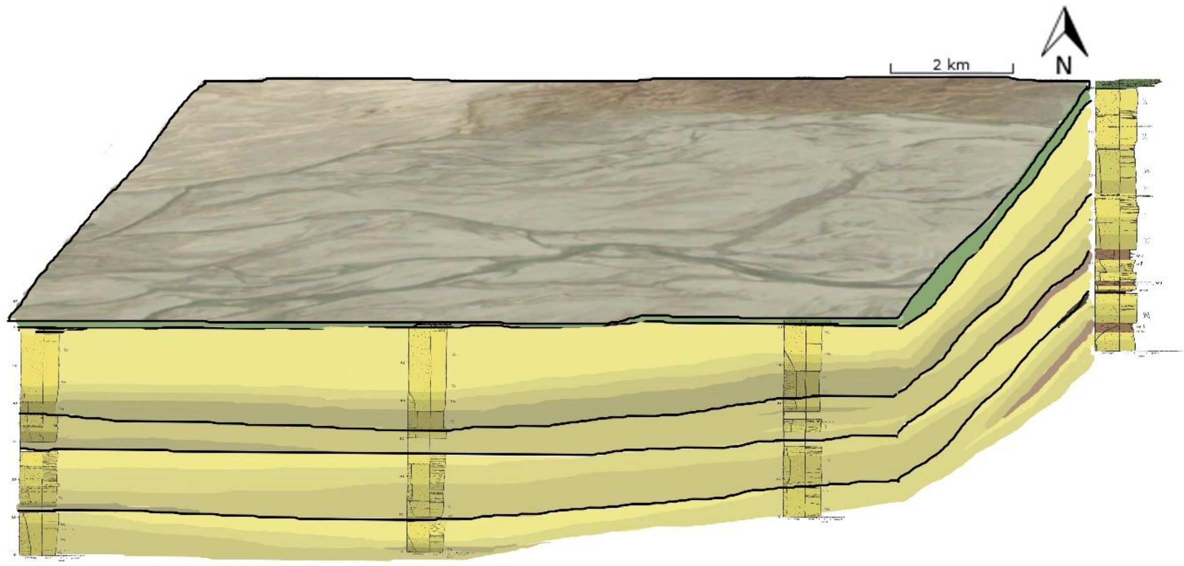

Figure 7.7 - Forced regression steepens the fluvial profile, leading to a braided river system covering the continental plain, eroding the underlying sediments. Only a thin layer of organics in the north-eastern part of the area is preserved. Surface layer from Google Earth.

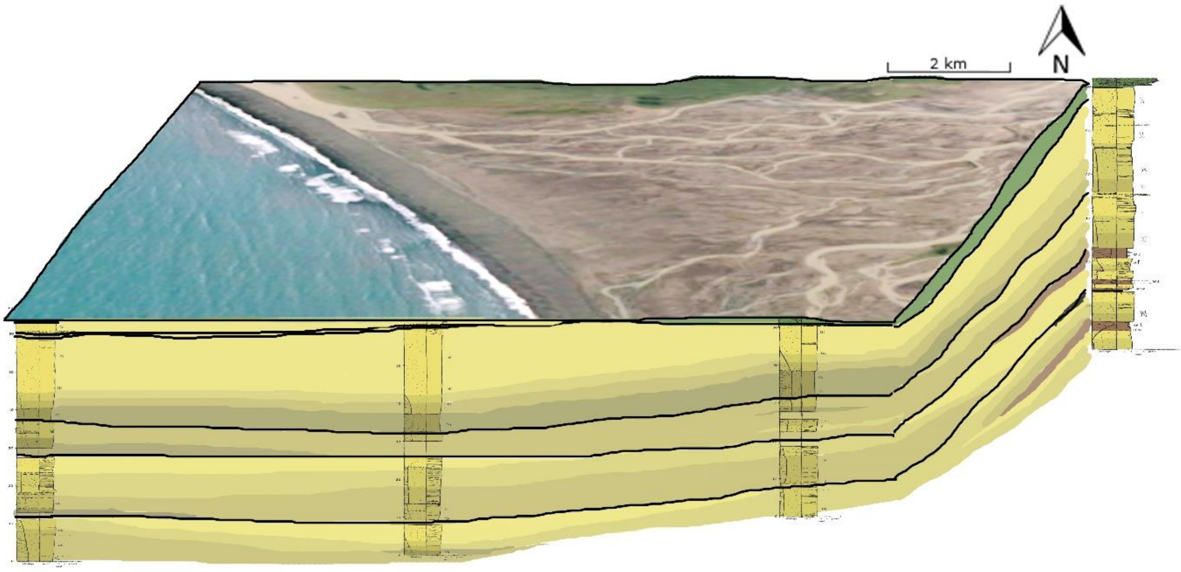

Figure 7.8 - A minor flooding in the south-western part of the area result in marine reworking of the fluvial material, and deposition of a wedge-shaped shoreface sand-body. Surface layer from Google Earth.

