Depositional Environment, Processes and Sequence Stratigraphy of the Paralic Helvetiafjellet Formation in Ullaberget, Southern Spitsbergen

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Depositional Environment, Processes and Sequence Stratigraphy of the Paralic Helvetiafjellet Formation in Ullaberget, Southern Spitsbergen

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The Early Cretaceous, Barremian – Aptian Helvetiafjellet Formation is a well exposed paralic succession deposited at ramp-type shelf of the Borealic sea in the Svalbard region. The Ullaberget section in the Van Keulenfjorden area is an important reference section for the formation, due to excellent exposures and great variation in facies associations. The formation is in this locality subdivided in a lower, middle and upper portion.

The lower boundary of the Helvetiafjellet Formation is a subaerial erosional unconformity, cut into the open-marine black shale of the Late-Jurassic – Early-Barremian Janusfjellet Subgroup. The erosional boundary is marked by a thin, discontinuous lag of fluvial channel conglomerate with extrabasinal clasts at the base of the Ullaberget Member. The Ullaberget Member is here suggested to be a tidally influenced delta introducing the Helvetiafjellet Formation, and *not* representing the top unit of the Rurikfjellet Formation in the Janusfjellet Subgroup, as previously published. The erosional unconformity represents a regional sequence boundary. The "Ullaberget delta" is a small delta, 11-18 m thick with an internal clinoform set, possibly formed as a bay-head delta during early sea level rise. The delta top facies is marked by a slight erosion which represents a bay or lacustrine ravinement surface which is succeeded by lacustrine or brackish-water mudstone, thin coal beds and thin crevasse or interdistributary bay sandstone units, overlain by thin fluvial channel sandstone beds. Crevasse and interdistributary bay sandstones have dinosaur foot imprints.

The middle portion of the Helvetiafjellet Formation is up to 50 m thick and comprises the major part of the Helvetiafjellet Formation. The lower boundary is a transgressive ravinement surface capped by up to 12 m thick lentoid sandstone bodies with large sets of planar cross-stratification showing tidal influence. These bodies are interpreted as formed as tidal sand ridges of a local estuary. The ridges are overlain by heterolithic mudstone and thin sandstone bed facies association, interpreted to have formed in small tidal channels within an intertidal mudflat and in a lower coastal plain environment. Some shale beds are supposed to be of marine bay origin, thus representing intermittent events of marine flooding. The facies arrangement within the middle portion reveals a vertically stacked pattern of parasequences, balanced by a rather constant A/S ratio.

The upper portion of the formation is characterized by a more complex retrogradational parasequence set. Its lower boundary is put at the first marine flooding surface below fully marine strata. The parasequences include lagoonal mudstone, marine embayment mudstone, tidal channel infill and marine sandstone beds. The marine sandstone beds, up to about 1 m thick, are characterized by large *Diplocraterion* burrows, probably formed during storm events, also being supported by hummocky stratification in some of the sandstone beds. The upper boundary of the Helvetiafjellet Formation is put at the onset of fully marine conditions without any further paralic facies interruptions. These facies associations characterize the Aptian – Albian Carolinefjellet Formation.

As an analog to paralic sandstone reservoirs, The Helvetiafjellet Formation in the Ullaberget section gives an interesting insight into rapid lateral and vertical variability and complexity of sandstone body geometries in such a marginal marine environment.

1

Introduction

Tidally influenced shallow-marine sandstone bodies deposited in marginal-marine to open-shelf setting form important sub-surface exploration targets both on the Norwegian shelf as well as in other petroleum provinces in the world. Many of such sandstone bodies occur stratigraphically bounded at the base and top by open-marine shelf formations and have been formed between the marine and the continental environment, i.e. in the *paralic setting*. The range in architectural properties such as facies, sand: shale ratio (net-to-gross), stacking pattern and geometry of sandstone beds within marginal-marine sandstone units reveal great variation. These internal relationships are controlled by changes in a series of processes and energy environments during deposition and together these are critical factors for reservoir properties in all sandstone units. The present study is a part of the project "Analogue studies of paralic sandstone bodies" at the Department of Geosciences, University of Oslo. The study object of this thesis, the Helvetiafjellet Formation in southern Spitsbergen, is a marginal-marine sandstone unit stratigraphically bounded by open-marine shelf shales

The Barremian - Aptian (Early-Cretaceous) Helvetiafjellet Formation (Parker, 1967; Nagy, 1970, Dallmann, 1999) is a well exposed marginal-marine to shallow marine formation deposited on a passive continental margin (Steel, 1977; Steel, et al., 1978; Steel and Worsley, 1984; Nemec, 1992; Gjelberg and Steel, 1995; Midtkandal, 2002). The adjacent lithostratigraphical units are characterized by open-shelf shale lithologies, the Janusfjellet Subgroup below and the Carolinefjellet Formation above (Dypvik, 1984; Dallman, 1999). This stratigraphical position of fluvial to shallow-marine sandstone bodies between open-marine shales is usually a result of mechanisms associated with eustacy, tectonics, or a combination of both. In the most recent published depositional model of Gjelberg and Steel (1995) the Helvetiafjellet Formation is explained as being formed by a fall in relative sea level in the Barremian, followed by aggradation in a back-stepping mode under rising relative sea level in the Aptian time. During this transgression, coastline was migrating from SE to NW. Later studies (Midtkandal, 2002; present study) reveal a wide spectrum of depositional sub-environments within the Helvetiafjellet Formation. Sedimentary stacking pattern of strata from these sub-environments reflect the depositional history, which would reveal the processes at work during the entire interval of fall and rise of the relative sea level.

The present study is twofold. Firstly, because stacking pattern of sandstone and shale units is fundamental in reconstructing depositional history and in understanding how sand is distributed on a continental margin in a transgressive systems tract, outcrops of the Helvetiafjellet Formation in southern Nathorstland in southwest Spitsbergen have been systematically investigated. The field study has been carried out in the Ullaberget, a steep mountain cliff section on the northern side of outer part of the Van Keulenfjorden. Observations from similar steep sections of the neighboring mountains Louiseberget and Annaberget are also included in the study. Paleocurrent, sedimentological and main structural elements are documented in high resolution field data. From large variability of facies and facies associations, both along and across the strike, an effort has been made to obtain a detailed sedimentological understanding of the formation, and reconstruct and evaluate the controlling factors for the depositional environment.

The second objective of this study has been to discuss the Helvetiafjellet Formation as a field analogue for tidal reservoir sandstones in a *paralic setting*. In such a marginal-marine setting, mixing of marine and terrestrial processes lead to an interfingering of mud and sand both onshore and offshore, often with several episodes of reworking before burial and preservation. Reservoir properties are highly sensitive to interlayers of shales as these could form barriers for hydrocarbon migration and cause inefficient exploitation of petroleum from reservoirs of this type. Understanding and ability to reconstruct possible hydrocarbon migration barriers is in particularly important in tidal sandstone reservoirs.

2

Fieldwork and data

2.1. Fieldwork

The present study is based on observations made over two field seasons on southern Spitsbergen, summers of 2002 and 2003. The field area is located on the western Nathorstland, bounded by Van Keulenfjorden in the south and Van Mijenfjorden in the north. During both seasons the Annahamna (by the Ullaberget) on the north side of the Van Keulenfjorden worked as the base from where the fieldwork was carried out. Figure 2-1 shows a map of Svalbard and localities on the Nathorstland in southern Spitsbergen.

During the first field season, logging and sampling was carried out with the assistance of Liv Hege Lunde Birkeland. In the second field season, understanding and recording of the internal geometry of tidal sandstone units and their relationships to the adjacent mountains were stressed. My fieldwork this season was integrated with the Ph.D study of Ivar Midtkandal on paralic sandstone bodies, including the Helvetiafjellet Formation. In all, 18 cliff sections, from 6 different localities, were logged through the Helvetiafjellet Formation during the two field seasons.

Hazardous conditions limited the logging in several locations. Transportation to the field area by boat was arranged by Norwegian Polar Institute and UNIS (University courses on Svalbard) in 2002 and together with field project of Statoil ASA in 2003 in the adjacent area. Radio communication was both times arranged through Norwegian Polar Institute. Safety equipment was distributed between Norwegian Polar Institute and Ingeniør G. Paulsen AS in 2002 and between Norwegian Polar Institute and Skandinavisk Høyfjelletutstyr in 2003.

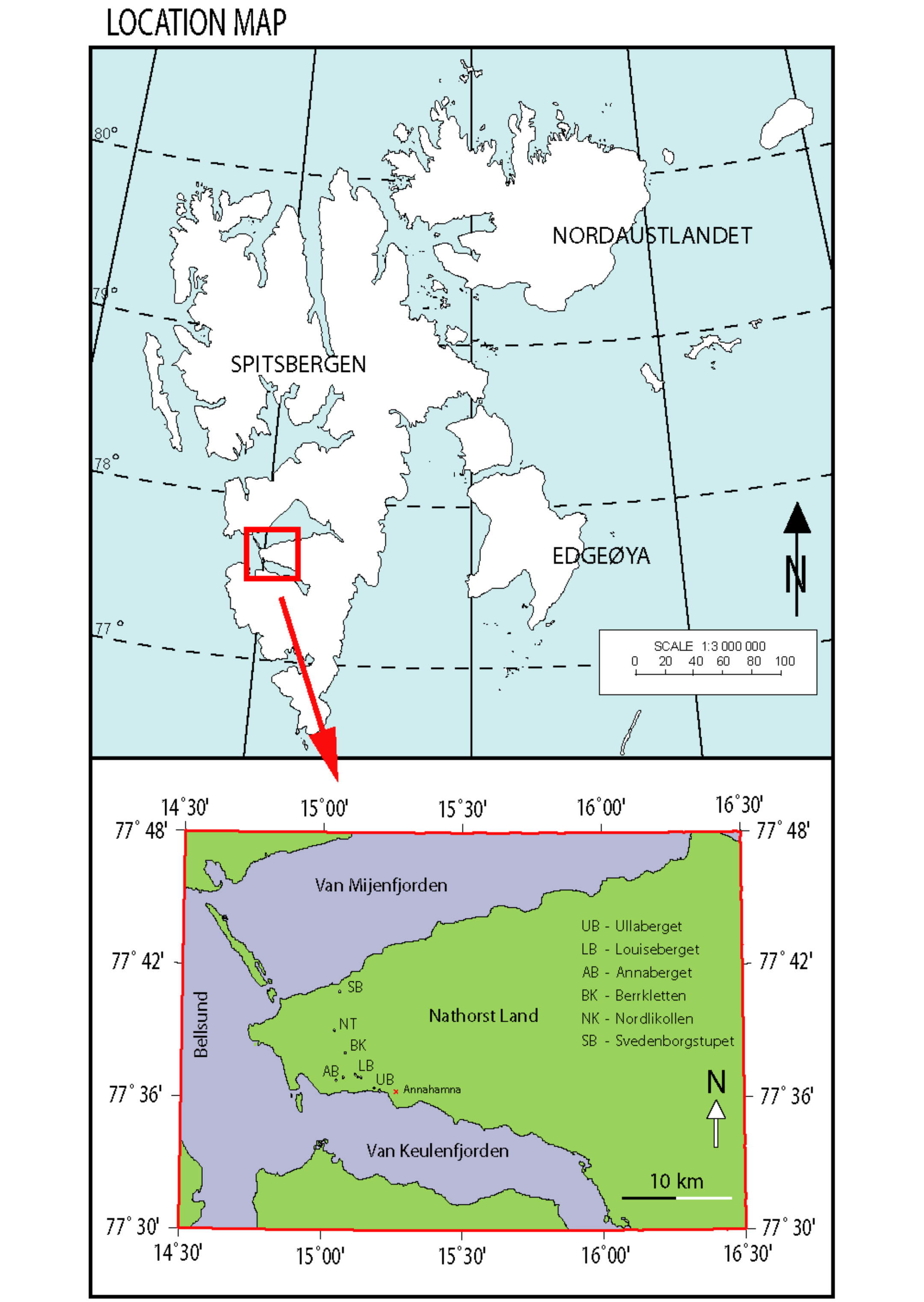

Figure 2-1: The upper location map shows a map of Svalbard (Modified from Dallmann, 1999). The lower map shows all the visited localities in Nathorstland in southern Spitsbergen. (Modified from Midtkandal 2004, personal communication).

2.2 Field data

Due to the scope of this study, the data presented in this paper is limited to consider mainly the Ullaberget section (Figures 2-1 and 2-2). Additional data in a wider perspective will be presented by Ivar Midtkandal et al. (unpublished).

The Ullaberget location is an approximately 1.5 km long southward facing well exposed mountain side situated on the north side of the Van Keulenfjorden. In general, outcrops are good, providing good lateral control of the Helvetiafjellet Formation through the Ullaberget section and over to the adjacent mountains in the west and northwest. In the Ullaberget, the Helvetiafjellet Formation can roughly be divided into three large-scale portions (Figure 2-2 and 2-3), referred to as lower (sandstones), middle (sandstones) and upper (sandstones and mudstones) portions of the Ullaberget section in order to separate these from the lithological term unit. This subdivision also makes it easier to apply this section of the Helvetiafjellet Formation into a sequence stratigraphic framework later in this thesis. The lower portion consists of lacustrine and alluvial deposits overlying the Ullaberget Member sandstone unit. The latter is lying unconformably over marine shales of the Rurikfjellet Formation in the upper Janusfjellet Subgroup. The Ullaberget Member is formally included in the Rurikfjellet Formation (Dallmann, 1999). However, in this thesis, it is considered to form the basal sandstone unit of the Helvetiafjellet Formation. Its stratigraphical relationship to the Rurikfjellet Formation and the Helvetiafjellet Formation will be discussed further later in this thesis. The middle portion consists of 2 to 3, less than 15 m thick sandstone units interfingering one another. These units comprise the bulk of the Ullaberget section and lie conformably above the alluvial deposits of the upper part of the lower portion. The upper portion consists of interfingering relatively thin heterolithic sandstone and shale deposits below the Carolinefjellet Formation shales and sandstones.

Along the Van Keulenfjorden, the thickness of the Helvetiafjellet Formation appears to be nearly constant, but decreases fairly rapidly northwards within about 5 km, being about 40 m in Nordlikollen and Svedenborgstupet (Figure 2-1). In the lower portion of the about 1.5 km wide Ullaberget section, the thickness of the Ullaberget Member increases from 5 m, at the first appearance in the east end of the section, up to 18 m in the middle of the section, and decreasing to about 10 m towards the western end of the section. Thickness of

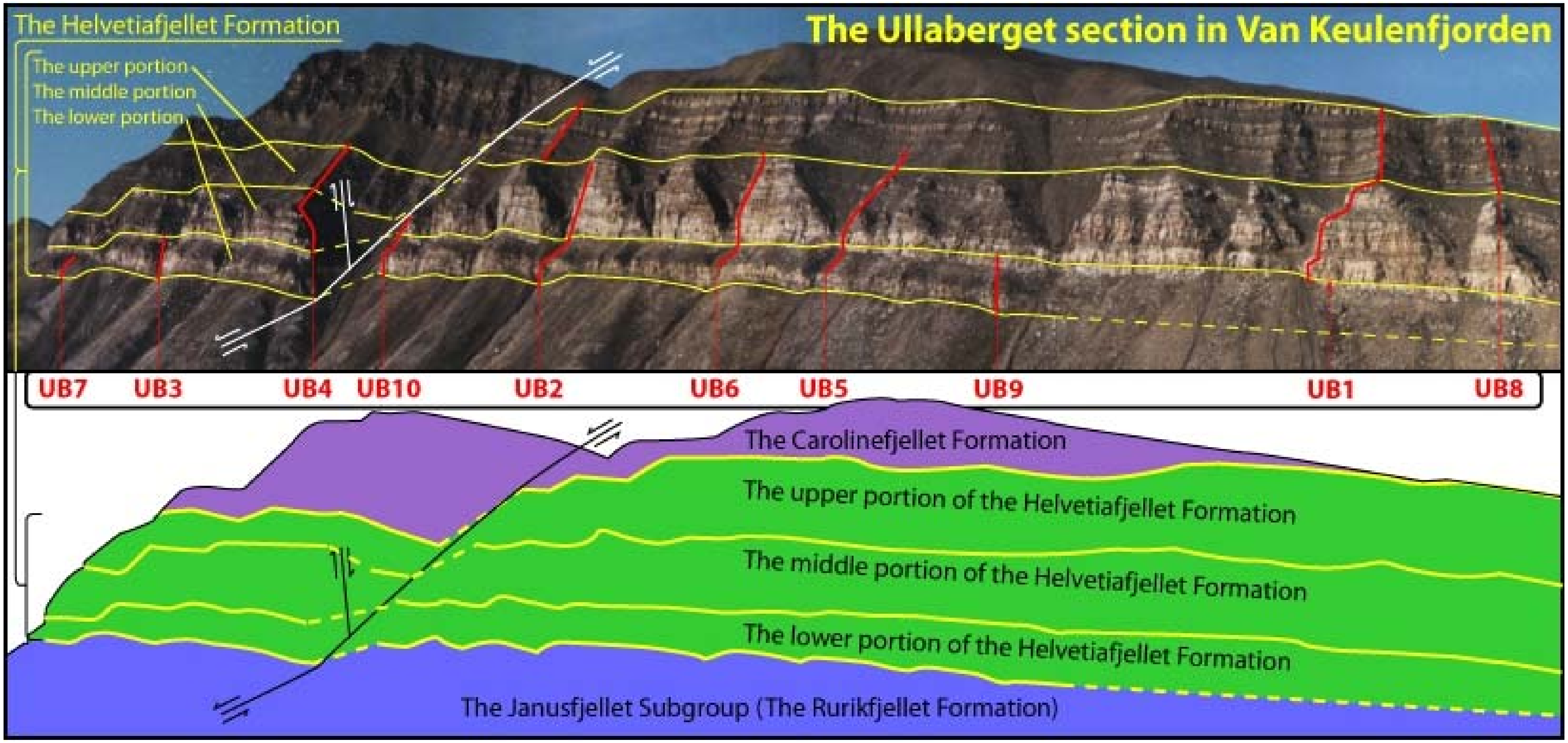

Figure 2-2: A photomontage of the Ullaberget section in Van Keulenfjorden. The upper photo shows sedimentary log-traces and the 3 portions of the Helvetiafjellet Formation sandstones. The lower figure illustrates the Helvetiafjellet Formation and its stratigraphic relationship to the underlying Rurikfjellet Formation shales of the upper Janusfjellet Subgroup (blue) and to the Carolinefjellet Formation shales and sandstones (purple) overlying the Helvetiafjellet Formation. (Photo by Ahokas, 2003).

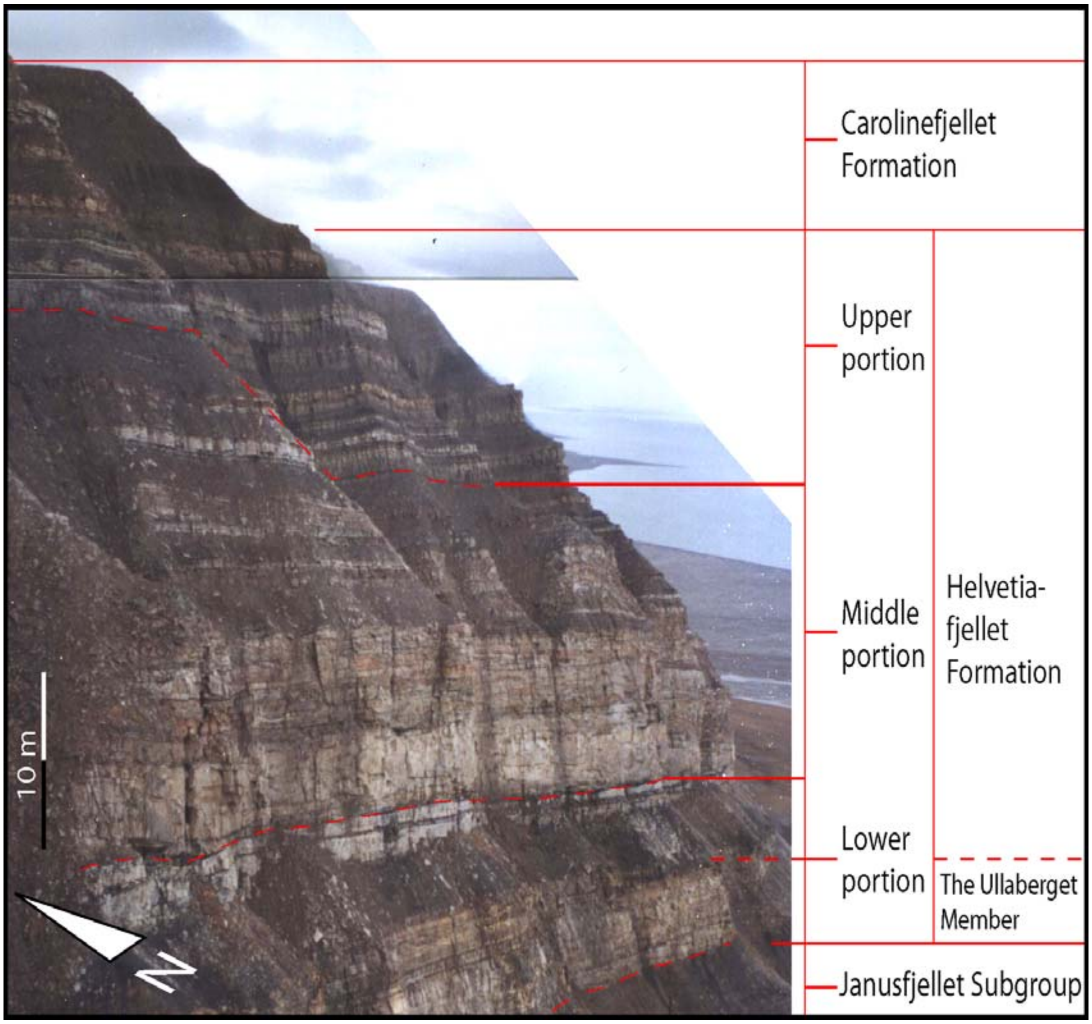

Figure 2-3: The Ullaberget section of the Helvetiafjellet Formation and its relationship to adjacent formations looking eastwards from the middle of the section. (Photo by Ahokas, 2002).

mudstone interval right above the Ullaberget Member diminishes in same direction from 9 m (Log UB9; 7-15 m) to only a few meters (Log UB7; 15-17 m). Alluvial deposits above mudstone interval stay somewhat constant throughout the Ullaberget section. Thickness of the middle and upper portions together is constantly around 90 m. The measurement is based on that the top boundary of the Helvetiafjellet Formation is here put on the top of the last transitional sandstone bed, since it can be followed along the whole cliff section and is topped by 15 m to 20 m thick shale. Placing of this boundary is more or less a matter of taste, in the sense of which deposits are defined as fully marine (Carolinefjellet Formation) and which are not. This is discussed in greater detail in chapter 5. All the outcrops start about 250 meters above the present sea level. Post-depositional faulting has offset the strata in the Ullaberget west from the succession in the Ullaberget east with down throw of approximately 10-15 m. This single normal fault is located in the middle part of the cliff section (Figure 2-2).

A total of 10 high resolution (1:100) sedimentary logs were made from the Ullaberget section to cover geometry and lateral variability of the sand deposits of the Helvetiafjellet Formation. Table 2.1 shows which portions of the Helvetiafjellet Formation individual logs seen in figure 2-2 cover.

Table 2.1: The table shows which large-scale portions of the Helvetiafjellet Formation are covered by the 10 sedimentary logs from the Ullaberget section.

Log code	The lower portion	The middle portion	The upper portion
UB1		X	X
UB2	X	X	X
UB3		X	X
UB4	X		
UB5	X	X	
UB6	X	X	
UB7	X		
UB8			X
UB9	X		
UB10	X	X	

3

Geological framework

The geological record on Svalbard stretches from the Palaeozoic (the Devonian) trough the Paleocene. The bulk of the sediments present in this semi-continuous record are silisiclastic. See Figure 3-1 for geological map of Svalbard.

During the Devonian, Svalbard was situated at equatorial latitudes. Drifting northwards to its present situation started in the Carboniferous, pausing around 50 degrees latitude in the Late Jurassic-Early Cretaceous (Figure 3-2). The Svalbard region has been tectonically relatively stable trough the Palaeozoic and the Mesozoic, showing nearly continuous sedimentation. The Early-Tertiary compressional-tectonic deformation accompanied with plate movements developed a large central depositional basin in Spitsbergen. Today the Mesozoic deposits are mainly exposed along the western and eastern margins of this basin.

3.1 The Mesozoic stratigraphy of Spitsbergen

Figure 3-2 shows the subdivision of stratigraphy from the Silurian to present on Spitsbergen (Worsley, 1986; Dallmann, 1999). As seen from the record, siliciclastic sediments of shelfal and marginal-marine origin are dominant with thickness around 2400 m. Thick shale intervals have been acting as décollement zones for the western Spitsbergen fold- and thrust-belt during the Tertiary, leading to an overthickened geological record of the stratigraphical succession in the western Spitsbergen (Parker, 1967). Three lithostratigraphic Groups have been identified, the Sassendalen Group, the Kapp Toscana Group, and the Adventdalen Group.

The Sassendalen Group was deposited during Early and Middle Triassic, and is about 700 m thick in the western Spitsbergen. It consist of three major coarsening-upward

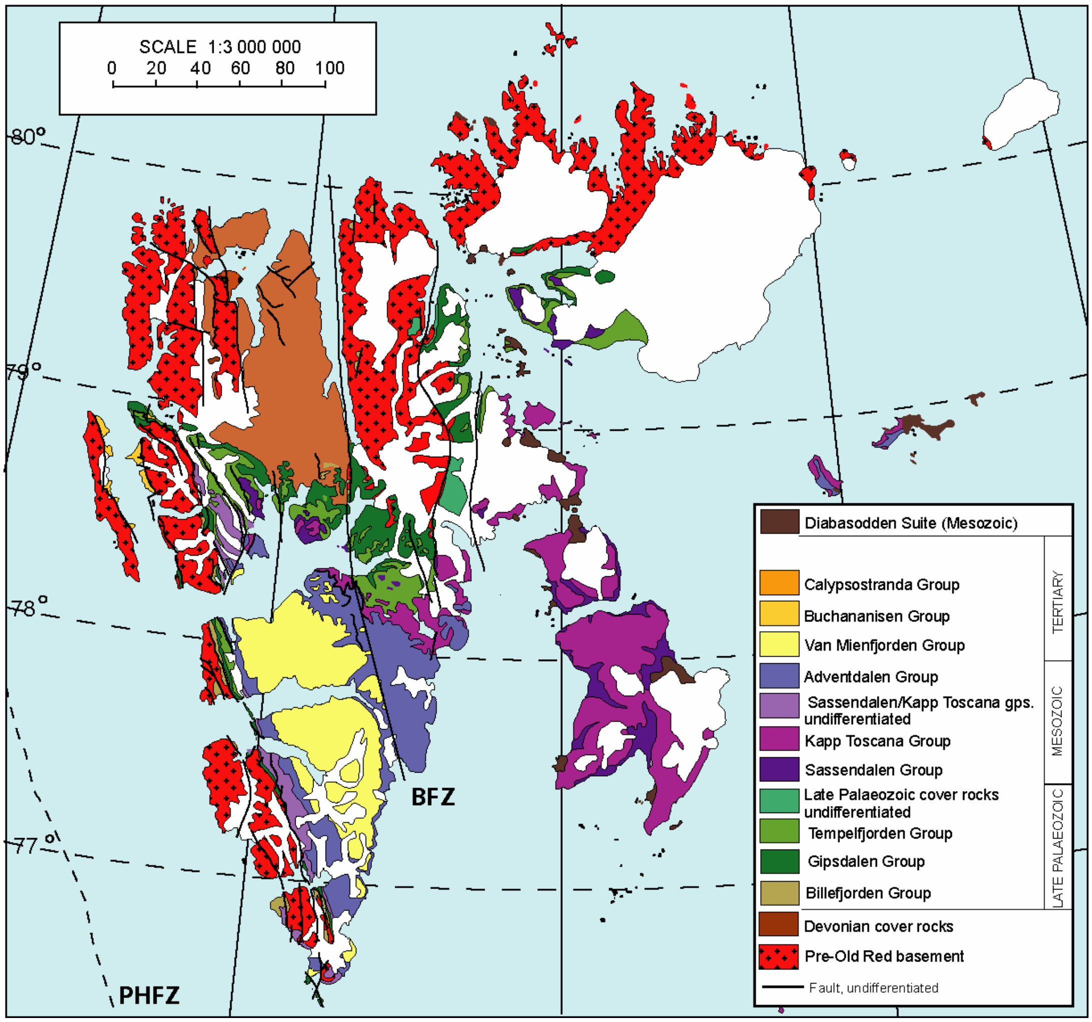

Figure 3-1: Geological map of Svalbard (Modified from Dallmann, 1999). BFZ = Billefjorden Fault Zone, PHFZ = Paleo-Hornsund Fault Zone.

successions, each representing a transgressive-regressive cycle. Each cycle is represented by three formations, being the Vardebukta, Tvillingodden and Bravaisberget formations, from oldest to youngest.

The Kapp Toscana Group was deposited from late Middle Triassic to late Bathonian, Middle Jurassic. The Group consists of sandstones and mudstones of a marginal-marine character, forming a series of mainly upward coarsening successions. The three formations are the Tschermakfjellet Formation, the DeGeerdalen Formation and the Wilhelmøya Formation, from oldest to youngest. The latter represents a shallow-marine basin with very low rate of sedimentation.

The Adventdalen Group reflects two cycles of marine transgression, basin sedimentation and regresession from late Middle Jurassic to Late Cretaceous. The Group is dominated by marginal-marine shales punctuated by episodes of sandstone deposition. The three lithostratigraphic elements are from oldest to youngest; the Janusfjellet Subgroup (mainly shales), the Helvetiafjellet Formation (mainly sandstones), and the Carolinefjellet Formation (shales, silt, and sandstones).

3.2 The Mesozoic structural setting in Spitsbergen

In the Mesozoic, the Svalbard region is considered to have been part of a large and stable continental-shelfal platform, mainly covered by an epicontinental sea. The main fault lines through Svalbard are oriented in a northwest-southeast direction (BFZ, PHFZ in Figure 3-1). Similar fault line orientation is also observed in Kilen in the northern Greenland (Trolle Land fault system). This is due to the vicinity of northern Greenland and Svalbard during the Palaezoic and the Mesozoic (Håkansson and Stemmerik, 1989).

During the Triassic western Svalbard emerged intermittently as a land block and was drowned repeatedly during sea level highstands. A land area existed northeast of Svalbard at least during late Triassic and early Jurassic (Steel and Worsley, 1984). Open-marine conditions prevailed over the whole region during late Jurassic and early Cretaceous as a result of Toarchian-Bajocian rise of sea level. Despite generally stable shelf platform in the Svalbard region during deposition of the Janusfjellet Subgroup, in Callovian - Hauterivian age, variations in the sediment record indicate differential tectonic subsidence related to pre-existing regional lineaments (Figure 3-1).

In the Barremian, the northwestern part of Spitsbergen was up-lifted (Steel and Worsley, 1984), most likely due to tectonic activity along paleo-Hornsund fault zone in the west (Figure 3-1). In response to the up-lift, an abrupt southeastern regression took place accompanied by strong fluvial influx from the up-lifted northwestern and western areas. An extensive braidplain developed and prograded to the east and southeast across most of the southern Spitsbergen, depositing the Festningen sandstone Member. The elevated land to the west of the paleo-Hornsund fault zone acted as the western margin of the depositional basin of the Helvetiafjellet Formation. Minor instabilities related to

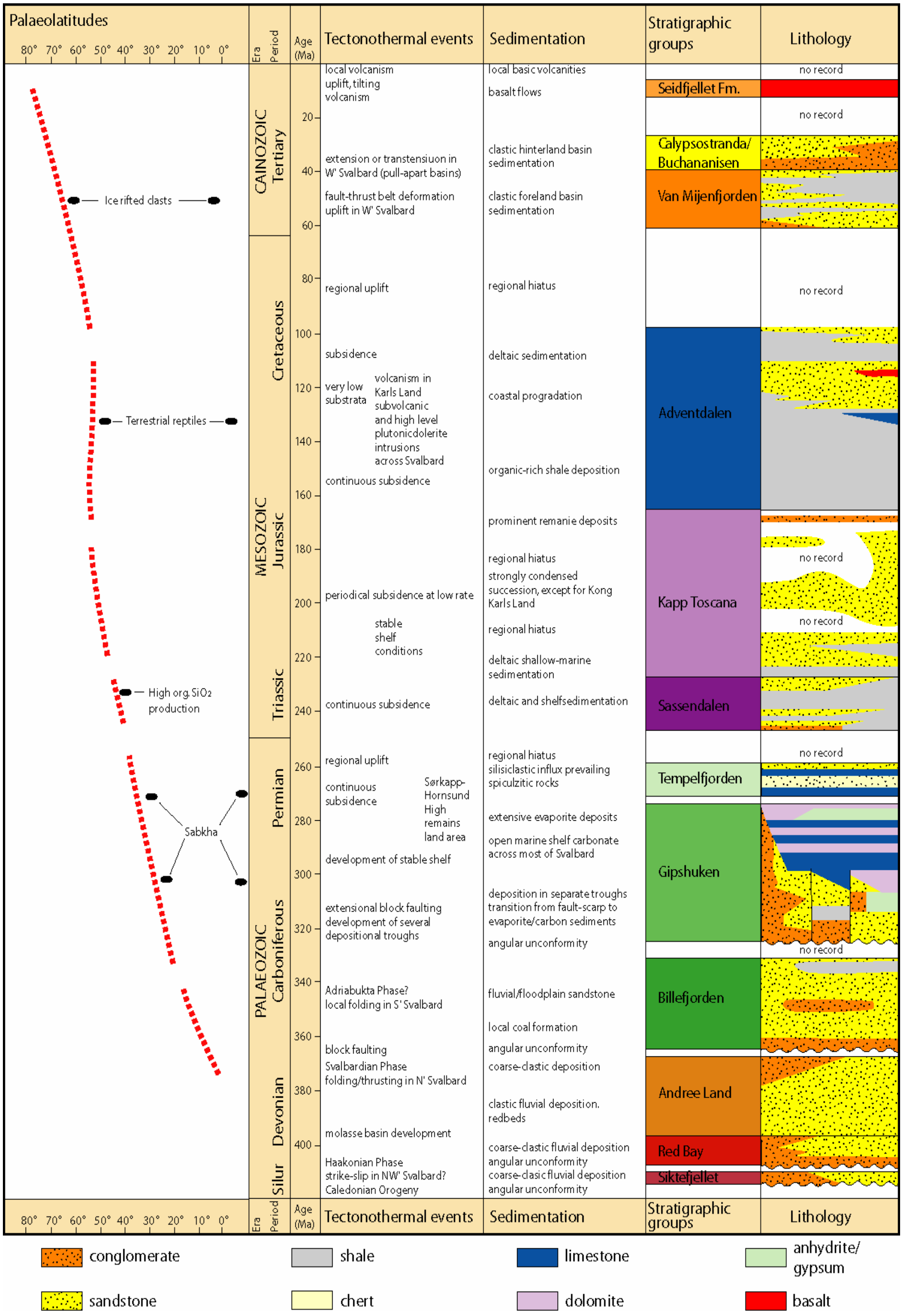

Figure 3-2: Subdivision of stratigraphy of Svalbard (Modified from Worsley, 1986; Dallmann, 1999).

movements along the Billefjorden fault zone (BFZ in Figure 3-1) in the middle of this depositional basin probably did not affect the regional depositional patterns.

A marine transgression took place in the late Barremian or early Aptian time, probably due to global sea level rise in early Cretaceous. Despite the high rates of fluvial clastic input trough the Early Cretaceous, deposition was outpaced by basinal subsidence and rising sea level. As a result the broad fluviodeltaic system gradually retreated landwards, to the northwest, over its feeder braidplain (Gjelberg and Steel, 1995). This is the Glitrefjellet Member.

During Aptian-Albian age open-marine conditions took over the transitional phase of interfingering marine and terrestrial strata. The top of the uppermost transitional sandstone unit, which is seen in the Ullaberget section in the Van Keulenfjorden in the present study area, denotes this lithostratigraphic boundary.

The early Tertiary thrusting and folding along the West-Spitsbergen fold- and thrust-belt, caused by strike-slip movement along the sea floor spreading axis between Greenland and Svalbard, has severely altered positions of large parts of the Mesozoic strata in western Spitsbergen (Dallmann, 1999).

3.3 Previous work

The Helvetiafjellet Formation was first named by Parker (1967), who interpreted the deposits as continental and assigned it, to the Barremian age. The sub-division into the lower Festningen sandstone Member and upper Glitrefjellet Member originates from the same paper. Steel (1976) and Steel et al. (1978) discussed first in detail what facies interpretations fit the deposits at both Festningen at the southern shore of the outer Isfjorden and elsewhere in Nordenskiøld Land, discussing also the possibility of the deposits being of deltaic nature. Later, Steel and Worsley (1984), Nemec et al. (1988), Nemec (1992), Gjelberg and Steel (1995), and most recently Midtkandal (2002) have discussed in greater detail about models to explain the depositional pattern of the formation. Figure 3-3 presents the different depositional models for the Helvetiafjellet Formation. A diagenetic study of the Helvetiafjellet Formation was carried out by Elverhøi and Bjørlykke (1978). Edwards (1979) and Nøttvedt et al. (1992) discussed the sandstone properties of the Helvetiafjellet Formation and its potential as hydrocarbon reservoir.

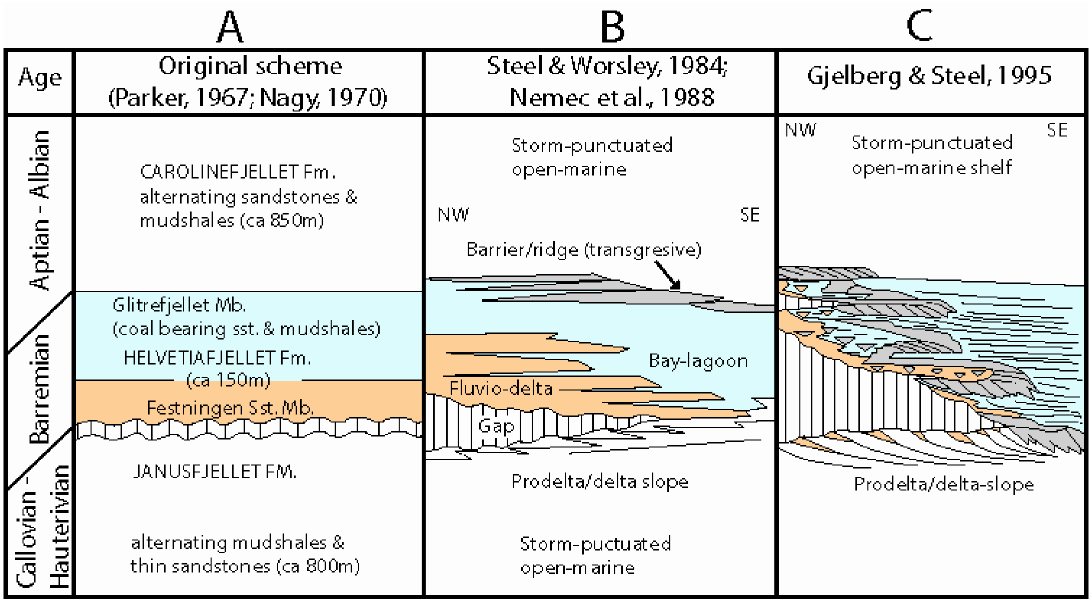

Figure 3-3: Evolution of the stratigraphic interpretation of the Helvetiafjellet Formation; A) Original model of Parker (1967) and Nagy (1970); B) The first backstepping model by Steel & Worsley (1984) supported by Nemec et al. (1988); C) The interpretation of Gjelberg & Steel (1995), supported also by the present study. (Modified from Gjelberg and Steel, 1995).

4

Facies

4.1 Introduction

Facies is determined from sedimentary rocks as a unit that differs macroscopically from the adjacent bodies of rock. Facies determination is based on a certain set of descriptive sedimentological criteria. One facies represents one unique and genetically constant depositional episode, which was controlled by one or several depositional processes.

The following sedimentary facies analysis of the Helvetiafjellet Formation in the Ullaberget section in Southern Spitsbergen is based on 10 logged sections ranging from 18-111 m in thickness (See figure 2-2 for log locations and appendix A for the detailed logs). Four main lithofacies conglomerate, sandstone, fine-grained deposits and coal are identified (Table 4.1). These four main lithofacies are further divided into 18 facies, which are separately described and interpreted based on their differing lithological properties, such as bed geometry, boundaries, colour, grain size (Udden-Wentworth scale), sedimentary structures, and texture.

4.2 Facies A: Conglomerate

The conglomeratic deposits recorded from the Helvetiafjellet Formation in the Ullaberget section are divided into two sub-facies; facies A1 (channel lag conglomerate) and facies A2 (shale conglomerate). This subdivision is adapted since in current study area both subfacies are abundant and appear systematic. However, they do also occur together.

Table 4.1: Summary of the different facies units recorded in this study of the Helvetiafjellet Formation.

Code	Facies	Stratigraphic occurrence	Interpretation of bedforms and processes
A1	Channel lag conglomerate	Lower and middle unit	Upper flow regime current
A2	Shale conglomerate	Lower and middle unit	High energy wave rip-up clasts
B1	Tabular cross-stratified sandstone	Middle and upper unit	2D subaqueous dunes
B2	Trough cross-stratified sandstone	All units	3D subaqueous dunes
B3	Plane-parallel stratified sandstone	All units	Upper flow regime and/or lower flow regime plane beds
B4	Planar laminated sandstone	All units	Lower flow regime plane beds
B5	Low angle cross-stratified sandstone	Upper unit	Low-relief 3D subaqueous dunes
B6	Wave ripple laminated sandstone	Middle and upper unit	2D wave ripples
B7	Current ripple laminated sandstone	Middle and upper unit	3D current ripples
B8	Hummocky cross-stratified sandstone	Upper unit	3D hummocks from high energy oscillatory wave
B9	Structureless sandstone	All units	Rapid deposition or collapse structures, high sediment-loaded flows
B10	Structureless sandstone with bioturbation	Upper unit	Structureless sandstone with marine *Diplocraterion* burrows
B11	Tabular cross-stratified sandstone with mud drapes	Middle and upper unit	Non-bioturbated 2D tidal bundles
B12	Trough cross-stratified sandstone with mud drapes	All units	Non-bioturbated tidal bundles
B13	Trough cross-stratified sandstone with mud drapes and bioturbation	All units	Bioturbated tidal bundles
C1	Siderite cemented siltstone	Middle and upper unit	Structureless secondary cementation
C2	Mudstone	Middle and upper unit	Vertical accretion from suspension or lower flow regime current
D	Coal	All units	Vertical accretion on a sub-aerial floodplain or overbank

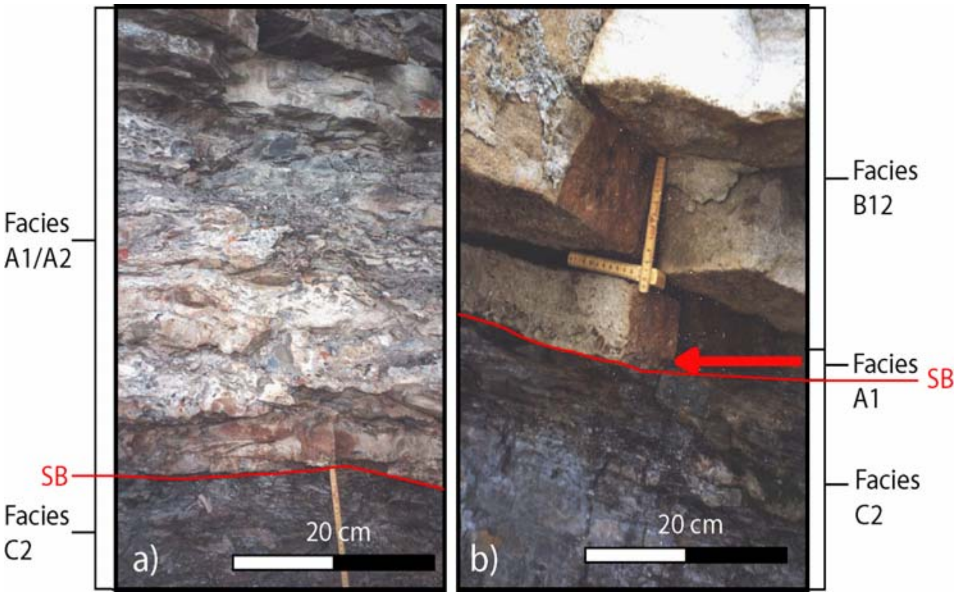

Figure 4.1: The two different appearances of conglomerate facies A at the base of the Ullaberget Member. a) Mixed appearance with dominating shale conglomerate (facies A2) above the basal lag of conglomerate facies A1. b) A clast size thick conglomerate bed of conglomerate facies A1 at the base of the Ullaberget Member. In both photos the sequence boundary (SB) in red marks the boundary between the Janusfjellet subgroup shales below and Ullaberget Member sandstones of the Helvetiafjellet Formation above. (Photo by Ahokas, 2002).

Facies A1: Conglomerate

Description:

The conglomerate beds are matrix supported with medium to coarse grain sand as matrix. Clasts consist of quartz and quartzite. Clasts are sub-angular to rounded and generally range from 1 to 10 cm in diameter. In addition, a few larger clasts (up to 30 cm in diameter) are found along the base of the formation in the Ullaberget section. Beds of facies A1 has been recorded from all localities where the base of the Helvetiafjellet Formation is well exposed. Beds are most frequent in the lower 0-5 m of the Ullaberget Member, where it occurs at the sole of progradational clinoforms. Beds of facies A1 has also been recorded at the base of thick tidal sandstone units in the middle and upper portions of the Ullaberget section.

Conglomerate facies A1 appears in three different settings: (1) Beds seemingly randomly mixed with shale conglomerate beds (facies A2) (Figure 4-1, a); (2) Single clast

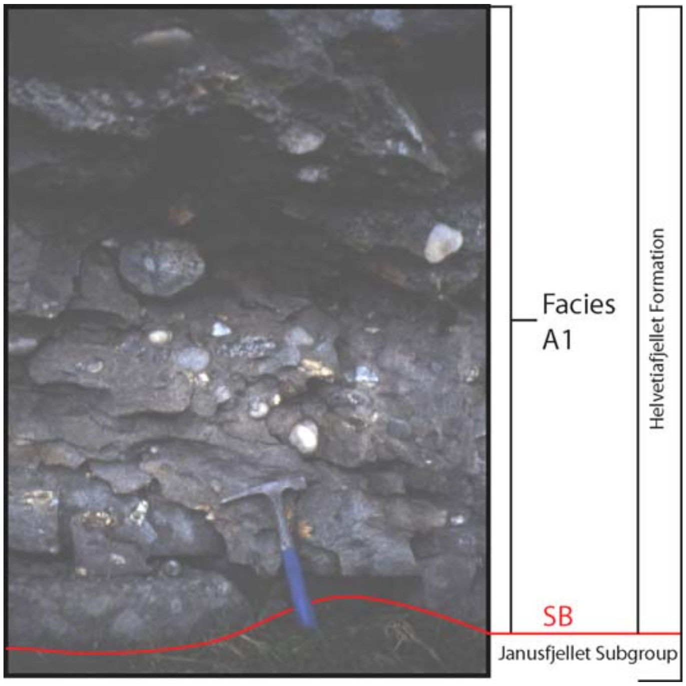

Figure 4-2: Facies A1 at the base of the western end of the Annaberget section. Note the bigger size of the clasts and thicker bed thickness compared to figure 4-1. The sequence boundary is marked in red. (Photo by Ahokas, 2003).

size beds where clasts (1-5 cm in diameter) are supported by coarse grain sand matrix. This is the most common appearance of the basal conglomerate (Figure 4-1 b); (3) Beds consisting of random single clasts ranging from 5 cm up to 30 cm in diameter. Bed thickness of the conglomerate beds and cosets of these varies from 2 cm to about 1 m, depending on the setting and locality. Thickness of the basal conglomerate bed generally increases from the Ullaberget section to the Berrkletten section in the north and through the Louiseberget section to the Annaberget section in the west. Abundance of larger clasts increases in the same directions. In the Ullaberget section, thickness of beds of facies A1 is generally thin, ranging from 2 cm to 15 cm (Figure 4-1), whereas at the base of the Annaberget bed thickness is about 1 m (Figure 4-2). The lateral range of the conglomerate beds ranges from few meters up to about 30 m. All beds lack visible internal stratification. General paleocurrent direction is south-southeast. Lower contacts are generally erosive, whereas the upper contacts are sharp and occasionally eroded by overlying finer grain sandstone unit.

Interpretation:

The beds are interpreted to be of extra-formational origin based on size of the clasts and their differing mineralogy from the overall sandstone matrix. Their lithology, roundness and size, indicate moderate transport distances most likely from Hecla Hoeck metamorphic sediment provenance area some tens of kilometers to the west. This interpretation is supported by the observed increase in bed thickness and size of the clasts towards west and north.

The conglomeratic bed at the erosional surface beneath the Ullaberget Member suggests that the basal surface of the tidal Ullaberget Member is a type 1 sequence boundary marking a sub-aerial exposure prior to sandstone deposition in the area. This is further discussed in Chapter 7. The conglomeratic beds mixed with shale rip-up clasts (facies A2) above the base of the Ullaberget Member indicate reworking of delta-front while it has been prograding seawards. Some of the conglomerate lenses higher up in the Ullaberget Member represent channel-bottom lag from distribution channels that occurred on the top of the tidally influenced prograding fluvial delta of the Ullaberget Member.

In the alluvial deposits above the Ullaberget Member the conglomerate beds are interpreted to represent both channel bottom lags and channel wall collapses. A very discontinuous horizon of both single clasts and thin coarse-clast conglomerate beds preserved at the contact of the overlying elongate tidal ridge sandstone unit marks the transition from fluvially dominated depositional environments to tidal ones. This boundary is interpreted as a tidal ravinement surface. This is also discussed further in chapter 7. Higher up in the stratigraphy conglomerate beds represent medium to very coarse grain sized alluvial gravelly sand deposits. These have been deposited during short lived events of the sea level fall and therefore rapidly shifting and interfingering adjacent depositional environments. Paleo-environments are discussed in greater detail in the facies association chapter 5.

Facies A2: Shale Conglomerate

Description:

Facies A2 consists of medium to very coarse grain sand-matrix supporting shale/mudstone clasts. In the Ullaberget Member the shale conglomerate occurs commonly mixed with or interbedded with conglomerate beds of facies A1. Higher up in the stratigraphy shale

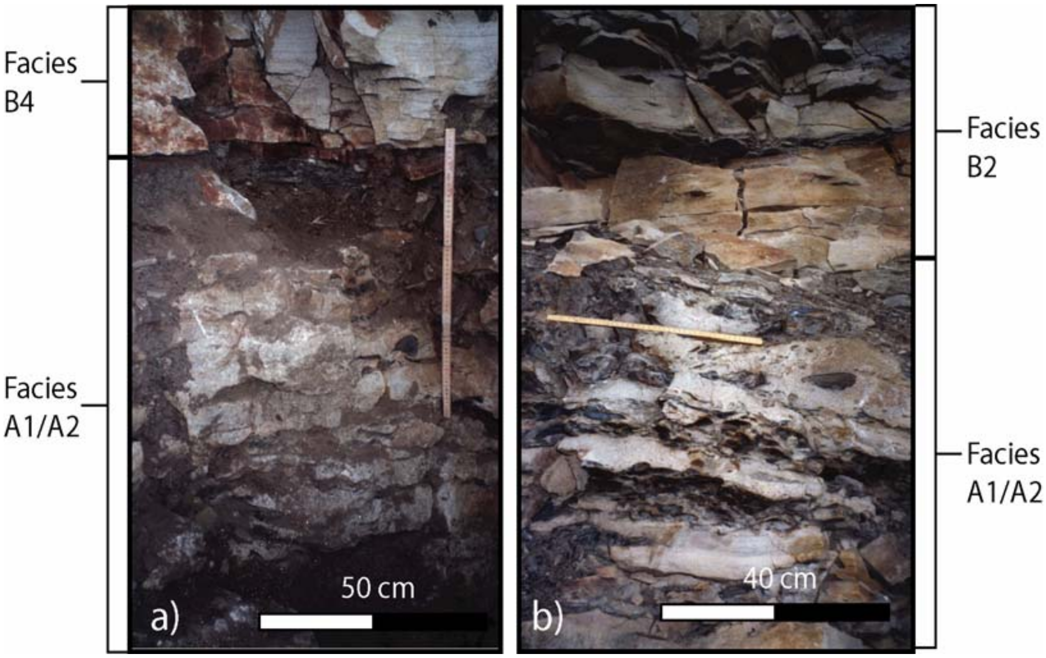

Figure 4.3: Shale conglomerate facies variations from the Ullaberget Member in the lower portion of the Ullaberget section. (Photo by Ahokas, 2002).

conglomerates are found adjacent to thick tidal sandstone units. Individual sets range from 10 cm to 20 cm in thickness (figure 4-3 a), making up cosets up to about 5 m thick. In the lower portion of the Ullaberget Member beds extend laterally some tens of meters and split in two or more separate branches. Higher up in the stratigraphy shale conglomerate beds are thicker (1-5 m) lenses stretching laterally several hundreds of meters. The lower boundaries of the beds are highly erosive, cutting 1-3 m into underlying sandstone units (facies B). Shale clasts are sub-angular flakes varying from less than 10 mm up to 10 cm in diameter. The general appearance of the shale conglomerate beds varies from weakly parallel stratified to seemingly non-stratified. No internal sedimentary structures are found and beds show no clear grading trends. Sorting is poor.

Interpretation:

The shale conglomerate facies in the lowermost part of the Ullaberget Member is interpreted to be shale rip-up clasts from the underlying shelf deposits of the Janusfjellet Subgroup. At the delta front shelf shales have been reworked by oscillating tidal waves and thrown back onto the tide-dominated prograding delta foresets. These clasts have then been mixed with fluvially derived sandstones. Shale conglomerates in the sandy middle portion of the Ullaberget section are here interpreted to be part of meandering channel deposits, such as point bars. These deposits are probably influenced by tidal forces based on overall setting and rhythmical parallel stratification of shale and silt (Figure 5-3). The paleo-environment will be discussed further in the facies association chapter 5.

4.3 Facies B: Sandstone

Sandstone facies comprise the bulk of the Helvetiafjellet Formation. The sandstone deposits recorded in the Helvetiafjellet Formation at the Ullaberget section are divided into 13 sub-facies (See table 4.1) based on their depositional processes and signature.

Facies B1: Tabular cross-stratified sandstone

Description:

Facies B1 is found scattered in the whole formation, usually as single individual sets of tabular inclined foresets. Bed thickness varies from 20 cm to 50 cm. Lateral extension is less than 5 meters and is usually terminated by adjacent trough cross-stratified sandstone units (facies B2). No bioturbation is found from the facies B1. Grain size is dominantly fine or very fine.

Interpretation:

Facies B1 is here interpreted to be 2D fluvial channel bedforms i.e. sub-aqueous dunes (figure 4-4) formed in unidirectional current in the lower flow regime. Facies B1 is separated from facies B11 with absence of mud drapes and therefore interpreted to represent a non-tidal depositional environment or environment out of the reach of tidal forces in proximal part of an alluvial plain.

Facies B2: Trough cross-stratified sandstone

Description:

The bulk of the facies B2 is found from the upper part of the lower portion of the Ullaberget section. Here, right below the middle portion of the section facies B2 interchanges laterally with structureless sandstone facies (B9) and erodes vertically into underlying planar laminated sandstone facies (B4), with erosion relief less

Figure 4-4: Tabular cross-stratified sandstone (facies B1) from the east end of the Ullaberget section. (Photo by Ahokas, 2002).

Figure 4-5: Facies B2 (trough cross-stratified sandstone) bounded by alluvial facies B4 (planar laminated sandstone), D (coal), and B9 (structureless sandstone). The picture shows a single laterally isolated trough-set at the top of the lower portion of the Helvetiafjellet Formation in the western Ullaberget section. The yellow line marks the correlation at top of the facies B9. The fluvial unit is approximately 3 m high. (Photo by Ahokas, 2002).

than 2 m. Individual trough sets are up to 2 m thick and range laterally from 2 to 3 m up to about 10 m. Cosets of stacked trough units have good lateral extend ranging from some 10 m up to few 100 m. Cosets are less than 3 m thick. The sandstone is light grey or nearly white due to high content of quartz. Grains are well rounded, and the sandstone beds have no clear internal grading. Towards the west in the Ullaberget section trough units change their character. They occur as single, multi-storey trough set, laterally isolated by planar laminated sandstone facies (B4), coal (facies D), and structureless sandstone (facies B9) (Figure 4-5). Whereas, in the eastern parts of the Ullaberget section facies B2 occurs as vertically smaller and chaotic trough sets, which erode layterally into one another (Figure 4-6). In the middle portion of the Ullaberget section, facies B2 is nearly absent. However, in the upper portion the Ullaberget section several less extensive separated cosets of facies B2 are found associated commonly with tidal sandstone facies B12. In this case general trough thickness is around 30 cm and cosets are less than 1 m thick, topped by fine grain deposits and penetrated by roots or deformed by bioturbation. Facies B2 have no mud drapes. Several sand filled tree trunks have been registered along the base of the beds facies B2 especially in the eastern end of the Ullaberget section (Figure 4-7).

Interpretation:

Facies B2 is interpreted to be fluvial channel bedform like 3D sub-aqueous dunes formed on the channel floor currents in the lower flow regime. In the western parts of the upper part of the lower portion of the Ullaberget section facies B2 is interpreted to represent a meandering channel system, where single channels are isolated within the adjacent overbank, floodplain, and crevasse deposits. However, in the eastern parts of this same stratigraphic level facies B2 is interpreted to change into represent a braided channel system, where multiple feeder channels erode into one another due to higher current velocity causing generally chaotic character of the facies. This change may be the result of an increase in dip along the depositional strike accompanied with the relative sea level fall or lateral change of the feeder system which caused modification of the river profile. This will be discussed in greater detail in Chapters 5 and 6. In the upper portion of Ullaberget facies B2 is likely to represent deposition from short lived small braided channel systems feeding sediments into back-barrier lagoons or embayments, in an overall transgressive system. The tree trunks are likely be transported along the channel floors and dumped them when the current became too weak to carry them further and being later filled with sand.

Figure 4-6: Trough cross-stratification (facies B2) in the middle part of the upper part of the lower portion of the Ullaberget section showing lateral accretion of the facies B2. The yellow sandstone unit is overlain by coal (facies D) and tabular cross-stratified sandstone with mud drapes (facies B11). A Mauser riffle for scale. (Photo byAhokas, 2002).

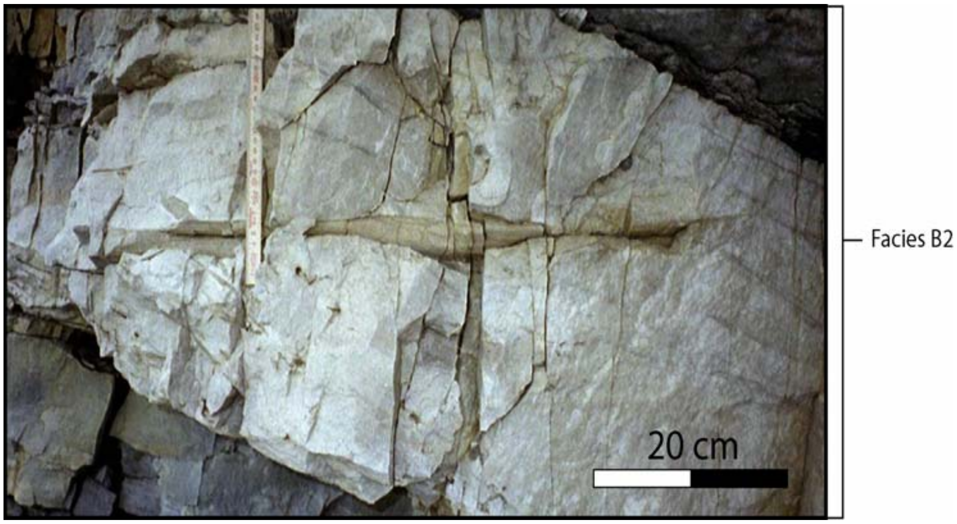

Figure 4-7: A sand filled tree trunk within the facies B2 in the eastern end of the upper part of the lower portion of the Ullaberget section. (Photo by Ahokas, 2002).

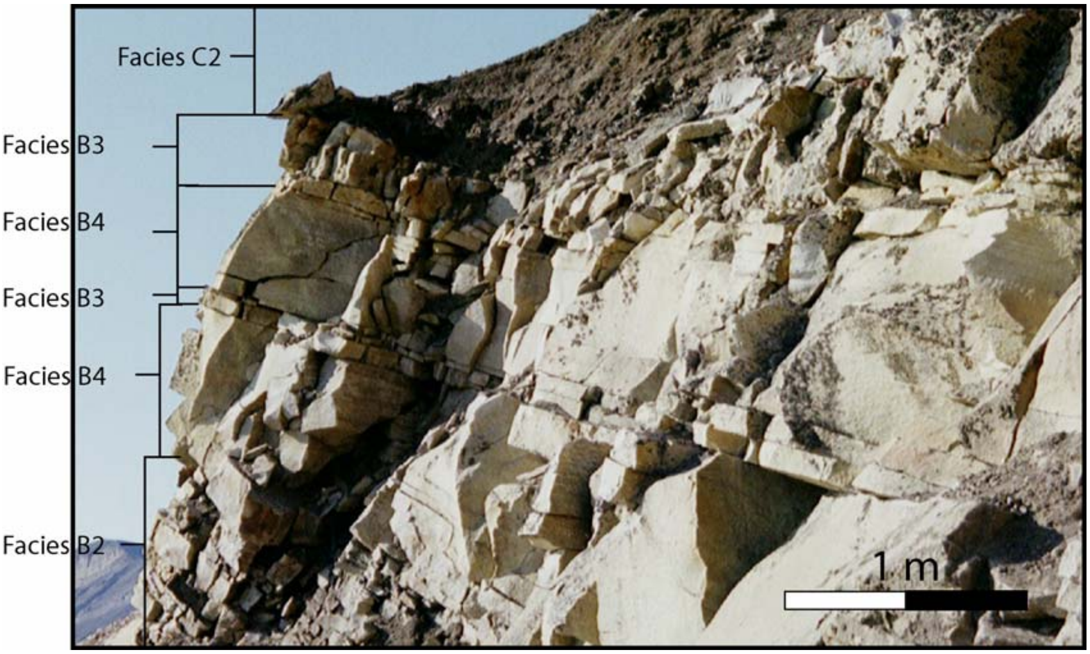

Figure 4-8: Interbedded parallel stratified sandstone (facies B3) and plane-parallel laminated sandstone (facies B4) in the upper part of the Ullaberget Member. (Photo by Ahokas, 2002).

Facies B3: Plane-parallel stratified sandstone

Description:

Sandstone beds of facies B3 are generally thin, ranging from 5 cm to 30 cm (see log UB6, log sheet 2, 29.5-31 m). Cosets composed of several (5-20 or more) sets of facies B3, making up units up to 6 meters thick, are common (see figure 5-8 from the Ullaberget Member). Units of facies B3 usually overlie tidal cross-stratified sandstone (facies 12, B13) units resting conformably on a non-erosive surface. Fine or very fine sand is the dominating grain size. Primary sedimentary structures are plane-parallel stratification and near horizontal parallel stratification. Facies B3 is separated from facies B4 by thicker bed thickness, which lack internal lamination. In the upper portion of the Ullaberget section individual beds are often thinner and undulating while remaining parallel to one another. Appearance is originally light grey, but pale yellow secondary color is dominating in the Ullaberget Member. In addition to significant amount of possible bioturbation or possible root structures plant fragments and soft sediment deformations, such as water escape structures, are recorded in the upper portion of the Ullaberget section. Facies B3 is registered in all the portions of the Helvetiafjellet Formation at the Ullaberget section.

Interpretation:

Facies B3, in the upper part of the Ullaberget Member, is most likely connected to the delta prograding and represents the topsets of the large-scale clinoforms and upper flow regime with little deposition (Reading, 1996). This is based on lack of bioturbation in this unit (Figure 4-8). When beds are thinner and bioturbation is abundant parallel stratified sandstone are most likely deposited under conditions of relatively low hydraulic tidal energy. This occurrence may be connected to adjacent tidal channel and low-intertidal flat deposition, during the neap-tide phase.

Facies B4: Planar laminated sandstone

Description:

Beds with facies B4 are generally relatively thin, ranging from 1 cm to 15 cm, but beds up to 2.5 m are found (Figures 4-8, 5-5 and log UB1; log sheet 2, 22-24.5 m). Individual sets occur within several different lithological environments and are found through the Helvetiafjellet Formation. Fine sand is the dominating grain size and appearance is primarily light grey coloured with yellow colour as secondary. Primary sedimentary structures are horizontal laminae of interchanging light coloured sand and dark silt (Figure 4-9). The upper and lower boundaries are usually conformable with surrounding finer grained strata. Overlying sand beds do occasionally erode into planar laminated beds with up to moderate relief (< 5 cm). Root structures appear to intrude into the beds from overlying sand (same facies) and coal beds (facies D). No bioturbation is registered within facies B4. Figures 4-8 and 4-9 show two examples of facies B4 from the upper part of the lower portion of the Ullaberget section.

Interpretation:

Facies B4 is interpreted to be deposited under fluvial conditions where there is little siliciclastic material and low hydraulic energy levels. Depositional environment is suggested to be interdistributary areas where small increase in siliciclastic input forms planar laminated sand sheets within otherwise generally heterolithic deposits. Facies B4 may have been deposited in floodplain areas such as most distal parts of a crevasse splays where sand influx is low and seasonal changes may deposit mud laminae in between sand. Bed thickness supports this kind of depositional setting (Figure 4-9). Where planar

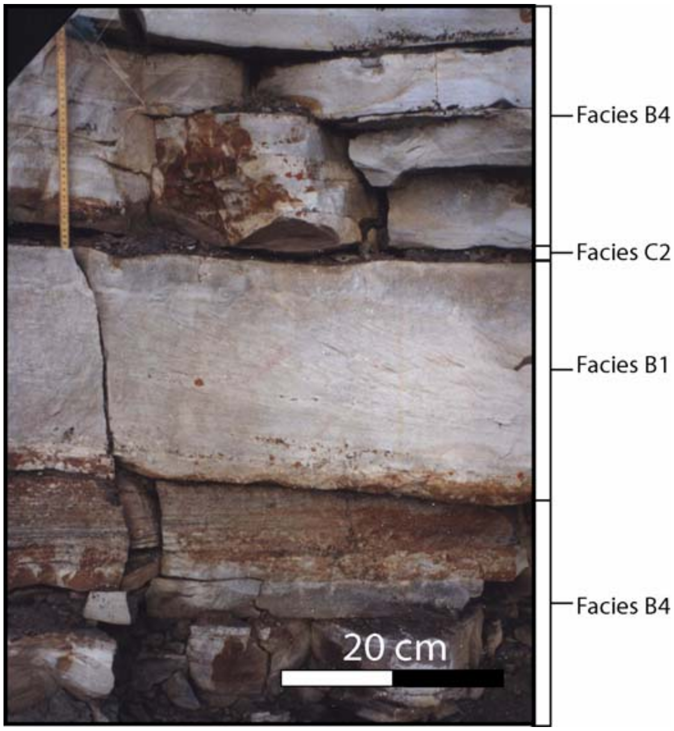

Figure 4-9: Thin beds of planar laminated sandstone facies (B4) and part of a small laterally accretional dune of tabular cross-stratified sandstone facies (B1) in the top part of the lower portion of the Helvetiafjellet Formation in the eastern end of the Ullaberget section (log UB1; 0-3 m). (Photo by Ahokas, 2002).

laminated sand is seen within sandstone units, it probably reflects a period of low hydraulic energy, resulting in fine sand settling undisturbed on a channel floor. Another possibility is landward spill-over deposition over sand barriers or bars. Facies B4 might also be deposited from suspension by weak tidal currents which are not strong enough to develop ripple cross-lamination. Therefore depositing planar laminated, interchanging mudstone and very fine grain sandstone possibly during neap-tide phase of the lunar tidal cycle.

Facies B5: Low angle cross-stratified sandstone

Description:

Facies B5 is found from the middle and upper portions of Ullaberget. In the upper portion facies B5 occurs as medium thick beds usually overlying mudstone (facies C3) and hummocky cross-stratified sandstone (facies B8). These beds are sometimes partly bioturbated by big marine trace fossils, *Diplocraterion* and *Skolithos sp.*, which range between 3 to 8 cm in width and from 5 to 25 cm in length. Both bounding surfaces are non-erosional, and there is a gradual change towards the sandstone facies above and below. The beds show inverse grading and are well sorted, consisting almost purely of quartz grains. Grain size varies from very fine at base to fine in the upper parts of the beds. The color is pale yellow. In the middle portion beds of facies B5 are thin and interchange with very thinly interlaminated planar laminated sandstone (facies B4) and mudstone (facies C3). Diverging paleocurrent directions are recored.

Interpretation:

Low-angle cross laminated sandstone beds are deposited in the swash-zone on beaches and barrier bars. The good sorting is produced by high wave energy which transports the finer particles away, leaving only grains larger than a critical grain size related to actual wave energy. Diverging paleocurrent directions are due to the oscillatory motion of the wave energy in the upper portion of the Ullaberget, whereas bipolar paleocurrent directions in the middle portion of Ullaberget are produced by tidal forces.

Facies B6: Wave ripple laminated sandstone

Description:

This sandstone facies usually occurs on the top of any sandstone unit at the contact to overlying mudstone deposits most frequently in the upper portion of the Ullaberget section. Sedimentary structures are chevron type wave ripples with occasionally mud drapes.

Interpretation:

Wave ripples are shallow water depth bedforms originated in environments where wave activity causes sediment motion. These structures are expected to be formed in both marine and lacustrine shallow water bodies as tidal flats, and the bottoms of small lakes and ponds. These environments are all low-energy environments that also are essential for preservation of wave ripple facies in a geological record. When wave ripple sandstone beds are found accompanied with units of low angle cross-stratified sandstone, tidally influenced trough cross stratified sandstone, with or without bioturbation (facies B5, B12, B13 respectively) they are here interpreted to have been developed within the upper parts of intertidal flat settings. Where facies B6 is found topping any other sandstone unit the most likely depositional environment have been in a pond or small lake right before drowning of the sandstone units during a transgression.