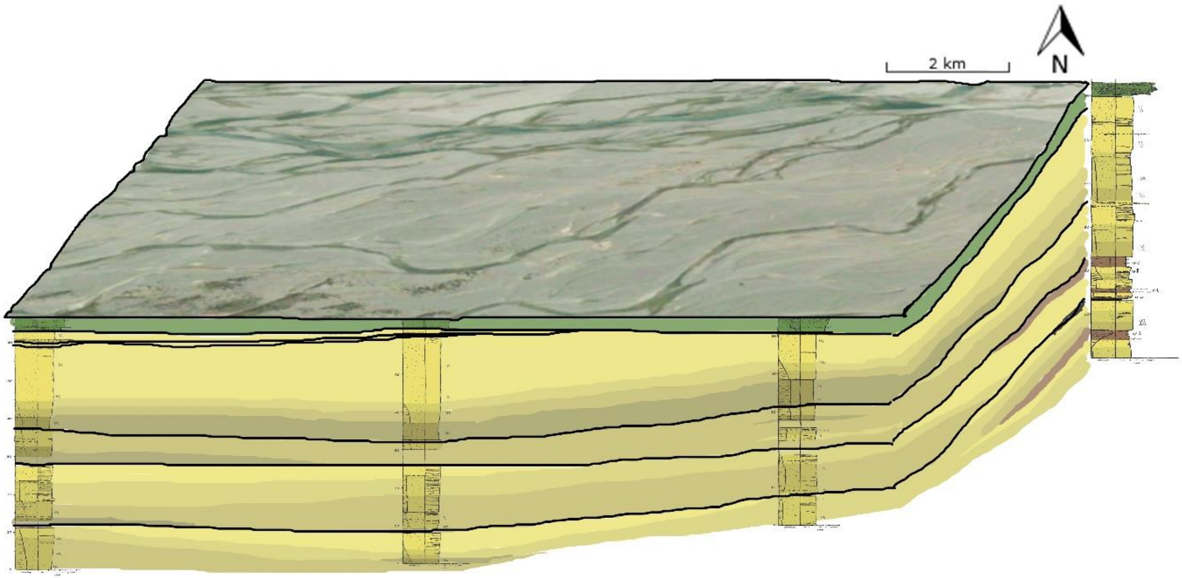

Figure 7.9 - Further regression and progradation of the continental fluvial system covering the entire study area, marking the top of the Endalen Member stratigraphy as it is expressed in the Adventdalen Area. Surface layer from Google Earth.

As the flooding of parasequence B is interpreted as the most important flooding surface within the Endalen member, its stratigraphic importance to other parts of the stratigraphy in the Van Mijenfjorden Group can be discussed. As parasequence C and D show a deeper deposition of lower shoreface sediments than parasequence B, this surface is the second major surface in a series of flooding events related to a gradually deeper and deeper foreland basin. The flooding surface terminating the Endalen Member is of an even larger magnitude in a deepening trend which continue to the Frysjaodden Formation (see figure 2.3).

7.3. Further studies for the Endalen member.

Although important aspects of the regional coastal morphology have been clarified in this study, there is still further work which can be performed to improve the understanding of the investigated member. Here are some recommendations for further work.

This type of study could benefit a lot from drone footage of the rock faces. That would make it possible to take photographs from a fitting distance with a lot less geometric distortion than what is possible from a camera along the outcrop. It would also enable 3d photo-modelling which would better reveal the 3d architecture of the sand-bodies.

A scientific problem for further discussion is the cause of shift in the upper parasequence D, from the fine sandstones, organic rich coastal plain deposits and coal layers, to the braided river system.

8. Conclusions

This is the first architectural analysis on the Endalen Member based on lateral extensive photo-models. The study has aimed to describe both large and small-scale depositional architecture within the Member to shed more light on the coastal morphology during deposition. Based on the results of this study with incorporation of both old and more recent regional work, the following conclusions has been made:

- Four distinct upwards coarsening parasequences have been recognized, showing a gradual deepening of the basin during the deposition of the Endalen Member. From both photo-models and correlation of logs, proximal facies are seen thinning towards the south-west, with the opposite trend for distal facies. This confirms a NW-SE trending shoreline prograding in a south-western direction.
- Storm-event beds and a northwards migrating bar has been observed from internal geometric assemblage of bedding planes in photo-models.
- A distinct change in architectural properties reveal a transition in coastal morphology from a deltaic deposition in a shallow basin to a linear shoreline with storm dominated deposition in a deeper basin.
- A lowering of the lower Endalen Member boundary north of Adventdalen has allowed a chronostratigraphic correlation of the two lower parasequences from Longyearbyen area to the Operafjellet area.
- A relative sea level model for the upper part of the Endalen Member shows the evolving shoreline morphology of the Endalen Member with special focus on the sea level fluctuations in the upper part of the succession. A local marine-reworked conglomerate reveals a transgression in the Longyearbyen and Endalen areas, which cannot be traced further north and eastwards.
- The shoreface sandstones of the Endalen Member were overlain by a coastal plain in the Operafjellet area, resulting in a thin coal seam. This environment is quickly overlain by a wide alluvial plain, covering the entire area with fluvial conglomerates and coarse stratified sandstones.

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Appendix:

1 – 8: Sedimentary logs

9 - 12: Panorama models

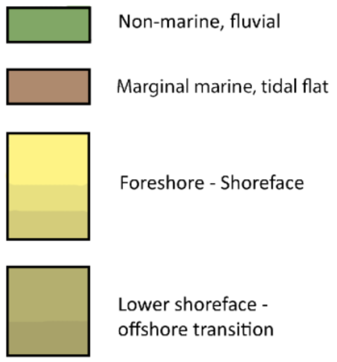
13 – 15: Sequence stratigraphic transects

All appendixes can be found in full resolution online in Microsoft Onedrive:

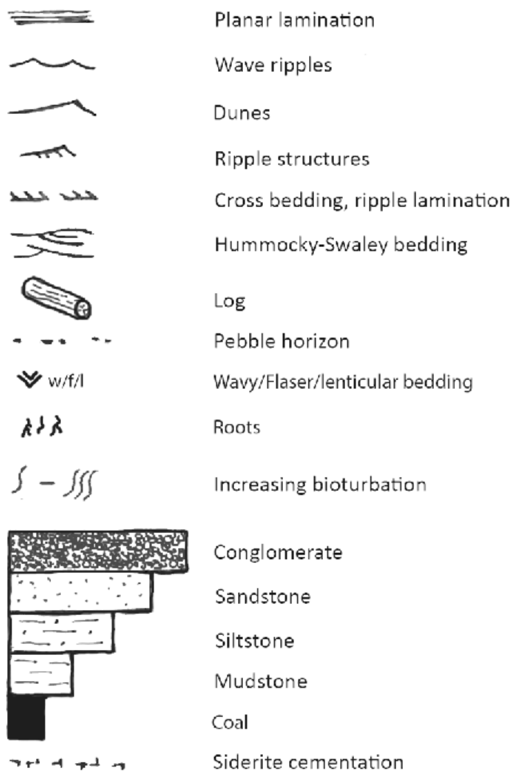
https://1drv.ms/f/s!Ag7BCAeoEdp1adc7GfV-K8f4t3Q