Figure 4-10: Facies B6 (Wave ripples) and B7 (current ripples) from the western end of the Ullaberget section situated above the Ullaberget Member. (Photo by Ahokas, 2003).

Figure 4-11: Combined ripples of facies B6 (wave ripples) and B7 (current ripples) lying seemingly conformably above facies B4 in lowermost exposure in the middle of the Louiseberget section. (Photo by Midtkandal, 2003).

Facies B7: Current ripple laminated sandstone

Description:

The current ripple laminated sandstone units are found throughout the Ullaberget section. These beds are usually relative thin, being generally less than 5 cm thick. Facies B7 occurs closely related to sandstone facies B12, B13, B4 and B5. In cross section facies B7 shows asymmetrical ripples with steep sides of foreset laminae and gentler slopes, if not truncated by another set, making individual laminae indistinguishable. These thin sets usually show climbing ripple sedimentary structures and make up cosets up to 15 cm thick (Figures 4-10 and 4-11). Bounding surfaces of the individual sets are marked by semicontinuous mud drapes showing erosive relief less than 1 cm into underlying set. Bounding surfaces of the cosets are sharp and unconformable with erosive relief under 2 cm. The cosets truncate into one another. The dominating grain size ranges from very fine to fine sand. Cosets of facies B7 are bounded by very thin beds of interbedded mudstone (facies C3) and planar laminated sandstone (facies B4). Bipolar paleocurrent directions are also recorded.

Interpretation:

Current ripple laminated sandstone develops in lower flow regime with unidirectional flow. Bipolar paleocurrent directions are interpreted to be of tidal origin. Beds of planar laminated finer material in between cosets of facies B7 indicate possible tidal influence in the actual depositional environment rather than purely fluvial channel top environment. Likely depositional environment is therefore channel infill in a tidal flat setting.

Facies B8: Hummocky cross-stratified sandstone (HCS)

Description:

Beds of hummocky cross-stratified sandstone are thin beds of parallel laminated darker silt, and lighter colored very fine grain and fine sand found only from the heterolithic upper portion of Ullaberget. These three dimensional hummocks occur within both sandstone dominated lithological units (pale yellow) as well as within the shale and silt dominated units (grey). Bed thicknesses range from 10 cm to 20 cm in the finer grain size units and from 20 cm to 60 cm in the sandy units. Grain size varies from silt to fine sand. Beds are well sorted and show no internal grading. Lower contacts of the cosets are generally lithologically conformable to underlying mudstone deposits. The upper coset boundary is marked by sharp transition into mudstone. Within sandstone units lower and upper transition is gradual into another sand facies. Bounding surfaces of the individual hummocks are sharp where lower concave part is cut by the draping cuspate upper part, which is therefore more continuous in form. Hummocky cross-stratification is closely associated with low angle laminated sandstone facies (B5) above, wave ripple laminated sandstone facies (B6) and current ripple laminated sandstone facies (B7) below. In several

Figure 4-12: Hummocky cross-stratification facies (B8) from the Ullaberget section log 1. Note the 3D form of the hummocks around the corner on the left. (Photo by Ahokas, 2002).

beds marine trace fossils are observed laterally within same bed or in vertically adjacent beds usually above hummocky cross-stratification.

Interpretation:

Hummocky cross-stratification (HCS) is interpreted to have deposited below fair-weather wave base (FWWB) during storm events when coarser material is transported into more distal position (Walker 1984) and found interchanging with darker finer grain size distal deposits. This interchange results a distinct hummocky form. HCS sandstones in the Helvetiafjellet Formation have been deposited in a transgressive setting and represent the transition zone between shelf and foreshore/shoreface deposits. This interpretation is based on the observation that HCS sandstones are both laterally and vertically associated with low-angle cross-stratified sandstones (facies B5) above and sandstone beds with marine trace fossils (facies B10). Wave- and current ripples, facies B6 and B7 respectively, are also closely associated with HCS. These deposits represent either the more distal parts of the shoreface prior to storm events or less extensive storm periods.

Facies B9: Structureless sandstone

Description:

Sandstone beds with facies B9 are grey in colour and consist almost purely of quartz. These beds define the top of the lower portion of the Helvetiafjellet Formation and extend over the whole Ullaberget section. Beds are generally chaotic and occur closely with trough cross-stratified sandstone (facies B2) (Figure 4-13) and plane parallel stratified sandstone (facies B3) and coal (facies D). Thickness of the sets varies from about 20 cm to 1 m, with cosets making up units up to around 3 m. Cosets are composed usually of 1 to 4 or more sets all bounded by facies D (Figure 4-5). Coal filled root structures, as well as coal fragments, are found from these beds. Peaces of non-coalified wood and tree trunks both filled with fine grain size sand are found often at the base of the thicker beds (Figure 4-7). Upper contacts are lithologically sharp. Lower boundary is highly erosive truncating up to 2 meters down into underlying beds of facies B4 and B5. Lateral accretion is significant. Medium sand is the dominant grain size of this facies in the lower part of the Helvetiafjellet Formation, whereas fine and very fine sand is dominating grain size in units lying higher up in the stratigraphy. Grains are well rounded and sorted, but no significant grading is recorded.

Interpretation:

The structureless sandstone facies B9 is here interpreted to originate from laterally migrating high sediment loaded currents based on the high quartz content and generally chaotic appearance. The main depositional environments may have been low sinuosity meandering fluvial channel and adjacent overbank areas. Chaotic appearance of facies B8 may also be caused by slope failure, which causes slumping and subsequent movement of large amounts of sediment at the same time (Reading, 1996), thus yielding general lack of sedimentary structures (*See log UB1, log sheet 1*). The overbank deposits include sand surges which appear either as single sets or cosets, composed of a few medium thick sets bounded by coal facies (D) from periods of sub-aerial exposure (*See log UB1, log sheet 1).* These overbank depositional environments include crevasse splays, small laterally aggrading channels and sand surges.

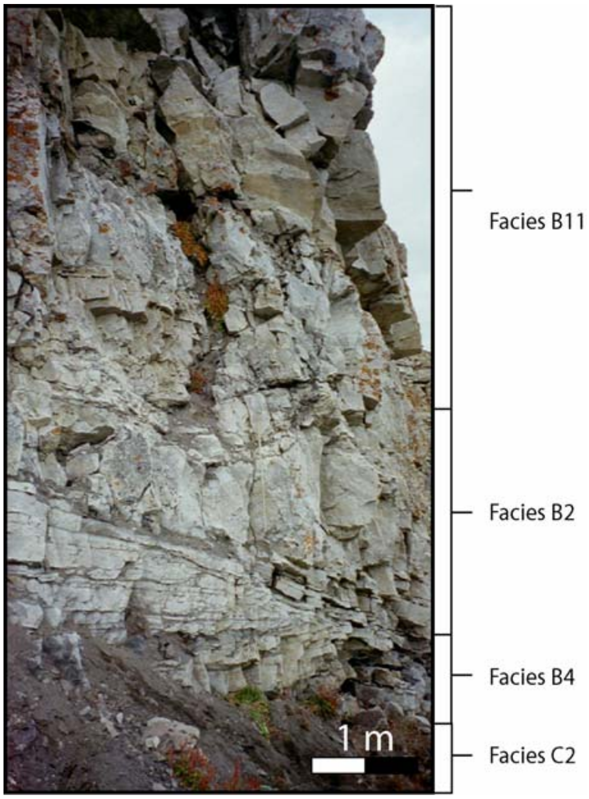

Figure 4-13: Large scale trough cross-stratification (facies B2) in the middle part of the Ullaberget section. This facies B2 is sometimes difficult to separate from the structureless sandstone facies B9. (Photo by Ahokas, 2002).

Facies B10: Structure-less sandstone with bioturbation

Description:

Sandstone beds that are intensely bioturbated by marine *Diplocraterion* trace fossil are found in the shale and siltstone dominated upper part of the Helvetiafjellet Formation. Some of these units can easily be traced over the whole Ullaberget section, while most of them are replaced by other sandstone deposits towards the west. Dominating colour is yellow, but some of the beds are light grey. In the latter case, *Diplocraterion* traces fossils are filled with well cemented iron-mud (red/brown), while sand is otherwise dominating infill. These highly bioturbated units also occur within thicker sandstone units. Both lower and upper boundaries are lithologically sharp (conformable). Textural transition occurs from shale and siltstone to sandstone, as well as from sandstone to shale and siltstone. However, the lower boundary is usually hard to pinpoint since burrows often extend down into underlying beds and therefore make the boundary diffuse (fig. 4-14). The bed

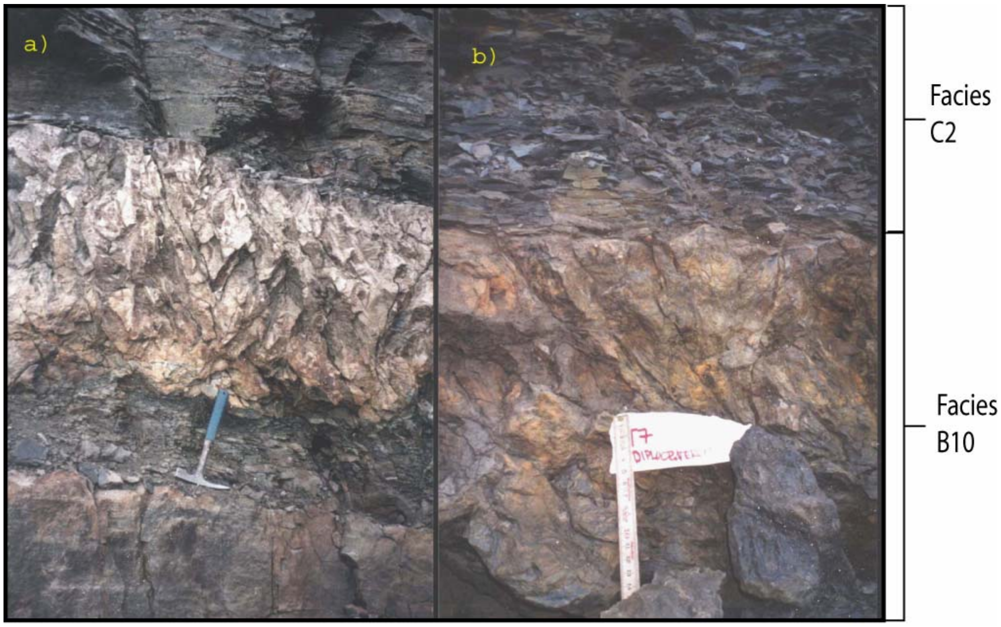

Figure 4-14: The two different appearances of facies B10 along one bed, where a) is in the west and more proximal, where as b) is from the east and more distal. On the left light grey matrix and red/brown trace infill from the Ullaberget section log UB3. On the right sand matrix and sand filled traces from the Ullaberget section log UB1. The distance between locations is about 600 m. Note the diffuse lower boundaries and more conformable upper boundaries. (Photo by Ahokas, 2002).

thickness ranges from 10 cm to 1 m. Grain size is fine sand and the beds are well sorted. Neither sedimentary structures nor grading has survived the intense bioturbation, with few exceptions.

Interpretation:

Facies B10 is interpreted to be marine influenced sand deposits that had optimal conditions for colonization of marine organisms, forming the *Diplocraterion* trace fossil. Some of these “colonization windows” appear to have been more optimal than others, as indicated by size of the burrows, varying lateral extension of the beds and varying bioturbation grade. The distinct marine character of facies B10 beds favours that deposition took place in an overall transgressive phase. Sorting, lateral extension and overall setting suggest generally shelfal depositional environment into which sand occasionally was brought, probably during storms. See facies association chapter for discussion of the origin of the sand.

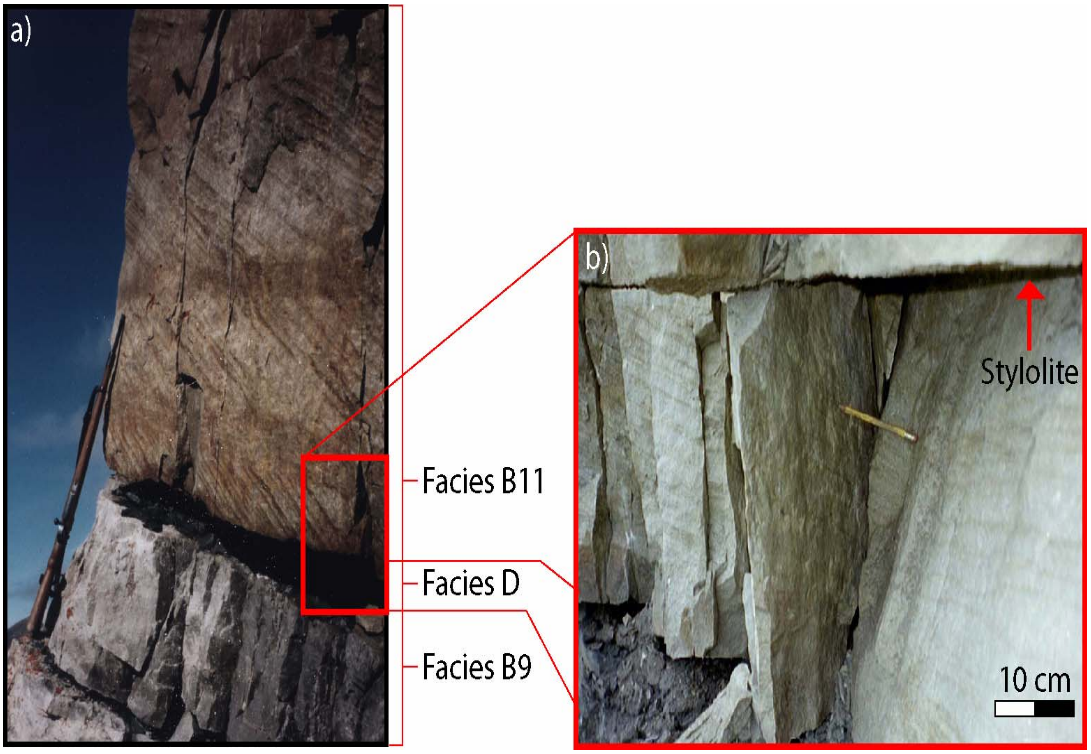

Figure 4-15: Facies B11 (tabular cross-stratified sandstone with mud drapes) overlying facies D (coal) and facies B9 (structureless sandstone) seen at the boundary between the lower and the middle portions of the eastern Ullaberget section. (Photo by Ahokas, 2002).

Facies B11: Tabular cross stratified sandstone with mud drapes

Description:

The bulk of the facies B11 is seen as very thick, semicontinuous, reddish and grey sandstone unit defining the base of the tidal middle portion of the Helvetiafjellet Formation. Individual bed thickness ranges from about 20 cm to 50 cm occurring commonly in cosets composed of 3-10 beds. Thickness of cosets ranges from 1 m up to 8 m (See logs UB2 and UB6; log sheets 2 and 1, respectively). Lower boundaries of cosets of facies B11 are sharp with erosive relief up to 10 cm. A discontinuous horizon of pepples (facies A1) is observed along this boundary, as well as individual cobble sized clasts of quartz and quartzite (facies A1). The upper boundaries of cosets are truncated by overlying finer grain deposits. In the eastern Ullaberget section, upper parts of the cosets of facies B11 change gradually into finer grain sandstone with discontinuous parallel coal flake lamination (facies B9 in log UB1; 10-12 m). Medium sand is the dominant grain size, but apparent random bands with grain size varying from coarse to very coarse sand are recorded within and at the base of the beds. Beds of facies B11 are normal graded and show moderate sorting at the base and good sorting in the top. Primary sedimentary structures are relatively steeply inclined straight foresets with mud drapes, which show angular termination against near horizontal bedding boundaries above and below (Figure 4-15). Foreset thickness is from 2 to 4 cm, and the foresets also show normal grading and improved upwards sorting relative to the general sorting of this facies. Secondary stylolite formation is seen along these bounding surfaces.

Interpretation:

Beds of facies B11 are interpreted to represent cross sections trough 2D tidal bedforms developed in lower flow regime. This interpretation is based on the straight foresets with mud drapes. The latter sedimentary structure is generally considered the most distinctive feature in tidal deposits. Straight crested 2D dunes and 2D ridges develop from bedload depositional processes where bottom tidal current velocities have been strong, subjecting the sea bed to a large rate of sand transport. Unimodal orientations of internal cross-strata are in agreement with local dominant flow direction of ebb-tidal current, during which the bulk of deposition and progradation of 2D intertidal sand bodies takes place (Klein and Whiley, 1972; Dalrymple et al., 1978). Migration of sand bodies is accomplished during very short period. However, migration might as well result from high rate of fluvial input accompanied with in this case apparently dominant ebb-tidal current. Depositions during subordinate flood tidal current have been eroded by the dominating phase. Mud drapes accumulate from suspension during high- and low-tidal slack-water stages. Lateral and vertical thickness variations of beds of facies B11 can be due to differences in bottom current magnitude during the dominant phase (spring-tide) and the subordinate phase (neap-tide) of the lunar tidal cycle. The dominant phase yields to higher rate of sedimentation and subordinate results near zero rate of sedimentation.

Possible depositional environments are the low-tidal flat zone, the distal part of the intertidal flat setting, or along the feeder channel floors in a wide braided fluvial setting. High rate of mud drape preservation points to inshore area or coastal embayment instead of offshore environment (H.D Johnson & C.T Baldwin). This is furter discussed in chapter 6.

Figure 4-16: Facies B12 in the lower part of the Ullaberget Member shows the lateral variation of thicker and thinner bundles reflecting sedimentation during spring and neap tide, respectively. (Photo by Ahokas, 2003).

Facies B12: Trough cross stratified sandstone with mud drapes

Description:

Facies B12 make up the bulk of the lower and the middle portions of the Ullaberget section. In the lower portion of Ullaberget section, beds of facies B12 have dark yellow colour, whereas in the middle portion colour is red or grey. Fine sand is the dominating grain size in the lower portion of the section, whereas very fine sand is the dominating in the middle portion. The dominating paleocurrent direction is towards East-SE. Bed thickness increases towards the west, while thickness of cosets decreases in same direction. Thickness of individual beds of facies B12 ranges from 10 cm up to about 1 m. Thickness of individual foresets within the beds varies laterally from < 1 cm to 4 cm. Foresets terminate tangentially against near horizontal lower and upper bounding surfaces. The angle of termination is generally low, around 10 to 15 degrees, but deeper inclined foresets are recorded. Single and double mud drapes are clearly visible within all beds of facies B12, situated usually at the base of the tangetial foresets (Figure 4-16). The beds of facies B12 are bounded by continuous and thin parallel laminated silt and/or mudstone beds, which drape the whole sandstone bed until they eventually are truncated by another sandstone bed or silt and/or mudstone bed. Thickness of this thin laminated bed ranges from 5 cm to 15 cm. Cosets of facies B12, composed of several tens of individual sets, make up to 10 m in thickness. The middle portion of the Ullaberget section is composed of 2 or 3 vertically stacked cosets of facies B12, depending on the horizontal position in the section (see figure 2-2). These sandstone units are separated by thick beds of finer grain deposits, which commonly are covered by debris. Lower contacts of cosets are lithologically sharp and unconformable change from underlying finer grain size sediments (Figure 4-16). The contacts have erosion relief of less than 10 cm. Cosets of facies B12 are overlaid by sandstone beds with finer sediments and smaller sedimentary structures (figure 4-16).

Interpretation:

Facies B12 is here interpreted to be a cross section of 3D tidal bundles deposited in the non-vegetated mid-flat zone within an intertidal near-shore setting. The interpretation is based on the abundance of single and double mud drapes and laterally varying foreset thickness indicating spring-tide (thicker bundles) and neap-tide (thinner bundles) variations. In the lower portion of the Ullaberget section, tidal forces have most likely been strong enough to re-deposit the fluvial delta sands. In the middle portion of the Ullaberget section, rhythmically interbedded thicker sandstone beds and thinner, finer grain size sandstone/siltstone beds indicate differences between the deposition from bedload and deposition from the suspension during spring-tide and neap-tide phases of the lunar tidal cycle. The thickening of individual beds of facies B12 towards the west in the middle portion of the Ullaberget section may be due to landward lateral narrowing of the area of deposition. This might have resulted in stronger effects of tidal currents where returning tidal wave strengthens new incoming tidal wave yielding to thicker beds. Westward from the post-depositional fault (Figure 2-2), bed thickness decreases again and in the Louiseberget section tidal energy have been lower and sandstone bodies change to less sandy high-tidal flat and/or supratidal deposits. Depositional environment is further discussed in Chapter 6.

Facies B13: Trough cross-stratified sandstone with mud drapes and bioturbation

Description:

The bulk of facies B13 is only found interbedded with facies B12 in the middle portion of the eastern Ullaberget section (See log1; UB1, 15 – 22 m, 25 - 42 m), and in parts of the Ullaberget Member. Sedimentary structures are in general same as in facies B12, but beds

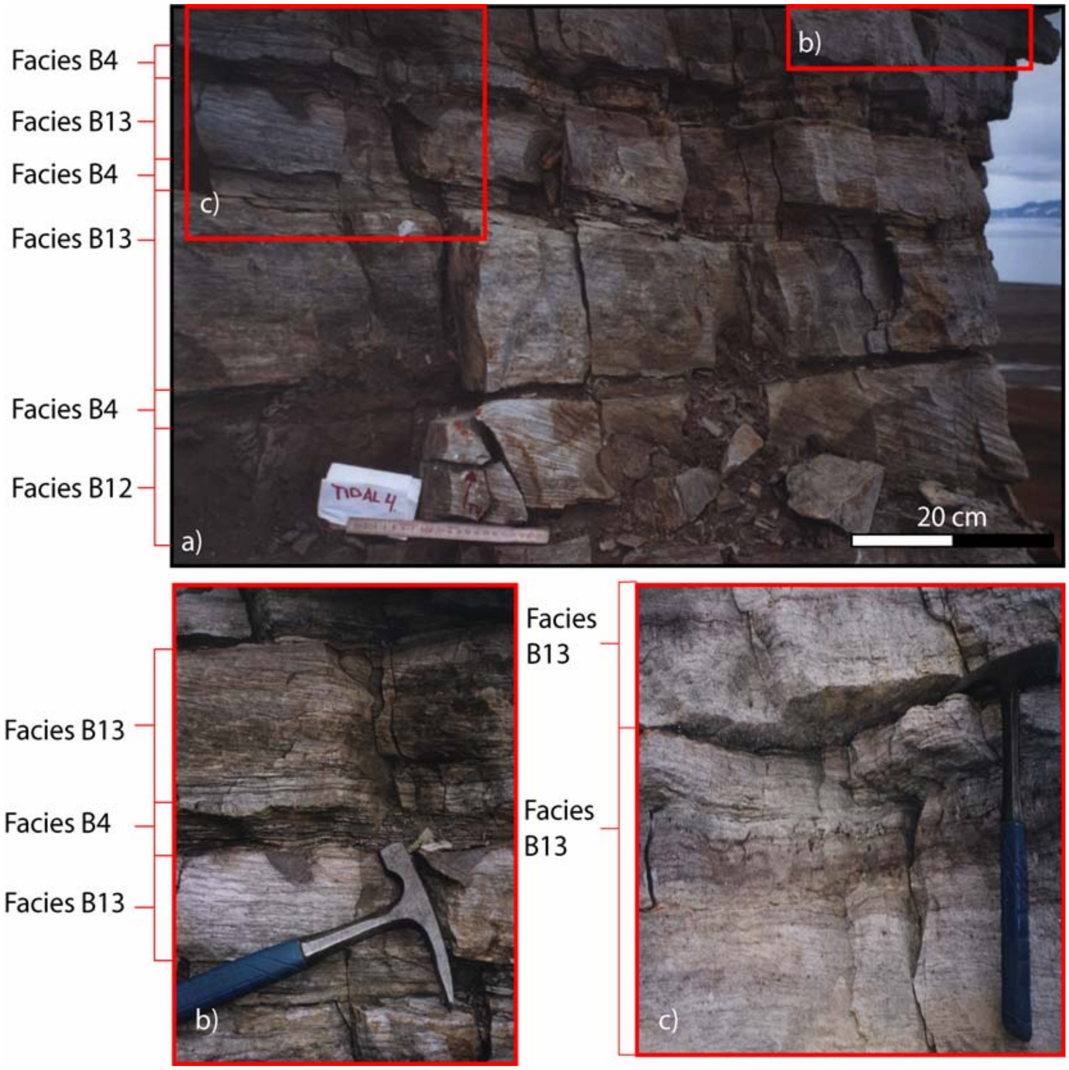

Figure 4-17: Figure a) shows interchanging beds of facies B4, B12 and B13 in the eastern end of the middle portion of the Ullaberget section. Figure b) shows a close-up of bioturbation (facies B13) within a tidal flat sandstone bed. Figure c) shows a close-up of the most common kind of bioturbation (?*Skolithos sp.*) within beds of facies B13. Photo is taken from the Ullaberget section log1 (UB1; 15-16m). (Photo by Ahokas, 2003)

of facies B13 are bioturbated and therefore separated from facies B12. The separation is made due to abundance of these beds. Individual bed thickness of facies B13 ranges from 15 to 32 cm. The dominant grain size is fine sand in the Ullaberget Member and lower parts of the middle portion of the Ullaberget section whereas very fine sand is dominating in the upper parts of the middle portion of the Ullaberget section. Beds of facies B13 are bounded by thin continuous beds of finer grain size sand and silt. Thickness of these interlayering thin parallel laminated beds range from 2 to 8 cm. Primary sedimentary structures in beds of facies B13, where preserved, are discontinuous, but

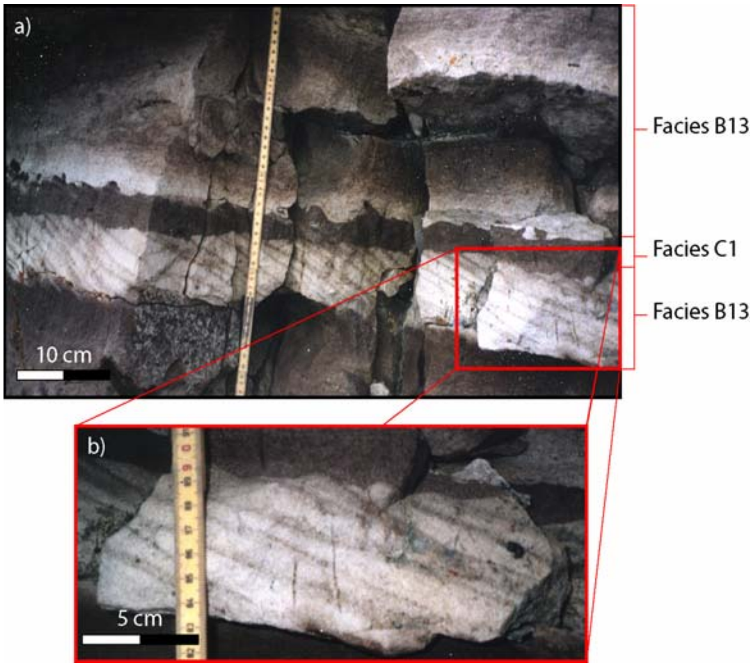

Figure 4-18: Vertical trace fossils and flame structures within tidal bar sandstone (facies B13). Photo is taken from the eastern Ullaberget (Log UB5; ~26 m). (Photo by Ahokas, 2003).

parallel, low-angle foresets. Angle of inclination is generally about 10 degrees (Figure 4-17a, b and c). All the beds show unimodal paleodirection towards east-southeast. Bounding surfaces of the individual beds of facies B13 are, similarly as in facies B12, sharp and unconformable. The erosive relief is usually less than 2 cm. In the eastern end of the Ullaberget section, mud drapes are generally discontinuous occurring along the sandstone foresets as single and double drapes with a little sand in between the two drapes. The colour of the drapes is generally reddish. Both mud drapes and the sandstone foresets are punctuated by small and thin vertical bioturbation. Intensity of bioturbation varies from bed to bed and is up to grade 3 at highest (Figure 4-17). Size of the burrows is less than 0.5 mm in diameter and up to 5-6 cm in length (Figure 4-18). Burrows occur with or without lining i.e. membrane around the burrow. Soft sediments deformations are also registered as shown in figure 4-18.

Interpretation:

Facies B13 is interpreted as cross sections of 3D bedforms, termed tidal bundles, deposited from bedload in the high-intertidal flats. Bundles of unimodally cross-stratified zones are grouped laterally into thicker and thinner units, representing spring and neap tide sedimentation, respectively (Boersma and Terwindt, 1981; Klein, 1985). In this environment, exposure during the low-tide has been sufficient for colonization of trace fossils (?*Skolithos sp.)* compared to subtidal environment, which is always subaquaeous. Varying vertical occurrence of the "colonization windows", i.e. periods when bioturbation could have taken place, indicates a possible embayment or a fall in relative sea-level. In turn, the absence of bioturbation in beds of facies B12 may indicate changing energy environments, thus yielding to cosets of interbedded bioturbated and non-bioturbated sandstone beds deposited in the intertidal zone.

4.4 Facies C: Siltstone and Mudstone

Facies C1: Siderite cemented siltstone

Description:

Beds of facies C2 are found scattered from the middle and the upper portions of the Ullaberget section. Bed continuity ranges from very good to poor, from horizons of hundreds of meters to lenses of few meters, respectively. Bed thickness is generally between 10 cm and 30 cm. Beds of facies C2 are very well cemented and hard. They have distinctive secondary dark red outlook. However, from inside these beds are primarily dark grey containing commonly small (< 5 cm in diameter) coal flakes and coaly plant imprints like leaves, branches and roots. Grain size is hard to define, but silt sand dominates over mudstone.

Interpretation:

Facies C2 is here interpreted to be siderite cemented siltstone. Siderite is early authigenic cement. Formation of siderite ($FeCO_3$) requires reducing conditions and low sulphate activity. Siderite typically forms in one of two distinct environments. 1) Strongly reducing continental and freshwater lacustrine conditions (methanogenic zone). These environments of low sulphate concentration, and high organic carbon concentration (Coleman, 1985) include freshwater lakes, swamps and marsh deposits which are also appropriate for preservation of roots and plant fragments. 2) Slightly reducing marine conditions (post-oxic zone). These conditions are in turn commonly associated with marine environments of low concentration of organic matter and low sedimentation rate. Common for both type of environments are reducing conditions and low sulphate activity in water. High sulphate activity in turn would lead to reaction between iron and sulphate producing pyrite instead of siderite.

Marine and fresh-water siderites could be identified from each other by chemical and isotope compositions. Fresh-water siderite (pure siderite) contains minor concentrations of Mn and high concentrations of Ca relative to Mg, whereas marine siderite (impure siderite) contains high concentrations of Mg and little Ca. This is not further discussed in this thesis.

Facies C2: Mudstone

Description:

Black and grey mudstone units are commonly less consolidated in the Ullaberget section of the Helvetiafellet Formation. These fine grain size lithologies are thus usually covered by vegetation and or talus material. Despite the cover, these intervals are here generally assumed to be mudstone dominated. Grain size is dominantly clay, silt and very fine sand and units of facies C2 are generally composed of interfingering beds of clay, siltstones and fine grain size sandstones.

In the upper part of the lower portion of the Ullaberget section units of facies C2 include coal (facies D) and siderite cemented concretion horizons. This unit is about 9 m thick in the east end of the section and decreases in thickness into only few meters in the western end of the Ullaberget section. In the middle portion of the Ullaberget section facies C2 is generally interbedded with facies A2 or occurs as thin beds between thicker sandstone beds. In the upper portion of the Ullaberget section beds of facies C2 have dark black or grey colour throughout the units, and weak general upwards coarsening trend is registered. These beds are usually associated with HCS (facies B8) and low angle cross-stratified sandstone (facies B5).

Main sedimentary structures of facies C2 in all portions of the Ullaberget section are parallel lamination, which are occasionally convoluted where the contact with the overlying unit shows loading structures. Thickness varies from thin horizons of around 1 cm to several meters of shale. Below the Ullaberget Member, in the Janusfjellet Subgroup, marine macrofossils such as *Belemnites* are found in the facies C2. From the samples taken from the mudstone unit right above the Ullaberget Member in the top part of the lower portion of the Ullaberget section no microfossils have been found in a few preliminary laboratory analyses. And, due the scope of the study, none of the samples from the whole Ullaberget section have not been further investigated.

Interpretation:

It is difficult to make a general interpretation of the mudstone units of the Helvetiafjellet Formation in the Ullaberget section. However, two generally different interpretations are made. Mudstone unit lying conformably above the Ullaberget Member is interpreted as brackish or lacustrine mudstone unit based on the coal seams (facies D) and horizon of siderite cemented concretion (facies C1). Mudstone units in the middle and the upper portions of the Ullaberget section are interpreted as marine shale based on the stratigraphic context. These units have been deposited in interplay between tidally influenced marginal marine and fully marine deposition. Common for both interpretations is the absence of bottom currents present at the time of deposition. If *Foraminifera* were found from the marine or brackish mudstone units of the upper portions of the Helvetiafjellet Formation, it would indicate a semi-enclosed bay or lagoon.

Facies D: Coal

Description:

Coal beds are continuous black beds mainly found at the contact between the lower and the middle units in the Helvetiafjellet Formation. The coal beds show cubic break-up pattern and have metallic glitter. These beds are of medium bed thickness (10-30 cm). Few of them can be followed over a distance of ~1.5 km throughout the whole Ullaberget section. In the middle and the upper portions facies D occurs only as thin (<3 cm thick) seams. In the upper portion coal occurs also as small flakes (<1 cm in diameter) within very fine grained sandstone matrix. Beds of facies D are sometimes shaley.

Coal beds are sharp-based and non-erosive, usually with coal-filled root structures intruding into the underlying beds. The upper lithological boundary is sharp with abundant loading structures like cutter casts, fluid casts. Above lying sandstone beds usually also cut

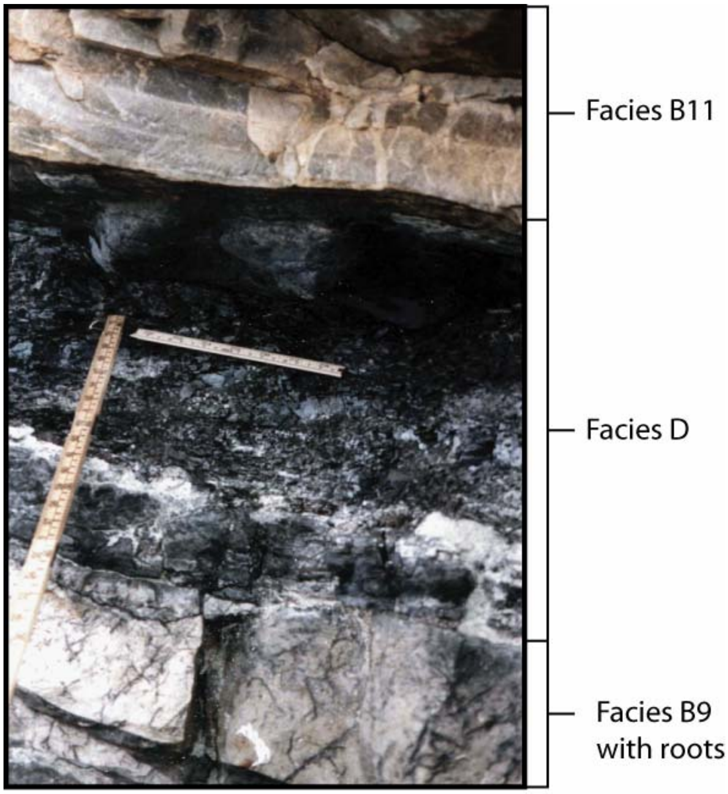

Figure 4-19: A possible dinosaur footprint in coal (facies D) near log 3/4 in the western Ullaberget section. (Photo by Ahokas, 2003).

into coal beds making upper contact wavy. Among the loading structures several prominent dinosaur tracks can be recorded (Figure 4-19).