1: Legend

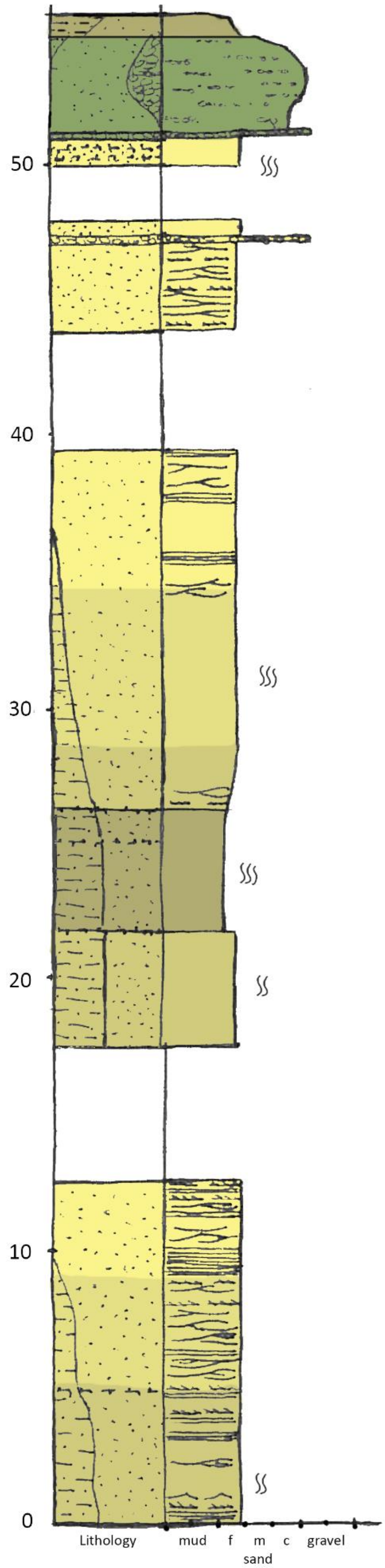
Facies Associations



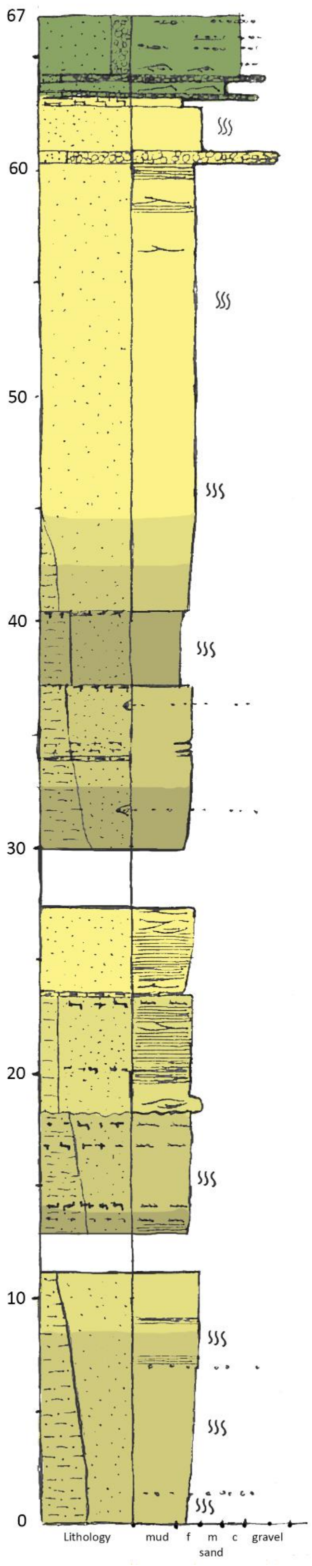
Symbol Legend



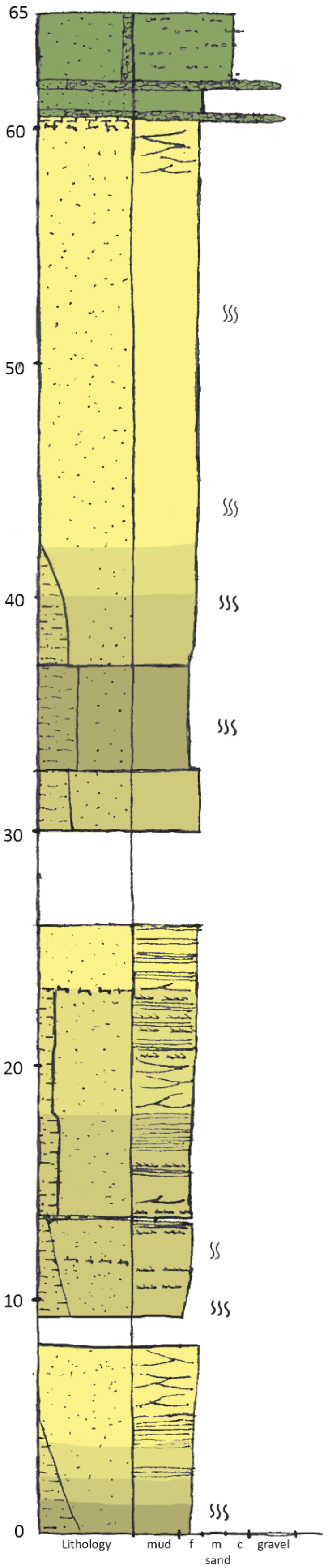
2: Locality 1: Sverdrupbyen