Interpretation:

Coal is formed as a result of compaction of vegetation debris accumulated in marshes and swamps. These are low-lying areas where ground water table is high compared to the surface, giving rise to high organic production (Midtkandal, 2002). Coal beds are interpreted to represent a sub-aerial overbank and/or floodplain depositional environments in an alluvial setting. The lateral extension of some of the beds points to an allocyclic regional reorganization of the drainage system or to changes in base level (Belt, Sakimoto and Rockwell, 1992). On the contrary, thin and laterally limited coals point to active braidplain regimes where overbank settings were short-lived (Nemec, 1992).

5

Facies associations

Grouping facies together into associations, which are interpreted to represent a certain depositional environment, eases the effort in understanding the overall development of a sedimentary succession and its depositional processes.

Table 5.1: Summary of the facies associations described in this study.

Code	**Facies associations**
FA1	Alluvial plain
FA2	Meandering tidal channel
FA3	Intertidal channel/flat
FA4	Elongate tidal ridge
FA5	Lacustrine embayment/lagoon
FA6	Tidally influenced delta
FA7	Transgressive marine sandstone
FA8	Marine mudstone

Facies Association 1 (FA 1): Alluvial plain

Description:

FA1 includes facies B1 (tabular cross-stratified sandstone), B2 (trough cross-stratified sandstone), B3 (plane-parallel stratified sandstone), B4 (planar laminated sandstone), B7 (current ripple laminated sandstone), B9 (structureless sandstone), and D (coal). Facies A1

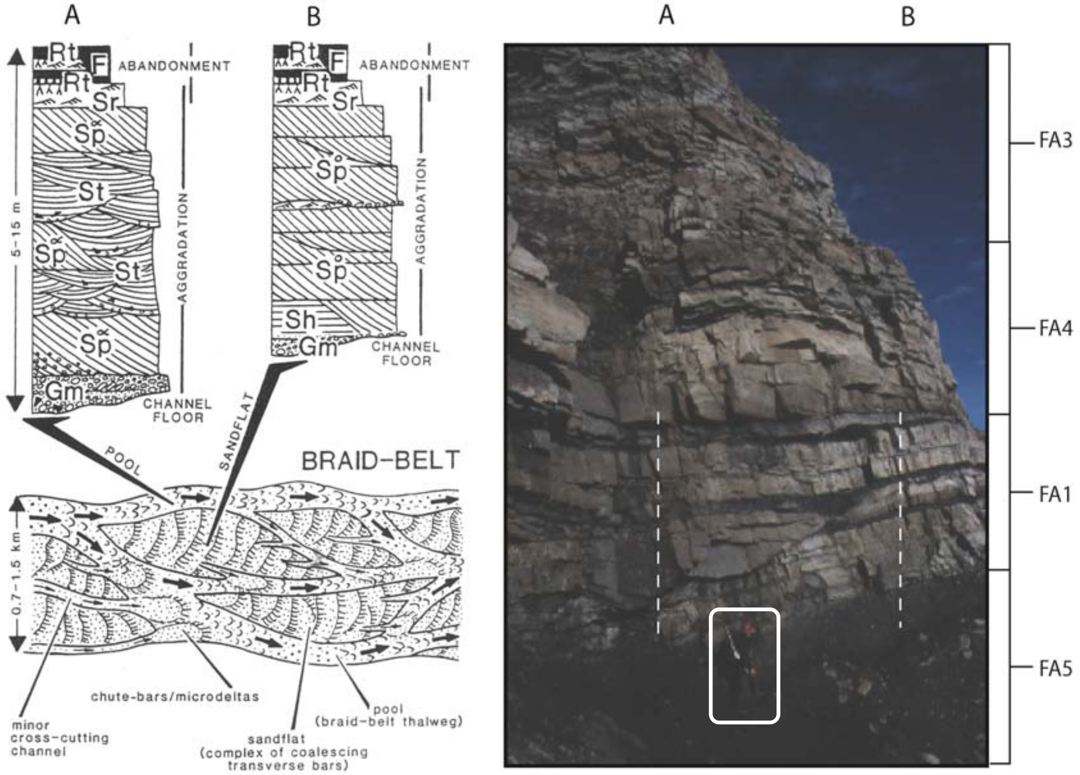

Figure 5-1: Channel and sand flat models for the distributary sandstones in the Helvetiafjellet Formation on the left. (From Nemec, 1992). On the right, a photo from the western end of the upper part of the lower Ullaberget section shows a channel and associated sand flat facies included in facies association FA1. Dotted lines marks two similar cross-sections through FA1 (A and B) in the Ullabergetsection as in the Nemec's figure on the left. I. Midtkandal for scale. (Photo by Ahokas, 2003).

appears occasionally at the base of the FA1 units. Among these facies, B2 and B4 are dominant, as they reflect different hydraulic energy. FA1 occurs as laterally continuous sandstone unit throughout the Helvetiafjellet Formation at the top of the lower portion of the Ullaberget section. Thickness of FA1 is constantly about 3-4 meters and beds are easily recognized from distance as a white/light grey coloured unit below the thick sandstone unit of the middle portion of the Ullaberget section (Figures 2-2 and 5-8). The lower boundary of FA1 is covered by FA5 and not seen in the lower portion of the Ullaberget section. In this section the facies reflecting the lowest hydraulic energy (facies B4, B3 and B7) is found toward the bottom of units of FA1, followed by higher hydraulic energy facies (facies B2 and B9), which in turn are topped by lower energy deposits (facies D). The latter beds (2 or 3 depending on the lateral position within the section) include apparent dinosaur footprints, seen as loading structures from above lying deposits of FA3 and/or FA5. The upper boundary of FA1 in the Ullaberget section is lithologically sharp, where little or no erosion relief is recorded, except above mentioned loading structures. In the eastern Ullaberget section single beds of higher energy facies within FA1 can not be correlated laterally for more than few meters, before they are truncated and replaced by another bed of the same facies. In the western parts of the Ullaberget section, single beds of higher energy facies within FA1 are in turn isolated laterally by lower energy facies.

FA1 appears in all the logged localities. It is found as two units, separated by fine grained interval, in the bottom third of the Helvetiafjellet Formation in the Louiseberget section and as one thick unit covering the bottom half of the Helvetiafjellet Formation in the Annaberget section. In the Berrkletten and Sverdrupstupet cliff sections FA1 is found as relatively thin unit at the base of the cliff sections. All these sections are associated with basal conglomerate lag (facies A1), which in these locations mark the lower boundary of FA1. Within the Louiseberget and the Annaberget sections FA1 shows a general gradual upward decrease in energy and in grain size. In these sections same type of cross-strata has been identified as within the Ullaberget section, but appearing in different stacking pattern. In the both sections the most common facies is medium to coarse grained trough cross-stratified sandstone (facies B2), whereas plane-parallel stratified sandstone (facies B3), tabular cross-stratified sandstone (facies B1), and current ripple laminated sandstone (facies B7) are the secondary sedimentary structures. The upper boundary of FA1 is marked by sharp lithological contrast to overlying silt and mudstone deposits. Coal (facies D) is only recorded on the top of the FA1 units in the Louiseberget section. Dinosaur foot imprints associated with FA1 have not been found elsewhere, except from the boundary between the lower and the middle Ullaberget section.

Interpretation:

In general, FA1 could be divided into two, higher energy channel bedforms and lower energy overbank fines and crevasse deposits, but these are in this thesis considered as one facies association, due to their closely related depositional environment. Therefore, seen as one, FA1 represents a vertical and lateral collection of facies, reflecting interplay of deposition by moving and/or standing water (higher energy and lower energy, respectively) topped by subaerial exposure. The changes in hydraulic energy may reflect waning flow, where moving water either decreases in quantity or it finds new flow routes. This is in agreement with general dynamics of fluvial channels (Reading, 1996). The abrupt increase in energy and change into coarser facies within the lower part of FA1 unit in the upper lower portion of the Ullaberget section is interpreted as a result of basinward change of facies belts. This change led to truncation of the lacustrine embayment facies association (FA5) by FA1 deposits. The following decrease in energy and upward fining grain size character in the upper part of the same FA1 unit in the lower portion of the Ullaberget section is interpreted to be caused by a change from higher energy channel-floor deposits into the abandonment facies (coal). This probably reflects the migration and aggradation of the fluvial channel-floor deposits prior to fine sandstone and mudstone deposition during the abandonment stage of the channel infill. Nemec (1992) has suggested that vertical aggradation of alluvial deposits (FA1) in the Helvetiafjellet Formation can take place either as braided channel aggradation and aggradation on the laterally associated sandflat areas (Figure 5-1). This suggestion corresponds well with the interpretation made in this thesis.

Facies Association 2 (FA 2): Meandering tidal channel

Description:

FA2 includes facies A2 (shale conglomerate), B2 (trough cross-stratified sandstone), B11 (tabular cross-stratified sandstone with mud drapes), and B12 (trough cross-stratified sandstone with mud drapes). Lateral and vertical interchanging heterolithic mudstones and sandstones (facies A2 and B11) are dominant. Thickness ranges from about 1 m up to 4 m and show clear upward fining trend, where thin interbedded siltstones and mudstone overlay tidally influenced fine grain size sand channel infill deposits. FA2 has unconformable bounding surfaces both above and below. Whereas, the upper bounding surface lacks significant erosion relief, the lower bounding surface is undulating and truncates up to 1.5 m into underlying FA4 (Figure 5-2). A few scours up to 3 m has been observed (see log UB3; 13-17 m). The most distinctive feature in FA2 units is the lateral accretion of the interbedded heterolithics. This is best seen in the Annaberget section (Figure 5-3). In the eastern part of the Ullaberget section heterolithic mudstones (facies A2) show also an inclined parallel stratification (see log UB6). Plant debris is recorded within the channel bottom deposits in both the lower and the middle portions of the Ullaberget section (Figure 5-4).

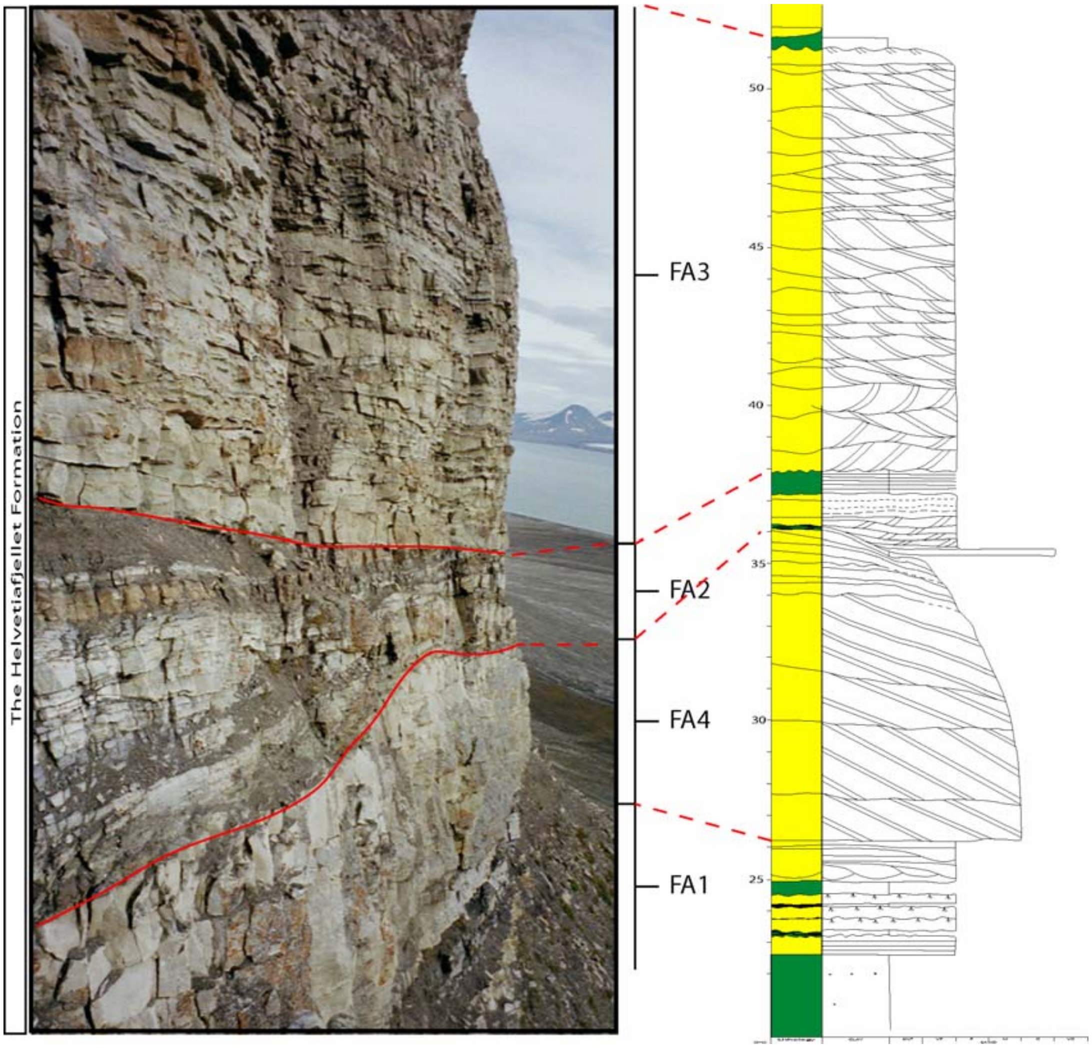

Figure 5-2: Meandering tidal channel infill (FA2) between elongate tidal ridge facies association (FA4) below and tidal channel/flat facies association (FA3) above in the middle portion of the Ullaberget section (Log UB2; 21 -51 m). (Photo by Ahokas, 2002).

Interpretation:

These deposits are interpreted as *meandering tidal channels* adjacent to elongate tidal ridge sandstone (FA4). The clinoforms internally in the units of FA2 are thought to represent lateral accretion surfaces in meandering channels, deposited by the same processes as epsilon (ε) cross-bedding deposited in the inner meander of the meandering stream (Figure 5-3). The channels seem to have carried almost exclusively mud and silt, but the channel current has eroded laterally and vertically into adjacent sand deposits (FA4) in the underlying strata, thus reworking and re-depositing the sand at the inner bend of meanders, where sediment transport energy was low.

Figure 5-3: Figure shows epsilon (ε) cross-bedding deposited in the inner meander of the meandering tidal channel within the meandering tidal channel facies association (FA2) in the upper part of the Annaberget cliff section, southern Spitsbergen. Note the two opposite directions of the cross bedding in the middle of the figure. The author and I. Midtkandal for scale. (Photo by Nystuen, 2003).

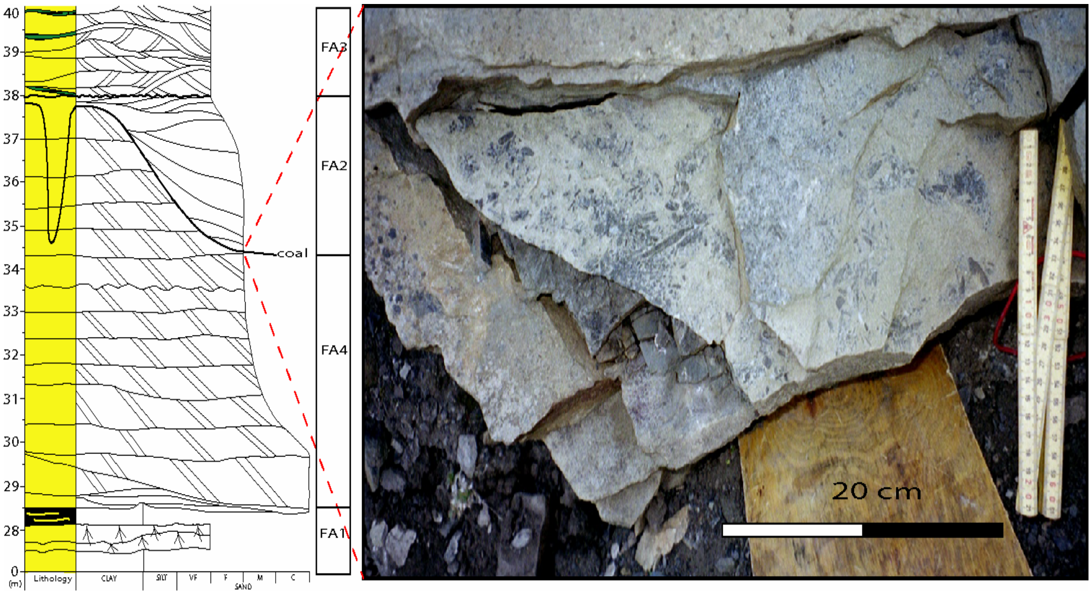

Figure 5-4: Plant imprints at the base of a meandering tidal channel registered in the Log UB4 from the middle portion of the western Ullaberget section. Figure shows a tidal channel eroding into underlying elongate tidal ridge facies association (FA4) . (Photo by Ahokas, 2002).

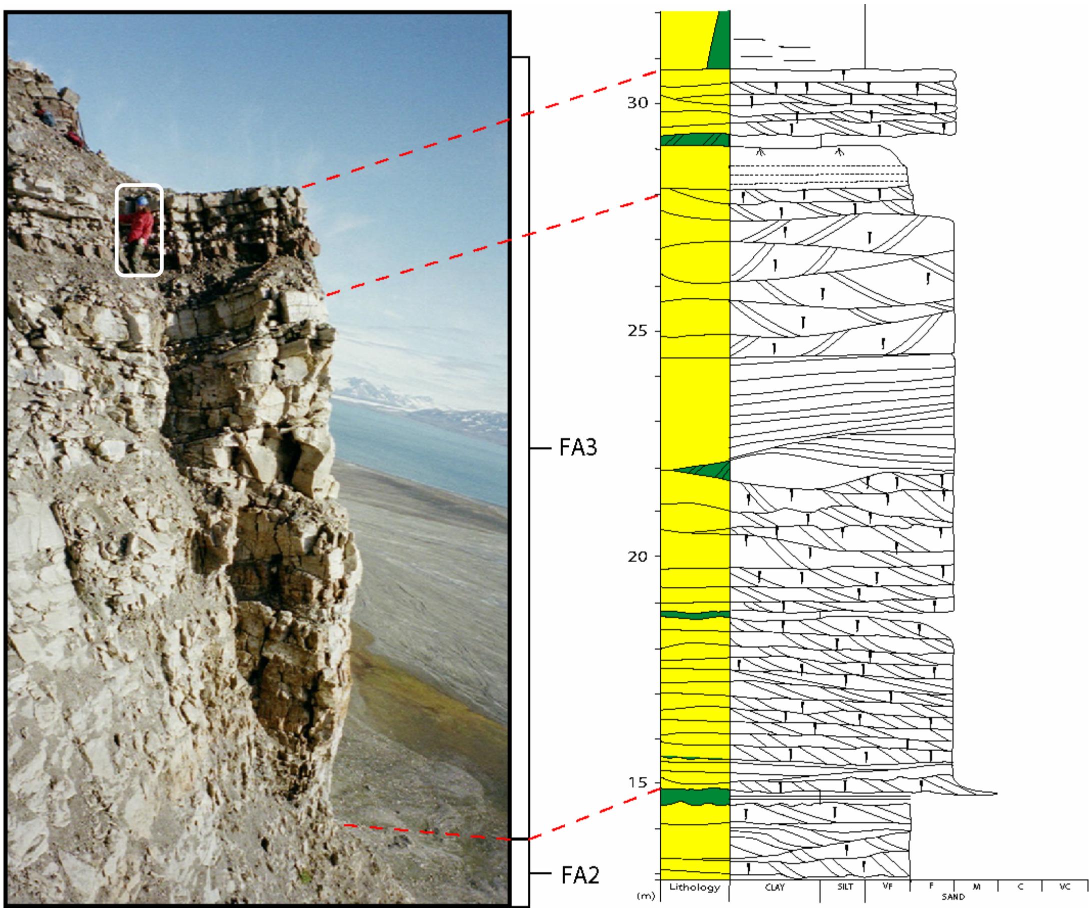

Figure 5-5: Figure shows the lowermost FA3 unit in the eastern end of the middle portion of the Ullaberget section (Log UB1; 13-32 m), where thickness of individual beds within the lowermost unit of FA3 is thicker than in the west (see figure 5-2). Note the upward fining trend similar to figure 5-2 and abundance of bioturbation compared to its absence in figure 5-2. L-H Lunde Birkeland for scale. (Photo by Ahokas, 2002).

Facies Association 3 (FA 3): Intertidal channel/flat

Description:

FA3 includes facies A1 (channel lag conglomerate), A2 (shale conglomerate), B (plane parallel stratified sandstone), B4 (planar laminated sandstone), B11 (tabular cross-stratified sandstone with mud drapes), B12 (trough cross-stratified sandstone with mud drapes), B13 (trough cross-stratified sandstone with mud drapes and bioturbation), C1 (siderite cemented siltstone), and C2 (mudstone). Sandstone facies B11, B12 and B13 are the most frequently occurring facies. FA3 covers the bulk of the middle portion of the Ullaberget section.

Depending on the lateral position in the section, the FA3 makes up 2 or 3 thick, generally upward fining sandstone units separated by few meters thick finer grain size intervals. Thickness of coarse grained FA3 units range from 6 m up to about 15 m. These units can be traced throughout the Ullaberget section, despite the rapidly shifting internal geometry of sandstone bodies, which in turn, can not be traced more than a few tens of meters. Individual bed thickness within FA3 units decreases towards the west. Figure 5-2 shows the lowermost unit of FA3 approximately 500 m west of unit of FA3 shown in figure 5-5. Internally within FA3 units, from base and upwards, coarser grain size sandstones with mud drapes are dominating and make up the bulk of FA3. Sandstones are rhythmically arranged with abrupt facies changes and show diverging paleocurrent directions. Towards the top of individual FA3 units a gradual change into finer grain size sediments with smaller sedimentary structures is common. Finer grain size intervals, in turn, lie unconformably below the next above lying coarser grained unit of FA3. The facies association FA3 is observed overlying both FA2 (meandering tidal channel facies association), and FA4 (elongate tidal ridge facies association) (Figure 5-2). At the base of coarser grained FA3 units, an occasional thin (clast size) layers of quartzite and crystalline quartz conglomerate (facies A1) is observed. Bioturbated units of FA3 (facies B13) are recorded only in the eastern part of the Ullaberget section.

Interpretation:

FA3 is here interpreted as *low- and mid-intertidal flat* deposits, due to higher sand content relative to mud content. The intertidal flat is considered to have been a coast parallel zone, characterized by mixed low sloping lateral accretion and suspension deposition between mean high- and low-tide levels. Other tidal-flat depositional environments are the supratidal zone, which lies above normal high-tide level, and subtidal-flat, which lies below mean low-tide level. Intertidal depositional environment include coastal plain dissected by a network of tidal channels, creeks and surrounding broad flats that are largely exposed during low tide. Bedload transport and deposition of the dominating sand takes place during the higher-velocity phases of tidal cycle, either rising or falling tide, whereas mud is deposited from the suspension during lower-velocity or zero-velocity flow accompanied with high-tide and/or low-tide slack water stages. During the dominating spring-tide phase of the lunar tidal cycle intertidal sand bodies are characterized by greater sediment transport rates and distances of bedform migration (Boersma and Terwindt, 1981), and enclosed by reactivation surfaces (Klein, 1985), which represent nondeposition

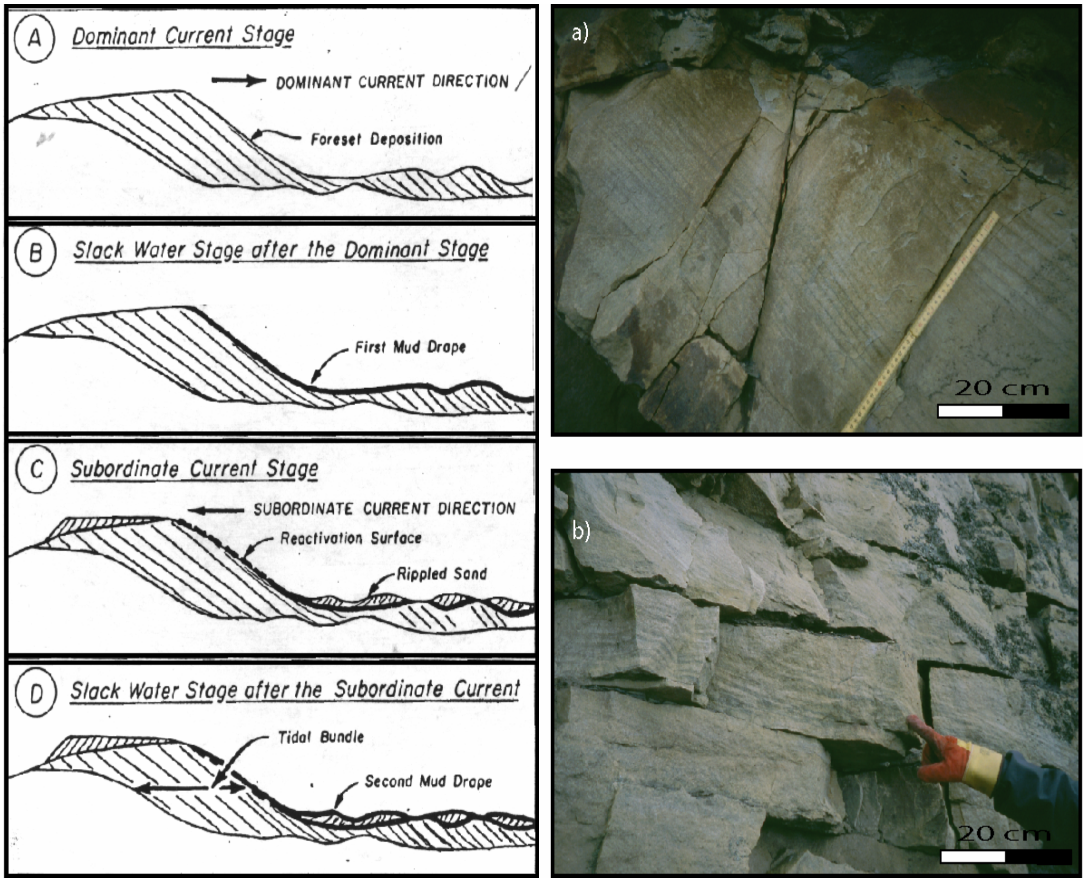

Figure 5-6: Stratification produced in a tidal sand dune during a highly asymmetrical tidal cycle is shown in the left. (From Dalrymple, 1992, based on Visser, 1980). a) An example of spring and neap tidal bundles within the Ullaberget Member in the eastern Ullaberget section. Foreset thickness from one mud drape to another in the middle of the photo is approximately 1 cm and represents neap-tidal phase. Foreset thickness from one mud drape to another has increased into approximately 2 cm towards the upper right corner and represents spring tidal phase. (Photo by Nystuen, 2003). b) A rhythmical set of tidal sandstone beds in the Ullaberget Member in the Ullaberget section. (Photo by Nystuen, 2003).

during the subordinate tidal phase. In such a sand body, the internal organization of cross-strata and reactivation surfaces differ between neap and spring phase because the neap phase shows thinner bundles and thinner cross-strata sets, reflecting smaller bottom current velocities, whereas the spring tidal phase shows thicker sets of cross-strata and longer bundles, reflecting greater velocities and greater sand transport rates (Klein, 1985). Thus the lateral dimensions and sediment volume permit recognition of spring and neap tidal phases (Figure 5-6a).

Upward fining trend of FA3 is probably developed due to local progradation of intertidal zones. Such units consist of, from the base upward, low-tidal flat sands, overlaid by mid-flat mixed lithologies of sand and mud, and capped by high-tidal muds. The thicknesses of individual units coincide with mean tidal range, which in current area has been estimated to have been within mesotidal range (1 – 4 m). The basal conglomerate layer that marks the boundary between sand-rich FA3 from FA2 below is interpreted as deposited on a tidal ravinement surface.

Facies Association 4 (FA 4): Elongate tidal ridge

Description:

FA4 includes multiple interchanging tidally influenced sandstone beds of facies B4 (planar laminated sandstone), B11 (tabular cross-stratified sandstone with mud drapes), and B12 (trough cross-stratified sandstone with mud drapes). Cosets composed predominantly of facies B12, range from 1 to 8 m in thickness, marking the basal sandstone unit of the middle portion of the Ullaberget section. This unit can be traced throughout the Ullaberget section as a continuous massive unit above light coloured unit of FA1. At the base of FA4, a thin (clast size thickness) discontinuous layer of quartzite and crystalline quartz conglomerate (facies A1) marks abrupt transition from fully fluvial regime (FA1) below, into a tidally influenced regime above. This surface is a tidal ravinement surface and will be described in detail in Chapter 7. This surface displays no significant erosion relief, whereas upper boundary of FA4 shows high truncating relief filled with FA2 mudstones and/or sandstones (facies A2 and facies B12, respectively) (Figure 5-7). Between logs UB2 and UB6, units of FA2 are observed cutting through the whole FA4. Above the base, tidally influenced sandstones show unimodal paleocurrent direction.

Interpretation:

The above described deposits are here interpreted as 2D *elongate tidal ridges* (intertidal sand bodies) formed within feeder channels, where they enter straight to the sea and relatively high velocity tidal bottom currents rework the fluvially supplied sand deposits. Within the channels, sand is redeposited by oscillatory tidal currents forming sand ridges that migrate and aggrades along the channel floor. Significant thickness of these units

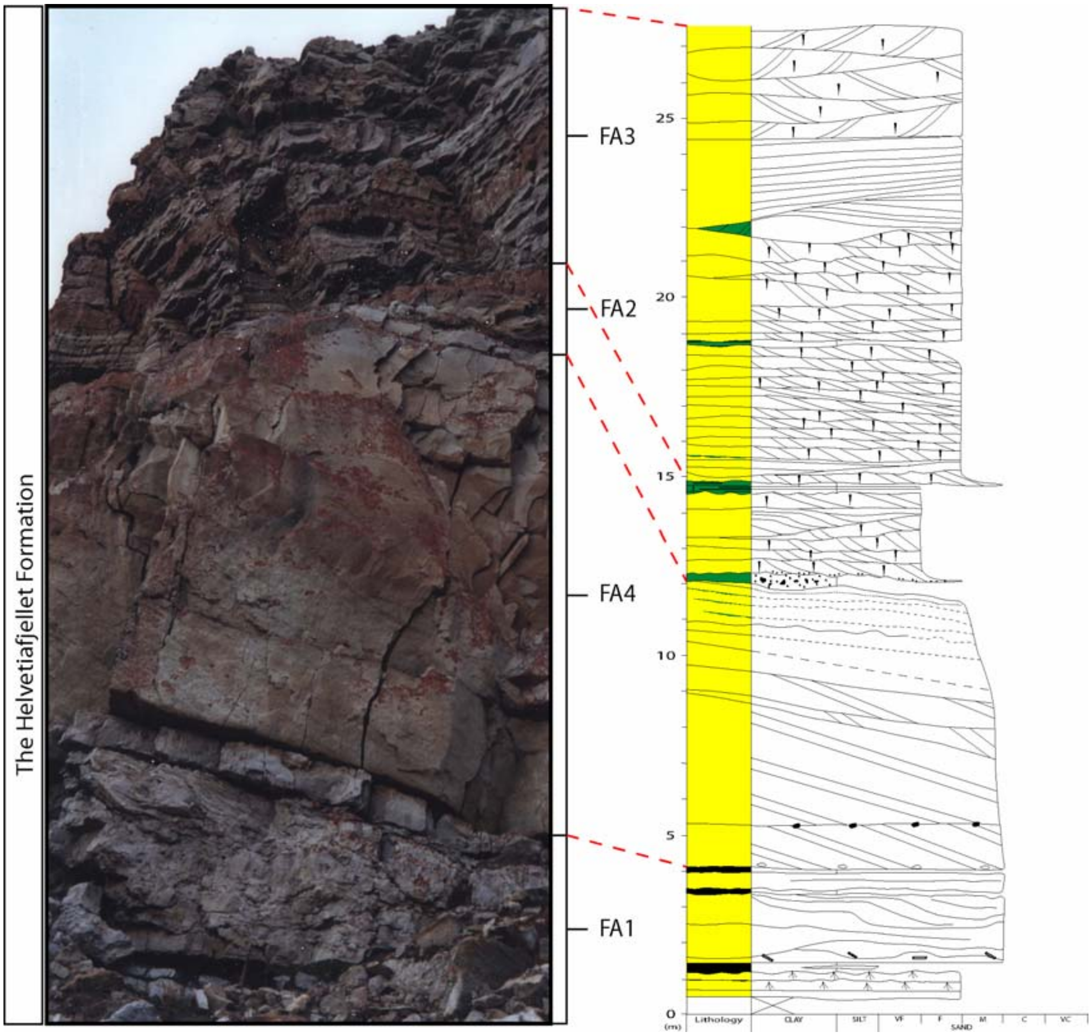

Figure 5-7: Figure shows elongate tidal ridge facies association (FA4) in relation to alluvial facies association (FA1) below and tidal channel/flat facies association (FA3) above in the eastern end of the Ullaberget section. The boundary between FA1 and FA4 separates the lower and the middle portions of the Helvetiafjellet Formation in the Ullaberget section. (Photo by Ahokas, 2002).

points to equal rate between sedimentation and freed accommodation space (A=S), which will be further discussed in Chapter 7. The upward fining trend of FA4 is probably developed by progradation of individual sand ridges. Progradation may have been caused by higher rates of sedimentation during spring tidal phase because sand bodies deposited during spring tidal phase show greater lateral extension (Boersma and Terwindt, 1981) (Figure 5-6). The sand bodies are enclosed by reactivation surfaces formed during the subordinate tidal phase (Klein, 1985, p 195, his figure 3-5). Unimodal paleocurrent direction is owing to migration and deposition only parallel to the dominant flow (Klein and Whaley, 1972; Dalrymple et al., 1978), and much of it is accomplished during very short periods of time. The orientation of internal cross-stratification is also in agreement with one dominant flow direction, which in the Ullaberget section has been east-southeast orientated ebb-tide. Truncation from above is caused by lateral movements of adjacent and above lying FA2 (meandering tidal channel). When the channels distributed the masses of water, which were displaced by tidal forces, they caused eroding, redistributing and reworking of the sand ridges.

Facies Association 5 (FA 5): Embayment / Lagoon

Description:

Facies association FA5 include facies C1 (siderite cemented siltstone), C2 (mudstone), and D (coal). The facies C2 is dominant. FA5 defines one unit lying directly above the Ullaberget Member (Figure 5-8). It is a mudstone dominated interval with occasional fine grain size sand and coal horizons as well as a few bands of siderite cemented siltstone/mudstone concretions. The congretions are from 2 to 15 cm in diameter. FA5 is bounded between tidally influenced delta facies association (FA6), the Ullaberget Member, below and alluvial plain facies association (FA1) above. Lower boundary is commonly a diffuse change from the tidal sandstones into mudstone and generally covered by depris. The upper boundary is also commonly covered and therefore not described. FA5 is thickest in the east parts of the Ullaberget section, but decreases in thickness to the west. In the western end of the section thickness has decreased to 2-3 meters. Here, both bounding surfaces seem to be lithological sharp, but inaccessible due to steep and loose cliff faces. No microfossils have been found from the mudstone samples collected from FA3 unit in the Ullaberget section. FA5 is also found in the upper portion of the Ullaberget section, but is included in the transgressive marine sandstone facies association (FA7) due to vertical and lateral stratigraphic context.