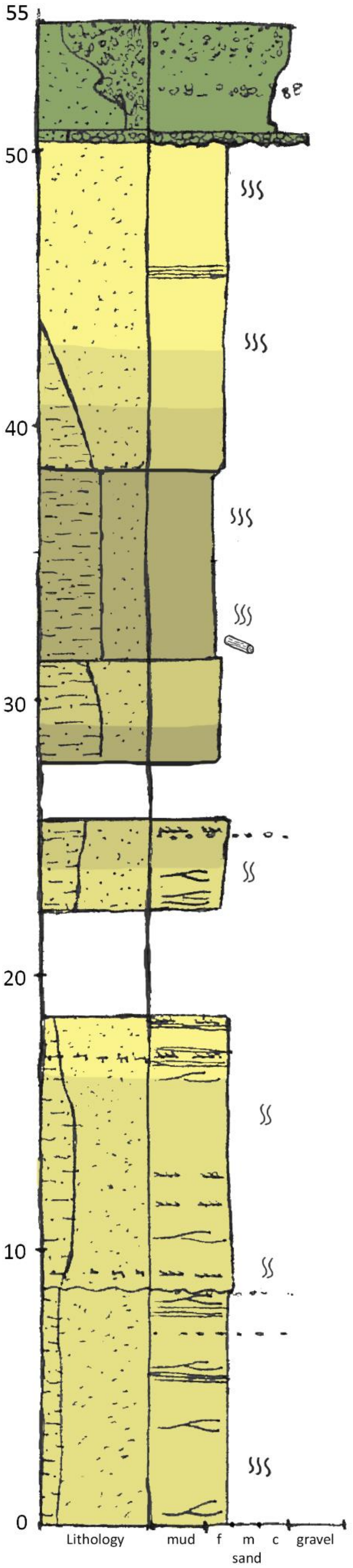
3: Locality 2, Nybyen



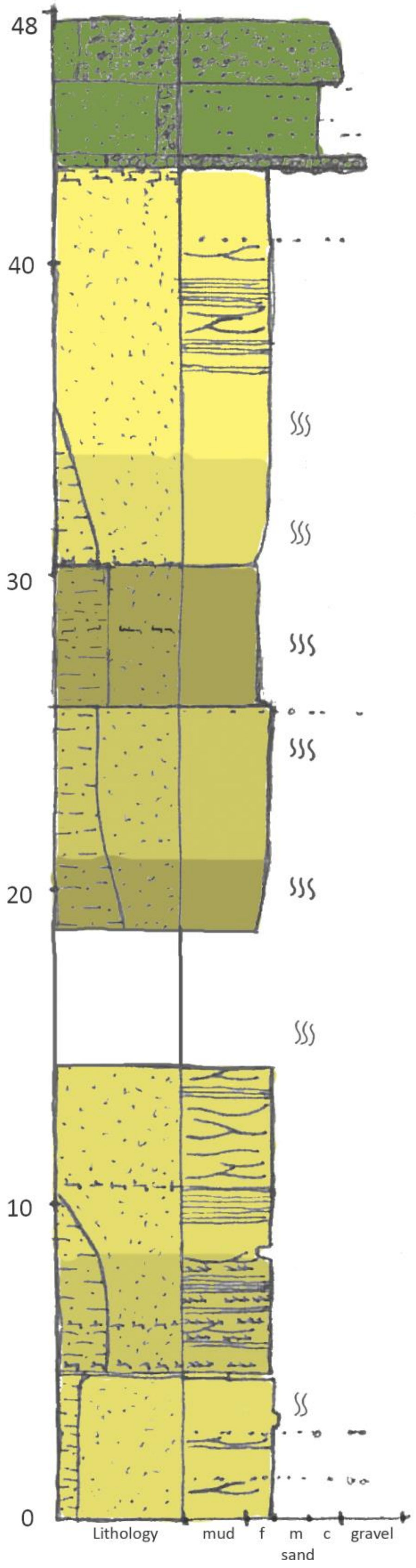
4: Locality 3: Endalen



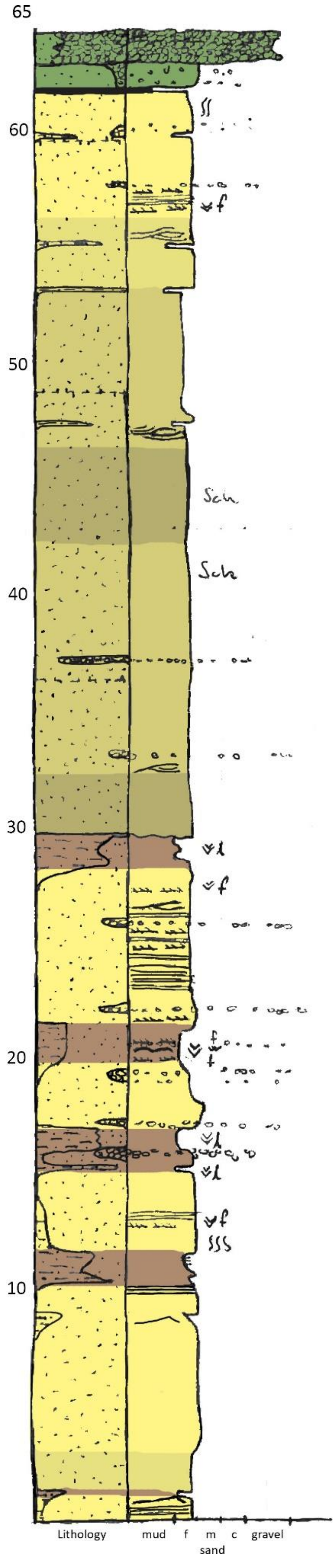