Interpretation:

FA5 is interpreted as deposited in a lacustrine embayment. The interplay between mudstone, coal and occasional fine grain sand/silt indicates occasional silisiclastic deposition, but no trend or periodical change of these horizons is registered. The silisiclastic material has therefore likely to have been deposited during short-lived pulses caused by storms or shifting of fluvial distributary channels along the shoreline. Coal may

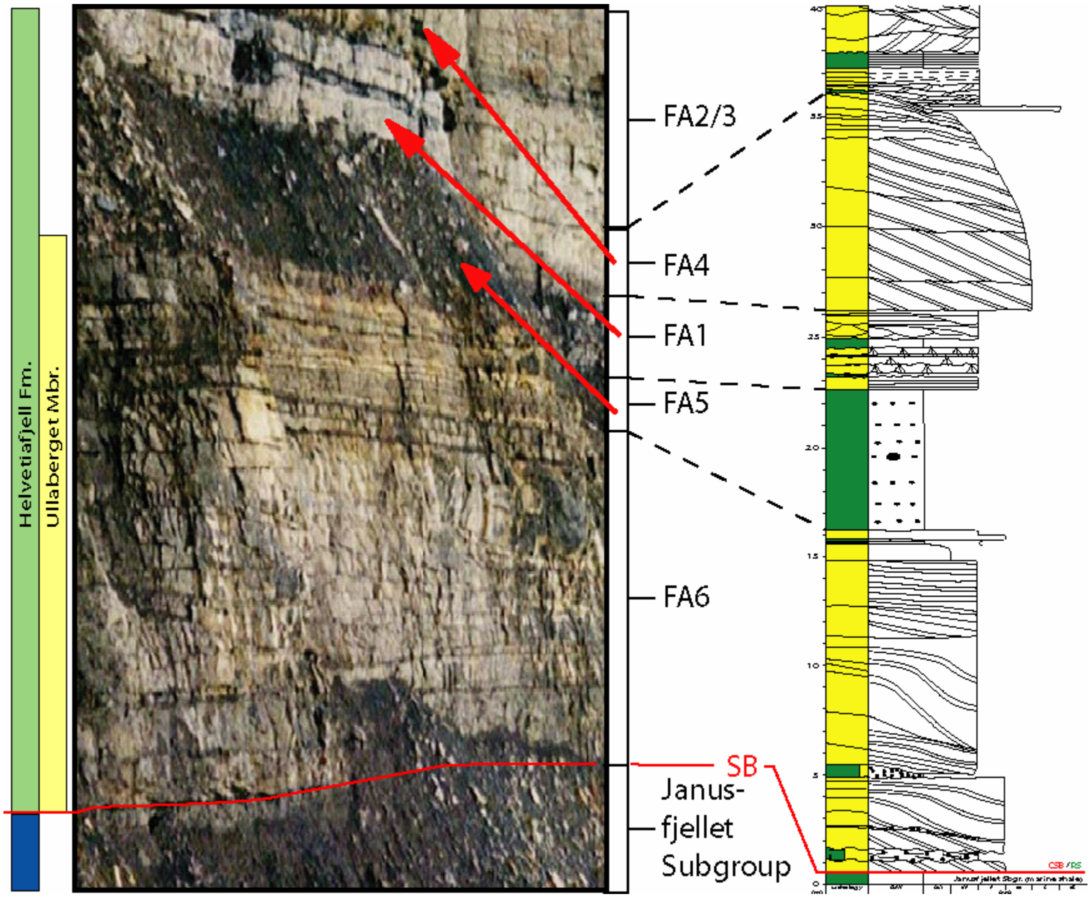

Figure 5-8: Tidally influenced fluvial delta facies association (FA6), the Ullaberget Member, overlain by brackish or lacustrine embayment facies association (FA5), alluvial plain facies association (FA1), tidal channel/flat facies association (FA3), respectively. Photo is taken from the lower portion of the Ullaberget section (Photo by Ahokas, 2002).

have been formed from higher rates of deposition of terrestrial plant material caused by local or regional fall in relative sea-level. Westward decreasing thickness of FA5 is likely to reflect change in depositional environment into more proximal fluvial system. This will be further discussed in Chapters 6 and 7.

Facies Association 6 (FA 6): Tidally influenced delta (The Ullaberget Member)

Description:

The Ullaberget Member is formally included in the Upper Rurikfjellet Formation (Dallmann, 1999). It marks an abrupt transition from open-marine mud deposition to sand dominant deposition caused by a significant fall in relative sea level. FA6 is predominantly composed of interfingering sets of facies B2 (trough cross-stratified sandstone), B12 (trough cross-stratified sandstone with mud drapes). These facies are arranged in 6-10 m high laterally accretional clinoforms, stretching about 30 m from topset to bottomset and compose the lower half of the Ullaberget Member. These are overlaid by facies B3 (parallel stratified sandstone), and B4 (planar laminated sandstone), which cover the upper half of the Ullaberget Member in the eastern Ullaberget (see logs UB2, UB3, UB4, UB7, UB9 and UB10). FA6 includes also facies A1 (channel lag conglomerate) and A2 (shale conglomerate).

The lower boundary of the Ullaberget Member (FA6) is a lithologically sharp (unconformable) boundary with discontinuous layers of quartz conglomerate (facies A1) at and right above the base of the sandstone beds. These beds are commonly associated with more continuous shale rip-up conglomerate beds (facies A2). The Ullaberget Member can be traced laterally throughout the Ullaberget section, and picked up again at the base of the eastern Louiseberget in the west, where it is poorly exposed. Thickness of the FA6 ranges from 5 m, in the east end of the Ullaberget section, to about 10 m in the west. In between these end points thickness of FA6 ranges up to 18 m. A few 3-5 cm thick discontinuous mudstone beds are recorded internally in the units. Commonly, a 5-15 cm thick layer of matrix supported, well rounded quartz and quartzite conglomerate (facies A1) is found at the base of beds of facies B12. These clast size conglomerate layers are most frequent in the lower 0-5 m of the Ullaberget Member. The conglomerates are absent within parallel bedded upper part of the member. Paleocurrent directions are predominantly towards 135° (southeast), with flow divergence within +/- 45°. The upper boundary of the Ullaberget Member is generally covered, but in a few places where seen, it show diffuse transition form sandstone into coaly mudstone (FA5). The main colour of FA6 is yellow.

Interpretation:

The Ullaberget Member is here interpreted as a *tidally influenced delta*, where coarse grain sediment is being transported by braided rivers directly into sea, thus depositing conglomeratic beds alongside tidally reworked finer grained sandstone beds. The conglomeratic bed at the base of the unit indicates a subaerial exposure prior to sandstone deposition in the area. From this follows that the lower boundary of the Ullaberget

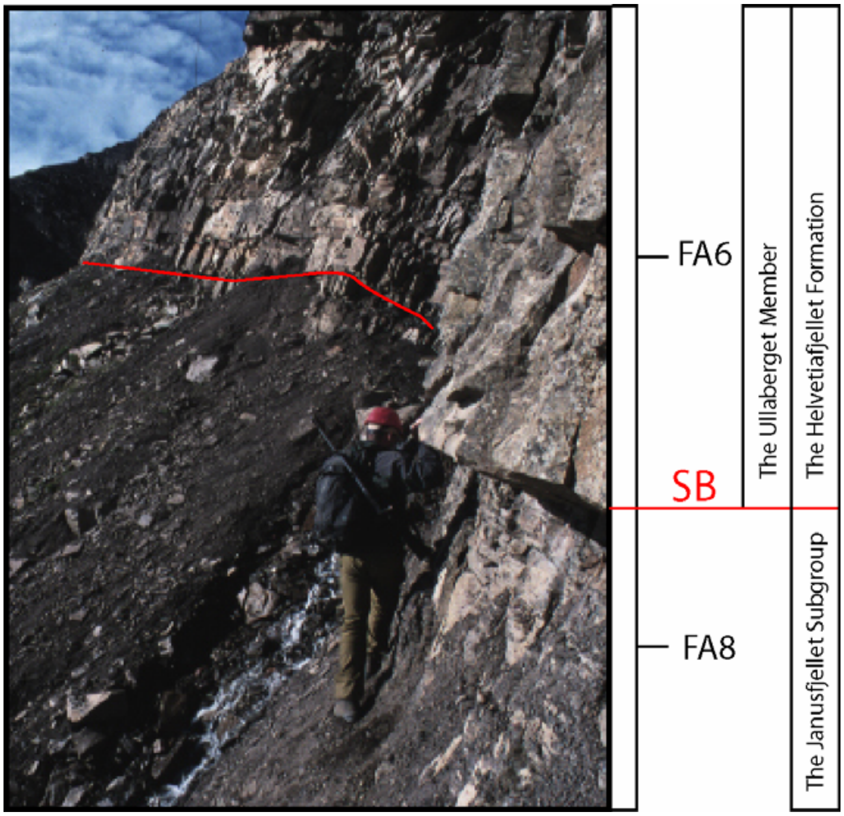

Figure 5-9: The sequence boundary (red line) at the base of the Ullaberget Member. Photo is taken around the middle of the section. I. Midtkandal for scale. (Photo by Ahokas, 2003).

Member is a type 1 sequence boundary (Figure 5-9) and will be further discussed in the Chapter 7. The laterally accretional clinoform sets (Figure 5-8) indicate a strong basinward progradation of sand during deposition of the Ullaberget Member, whereas tidal forces have obviously been strong enough to reach far upstream to rework otherwise fluvial deposits. Progradation can have taken place during spring-tide phase of the lunar tidal cycle, which generally favours longer distances of lateral migration and vertical accretion. Planar laminated sandstones in the upper part of FA6 have been deposited when tidal forces were too weak to build up any typical tidal bedforms, thus making it possible for mud and sand to deposit from suspension into interbedded lamination. This has taken place during the last stages of delta progradation before FA6 was overlaid by terrestrial embayment mud (FA5).

Facies Association 7 (FA 7): Transgressive marine sandstone sheets

Description:

As mentioned in Chapter 2, the boundary between the Helvetiafjellet Formation and the overlying Carolinefjellet Formation is difficult to define, because there often is interfingering between the fluvial-dominated bay-fill deposits (FA1 and FA5) and the transgressive open-marine facies associations (FA8). Included in FA7 are facies B1 (tabular cross-stratified sandstone), B2 (trough cross-stratified sandstone), B3 (plane-parallel stratified sandstone), B4 (planar laminated sandstone), B5 (low-angle cross-stratified sandstone), B6 (wave ripple laminated sandstone), B7 (current ripple laminated sandstone), B8 (HCS sandstone), B10 (structureless sandstone with bioturbation), B11 (tabular cross-stratified sandstone with mud drapes), B12 (trough cross-stratified sandstone with mud drapes), B13 (trough cross-stratified sandstone with mud drapes and bioturbation), C1 (siderite cemented siltstone), and C2 (mudstone). All facies are nearly equally represented in FA7. Sandstone units of the FA7 typically show coarsening-upwards characters, from a silty and shaley basal part into a heterolithic interval of flaser and lenticular bedding, finally topped by fine-grained sandstone interval. The upper part of these sandstone units generally show fining-upwards character. This thin topmost part is commonly overlain by marine shale (facies C3). Eight such units have been recognized in the Helvetiafjellet Formation in the upper portion of the Ullaberget section. The upper and lower boundaries of these sandstone units are generally sharp lithological change into finer and coarser deposits, respectively. Thickness of the units range from 2-5 m and they are laterally extensive extending throughout the upper portion of the Ullaberget section.

Sandstones within FA7 commonly have distinctive yellow weathering colour and contain abundant trace fossils such as *Diplocraterion* and *Skolithos*. These trace fossils have been found in several beds occurring not only at the top, which is the most common case, but also within coarsening-upwards sandstone units. Intensity of bioturbation varies from one sandstone unit to another leaving part of the primary sedimentary structures intact. The most common sedimentary structures are wave-generated ripple lamination (facies B6), hummocky cross-stratification (HCS), and low-angle cross-stratification facies B5). Few thin interbeds of coarse grained sandstones are registered within some sandstone units.

Figure 5-10: Transgressive marine sandstone sheets in the upper portion of the Helvetiafjellet Formation in the eastern end of the upper portion of the Ullaberget section near log UB8. (Photo by Ahokas, 2003).

Interpretation:

FA7 is interpreted as transition zone deposits accumulated in the later stages of deposition of the Helvetiafjellet Formation. Deposition took place when rate of the relative sea-level rise accelerated and accommodation space created for deposition exceeded sediment supply. Thus these relatively thin sandstone sheets represent complex interplay of transgressive barrier, shoreface, beach and shelfal deposits produced by waning and probably in some extend cyclic shoreface retreat. This interpretation is based on sedimentary structures and the vertical arrangement of lithofacies (coarsening-upwards character). The sandstone-dominated parts of this FA7 are interpreted to represent storm deposited lower shoreface sediments, which could be colonized predominantly by *Diplocraterion* and *Skolithos* trace fossils. Colonization was later abrupt truncated by marine flooding creating a transgressive ravinement surface and lower order sequence boundaries, which will be further disussed in Chapter 7.

Facies Association 8 (FA 8): Marine mudstone

Description:

Included in FA8 are facies C1 (siderite cemented siltstone) and C2 (mudstone). FA8 is found both below and above the Helvetiafjellet Formation sandstones. The lower boundary of FA8 deposits belonging to the Janusfjellet Subgroup is not described as the subgroup is some 400 m thick (Dypvik, 1992). The upper boundary of the Janusfjellet subgroup shales, at the base of the Ullaberget Member, is lithologically sharp and erosive. This is a unconformable change from marine shale deposits containing sulphur, bands of siltstone, and horizons of siderite cemented siltstone/shale (facies C1) congretions (5 to 40 cm in diameter) into tidally influenced sandstones. Overlying sandstones of the Ullaberget Member have eroded into underlying Janusfjellet Subgroup shales with unknown magnitude. At the top of the Helvetiafjellet Formation (see Chapter 2) the lower boundary of FA8 is non-erosive and shale deposits of the Carolinefjellet Formation rest conformably on the Helvetiafjellet Formation. The upper boundary of FA8 deposits of the Carolinefjellet Formation (above the Helvetiafjellet Formation) is not described in this study.

Interpretation:

The deposits described above are interpreted as deposited in an open-marine shelf environment. The fully marine deposits below and above the Helvetiafjellet Formation reflect how little or no fluvial or marginal marine material was deposited in the region before and after the period of deposition of the Helvetiafjellet Formation (Barremian - Aptian) while relative sea-level was falling and rising again. Thus, the deposits of FA8 are not included into the Helvetiafjellet Formation, and work primarily as indicators of the formation boundaries.

6

Depositional environment

6.1 Introduction

Depositional environment is a result of constructive processes of sediment accumulation into units with different stacking character caused by changing natural agents. Building blocks for depositional environment are facies associations. The depositional environment can be determined from varying stacking patterns of facies associations in a similar manner as facies associations are composed of varying stacking of single facies.

Firstly, this chapter will go through the correlation of the sedimentary logs within the Ullaberget section. Secondly, and for practical purposes, the Helvetiafjellet Formation in the Ullaberget section is divided into three major portions based on lithological properties and the facies associations. The lower portion consists of south-eastwards laterally accretional sandstone units, the middle portion of a vertically aggradational sandstone unit and the upper unit of north-westwards laterally accretional heterolithic strata. The lower portion of the Ullaberget section is subdivided in two subunits: the lower subunit is the Ullaberget Member, that formally is included in the Janusfjellet Subgroup (Dallmann, 1999), but which in this thesis is interpreted as a part of the Helvetiafjellet Formation (see Chapters 2 and 7). The upper subunit of the lower portion comprises terrestrial mudstones and fluvial sandstones overlying the Ullaberget Member. The middle portion of the Ullaberget section is composed of one single aggradational sandstone unit. The upper portion is subdivided into eight upward coarsening subunits separated by marine flooding surfaces, intervals 1 to 8. The flooding surfaces are marked as FS1 to FS8 in the figure 6-1. The depositional environments of the Helvetiafjellet Formation at the Ullaberget section will be discussed in the light of above mentioned major divisions and in lesser extend in subdivisions. Finally, an effort is made to correlate the stratigraphic sections that represent

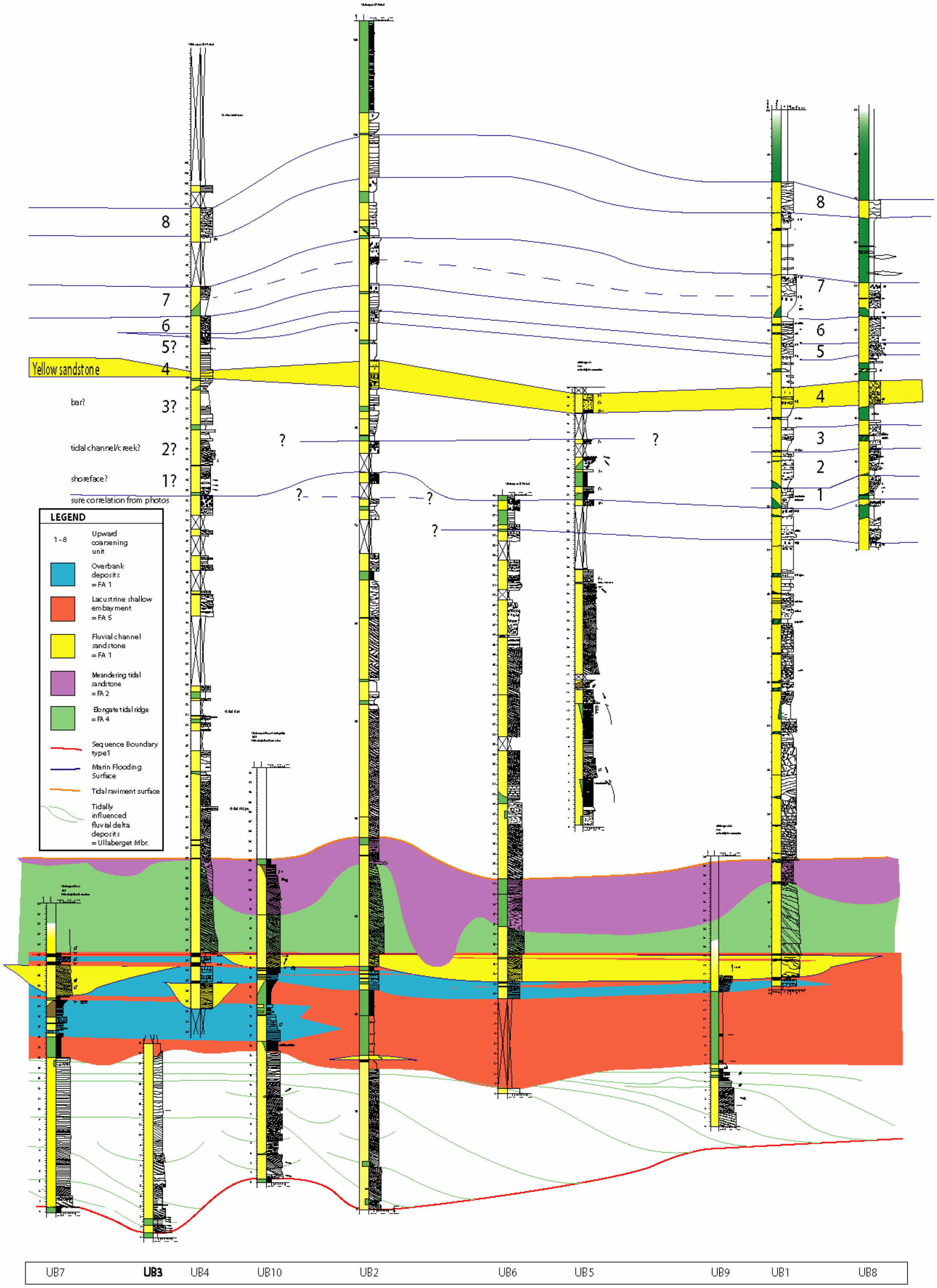

Figure 6-1: Simplified sedimentary logs from the Ullaberget section. The numbers indicate coarsening-upward units of FA7 (transgressional sand sheets). Green lines in the lower part of the Helvetiafjellet Formation mark prograding clinoforms of the Ullaberget Member.Yellow section in the upper part of the figure illustrates one readily correlative transgressional sandstone bed with bioturbation (*Diplocraterion* trace fossils).

different depositional environments in the Ullaberget section towards the adjacent localities.

6.2 Log correlation within the Ullaberget section

This subchapter will discuss how the outcrops in the different parts of the Ullaberget section are connected in terms of lithology and sedimentary environments. In general, correlation of sedimentary logs made in Ullaberget section is uncomplicated due to close vicinity of the different logged sections (maximum of 1.5 km). It is obvious that within such a short distances, relatively minor, internal variations in lithology effectively limit the amount of possible approaches to connect different parts of the section. Thus, helping to establish a high resolution interpretation of how the Helvetiafjellet Formation was deposited in the Ullaberget section. Such an interpretation still relies on accurate correlation between logged sections. Figure 6-1 shows a simplification of all the logs from Ullaberget section together, with marine flooding surfaces marked with “FS” and ravinement surfaces marked with “LRS” (lacustrine ravinement surface) and “TRS” (tidal ravinement surface). Of these surfaces, the marine flooding surfaces are generally considered as good correlational horizons, as a marine transgressional pulse is likely to be shown in the geological record over a wide area (Van Wagoner et al., 1998; Emery and Myers, 1996).

The correlation models presented are based on a datum plane placed at different stratigraphic levels within the formation. Three surfaces chosen as datum planes within the Helvetiafjellet Formation in the Ullaberget section are the base of the formation, the top of the formation, and the lithological boundary where coal overlies the alluvial deposits (FA1) at the top of the lower portion of the Ullaberget section.

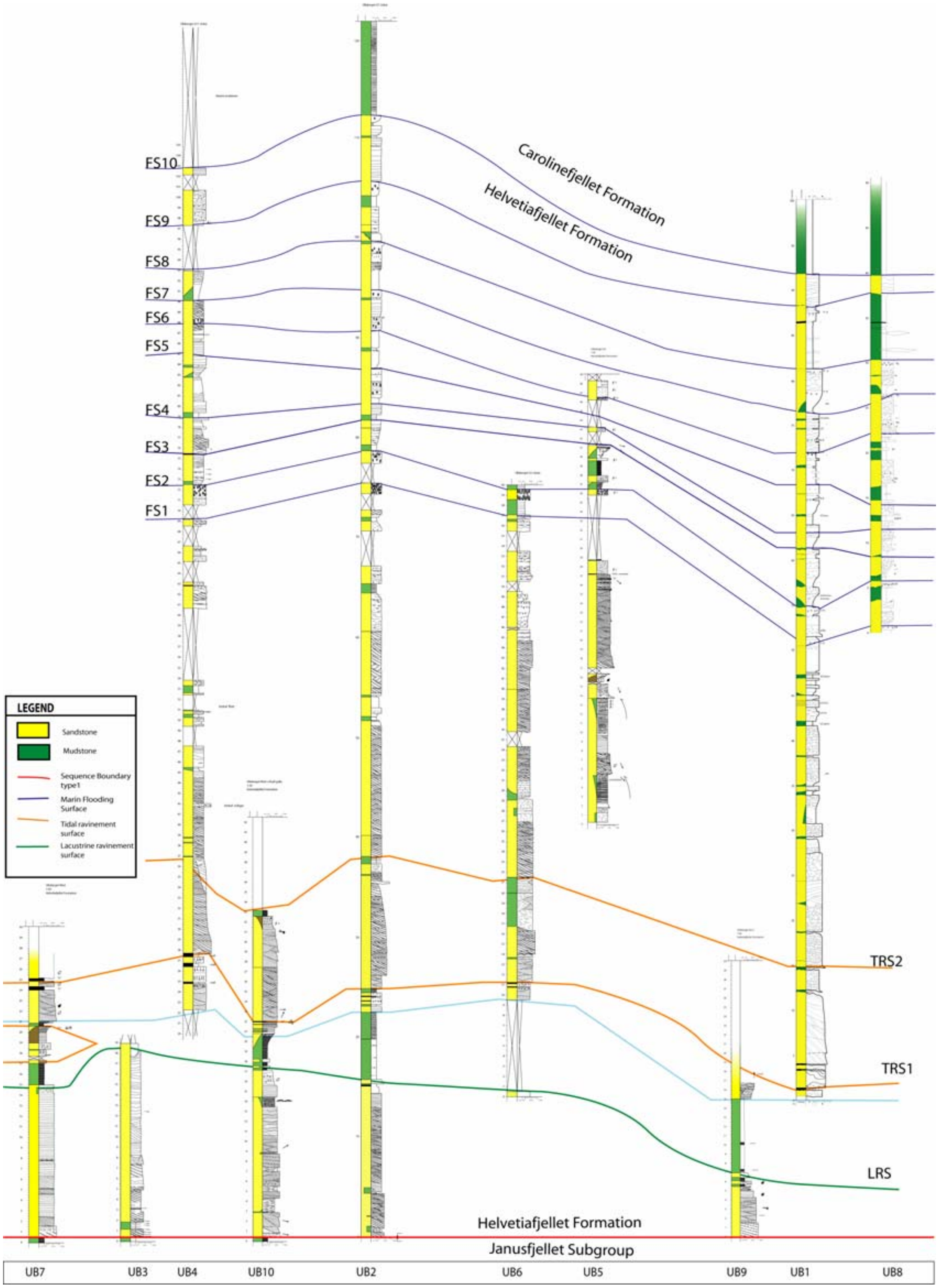

Figure 6-2: The correlation model 1 with the base of the Helvetiafjellet Formation as datum plane. All the correlated surfaces show relatively similar trend, but due the nature of the unconformity at the base of the formation this model is unlikely.

Correlation model 1:
Base of the formation as datum plane

Assuming that the lower boundary of the Helvetiafjellet Formation, which in this study is placed below the Ullaberget Member (see Chapters 2 and 7), is an approximately isochronous surface marked by low-relief topography, an alignment of the logged sections would lie on a horizontal correlative surface, which marks the boundary between the Janusfjellet Subgroup and the Helvetiafjellet Formation (Figure 6-2). During the relative sea-level fall, this erosional unconformity must have been at least of local extent, possibly also of regional extent, forming the surface on which the Helvetiafjellet Formation could deposit. However, the way the Ullaberget Member rests on the shales of the Janusfjellet Subgroup strongly suggest a period of erosion prior to deposition of the sandstone unit. The erosion is likely to have caused development of a subaerial erosion surface with moderate relief which now marks the contact between the Janusfjellet Subgroup and the Helvetiafjellet Formation. The presence of such a subaerial erosion surface, due to regional fall in relative sea-level, makes the scenario illustrated in figure 6-2 unlikely because the base of the Helvetiafjellet Formation in the Ullaberget section can not have been represented by a horizontal surface without topographic relief. This is also supported by lithofacies at and right above the base

Correlation model 2:
Top of the formation (FS) as datum plane

In figure 6-3 the Helvetiafjellet Formation in the Ullaberget section is correlated with the top of the formation as a datum. This surface is also the boundary between the Helvetiafjellet Formation and the overlying Carolinefjellet Formation. As the entire Helvetiafjellet Formation in the Ullaberget section is interpreted in this thesis to have been simultaneously covered by marine shales of the Carolinefjellet Formation, the scenario presented in figure 6-3 is likely. It is also supported by the arrangement of the lithofacies at the top of the upper portion of the Ullaberget section. The lateral similarity between deposits found at the top of the Helvetiafjellet Formation is therefore likely to represent an isochronous surface locally in the Ullaberget section. Thus, the correlation shown in figure 6-3 is regarded as likely in the local scale. This scenario implicates also that the local

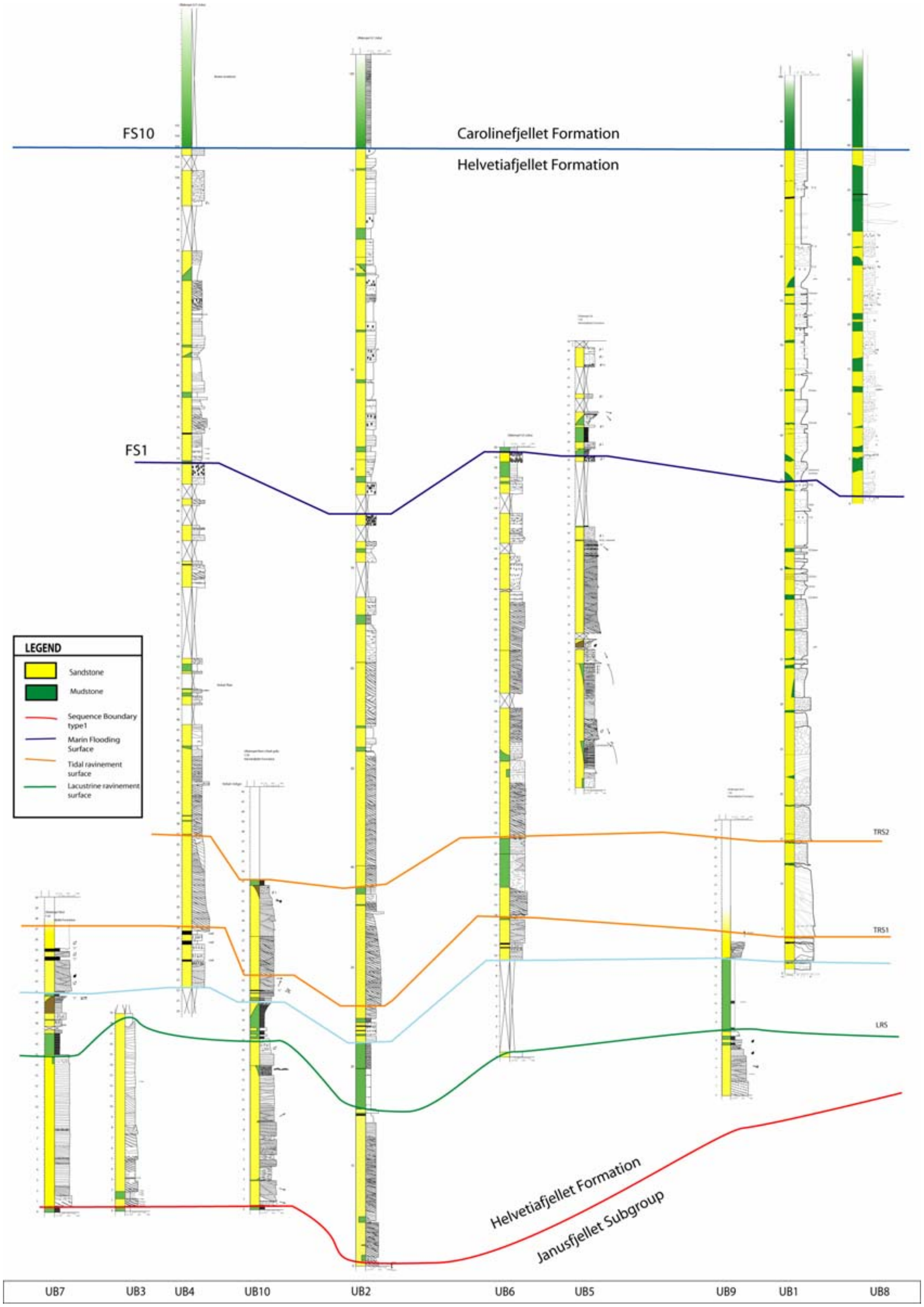

Figure 6-3: The correlation model 2 with the top of the Helvetiafjellet as datum plane. This model gives relatively similar result as the model 3.

unconformity at the base of the Helvetiafjellet Formation have been continuous throughout the section.

Correlation model 3:
Top of the alluvial deposits (TRS) as datum plane

Figure 6-4 shows the Ullaberget section correlated with the uppermost coal bed of the alluvial facies association (FA1) as datum surface. This bed marks also the top of the lower portion of the Helvetiafjellet Formation in the Ullaberget section. In the Facies Association chapter 5 this lower portion is interpreted as prograding tidal delta overlain by lacustrine mudstones topped by alluvial plain deposits. The coal bed at the top of the alluvial deposits can be traced throughout the section. It marks a very low relief subaerially exposed surface, which is interpreted to be practically isochronous. Abrupt change in facies above the coal bed marks a local flooding surface. This scenario suggests that the deposits of the lower portion of the Ullaberget section accumulated in the accommodation space generated during the fall of the relative sea-level in the Barremian, which later was filled during the initial stage of relative sea-level rise. At the time when this accommodation space was filled, a modest rise in relative sea-level would have caused a virtually instantaneous local, as well as regional, flooding. This is supported also by Midtkandal (2002). Such a local isochronous surface, which in this case is a marine/tidal ravinement surface, is a good marker horizon to be used to correlate all the logs from the Ullaberget section.

Selected model

The last correlation model (model 3), with datum plane at the top of the lower portion of the Ullaberget section is chosen to represent the most correct model for the internal stratigraphical sections of the Helvetiafjellet Formation within the Ullaberget section. The stratigraphical surface is a tidal ravinement surface and had least uncertainties in correlation.