5: Locality 4, Todalen



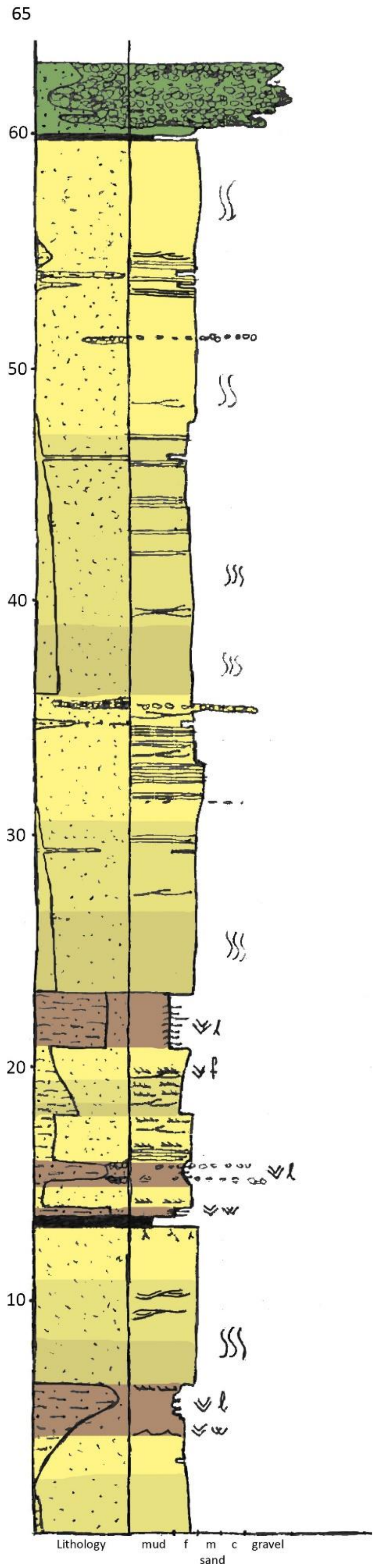
6: Locality 5, Todalen



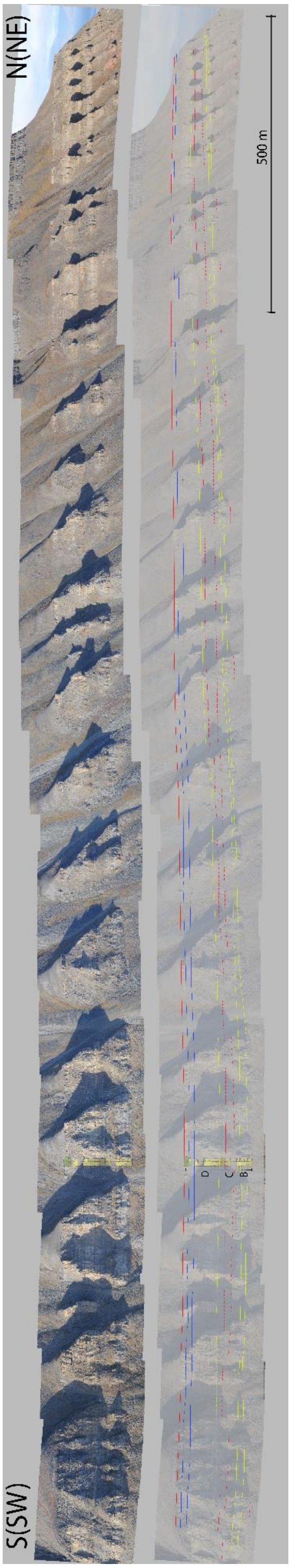
7: Locality 6, Bassen



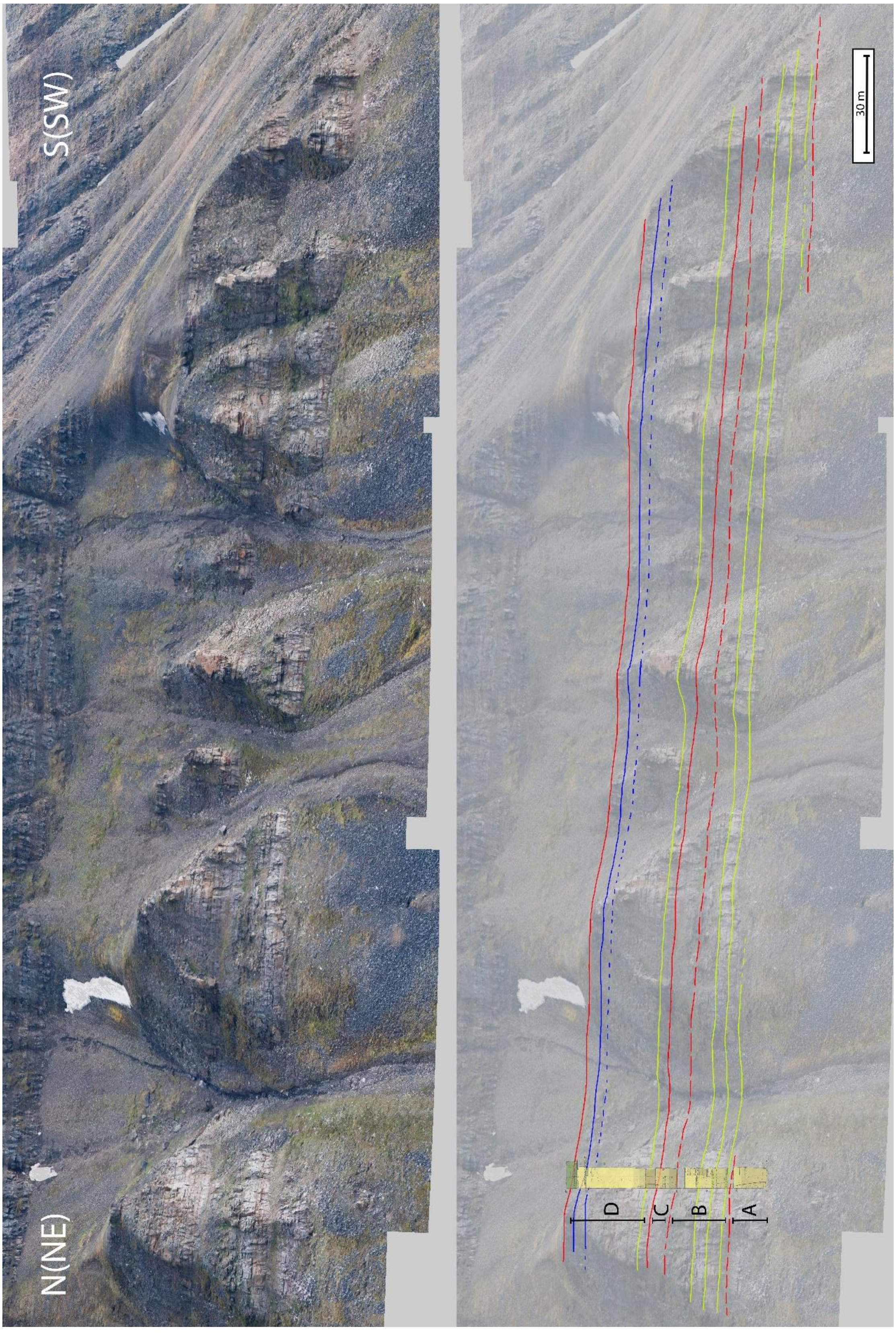