The base of the Helvetiafjellet Formation in the Ullaberget section probably still represents a time-correlative surface, a diachronous surface, because differential sedimentation rates in the area, caused by infill of the local erosional relief, gave rise to

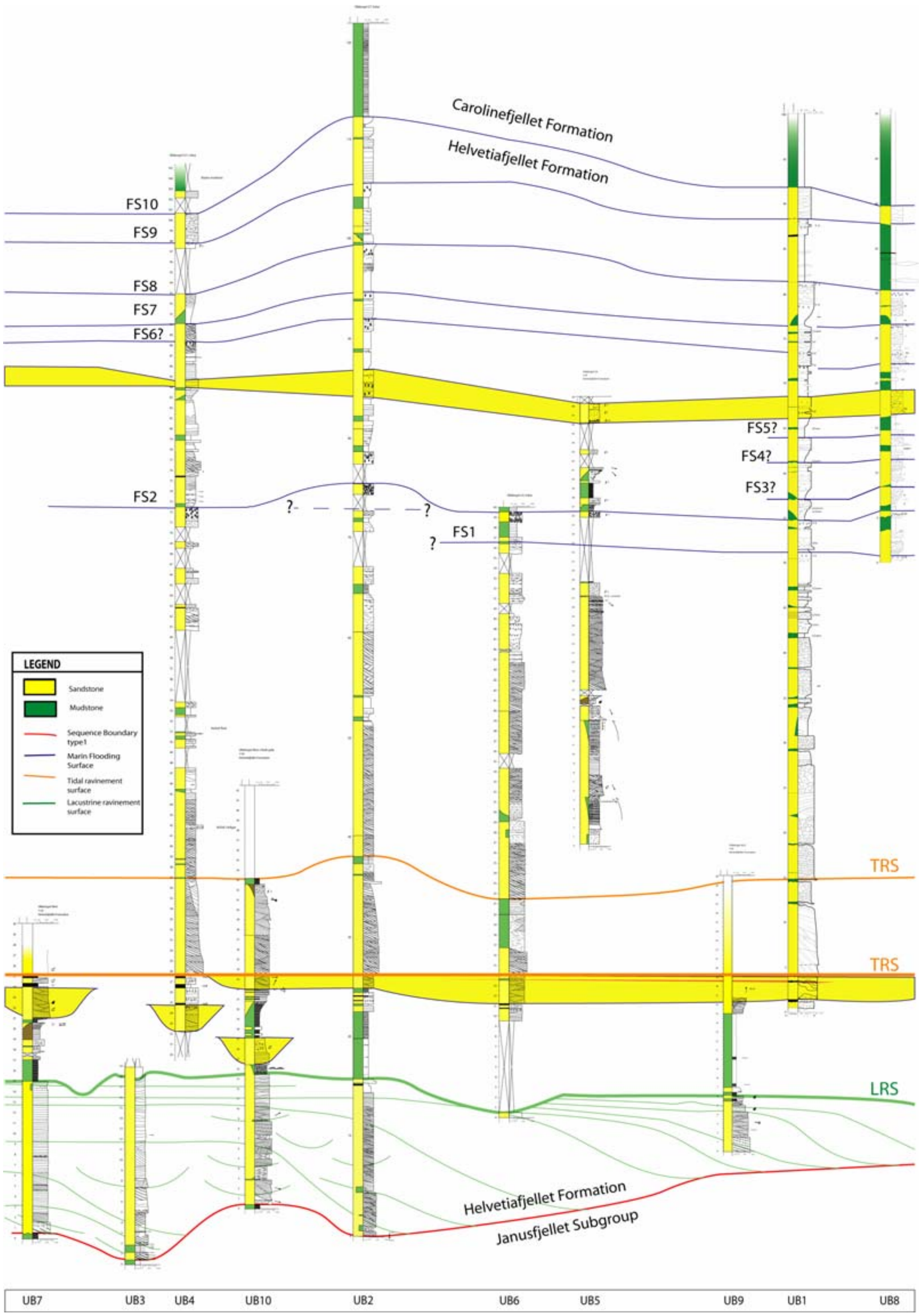

Figure 6-4: The correlation model 3 with the coal bed at the top of the alluvial facies association (FA1) as datum plane. This model gives, if possible, the most realistic correlation over the Ullaberget section.

variations in thickness of the lowermost sandstone unit, the Ullaberget Member. The correlation model two coincides well with the chosen model three. Except undulating top of the formation in the model two, which may result from measurement differencies, since all the litholofacies at the top of the formation indicate simultaneous flooding of the whole Ullaberget section. The three correlation models presented illustrate which consequences a choice of datum plane may have for the overall interpretation of a depositional history.

6.3 The lower portion of the Ullaberget section

As mentioned in the facies association chapter, the basal sandstone unit of the Helvetiafjellet Formation, resting directly on the Janusfjellet Subgroup, forms a continuous lithofacies unit throughout the Ullaberget section. The up to 25 m thick sandstone dominated basal unit of the Helvetiafjellet Formation is interpreted to be composed predominantly of a prograding tidally influenced sandstone dominated delta, the Ullaberget Member, followed by vertically aggrading terrestrial/lacustrine mudstones with westward decreasing thickness, and topped by continued basinward shifting fluvial strata. The basal bounding surface of the prograding delta is a subaerial erosional unconformity formed during the relative sea-level fall, which probably left the shelfal strata exposed. The upper bounding surface is marked by the laterally extensive surface of subaerial exposure, a coal bed. Together these three parts of the lower portion of the Ullaberget section comprise a southeastward prograding parasequence set.

The Ullaberget Member

Situated directly above the Janusfjellet Subgroup, on a subearial erosional unconformity, the Ullaberget Member is interpreted to be a prograding tidally influenced sandstone dominated fluvial delta, formed during early rise of the relative sea-level. The south-eastwards laterally accretional sandstone unit consists of laterally extensive clinoforms, up to 30 m in length and up to 5 – 6 m in thickness. The clinoforms include numerous tidally influenced laterally and vertically stacked distributary channel sandstones, with variable width/depth ratio, thus indicating a multilobate distributary system. The distributary channels migrated across a tidally influenced lower delta plain that moved basinward during delta outbuilding in the early stages of rising relative sea-level. The basal surface is, as mentioned above, a surface of subaerial erosion, whereas the upper boundary represents a gradational facies change into more terrestrial strata and therefore hard to pinpoint. This vertical change in facies reflects the continued basinward delta progradation.

Terrestrial mudstones and fluvial strata

Upward fining and gradational change of Ullaberget Member sandstones into terrestrial mudstones is, as mentioned above, interpreted to be formed due to basinward shift of facies belts. The progradation probably led to some recurrent lateral shifting between the multilobate fluvial distributary channel systems and interdistributary bays or embayments across the delta plain. Thus, a low salinity lacustrine embayment was created directly above the Ullaberget Member sandstones prior to subsequent alluvial deposits overlying the mudstones. The boundary between the Ullaberget Member and overlying lacustrine mudstones is interpreted as a lacustrine ravinement surface that is very irregular. It is therefore hard to point out the exact lithological boundary. These terrestrial delta top/embayment deposits were later truncated by another lateral shift of the distributary system, thus forming another abrupt vertical change in facies. This contact is not exposed. The laterally and vertically interchanging interdistributary-, crevasse-, and distributary deposits, topped by 2 or 3 coal beds, compose the uppermost part in the lower portion of the Ullaberget section. These are surfaces of subaerial exposure formed when the basinward progradation of the terrestrial strata reached its maximum point of regression. As emphasized in the log-correlation subchapter, these beds are probably the best fit for a regional datum plane as they may be correlated with similar deposits in Festningen and Sassenfjorden areas, a correlation that also was suggested by Midtkandal (2002).

6.4 The middle portion of the Ullaberget section

The middle portion of the Helvetiafjellet Formation in the Ullaberget section consists of vertically aggarded sandstone units, followed by transgressional upwards coarsening heterolithic units of the upper portion in the Ullabeget section. The middle portion forms the bulk of the Helvetiafjellet Formation in this section. This up to 50 m thick stacked sandstone unit is interpreted as vertically aggraded intertidal flat deposits formed during a relative sea-level rise, thus comprising an aggradational parasequence set. According to Klein (1998), intertidal flats are low-sloping features that are exposed at low-tide stage. The middle portion of the Ullaberget section is interpreted to represent a stage

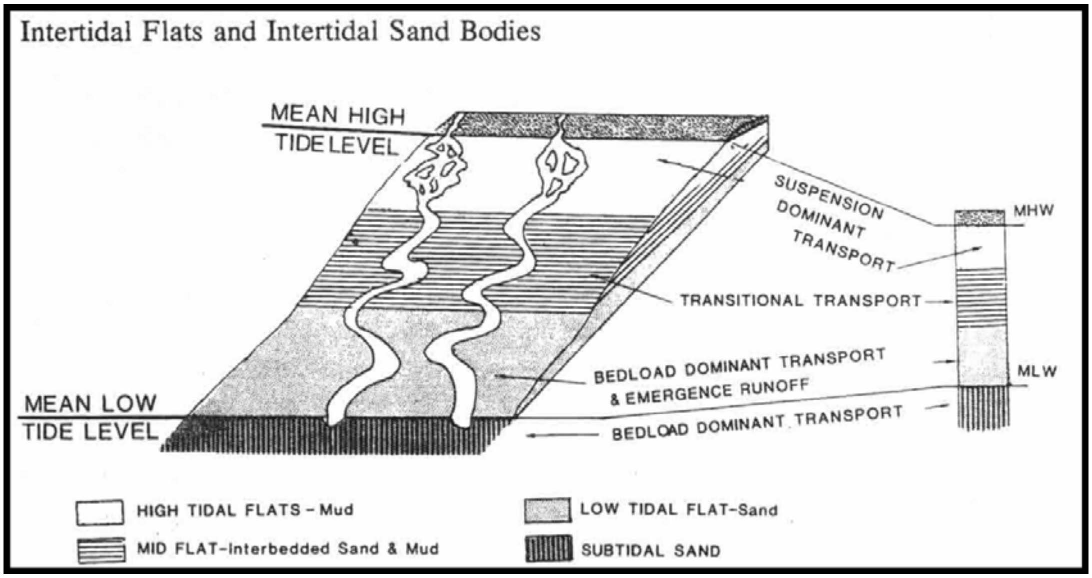

Figure 6-5: Division of intertidal zone into bedload dominant, transitional and suspension dominant parts. (From Klein et al., 1972).

of relatively continuous deposition and near equilibrium between rate of the accommodation space created and rate of sediment supply (A/S=1).

The basal unit of the middle portion of the Ullaberget section is composed of, as described in the chapter 5, laterally relatively continuous sand bodies, an elongate sandstone ridges. These intertidal sand bodies occur in the lower portions of intertidal flats and intertidal zone (Figure 6-5). They are also exposed at low-tide, in contrast to tidal current sand ridges, which are always subtidal (Klein, 1998). The intertidal sand ridges are overlain and truncated by heterolithic sand/mudstone deposits formed as water ways shifted their position laterally between the sand ridges in a near shore setting. These deposits are interpreted in chapter 5 as meandering tidal channel deposits (FA2). The upper boundary of the FA2 is lithologically conformable surface, as it is not showing any erosional relief. Sediments accumulated above this boundary are deposited in the intertidal zone (Klein, 1998) and include small tidal channels, -creeks, and interdistributary sand flats exposed during low-tide stages.

6.5 The upper portion of the Ullaberget section

As mentioned earlier, the upper portion of the Ullaberget section is divided into coarsening-upward intervals between the 8 marine flooding surfaces, marked as FS1- FS8 in figure 6-1. These intervals have been deposited in the transitional zone in the marginal marine upper portion of the Helvetiafjellet Formation, underlying the fully marine Carolinefjellet Formation. Internal stacking geometry of the upper portion of the Helvetiafjellet Formation is more complex than the lower and the middle ones. The vertical stacking of deposits in the upper portion indicate significantly fluctuating rates between rate of accommodation space generated and rate of sediment supply (A/S-ratio). Generally, rate of accommodation space generated was increasing faster than rate of sediment supply, thus leading to sediment partitioning during deposition of the upper portion of the Helvetiafjellet Formation. As the sandstone units are vertically stacked in a backstepping manner, as suggested by Gjelberg and Steel (1995), and bounded by flooding surfaces they can be regarded as parasequences, thus forming a north-westward retrogradational parasequence set.

The upper transitional portion of the Helvetiafjellet Formation in the Ullaberget section is considered to have its lower boundary at the first occurrence of fully marine strata. This first flooding surface is put at the top of the intertidal flat deposits where the first transgressional marine sandstone sheet includes *Diplocraterion* trace fossils. The upper boundary is put at the flooding surface which marks the end of the interbedding of the marginal/fully marine and continental (bay/lagoon) facies. Therefore, despite its marine dominance, the upper portion of the Ullaberget section is included in the Helvetiafjellet Formation. The stratigraphic boundary between the Helvetiafjellet Formation and the Carolinefjellet Formation does not follow any regionally distinct lithological boundary, as the Carolinefjellet Formation rests conformably on the Helvetiafjellet Formation. Because a marine flooding of a sinuous coastline would lead to several coexisting continental and marine environments, it is obvious that this lithostratigraphic boundary has to transect stratigraphic time-lines in a regional scale, but not necessarily in such a local scale as is the case in the Ullaberget section. Whether the sandstones of the upper portion of the Helvetiafjellet Formation should be included in the Carolinefjellet Formation or not will not be discussed further in this thesis.

The transition from sandstone to shale is a sharp lithological contact with no visible erosional relief recorded, as with the other flooding surfaces within the Ullaberget section. Thus these contacts are considered as conformable. For closer description of the units see FA7 in the Chapter 5. The initial marine flooding surface above the first occurrence of *Diplocraterion* trace fossils does not cover the whole Ullaberget section as it disappears between the logs UB6 and UB2. However, the second flooding surface does cover the whole section and is probably also correlative to the Louiseberget section. This will be further discussed in subchapter 6.7. There is no significant difference between the individual coarsening-upwards units within the upper portion of the section. They are all laterally relatively continuous over the Ullaberget section. Sandstone units and shale intervals are located stratigraphically equivalent levels indicating simultaneous deposition of mud and sand. This has probably taken place along a sinuous coastline where river mouths and bays occur alongside one another. As the rivers migrate laterally and active delta lobes change their position the locus of sediment deposition moves laterally along the coast. During the rise of the relative sea-level, a river mouth may migrate along the coastline depositing nearly continuous sand body, which may have been covering laterally adjacent embayment deposits of the same age and later be reworked by tidal forces. The sandstone units are interpreted to result from two different processes depending on the lithofacies. Sandstones deposited by fluvial channels and reworked by tidal forces as described above or sandstones deposited as transgressive marine sand sheets generated by storms. The latter is also supported by occurrence of HCS facies within several of the sanstone units.

6.6 Summary of the depositional environment

Seen as one, the sedimentary environment that existed during the Barremian - Aptian was an overall backstepping by nature, with several short lived events of relative sea-level fall interrupting the general relative sea-level rise. The Paleo-Hornsund Fault line (figure 3-1) may have acted as the western margin for the basin (Steel and Worsley, 1984). Sedimentation took place on a relatively wide zone across the central Spitsbergen during the initial stage of rising relative sea-level (lowstand and transgressive systems tracts) after relative sea-level fall (forced regression systems tract). Systems tracts will be further discussed in Chapter 7.

The lower portion of the Helvetiafjellet Formation in the Ullaberget section was deposited on a subaerial unconformity in a local incision on the emerged Janusfjellet Subgroup shelf. The incision was caused by fall in relative sea-level. By the time when this incised valley was filled up, a modest rise in relative sea-level drowned the entire coastal plain and deposited the tidally dominated middle portion of the Helvetiafjellet Formation in the Ullaberget section. Later, when rise of relative sea-level accelerated, rate of accommodation space generated exceeded rate of sediment supply causing interbedding of continental and marine strata in a backstepping manner. This comprises the upper portion of the Helvetiafjellet Formation in the Ullaberget section. The entire formation is considered to have been deposited in the backstepping manner by Gjelberg and Steel (1995).

6.7 Correlation to the adjacent mountains and earlier studied localities of Helvetiafjellet Formation in southern Spitsbergen

Gjelberg and Steel (1995) discussed how the development of the Helvetiafjellet Formation was time transgressive, backstepping from southeast to northwest. The lower portion of the Helvetiafjellet Formation in the Ullaberget, Louiseberget and Annaberget sections could be interpreted to be deposition in this manner. As follows, the predominantly fluvial basal half of the Annaberget section represents a time equivalent deposition with the thinner fluvial deposits and bypass in the basal third of Louiseberget section. These fluvial deposits are interpreted as time equivalent with the deposition of the Ullaberget Member and overlying lacustrine mudstones and basinward shifting fluvial facies deposited on the basinward side of the knickpoint (Leckie, 1980) (see also Chapter 7). This interpretation is based on the possible correlativity of the coal beds at the top of the lower portion of the Helvetiafjellet Formation over to the Louiseberget and Annaberget sections. This correlation is further strengthened by the occurrence of basal conglomerate bed at the base of the Ullaberget and Annaberget sections. This boundary is interpreted above as diachronous surface. The basal conglomerate bed is not seen in the Louiseberget section due to debris cover. The basal conglomerate bed at the base of the Annaberget show bigger clasts and is generally thicker than its counterpart at the base of the Ullaberget Member in the Ullaberget section, but both have same mineral composition. This basal conglomerate bed may be also correlative to basal conglomerate of the Berrkletten section. The basal fluvial unit of the above mentioned sections is probably not correlative to the Festningen Sandstone Member further in the north as it may represent proximal equivalent deposits for the upper portion of the Helvetiafjellet Formation in the eastern side of the central basin of Spitsbergen, as suggested by Midtkandal (2002).

The marine flooding surfaces in the upper portion of the Helvetiafjellet Formation in the Ullaberget section are generally correlative only within this section, with a few exceptions. It is generally hard to point out the equivalent flooding surface even in the closest section of the Ullaberget, in the Louiseberget section. However, some of the transitional sandstone beds with marine trace fossil *Diplocraterion* are registered also in the upper parts of the Louiseberget section and thus are probably correlative with ones in the Ullaberget section. The problem of which three of the several beds with *Diplocraterion* in the Ullaberget section are correlating with the three beds with *Diplocraterion* in the Louiseberget section remains unsolved in this thesis.

The top of the Helvetiafjellet Formation is equally easy to point out in the Louiseberget and the Annaberget sections as in the Ullaberget section, as the local thick fully marine shale interval is readily seen in the first two sections. Both the shale interval (20-30 m in thickness) and overlying marine siltstones and sandstones are included in the Carolinefjellet Formation. The Carolinefjellet Formation is not present in the Berrkletten section.

7

Sequence stratigraphy

7.1 Introduction

Sequence stratigraphy is the study of rock relationships within a time-stratigraphic framework of repetitive, generally related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities (e.g. Mitchum et al., 1977; Posamentier et al., 1988; Van Wagoner et al., 1988). Sequence architecture is a result of one cycle of falling and rising relative sea level. The scope of sequence stratigraphy is to establish a model to be used for recognizing, interpreting and predicting the occurrence and geometry of sediment facies based on the above mentioned concept, in which depositional facies associations, or systems tracts, have their specific positions within a sequence. Other sequence-stratigraphic models, conceptual approaches and methods include: (1) the genetic stratigraphic sequence model (Galloway, 1989); (2) the T-R sequence stratigraphy model (Embry, 1993); (3) models of forced regression (Posamentier et al., 1992); and (4) the shoreline trajectory concept (Helland-Hansen and Gjelberg, 1994), to name a few. All models use changes in base level as the main controlling factor, but different stratigraphic surfaces as sequence boundaries. This chapter will firstly discuss briefly the general concepts within the sequence stratigraphy and main factors controlling the evolution and preservation of a sequence. Secondly, this chapter applies these concepts to the Helvetiafjellet Formation in the Ullaberget section on southern Spitsbergen.

7.2 Key concepts, controlling factors and preservation of sequences

The term sequence, as applied in the sequence stratigraphy, was originally defined by the Exxon research group as “a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded by at its top and base by unconformities and their correlative conformities" (Mitchum et al., 1977, p 53). The bounding unconformities and their correlative conformities are referred to as sequence boundaries type 1 and type 2. Sequence boundaries separate always younger rocks above from older rocks below, but they do not imply any particular length in geological time. The type 1 sequence boundary (SB), as defined in the Exxon model (e.g. Van Wagoner et al., 1990), is marked by subaerial truncation, and the strata above by a basinward shift in facies compared to strata below. This means that SB is represented by an abnormal subaerial exposure, marked by a more proximal horizon lying unconformably on marine strata. This subaerial unconformity is a cronostratigraphic marker in the sense that it is normally not crossed by time surfaces, and therefore all sediments above the surface are younger than those below (Helland-Hansen and Martinsen, 1996). Type 2 SB (e.g. Van Wagoner et al., 1988) is a subaerial unconformity formed entirely on the landward side of the shoreline and without fall of relative sea level. If an incised valley is present, the SB will follow the erosional surface at the base of the valley, but it will follow the top of any adjacent terrace deposits.

The basic building blocks of sequences are *parasequences* (Van Wagoner et al., 1990). These genetically related beds or bedsets are bounded by marine flooding surfaces and can be arranged into *parasequence sets* which, in turn, define the systems tracts. Whether progradational, aggradational or retrogradational, the architecture of a parasequence set is dependent on available accommodation space and relative rates of sediment supply. Parasequences and parasequence sets are readily applied into the Helvetiafjellet Formation in the Ullaberget section to illustrate the interplay between accommodation space and sediment supply during the deposition (see Chapter 7). *Accommodation space* is the space made available for potential sediment accumulation (Jervey, 1988). *Sediment supply* is the amount of sediments transported into a depositional system. *Systems tracts* are three dimensional units of deposition bounded by depositional boundaries of onlap, downlap, etc. Systems tracts are recognized and defined by the nature of their boundaries and by their internal geometry. Within any one relative sea-level cycle, three main systems tracts that characterize different parts of the relative sea-level cycle are frequently developed.

(1) *The lowstand systems tract (*LST) is stratigraphically oldest and deposited during an interval of relative sea-level fall and subsequent relative sea-level rise.

(2) *The transgressive systems tract* (TST) is formed during that part of the sea-level rise cycle when rate of accommodation is increasing faster than the rate of sediment supply.

(3) *The highstandsystems tract* (HST) is stratigraphically youngest and represents the progradational top-set clinoform deposits after maximum transgression, when the rate of accommodation is less than the rate of the sediment supply.

A fourth systems track, *the forced regression systems tract* (FRST) has been proposed by Plint, 1988; Hunt and Tucker, 1992; 1995. It is considered as the youngest and uppermost systems tract of the sequence, located above the HST and below the next SB. The FRST is deposited during relative sea-level fall, when accommodation is negative and incision and bypass occur on the alluvial- and coastal plain and on the emerged parts of the shelf, whereas deposition occurs on the submerged parts of the shelf. It includes erosion based (detached), as well as gradually based (attached) deposits. The FRST is bounded below either by a marine ravinement surface of erosion formed during regression or by a conformable surface. Above, the FRST is bounded by the SB or/and a transgressive surface. Therefore, LST was restricted to the interval of lowest point of relative sea-level position to the beginning of the transgression.

Other key surfaces, which enable us to tie sedimentary successions into packages with genetic and chronostratigraphic significance, applied in this paper include: (1) *flooding surfaces* (FS), which are surfaces that separate younger from older strata, and across which there is evidence of an abrupt increase in either marine or lacustrine water depth; (2) The *transgressive surface* (TS) is the marine flooding surface beneath TST-deposits; (3) *maximum flooding surface* (MFS), which is the surface that marks the most proximal extend of landward stepping transgressive strata; (4) *ravinement surfaces* (RS), which are subaqueous erosional surfaces. In the current study area these RS surfaces are related both to relative rise of sea level as marine ravinement surfaces, formed by erosion from either wave-induced currents (WRS) or tidal currents (TRS). Lacustrine ravinement surface (LRS) is formed when lacustrine depositional environment occupies adjacent alluvial distributary system or preceding shallow marine environment.

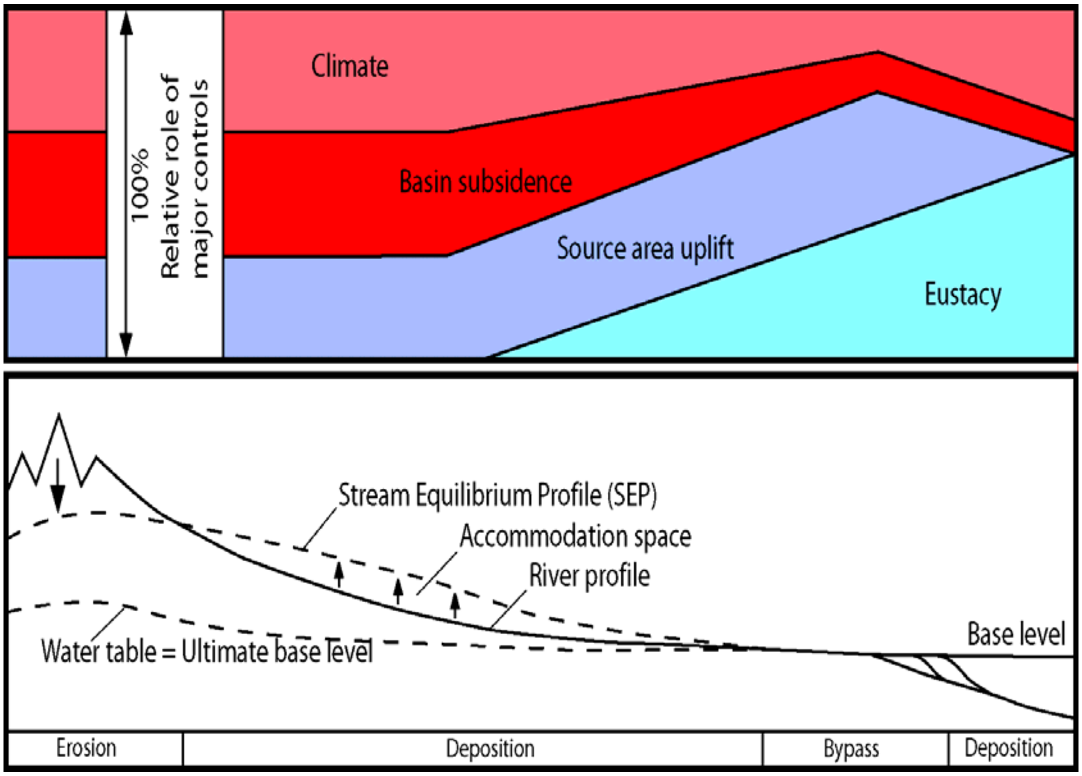

Figure 7-1: The upper part of the figure shows the relative role of the major controlling factors. The effect of the eustacy diminishes in a landward direction and climatic effect increases. The lower part show the difference of Stream Equilibrium Profile (SEP) and ultimate base level. The space between the SEP and the river profile is the potential erosional or depositional space. The horizon scale that should be applied to this figure is debated (Modified from Schumm, 1977; Shanley and McCabe, 1994).

Accommodation space

The accommodation space, the space made available for potential sediment accumulation, is thought to be driven by base level change caused by sea level fluctuation and tectonic subsidence (Figure 7-1) (Jervey, 1988; Shanley and McCabe, 1994). The interplay between accommodation space (A) and sediment supply (S), termed as A/S-ratio, is generally considered to control the geometry of strata (sedimentary architecture). Based on this interplay, basic building blocks of a sequence, parasequences, can be put into three categories. A progradational parasequence set occurs if the rate of S exceeds the rate at which A is created, an aggradational parasequence set forms when rates of A and S are equal, and a retrogradational parasequence set is created when the rate of S is exceeded by the rate at which A is created (Van Wagoner et al., 1988). Where A is zero, sedimentary bypass will occur and where A is negative, erosion and incision are likely to take place. All these different parasequence stacking patterns are clearly recognized in near-shore marine strata, but considerably more difficult to recognize and correlate in continental settings.

Base level

Base level is described by Shanley and McCabe (1994) as “an undulating surface of equilibrium that intersects the earth’s surface and fluctuates in response to forcing functions of such as tectonic subsidence, eustacy, sediment supply, discharge, etc.”. Amount of accommodation space is usually described relative to some conceptual hypothetical equilibrium surface, a *stratigraphical base level* (Shanley and McCabe, 1994), into which the actual topographic basinal surface always attempt to achieve. In shallow marine environments sea level is considered as the base level (ultimate base level or geomorphic base level). In a continental setting, the base level can take various forms like a regional water table, a lake level for lacustrine deposits, or *stream equilibrium profile* (SEP) for alluvial deposits, similar to Mackin’s (1948) *graded stream profile* (Shanley and McCabe, 1994). From here on *stratigraphic base level* or SEP will be used as base level for continental realm, and *base level* will reflect to the marine realm (Figure 7-1). Above the SEP, erosional processes are the most dominant, whereas below the SEP depositional processes are the most dominant. Both processes work at the same time, but in different rates, meaning that SEP will only last over a relatively short period of time. A change in relative sea level (base level) will cause a change of the stream profile and also instant change of the SEP. This will result in a change of accommodation space, leading to erosion, deposition or sedimentary bypass.

Climate

Changes in climate arise from plate movements, Milankovitch cycles, changes in volcanic activity, changes in air and sea currents, etc. Climate is the controlling factor for vegetation and rainfall. Dense vegetation cover, for instance, prevents high runoff rates, stabilizes the sediments and accelerates the weathering process. In other words, vegetation controls the erosion, sediment flux and river discharge both in the provenance area and in the drainage area (Shanley and McCabe, 1994).

Eustacy

Eustatic sea level change is a function of sea-surface movement relative to some fixed point such as the centre of the earth. Relative sea level change is a function of both sea-surface movement and sea-floor movement in the fixed frame (Posamentier, Jervey & Vail, 1988; Posamentier and James, 1993). The effects of sea level change are apparent in most stratigraphic successions of coastal deposits and together with tectonics largely affect to their preservation potential in the geological record. Changes in relative sea level (Posamentier et al., 1988) occur at various scales of time and magnitude of sea level fluctuation. It may also influence the elevation of the groundwater table, which is the ultimate base level in continental areas, even though lag time increases landward from the shoreline. Raised groundwater tables may result in development of lakes and ponds or lake expansion, and thus development of lacustrine flooding surfaces (LFS) (Emery and Myers, 1996).

Tectonics

Tectonics is a driving force behind changes in both climate and base level. An example of this could be uplift in a drainage area which could lead to increase in river gradient, coastal incision and increased sediment supply into the basin.

Preservation of a sequence

Preservation potential of a sequence is also controlled by several factors, with sufficient burial of sediments being the most important one to avoid erosion during the next erosive phase. To achieve sufficiently buried sediments the time and magnitude of tectonic subsidence and/or eustatic fluctuations are crucial. Thick accumulations of coastal deposits exist only in areas of long-term subsidence. The nature of sea level change can also remarkably influence the preservation, as proposed by Davis and Clifton (1987). According to them, most coastal deposits that are preserved in the geologic record formed under conditions of very slowly rising sea level. A falling sea level exposes the shoreline deposits to processes of subaerial erosion. Under conditions of rising sea level, a shoreline will prograde if the rate of sedimentation is sufficiently high. The preservation potential of both wave- and tide-dominated facies is high under such upward progradation. If the sedimentation is less, a retrograding shoreline (marine transgression) will take place, during which the potential for preserving tide-dominated facies is higher than that for wave-dominated facies.

7.3 The Helvetiafjellet Formation - a sequence stratigraphic approach

The Helvetiafjellet Formation represents one cycle within a sequence stratigraphic framework including the Janusfjellet Subgroup, the Helvetiafjellet Formation, and the Carolinefjellet Formation. The Janusfjellet Subgroup covers the highstand systems tract (HST) (Gjelberg and Steel, 1995). This HST is followed by the Ullaberget Member, deposited during the accretionary lowstand prograding wedge systems tract (LPWST) (e.g. Hunt and Tucker, 1995). The forced regression systems tract (FRST) deposits prior to the lowstand wedge deposition, the Ullaberget Member, are not found from the locality. The LPWST is followed by the bulk of the Helvetiafjellet Formation representing the last stages of the lowstand wedge- and early stages of the following accretionary transgressive systems tract. As the dominance of marine processes was established after continued transgression, the Carolinefjellet Formation comprises the deposition of another HST.

Relative sea-level fall

Based on the sequence stratigraphic model of Vail et al. (1977) and Van Wagoner et al. 1988 the contact between the Helvetiafjellet Formation and the Janusfjellet Subgroup is interpreted as a type 1 sequence boundary. Here, a tidally influenced delta, the Ullaberget Member, directly overlies marine shale with a lithological sharp, erosive contact (Figures 2-2, 2-3, 5-8 and 5-9). This contact marks the subaerial surface of erosion which developed when the relative sea-level fall caused exposure of the shelf, allowing fluvial streams to develop while eroding into the substratum. Despite the evident erosional relief at the base of the Ullaberget Member, no indicators are present reflecting magnitude of the erosional relief or whether the erosion was concentrated along an axis, forming a local or regionally incised valley, or not. No deposits at or near the base of the Ullaberget Member are interpreted as the Forced Regression Systems Tract (FRST). However, the Ullaberget Member is interpreted to represent an accretionary regression during the lowstand systems tract (*sensu* Helland-Hansen and Martinsen, 1996). Further north, along the subaerially exposed erosional axis (SB), through the Berrkletten section to the Festningen section, these deposits are decreasing in thickness, which means that little, non-accretionary deposition, or bypass occurred in these areas north of Van Keulenfjorden (Figure 2-1), during relative sea-level fall.

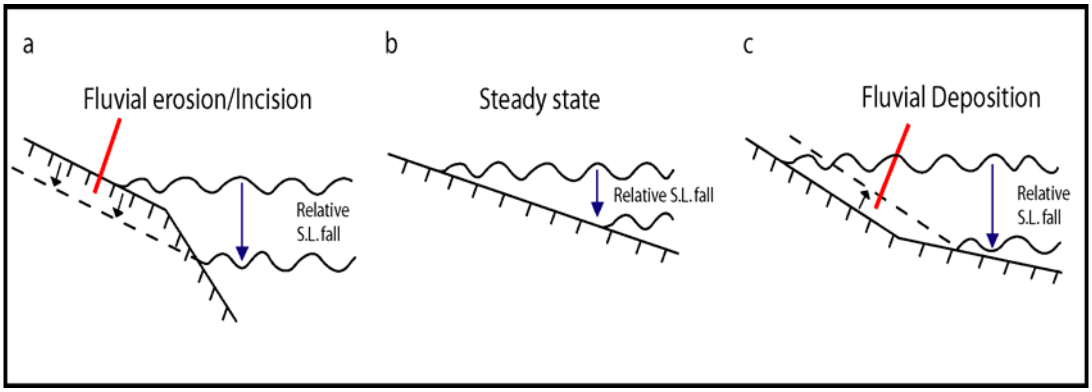

Figure 7-2: Slope gradient of alluvial plain vs. slope gradient of shelf determines whether incision (a) or deposition (c) occurs. (b) Illustrates the special case where the alluvial plain and shelfal gradients are equal, owing neither deposition nor erosion, resulting a bypass surface. (Modified from Shanley and McCabe, 1994).

The Janusfjellet Subgroup is characterized as deposited on a very low-relief, low-gradient continental shelf with large extent (Dypvik, 1985). Figure 7-2 illustrates theoretical relationships between alluvial plain and shelf during relative sea-level fall. If the gradient of the hinterland was steeper than the gradient of the newly exposed shelf, accommodation space would be generated in order of fluvial streams to attain the stream equilibrium profile (SEP), and deposition rather than erosion would take place (cf. Schumm, 1993). In turn, if the alluvial plain was of a lower gradient than shelf, erosion and incision would take place (Figure 7-2) (Shanley and McCabe, 1994). As mentioned earlier in this chapter, rivers work all times to achieve an optimal elevation and gradient, stream equilibrium profile (SEP), in which the least amount of hydraulic energy is wasted (Shanley and McCabe, 1994) (Figure 7-1). In general, incision took place during the relative sea-level fall, but some deposition might have taken place below the SEP on the newly exposed shelf during later stages of relative sea-level fall as alluvial facies belts were prograding basinward. In the light of the assumptions about the very low gradient nature of the shelf surface during deposition of the Janusfjellet Subgroup and relatively stable tectonic history of the area, the erosion of Janusfjellet Subgroup deposits prior to deposition of the Ullaberget Member might have been moderate or low.