8: Locality 7, Alten



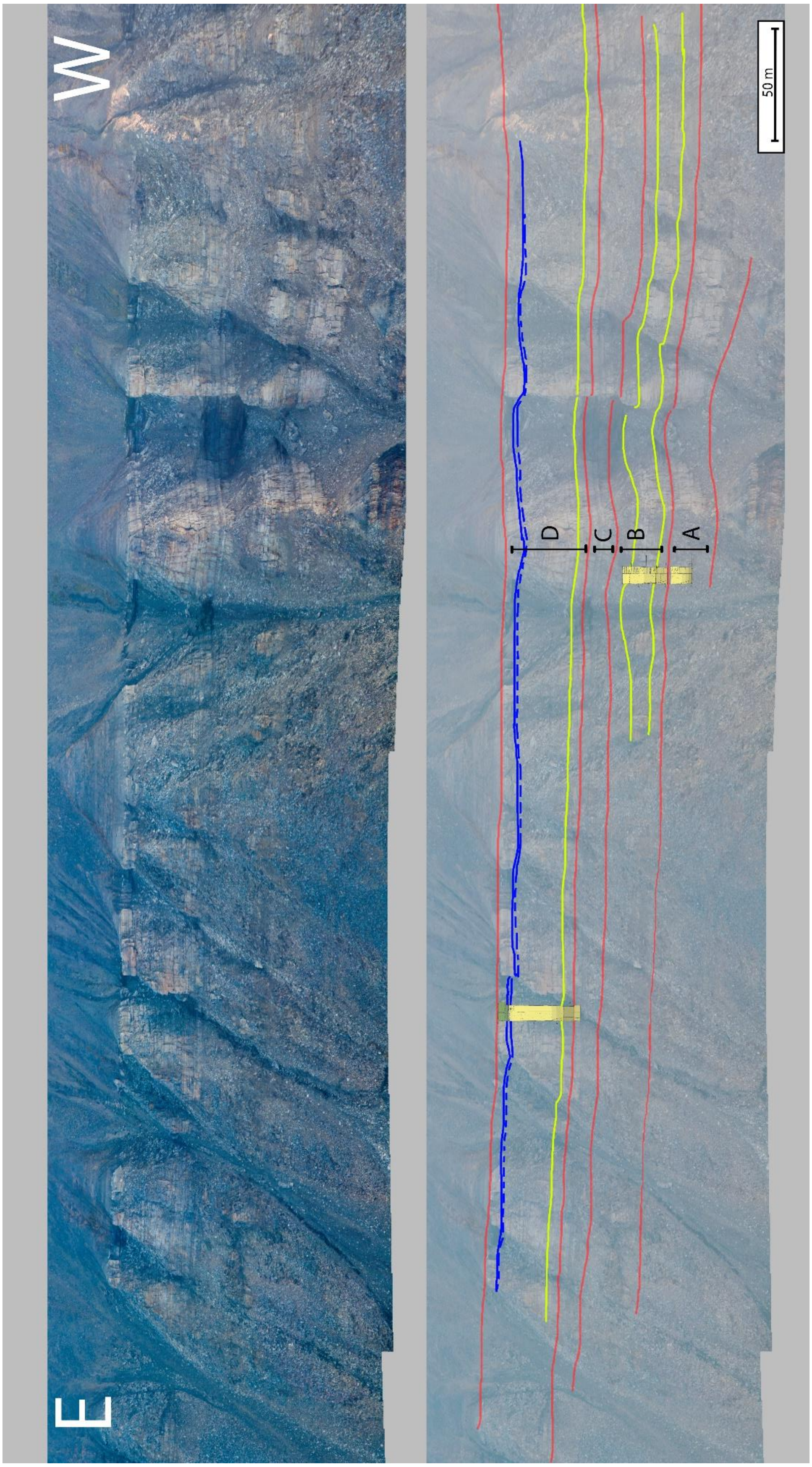
9: Western Longyeardalen



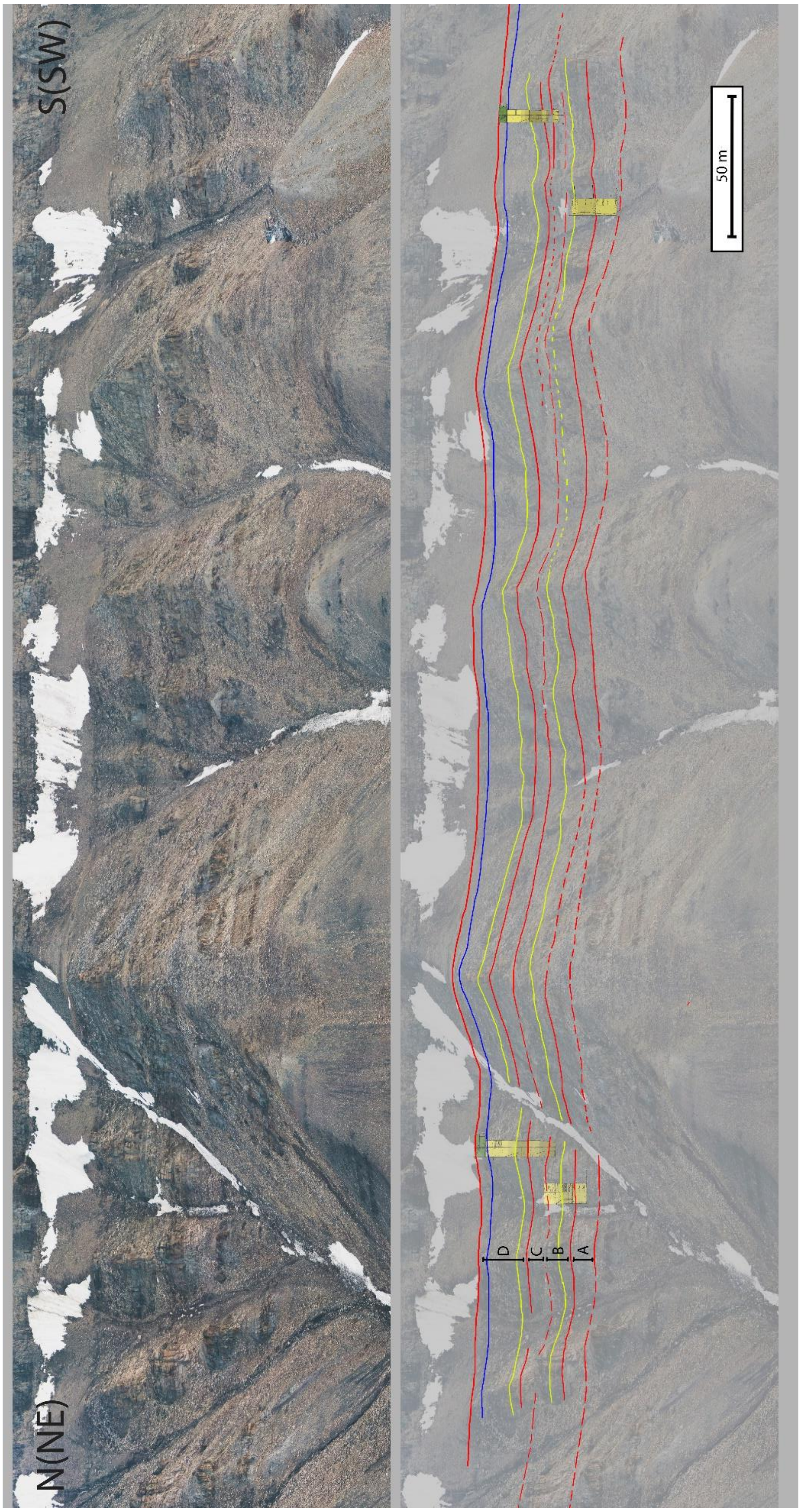
10: Eastern Longyeardalen