Relative sea-level rise

Accommodation space made available for deposition of the Helvetiafjellet Formation was generated after the fall of the relative sea-level, at the onset of the following transgression. During the initial stage of the relative sea-level rise, the Ullaberget Member was deposited

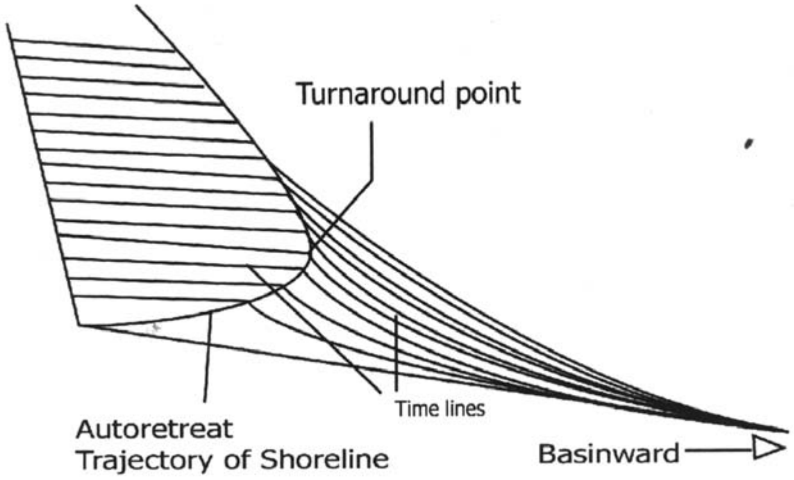

Figure 7-3: The concept of autoretreat, where sediment dispersal at the coastline causes a transgression despite an increase in sedimentation rate. This occurs due to the area over over which the sediments are distributet increases at a faster rate than the increase in sediment supply. (Modified from Muto and Steel, 1997).

in the incision created during preceding FRST. Lacustrine mudstones were then deposited above the Ullaberget Member on a lacustrine ravinement surface (LRS), followed by alluvial sandstones during the early stages of the relative sea-level rise. The latter deposits are topped by 2 coal beds marking the end of the lowstand and the top of the lower portion of the Ullaberget section. The coal beds (facies D) are probably reflecting increased rise of the relative sea-level, caused by the change from S>A towards S=A. The rising sea-level generally causes also the rise of the groundwater table, which in turn leads to forming of swamps on the coastal plain, which after burial turn into coal. This sharp lithological contact at the top of the lowstand prograding wedge (LPWST) (Hunt and Tucker, 1995) deposits shows some indications of erosion reflecting the development of a trangressive *tidal ravinement surface* (TRS). However, it is impossible to measure the magnitude of the erosion of the coal beds caused by tidal sandstone deposition on these. The low erosion relief could be a result of low rate of silisiclastic deposition during this stage of transgression. The TRS surface coincides with the most basinward position of the alluvial strata (FA1) also termed as the *maximum regression surface* (MRS). It marks the turn-around from where the transgression starts and deposition of facies belts is moving landward and not basinward as was the case during LPWST. This turn-around could be caused by autoretreat (Muto and Steel, 1997). This means that even with increased sediment supply will deposition automatically turn into transgression during constantly increasing accommodation space, because sediments are deposited in a wider and wider area and therefore can not keep pace with accommodation space created (Figure 7-3). The interesting aspect of this relationship is: can the autoretreat mechanism be applied to the whole depositional style of the Helvetiafjellet Formation in the Ullaberget section? In theory, the whole sequence, where a prograding parasequence set at the base (the lower portion of the Ullaberget) is followed by an aggradational parasequence set (the middle portion of the Ullaberget) and topped by a retrogradational parasequence set (the upper portion of the Ullaberget) probably could be explained with autoretreat.

During the initial stage of the relative sea-level rise, sediment supply into the Ullaberget section have been higher than accommodation space created for deposition (S>A), leading to the lateral accretion of the Ullaberget Member. The S/A-ratio became equal during the early stages of transgression, which is marked by above mentioned TRS/MRS surface. The change in A/S-ratio caused vertical aggradation instead of progradation of the tidal sandbodies of the Helvetiafjellet Formation in the Ullaberget section, and finally landward shifted deposition brought tidal sandstone deposits right above the subaerially exposed alluvial deposits.

The overall transgressional development of the Helvetiafjellet Formation was punctuated by higher frequency signals of smaller-scale sea-level fluctuations. Hence, several subaerial surfaces of exposure (facies D) found internally in the Helvetiafjellet Formation, in the upper part of the middle portion and especially through the whole upper portion of the Ullaberget section, reflect events of the relative sea-level fall during an overall relative sea-level rise. If we consider the Helvetiafjellet Formation to be part of a third order sequence in agreement with the sequence hierarchy proposed by Embry (1995), a fourth order signal could have been causing these surfaces. Potentially, they can have been formed during the early stages of transgression, when the relative sea-level rise still was slow, causing a gentle shoreline trajectory (cf. Helland-Hansen and Martinsen, 1996). This could have also been the case in the Ullaberget section, but after the end of the aggradational stage of deposition. By this time, rate of accommodation space created during the relative sea-level rise began to override rate of sediment supply. This led to several flooding surfaces (FS1-FS8), which are registered interchanging with subaerially exposed surfaces in the upper portion in the Ullaberget section. These surfaces are representing an abrupt increase in water depth and therefore drowning of the tidally influenced coastal plain deposits such as lagoons and small bays. During these relatively extensive flooding periods distinctive marine *Diplocraterion* trace fossils were produced on top of storm generated sandstone beds, which interfinger with the transitional heterolithic shales. The FS is put on top of these beds.

It is difficult to pin point that particular FS which marks the change to the fully marine Carolinefjellet Formation, deposited during the last stages of the TST and subsequent HST. The boundary is in this study put on the top of the last sandstone unit lying above the last occurrence of coal within the heterolithic shale beds.

The Helvetiafjellet Formation in the Ullaberget section is in this context interpreted to represent deposition after forced regression, during the lowstand prograding wedge- and the early transgressive systems tracts, while the Carolinefjellet Formation was formed during the later stage, when the rate of the relative sea-level rise was higher.

Lateral variability

As described earlier in this chapter the main factors controlling the progradation and retrogradation of the coastline is the interplay between the rate of the sediment supply and accommodation space generated, termed as the A/S-ratio (Muto and Steel, 1997). Lateral changes in A/S-ratio within the Ullaberget section (~1.5 km) are generally minor and concentrated within the upper portion of the succession. When compared with exposures in the adjacent mountain sides, in the west and north, greater variations in this ratio are revealed. The different sedimentary development of the Helvetiafjellet Formation between these outcrops can be explained with the presence of multiple feeder sources instead of a single point source. During transgression, a wide belt of multiple feeder systems deposit sand unevenly along the retreating coastline due to feeder channel avulsion events and differential sediment loading which follows local topography of the coastal plain. This gives rise to the local scale incision leading to local thickness variations, from which the Ullaberget section and its relationship to the adjacent mountains in the west may be a good example. Differential compaction and relatively abrupt lateral changes in depositional locus can be credited for the local changes in sedimentation patterns in the middle and upper portions of Helvetiafjellet Formation in the Ullaberget section. In addition, changes in sediment transport rate and route of multiple feeder streams, which fed the coastal plain with sediments, can have affected the net accumulation of deposits along the coast. A modest topographic relief is needed to cause differential flooding of the coastline, making development of small bays and headlands, with marine and continental deposition occurring simultaneously, laterally to one another possible.

Controlling factors of basin evolution

Whether the main depositional processes in the Helvetiafjellet Formation were allocyclic or autocyclic are unknown. The onset of the relative sea-level fall that led to the deposition of the Helvetiafjellet Formation may have been tectonically initiated. Thus, the stacking patterns observed in the field could also originate from changes in tectonic activity in the west.

The cause of the sea-level fall is probably a combination of eustacy and tectonics. Data from arctic Canada (Embry, 1989; 1992) suggest that allocyclic processes might have been active during the deposition of the Helvetiafjellet Formation. Active volcanism and plate tilting are the most probable causes for the initial sea-level fall. Posamentier and Allen (1993) stated that eustacy and sea floor subsidence/uplift determine the timing of formation of sequence bounding surfaces, whereas sediment influx and the sediment composition are most effective in determining the stratal architecture between those bounding surfaces. This does not apply completely to the internal stratal architecture of the Helvetiafjellet Formation, as the development of fourth order sequence boundaries and architectural configurations within the formation may well have been initiated by tectonic movements, or high-frequency relative sea-level fluctuations. Generally, the tectonic influence in the area caused the regional relative sea-level fall and is also believed to be present in the following infill of the basin as a background signal.

The internal strata were probably controlled by a combination of allocyclic and autocyclic processes. Deposition caused by autocyclic processes such as basin subsidence is hard to point out in the area. However, tectonic tilting of the region is credited for both the initiation of the silisiclastic influx to the area as well as for influencing the stacking patterns within the formation. It is therefore reasonable to assume that depositional events

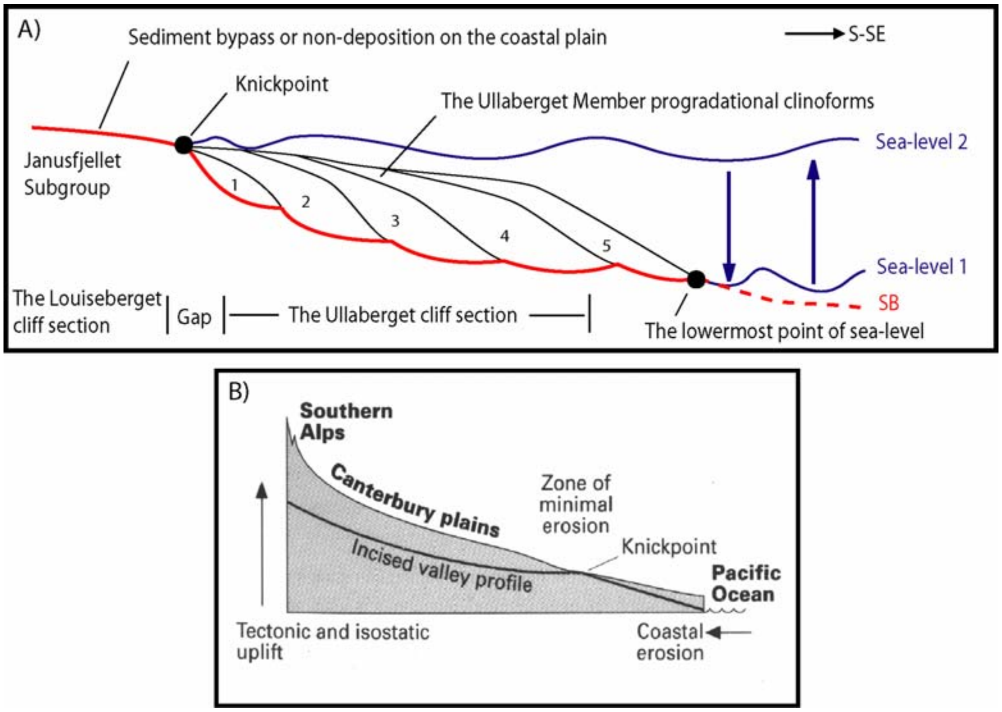

Figure 7-4: The upper figure shows the progradation of the Ullaberget Member during the early stage of the relative sea-level rise and the knickpoint. The lower figure shows the knickpoint in relation to Canterbury plains in New Zealand. (After Leckie, 1994)

initiated by allocyclic and/or autocyclic processes may have created a combined product as a result of all the processes working parallel during the development of the Helvetiafjellet Formation.

Depositional setting and formational boundaries

In the present stratigraphical understanding (Dallmann, 1999), the Ullaberget Member is included in the Rurikfjellet Formation in the top of the Janusfjellet Subgroup. According to one model of Gjelberg and Steel (1995, their figure 3), the Helvetiafjellet Formation lies above an SB formed above the Ullaberget Member in the Ullaberget section and is thus composed of thin basal fluvial sandstone unit, followed by thick vertically aggradational and retrogradational tidal sandstone unit, finally transgressed by heterolithic marine shale and silt formation (the Carolinefjellet Formation). Viewing the Ullaberget section of the Helvetiafjellet Formation in this light, may lead to an interpretation of the depositional environment to be a backfilled incised valley, an estuary. The type of stacking pattern recorded may fit into the general transgressive stratigraphic organization of tide-dominated estuaries, which from the base upwards are characterized by fluvial sandstones followed by central basin brackish mudstones, overlaid by tidal sandstones, and finally topped by ultimate flooding of the coast (Dalrymple, 1992; Zaitlin et al., 1994). In a wider regional context, the Helvetiafjellet Formation is problematic to explain by a single estuary model since there appear to have been sufficient lateral space available for deposition of sand across a broad plain.

Nemec (1992) stated that the width of the entire fluviodeltaic front in southeastern Spitsbergen might have been about 200 kilometres. Zaitlin et al. (1994) stated that an incised valley system may reach widths of some 10's of kilometres. As esturies are generally thought of as the sediments deposited during transgression of an incised valley (Dalrymple et al., 1992), a single estuarine system exceeding 200 km in width is thus unlikely.

As follows, the general width/thickness ratio of the Helvetiafjellet Formation, in general, points toward a regional non-incisional setting. However, evident local incisions do have taken place on the broad emerged shelf. In the present study, only the Ullaberget Member is interpreted to have been deposited in such a local incision, deposited after FRST and during the LPWST (see Chapters 2 and 6). Therefore, the Ullaberget Member is stratigraphically included in the sequence that comprises the Helvetiafjellet Formation in the Ullaberget section. The width of the incision is unknown, due to laterally limited exposures along the assumed paleocoastline, but vertically the incision probably has been around 20 m based on the thickness of the Ullaberget Member. As mentioned earlier, in the general and simplified understanding, incision of the shelf is likely to occur when base level falls. However, during the subsequent base level rise, coastal erosion may also occur in landward direction, back to a *knickpoint* (Leckie, 1994). In landward direction from the knickpoint, bypass or non-deposition occurs on the coastal plain, whereas incision or deposition might take place higher up on the alluvial plain, in accordance with how SEP responses to the base level change. The Ullaberget Member is here interpreted to be deposited basinward from a knickpoint (Figure 7-4), while sediment bypass took place landward from this point at the time of deposition.

After deposition of the Ullaberget Member, the SEP responded to a slowly rising base level by elevation and thus depositing the alluvial sandstone units at base of the Louiseberget and the Annaberget localities (Figure 2-1). The lacustrine or brackish and alluvial deposits lying immediately above the Ullaberget Member are interpreted to represent the distal part of this depositional setting. The abrupt change from the alluvial plain depositional setting into intertidal depositional setting, via subaerially exposed marshes and swamps, indicate that the area underwent landward change of facies belts during a transition from a sediment supply rate higher than rate of accommodation towards equal rates of sediment supply and accommodation (A/S=1). By the time of the second subaerial exposure (MRS/TRS/Exxon type 2 SB) the local incision was filled and the general depositional setting was a broad fluviodeltaic plain. This caused the sediment to be partitioned over a much wider area than during the initial stage of the relative sea-level rise and deposition of the Ullaberget Member. This increase in rate of accommodation space in relation to sedimentation rate (A/S<1), made it possible for distal intertidal and partly subtidal depositional environments to retrograde over the alluvial deposits, probably in an agreement with the mechanism of autoretreat. This aggradational parasequence set comprises the middle portion of the Ullaberget section.

As mentioned earlier, the upper portion of the Ullaberget section is enigmatic in the sense of sequence stratigraphic framework. When the rate of transgression increased and the aggradational parasequence set of the Helvetiafjellet Formation in the middle portion of the Ullaberget section changed into retrograding (backstepping) parasequences, the area underwent several flooding and exposure events. This resulted in a complex vertical stacking pattern of FS's and higher order (4th) SB's forming the retrogradational parasequence set. Definition of the FS that represents the change into the fully marine Carolinefjellet Formation is therefore difficult from the heterolithic transitional strata. The boundary is therefore, in this study, put on the top of the last transitional sandstone (FS8 in figure 6-1 and boundary in general in figure 2-2) and below the first fully marine shale unit. Another possibility would have been an apparently random position in the middle of the upper portion of the Helvetiafjellet Formation in the Ullaberget section. A third possibility would have been to put the boundary at the first occurrence of fully marine deposits, which in this cliff section is on the top of the first marine sandstone bed with *Diplocraterion* trace fossils located at the base of the transitional upper portion of the section. However, the latter position would include nearly one third of the whole Ullaberget section into the Carolinefjellet Formation. These heterolithic sandstone beds are here interpreted to be a part of the depositional sequence that comprises the Helvetiafjellet

Formation. Therefore, the formation boundary is put on the top of the last transitional sandstone unit.

Summary

In the Ullaberget section, the lower portion of the exposure represents progradational parasequence set, overlaid by an aggradational parasequence set, which in turn, is overlaid by a retrogradational parasequence set. Gjelberg and Steel (1995) correlated the individual depositional parasequences of the Helvetiafjellet Formation as offset to one another, suggesting that the deposits developed in a backstepping manner, during the transgressive systems tract, filling in the available accommodation space from the southeast to the northwest. This results in a situation where a depositional unit from an early depositional stage of the formation is physically disconnected from a unit of a later stage, making the chronostratigraphic correlation difficult. This depositional scenario gives rise to continuously landward onlapping parasequences and fits well to the middle and upper portions of the Ullaberget section.

The Helvetiafjellet Formation was deposited when the relative sea-level began to rise, subsequent to the relative sea-level fall in present day arctic areas in Late Hauterivian/Early Barremian. In a sequence stratigraphic context, the formation represents the deposits formed after forced regressive systems tract during the early phase of the transgression and is therefore interpreted as a trangressive systems tract. Forced Regressive Systems Tract was either not preserved in the geological record in the Ullaberget section, due to erosion associated with the falling sea-level, or these systems tract sediments occurs further basinward as a detached (erosion based) sandstone body.

The relative sea-level fall exposed the broad shelf represented by the uppermost depositional surface of the Janusfjellet Subgroup. A continental accommodation space was created by the extension and incision of the fluvial equilibrium profile (SEP) onto the lower gradient emerged shelf. Marginal marine conditions, paralic environments, were established during succeeding relative sea-level rise. Deposition of the formation occurred along an increasingly sinuous coastline which was transgressed from southeast to northwest, incorporating subtidal and intertidal flats, embayments and local small deltas and estuaries.

8

The Helvetiafjellet Formation in the Ullaberget section: an analogue for tidal sandstone reservoirs

8.1 Introduction

The intention of this chapter is not to discuss the Helvetiafjellet Formation as a reservoir itself, because of its present state of petrophysical properties and the burial history. Instead, it is within the scope of this paper to set the focus on the internal geometries and heterogeneities of tidal sandstone bodies, which form the bulk of the formation in the Ullaberget section, and discuss the Helvetiafjellet Formation as a possible analogue for similar deposits in prospective petroleum provinces. The tidal sandstone dominance and the stratigraphic position between two open marine shale formations, the Janusfjellet Subgroup below and the Carolinefjellet Formation above, makes the Helvetiafjellet Formation an interesting analogue for other reservoirs of corresponding setting, depositional history and heterogeneity properties. Firstly, a short review to the reservoir potential of the Helvetiafjellet Formation is given. This is followed by discussion of the different aspects of the usage of the formation as an analogue for similar deposits.

8.2 Hydrocarbon potential of the Helvetiafjellet Formation

Porosity and reservoir potential

Edwards (1979) stated that the porosity of the Helvetiafjellet Formation sandstones is very low in western Spitsbergen (about 5%), increasing up to 25 to 30% in eastern Svalbard

(Figure 8-1). The low porosities in the west are explained by the tectonic activity in western Spitsbergen and a higher geothermal gradient in this area, causing chemical compaction with quartz cementation. Thus, the sandstone units are of low potential as hydrocarbon reservoirs in the west, but the eastwards increasing porosity also increases reservoir potential in this direction (Nøttvedt et al., 1992). The reservoir potential is further reduced due to deep burial depth up to about 5 km and following overloading. This results in continuous cracking down of the possible hydrocarbon chains into smaller and smaller compounds, which can easily leak away from the sandstones.

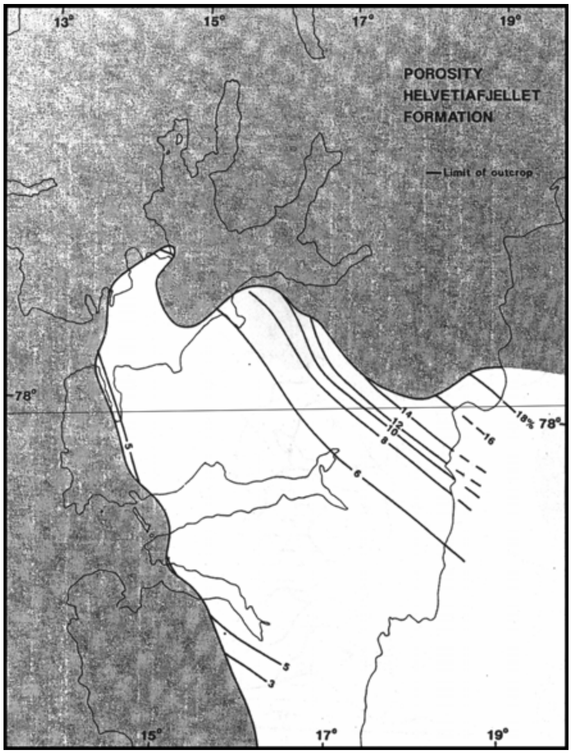

Figure 8-1: Porosity map of the Helvetiafjellet Formation. The white field indicates the area where the formation is exposed or present in the subsurface on Spitsbergen. From Nøttvedt et al. (1992).

Source and seal rocks

The Janusfjellet Subgroup (Bathonian - Hauterivian), underlying the Helvetiafjellet Formation (Barremian - Aptian), is dominated by dark marine shale deposits and some siltstones, with good source rock potential, holding kerogen of type II and III (Dypvik, 1985). During favourable conditions the Janusfjellet Subgroup could have produced significant amounts of hydrocarbons which could have migrated up into the Helvetiafjellet

Formation. However, Nøttvedt et al. (1992) suggested that the high sand/silt content of the Carolinefjellet Formation overlying the Helvetiafjellet Formation would have been a poor top seal for eventual hydrocarbons trapped in the Helvetiafjellet Formation sandstone units below. The sealing properties do also depend on local stratigraphic and geometric relations between the two formations. The coal beds, lying right above the Ullaberget Member in the lower portion of the Helvetiafjellet Formation, have a limited source potential, with kerogen type III/IV (Nøttvedt et al., 1992). The coals are very thin and they could not have been able to yield significant amounts of hydrocarbons on a local regional scale, even with high *total organic content* (TOC). Therefore, they are disregarded as potential source rocks.

Sandstone architecture in Ullaberget section

In the lower part of the Ullaberget section sandstone beds are more continuous than in the upper part and might have been well connected with one another. The discontinuous sandstone bodies interbedded with shale dominated intervals in the heterolithic upper part of the Ullaberget section have been likely to reduce possible hydrocarbon migration locally within the Helvetiafjellet Formation (Nøttvedt et al., 1992). This might have led to situation where isolated sandstone bodies were filled with oil, while on a general regional scale migration continued through the formation.

Summary

The Helvetiafjellet Formation in the Ullaberget section, as a possible hydrocarbon reservoir, has to be considered in a very hypothetical situation. Therefore, it is more reasonable to use it as a field analogue for similar deposits in a current subsurface position.

8.3 Tidal sandstone architecture and internal heterogeneities

Production of oil or gas from a tidally influenced sandstone reservoir, similar to the Helvetiafjellet Formation, is complicated due to the rapid lateral and vertical facies variations. Tidal sandstones can form good reservoirs if the interconnectedness between the units is good. The general interchange of three dimensional sandstone bodies and adjacent shale units strongly reduces connectivity between the large scale sandstone bodies, because sandstone bodies become isolated by the shale intervals, both laterally and vertically, forming stratigraphic traps. One must also bear in mind that internal textural composition in these sandstone bodies, especially when formed in a tidally influenced depositional environment, is likely to be complicated. Connectivity, lateral and vertical, is depending on the amount of mud deposited together with the sand as well as later compaction of mud to shale. This sand:shale, or net-to-gross ratio, depends on the currently active tidal depositional environment and depositional processes at work. In the case of the Helvetiafjellet Formation, active depositional environments have been tidally influenced, shallow water depth marginal marine and coastal plain environments. In these depositional environments, mud was deposited in the supratidal- and high-/mid-intertidal flat environments, in which mud deposition took place from the suspension during the high- and low-tide slack water stages. Thus, formation of single and/or double mud drapes over the sandstone bedforms depends on the magnitude of the energy of the following sand depositional current. Sand, in turn, was mainly deposited from the bedload in the mid- and low-intertidal flat and subtidal environments during the dominating tidal current stages (Klein, 1970). The formation of mud drapes between sandstone beds, as well as within these beds, significantly decreases connectivity within and between the single isolated sandstone bodies. From these, two scenarios can be worked out:

Sandstone architecture and fluid flow model one

Individual sandstone beds are separated from one another by beds of shale, forming single isolated “cells” which are laterally as wide as the three dimensional bedform itself. These include high mud content tidal flat and coastal plain depositional environments. This leads to stacked individual beds with extremely low connectivity between one another and therefore are of low prospect value for exploration, since hydrocarbons cannot migrate into the sandstone units no matter how good source rock they were lying on top of.

Sandstone architecture and fluid flow model two

Tidal sandstone beds are well connected to adjacent beds (cells). These include elongate tidal sandstone ridges and thick cosets of tidal flat deposits. Due to their good lateral extension these stacked tidal sandstone units, if sealed with shale, can yield to significant amounts of hydrocarbons being trapped in stratigraphical traps. However, internal heterogeneities can provide barriers for fluid migration and form series of completely or partly isolated sandstone bodies, which might be filled with oil and still provide good prospects for exploration. For exploration point of view, it would also be vital to know the possible volume of these sandstone units. For this purpose the lateral and vertical extension of the sandstone bodies, their form and orientation in 3D, and depositional orientation to the coastline have to be carefully considered. The latter feature concerns if the orientation of the sandstone units is along the depositional strike or perpendicular to it.

In lower portion of the Ullaberget section, the prograding deltaic Ullaberget Member forms a continuous, about 1.5 km long, sandstone dominated unit, containing no significant internal shale beds which could, totally or partly, prohibit fluid flow within the unit. Despite the abundant tidal bundles, this unit is considered to have generally good internal connectivity between sandstone beds, due to up to 20 m thick prograding clinoform stacking geometry along the depositional strike. Without post-depositional deformation and subsequent erosion in the west this sandstone unit would have been continuous further westward, although, changing its character into more proximal alluvial channel geometry. The stratigraphical position of the Ullaberget Member, lying directly on the marine Janusfjellet Subgroup shales, connects it directly with potentially good source rock which could produce type II kerogen, which in turn, with increased burial and temperature yields to oil. Despite the good reservoir properties of this sandstone unit, a good top seal is needed to fill the reservoir. This is not the case in the Ullaberget section. The overlying lacustrine mudstone deposits could, however, turn into sealing shales during burial and/or work as a source rock if TOC is high. A lot of terrestrial plant material deposited in lacustrine setting turn into humic, type III kerogen during burial, yielding usually CO_2-gas. It is unknown if the Ullaberget Member is laterally bounded by Janusfjellet Subgroup shales. This could be the case if the member was formed in a locally restricted shelf incision, forming a seaward prograding 3D sandstone body. The Ullaberget Member could therefore be compared to tidally influence incised valley reservoir sandstones that are well known to act as good reservoirs for hydrocarbons. Furthermore, one must bear in mind that the good lateral connectivity between sandstone beds might also lead to hydrocarbon migration out of the reservoir and possibly into the next sandstone unit, with or without the help of tectonic tilting, thus, leaving the first unit empty.

In the middle portion of the Helvetiafjellet Formation in the Ullaberget section, tidal flat sandstone bodies are laterally less continuous compared to the Ullaberget Member. These sandstone bodies show abundant shale contents in form of thin beds of shale draping the entire sandstone bodies. Such a shale drapes will significantly decrease connectivity between sandstone bodies. This leads to earlier mentioned series of completely or partly isolated sandstone bodies. The dimensions of individual sandstone beds in the middle portion of the Ullaberget section are relatively homogeneous within one depositional setting. Tidal-ridges are continuous units ranging 100 – 300 metres laterally and 0 – 8 m vertically. Tidal-flat sandstone bodies range from 10 m to about 30 m laterally and 10 cm up to 1 m vertically. Interlayering shale beds are laterally semicontinuous to discontinuous flasers or drapes ranging laterally from few meters to some tens of meters and from few cm up to 25 – 30 cm vertically. The orientation of these beds is hard to determine from the 2D cliff section, but first mentioned tidal ridges seem to occur parallel to the depositional strike.

Seal rocks

As in general, also in both of the above mentioned models, the quality of top seal has to be carefully considered. In the upper portion of the Ullaberget section, the Helvetiafjellet Formation is generally composed of shales, siltstones and very fine grained sandstones, therefore considered as poor top seal by Nøttvedt et al. (1992), also possibly allowing internal migration within the formation. It is obvious that this is an unwanted situation in petroleum exploration. If the seal, however, is good and solid enough to significantly slow-down or stop the hydrocarbon migration upwards, it should also be resistant for cracking during burial. The seal rock has to be solid enough to resist increased temperature and pressure caused by hydrocarbons below it and sediments above. If the seal is tight enough and connection between sandstone bodies is good, the hydrocarbons may leak laterally out or upwards, if the seal rock is cracking. Increased burial depth leads to cracking of the hydrocarbon chains and might therefore increase the leakage, because smaller hydrocarbon compounds, such as gas, leak easily through smaller cracks in the seal rock.

If the backstepping stratigraphic development, such as Gjelberg and Steel (1995) proposed in the Helvetiafjellet Formation, is considered, complications for hydrocarbon flow could be generated by the physically unconnected sandstone bodies. In these cases some or all of the shale beds deposited at the flooding surfaces during the backstepping development, may or may not act as seals for each individual sandstone body. Modelling of the connectivity of tidal sandstone bodies and fluid flow behaviour within these is depending on the choice of depositional model. Reservoir management strategies will be rather different according to which conceptual model is chosen for a reservoir sandstone unit formed by transgressive backstepping, such as the Helvetiafjellet Formation.

Summary

In general, marginal marine tidal sandstone dominated intervals like the Helvetiafjellet Formation in the Ullaberget section demand both excellent seismic and core data for construction of a reliable reservoir model. The continuously changing environments represented in the strata give rise to severely different reservoir properties as a result of lateral and vertical changes of facies and changes of the sandstone body geometries on the bed and bedset scale. Analogue studies, as the present study, of continental-to-marine sandstones in an epicontinental basin with ramp-type shelf setting, have potential for giving input parameters on modelling of this type of reservoirs. Directly analogous to tidal sandstones of the Helvetiafjellet Formation in the offshore Norway would be tidally influenced marginal marine sandstones of Tilje and Åre Formations, located on the Haltenbanken terrace in the offshore mid-Norway.

9

Discussion

High resolution facies analyses within the present study have given several new detailed informations about the environment in which the Helvetiafjellet Formation was deposited (Chapter 4). The majority of the sandstone facies indicates deposition of sand by tidal currents in varying extension. The heterolithic shale and mud facies indicate deposition from suspension by slack-water stages or by slowly moving water. Erosional facies boundaries and relatively thick shale units further indicate that shifts in the hydraulic energy levels occurred several times during the development of the Helvetiafjellet Formation in an environment varying from continental coastal plain to open-marine shelf.

The interpretation of the facies associations (Chapter 5) reveals how both deposition by fully marine conditions, coastal, and apparently fully continental conditions gave rise to interbedded sandstone and shale units in the Helvetiafjellet Formation in the Ullaberget section and further westward along the northern side of the Van Keulenfjorden. The fluvial deposits range from coastal plain sandstones to tidally influenced braided streams and point bars deposited by meandering rivers. Apparently, continental settings were repeatedly re-established during the development of the Helvetiafjellet Formation. The controlling factors were also different in different times and places. This is clearly seen in the variety of fluvial dominated deposits within the formation. The facies associations interpreted as marine reflect periods when the facies belts were repositioned landward. The way proximal and distal facies associations replace one another both vertically and laterally within the formation reflect highly dynamic depositional environment where sandstone and shale deposition was frequently shifting. Such frequent shifts reflect a fine balance of the ratio between the rate of accommodation space created and rate of sediment supply, termed as the A/S-ratio.

Interpretation regarding internal geometry of sandstone bodies in the Helvetiafjellet Formation depends on a choice of datum plane for chronostratigraphic correlation of the Ullaberget section over to adjacent cliff sections in the west and north (Chapter 6). Internally within the Ullaberget section, the chosen datum plane along the upper coal horizon in between the lower and the middle portions of the section gives good match between the internal sandstone geometries. The same horizon is also possibly correlative to the adjacent sections of the Louiseberget and the Annaberget in the west and maybe also to the overbank deposits above the Festningen Sandstone Member in the north, although the latter locality was suggested by Midtkandal (2002) to possibly correlate with the upper portion of the Helvetiafjellet Formation, at least in the Sassenfjorden area.

The subaerial unconformity at the base of the Ullaberget Member can not directly be correlated to the Louiseberget section, west of the Ullaberget section, because the base of the formation is not seen in this locality. However, the base of the formation in the Annaberget section, west of the Louiseberget section, is readily seen. Based on its lithofacies, it is considered to be time-equivalent with the base of the Ullaberget Member and termed as sequence boundary (SB). If this SB is time-correlative, i.e. diachronous, with the SB below the Festningen sandstone Member at Festingen locality the Festningen Sandstone Member should be of same age as the Ullaberget Member. But, after Gjelberg and Steel (1995) who suggested that the base of the Helvetiafjellet Formation rose diachronously to the northwest, the Ullaberget Member in the Ullaberget section could be actually older than the Festningen Sandstone Member at Festningen locality, although they have been deposited on a the same sequence boundary.

The middle portion of the Helvetiafjellet Formation is difficult to correlate with adjacent cliff sections due to rapid lateral changes in internal geometry of the tidal sandstone bodies and due to absence of major erosional surfaces. However, considering the middle portion of the formation in the Ullaberget section as one thick tidal sandstone unit, it is possible to recognize the landward (westward) shift from sandstone dominated low-intertidal zone facies in the Ullaberget section, to the Louiseberget section, where amount of mud deposited compared to sand deposited has increased. This increase resulted probably from deposition in high-intertidal and supratidal zones. Further in the west, in the Annaberget section, this now thinner and muddier tidal sandstone unit of the Louiseberget section changes into fully supratidal flat environment incised by laterally migrating meandering tidal channels and creeks. As follows, deposition of the middle portion of the Helvetiafjellet Formation in the Ullaberget section can be diachronous with the deposition in the adjacent sections.

The upper portion of the Helvetiafjellet Formation is very complex in its architectural organization, since most of the marine flooding surfaces have not extended over the whole coastal and alluvial plain. In the upper portion of the Helvetiafjellet Formation in the Ullaberget section, 10 major marine flooding surfaces associated with *Diplocraterion* trace fossils have been registered, whereas only three is registered in the upper Louiseberget section. Three marine flooding surfaces have also been registered in the Annaberget section, which are likely to correlate with the ones in the Louiseberget section. This would strengthen the idea of the three cliff sections being deposited simultaneously in a laterally extensive and very low angle coastal plain setting. Seen as one, each way of correlating the Ullaberget section has potential for significant consequences for prediction of the sandstone body geometry and distribution, within the rest of the Helvetiafjellet Formation.

Another problem is concerned with the choice of the lower and upper boundaries of the Helvetiafjellet Formation. Because the Ullaberget Member genetically belongs to the same depositional sequence as the rest of the Helvetiafjellet Formation in the Ullaberget section, it is in this study included in the Helvetiafjellet Formation, in the contrary to Dallmann (1999) who included it in the top of the underlying Rurikfjellet Formation in the upper Janusfjellet Subgroup. The Ullaberget Member is in this study separated from the Rurikfjellet Formation by the type 1 sequence boundary. The upper boundary is put on the top of the last transitional sandstone unit and below the first fully marine shale unit. This decision is made due to the same principle as adapted with the lower boundary. The transitional upper portion of the Ullaberget section covers the backstepping stage of the upper portion of the Helvetiafjellet Formation. This is the last stage of the depositional sequence of the Helvetiafjellet Formation and should therefore be included in the formation.