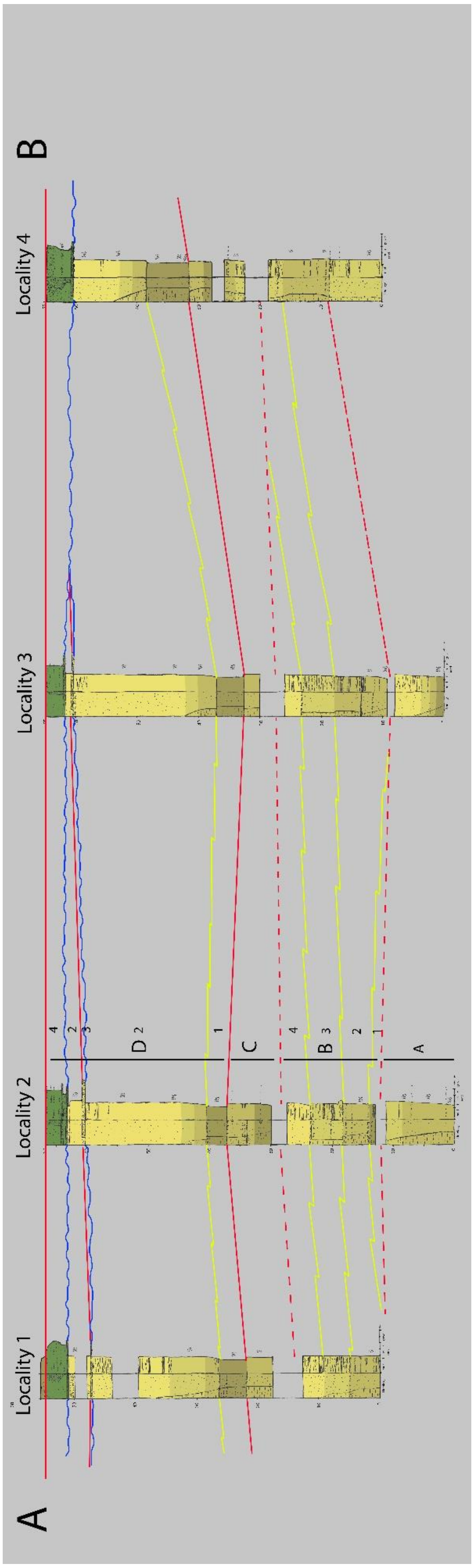
11: Endalen



12: Todalen



13: Locality 1 – 4



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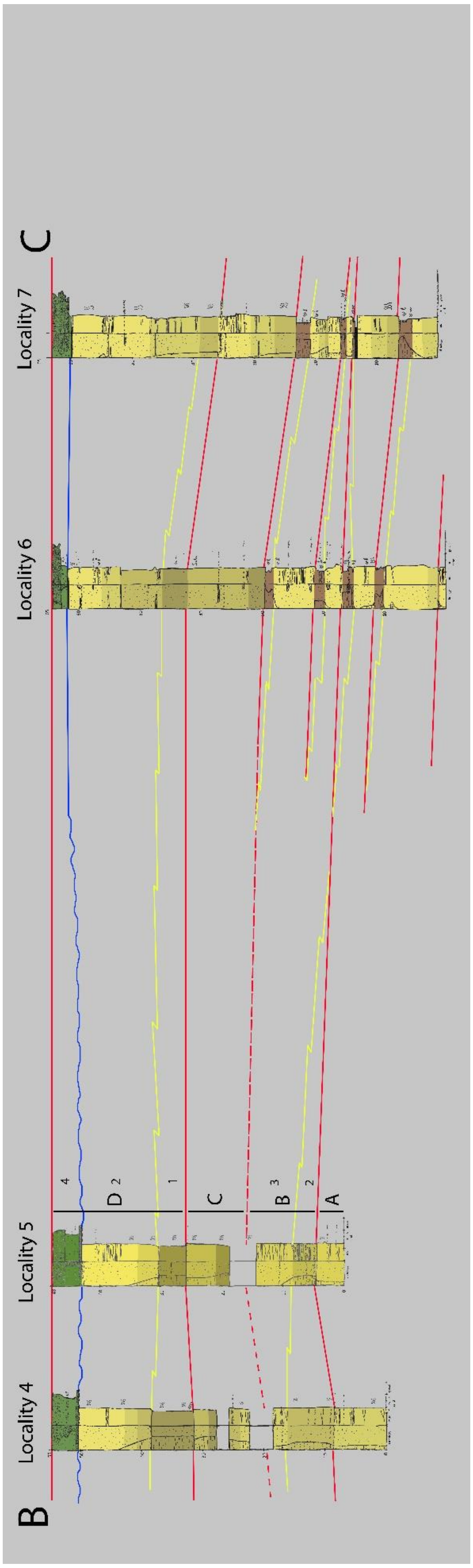

15: Locality 1 – 6