The final problem was the source for sand during the flooding events, where *Diplocraterion* trace fossils occur. These sandstones are likely to have been deposited on the near-shore coastal plain by extensive storm events. This interpretation is based on the internal geometry of the parasequences in the upper portion of the Ullaberget section.

These parasequences show an upward coarsening trend from previous flooding surface to next one, indicating local regressive events between the flooding events. The continental deposits interbedded with marginal marine deposits were accumulated when fluvial distributary channels changed their depositional locus due to rise of relative sea-level and therefore could migrate over time-equivalent embayment deposits. However, this kind of lateral change of depositional locus can not explain simultaneous sand deposition over a wide area. Therefore, deposition of extensive sand sheets in the transitional upper portion of the Helvetiafjellet Formation in the Ullaberget section was likely to being caused by significant storm events, which probably re-deposited sand derived from coast parallel currents on the low gradient coastal plain. While exposed, the uppermost parts of transgressive sandstone sheets could be totally or partly reworked by the *Diplocraterion* trace fossils indicating prior to significant marine flooding event, which closed the suitable “colonization window”.

10

Conclusion

The assemblage of facies and facies associations documented in this thesis from the Helvetiafjellet Formation in the Ullaberget section are interpreted to represent fluvial and marginal marine deposits with significant tidal influence, deposited during the lowstand prograding wedge systems tract and early transgressive systems tract in Barremian - Aptian age.

Tectonic tilting prior to deposition in late Hauterivian / early-Barremian led to an exposure of large shelfal strata known today as the Rurikfjellet Formation in the upper Janusfjellet Subgroup. The emergence of the shelf, accompanied with relative sea-level fall, caused regional erosion and significant basinward shift in facies belts. Re-establishing of the fluvial stream profiles at the surface of the shelfal shales caused subaerial erosion along the entire width of the area where the Helvetiafjellet Formation is exposed today. Thus, erosion by rivers was not concentrated along an axis to form a single incised valley, into which the whole Helvetiafjellet Formation could be deposited, but led instead to local incisions into shelfal substrata with moderate erosional relief.

During the subsequent initial stage of relative sea-level rise, the Ullaberget Member sandstone unit was deposited in a local incision and directly on the Janusfjellet Subgroup shales along a surface of subaerial unconformity. This surface is a type 1 sequence boundary (SB) and marks the boundary between the Janusfjellet Subgroup and the overlying Helvetiafjellet Formation. As follows, the Ullaberget Member is in this study included in the Helvetiafjellet Formation because it has been deposited within the same depositional sequence as rest of the formation. Deposition of the Ullaberget Member is considered as diachronous with the deposition of the fluvial basal portion of the Louiseberget and Annaberget sections in the west (Figure 10-1a). The knickpoint marking the change from sediment bypass to sediment deposition have been between the Ullaberget and the Louiseberget sections. Following deposition of the terrestrial mudstones and fluvial sandstones directly overlying the Ullaberget Member resulted from continuous basinward shift in facies belts during the lowstand prograding wedge systems tract. The coal beds directly overlying fluvial sandstones marks the most proximal position of the facies belts of the Helvetiafjellet Formation in the Ullaberget section. This is the surface of maximum regression (MRS) and coincide with the tidal ravinement surface (TRS) marked by directly overlying tidal deposits. This lower portion of the Helvetiafjellet Formation is interpreted as a progradational parasequence set (Figure 10-1b). Succeeding aggradational parasequence set, the middle portion of the Helvetiafjellet Formation, is composed of tidally influenced sandstones deposited during the initial stage of transgressive systems tract (Figure 10-1c). The following retrogradational parasequence set, the transitional upper portion of the Helvetiafjellet Formation, includes interbedded continental and marginal/fully marine deposits formed by changes in A/S-ratio, which in turn was caused by increase in rate of relative sea-level rise (Figure 10-1d). The general transgressive trend was interrupted by higher order sea-level fluctuations. The formation boundary between the Carolinefjellet Formation and the underlying Helvetiafjellet Formation in the Ullaberget section is put at the uppermost marine flooding surface, above which there is no more continental deposits interbedded with marginal marine deposits (Figure 10-1d).

The mechanisms leading to the depositional stacking patterns observed in the Helvetiafjellet Formation in the Ullaberget section ranged from autocyclic processes, such as channel wall failures and avulsion events, to allocyclic processes controlled by the tectonic activity and relative sea-level changes in the area.

The Helvetiafjellet Formation is generally considered as a good analogue unit for reservoir sandstone bodies formed in the paralic setting, i.e. deposited between continental and marine environment, on low gradient shelf ramps and bounded by two open-marine shale formations, such as the lower Jurassic Åre and Tilje Formations. This study shows that the highly various internal stacking patterns of tidally influenced sandstone bodies, similar to the ones recorded from the Helvetiafjellet Formation in the Ullaberget section, seriously affect the prospectivity evaluation of such reservoir sandstone. Thus, various reservoir models should be considered equally when determining reservoir properties and their possible hydrocarbon contents.

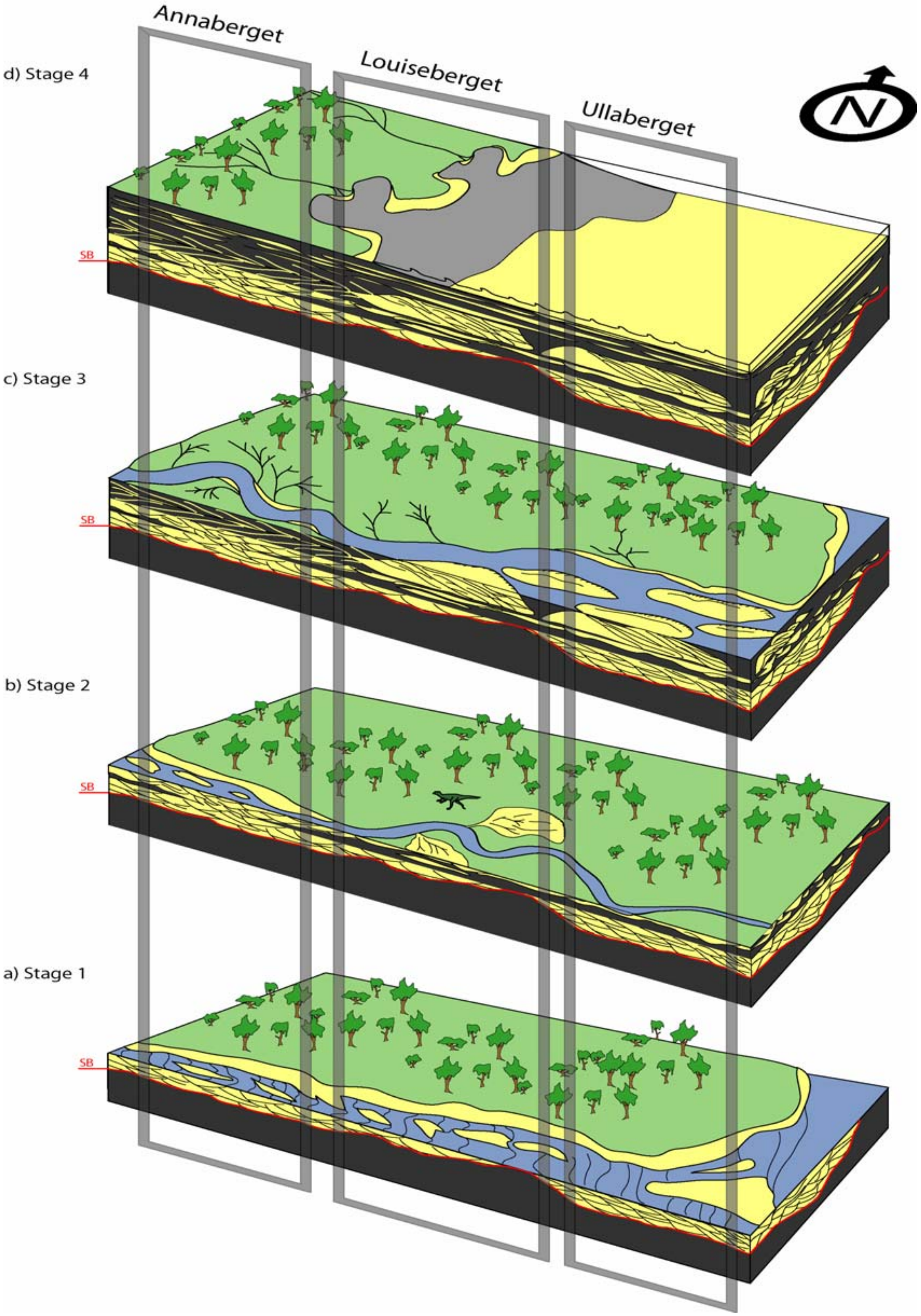

Figure 10-1: Paleoenvironment reconstruction of The Helvetiafjellet Formation in the Ullaberget section, southern Spitsbergen. See text for explanation (Modified from Midtkandal 2004, personal communication).

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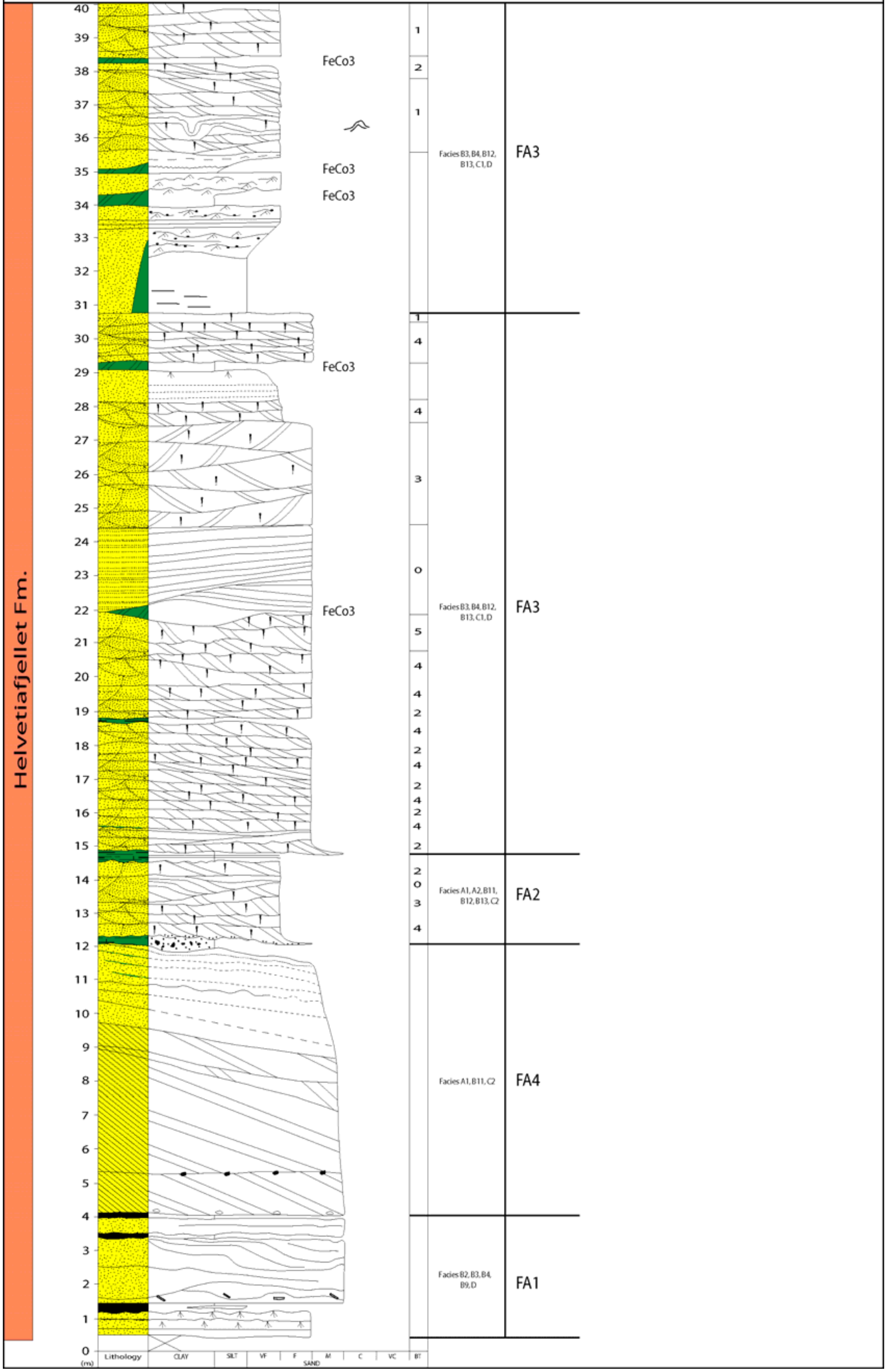
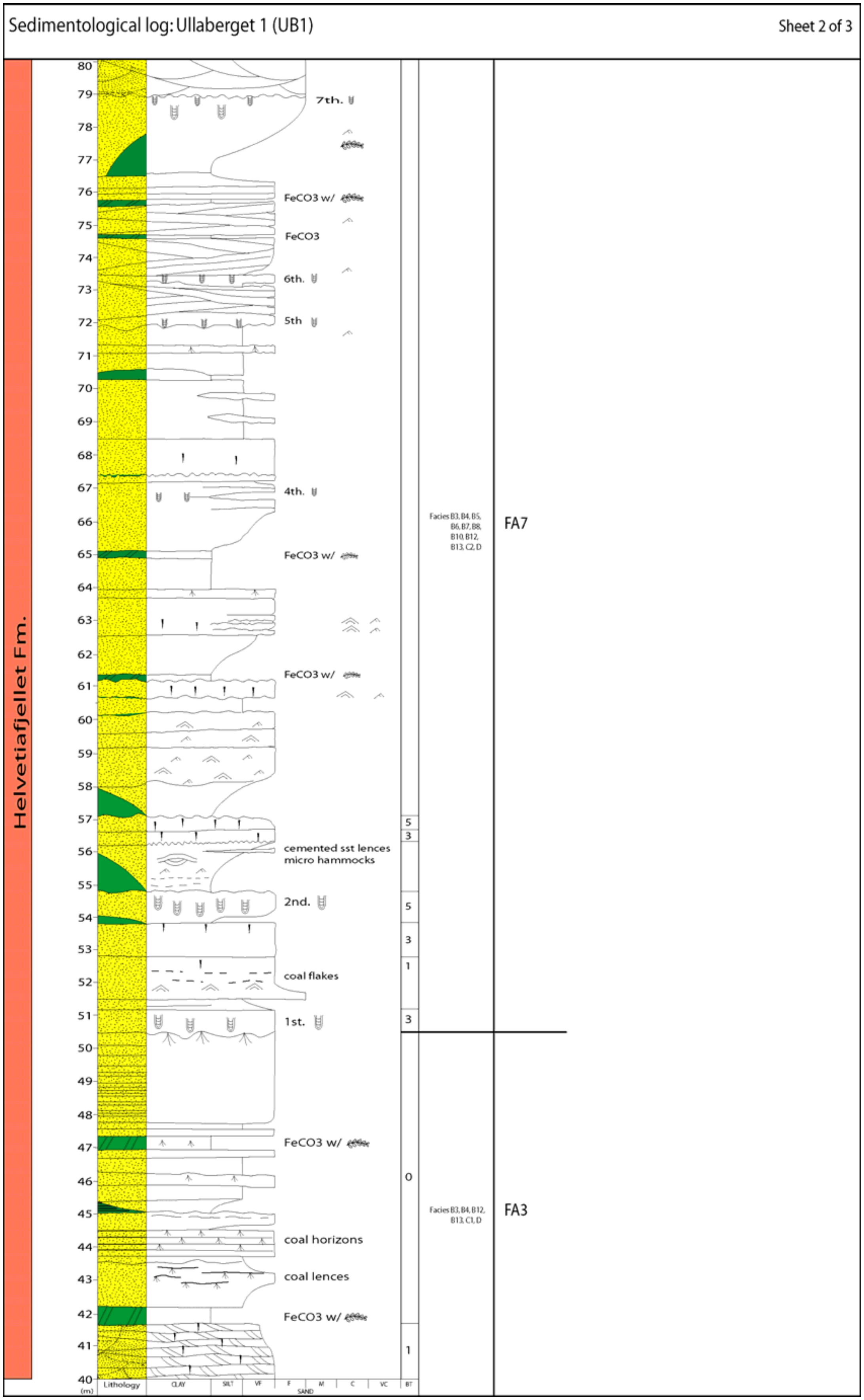
Appendix A

Appendix A represents sedimentary logs made in the Ullaberget section during field seasons 2002 and 2003. Logs UB1 to UB4, UB6 and UB 8 are drawn by the author. Logs UB5, UB7, UB9, and UB10 are drawn by I. Midtkandal and modified by the author.

Sedimentological log: Ullaberget 1 (UB1)

Sheet 1 of 3




Sedimentological log: Ullaberget 1 (UB1)
Sheet 2 of 3
Helvetiafjellet Fm.
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40
(m)
Lithology
CLAY
SILT
VF
F
M
C
VC
SAND
BT
7th.
FeCO3 w/
FeCO3
6th.
5th
4th.
FeCO3 w/
FeCO3 w/
cemented sst lences
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coal flakes
1st.
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coal horizons
coal lences
FeCO3 w/
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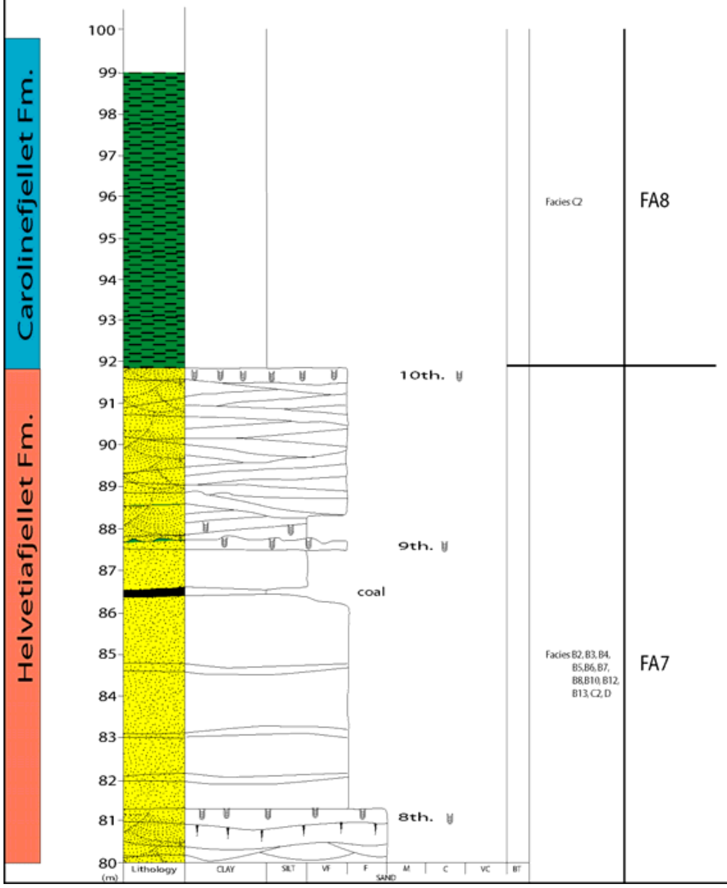
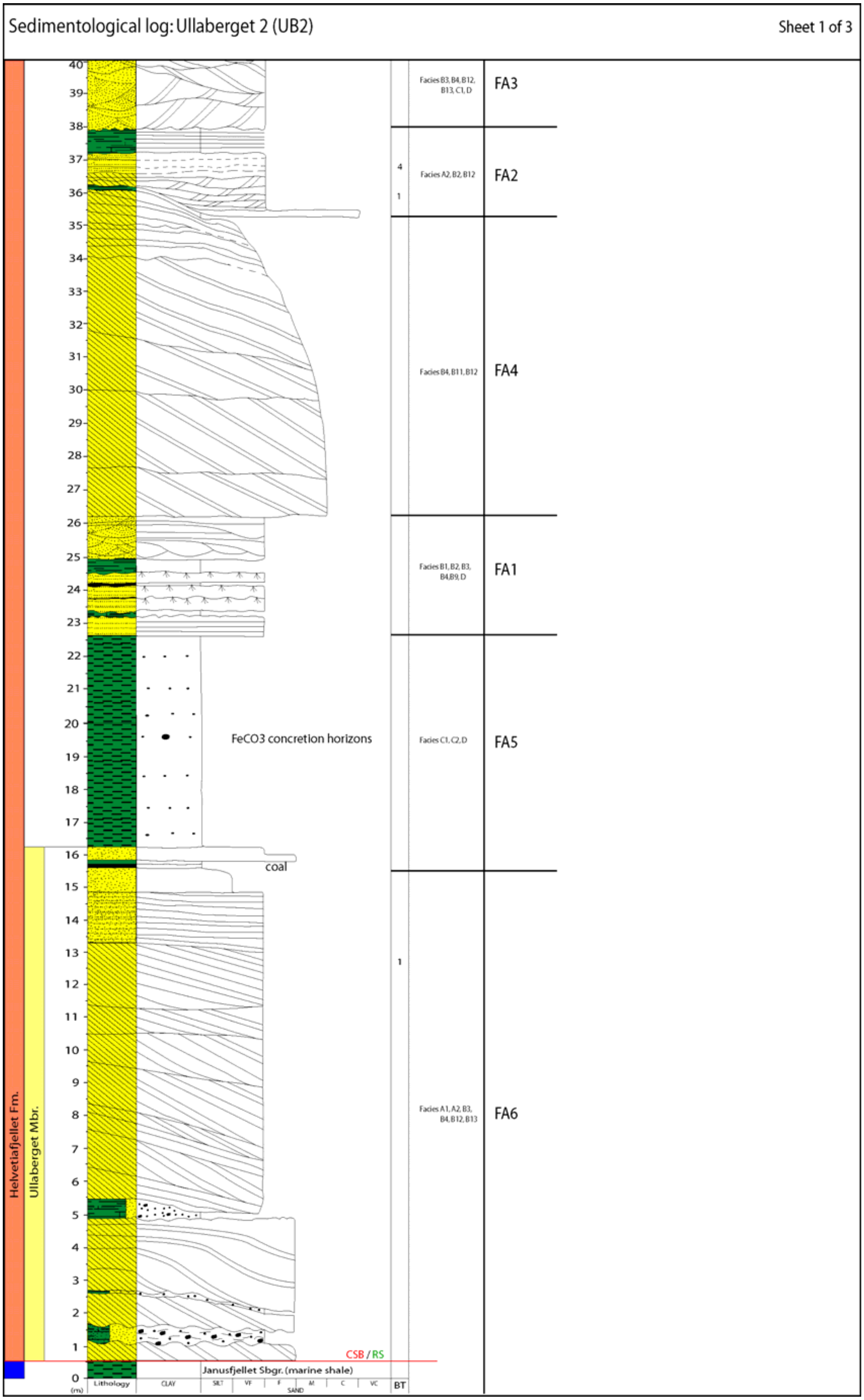
Facies B3, B4, B5, B6, B7, B8, B10, B12, B13, C2, D
FA7
Facies B3, B4, B12, B13, C1, D
FA3

Sedimentological log: Ullaberget 1 (UB1)

Sheet 3 of 3




Sedimentological log: Ullaberget 2 (UB2)
Sheet 1 of 3
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(m)
Helvetiafjellet Fm.
Ullaberget Mbr.
FeCO3 concretion horizons
coal
CSB / RS
Janusfjellet Sbgr. (marine shale)
Lithology
CLAY
SILT
VF
F
M
C
VC
SAND
BT
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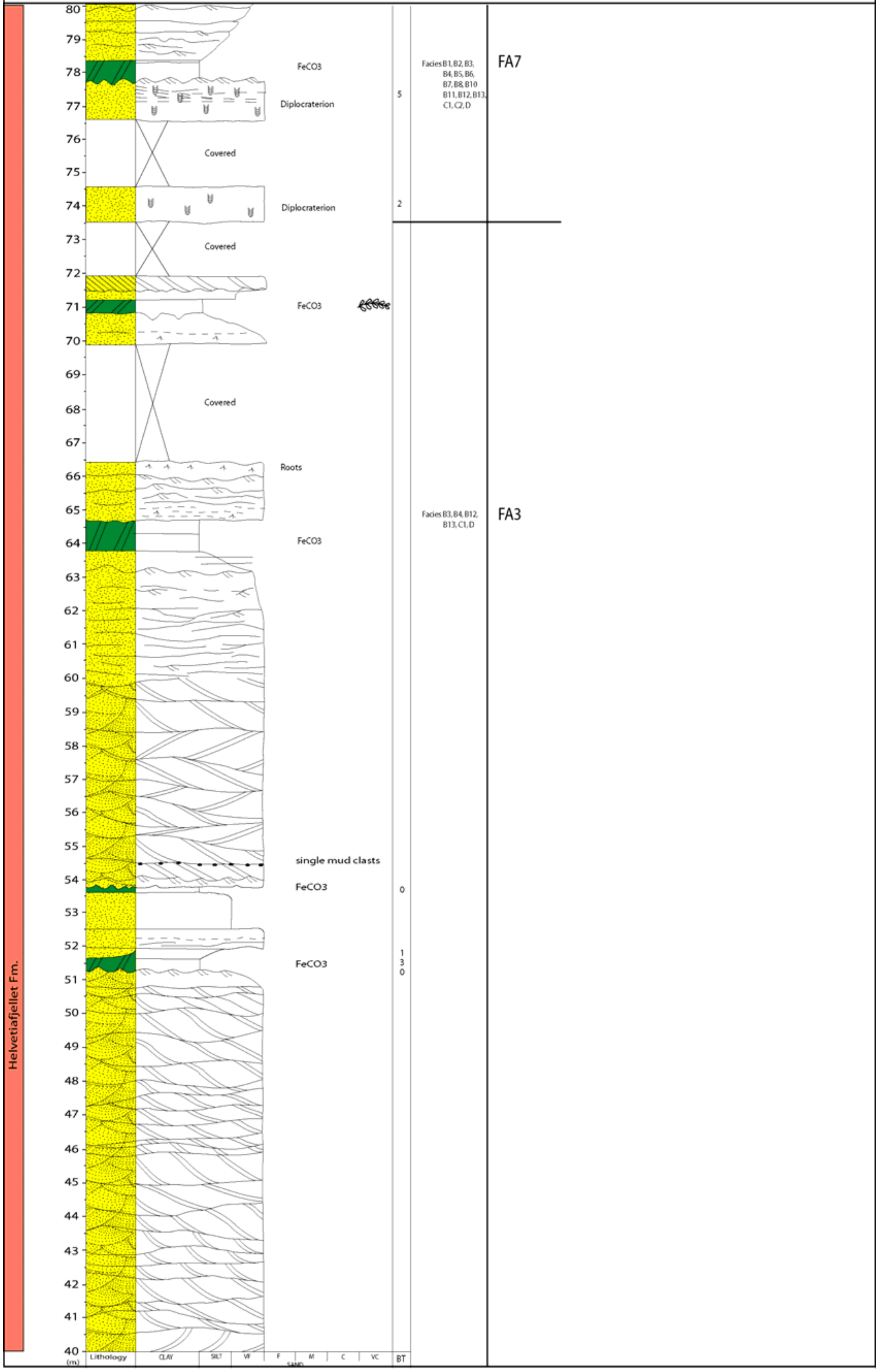
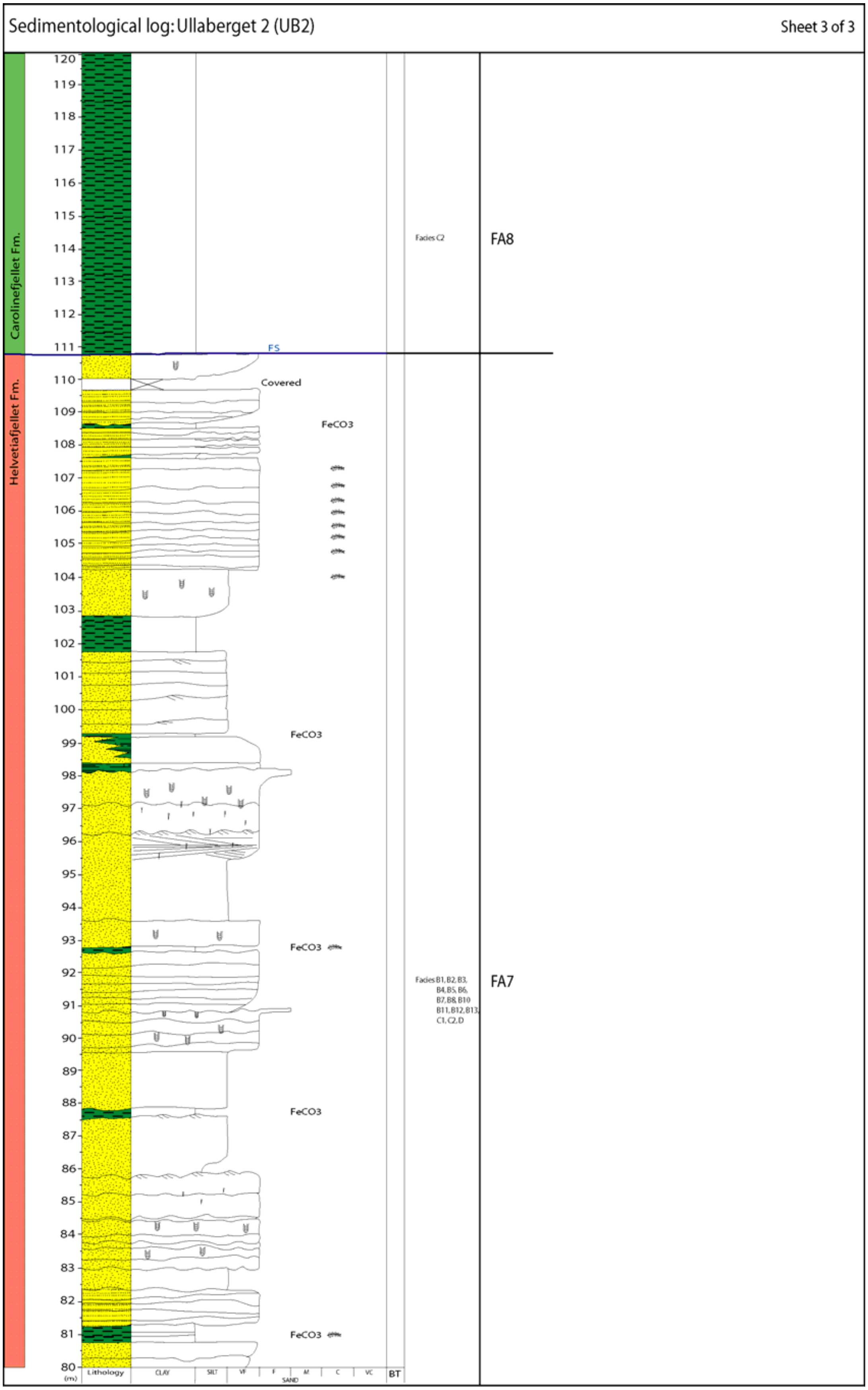
Facies B3, B4, B12, B13, C1, D
FA3
Facies A2, B2, B12
FA2
Facies B4, B11, B12
FA4
Facies B1, B2, B3, B4,B9, D
FA1
Facies C1, C2, D
FA5
Facies A1, A2, B3, B4, B12, B13
FA6

Sedimentological log: Ullaberget 2 (UB2)

Sheet 2 of 3

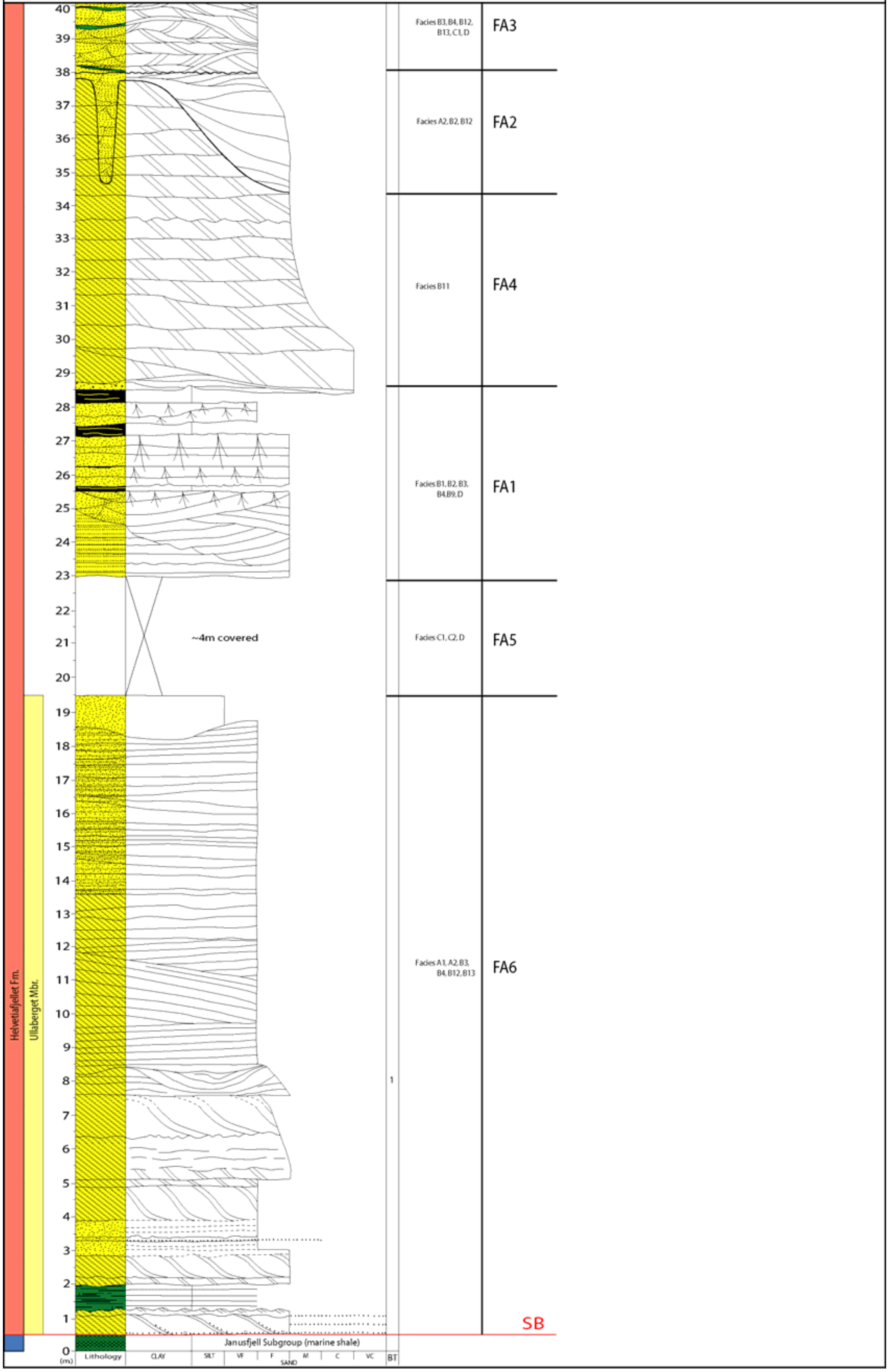


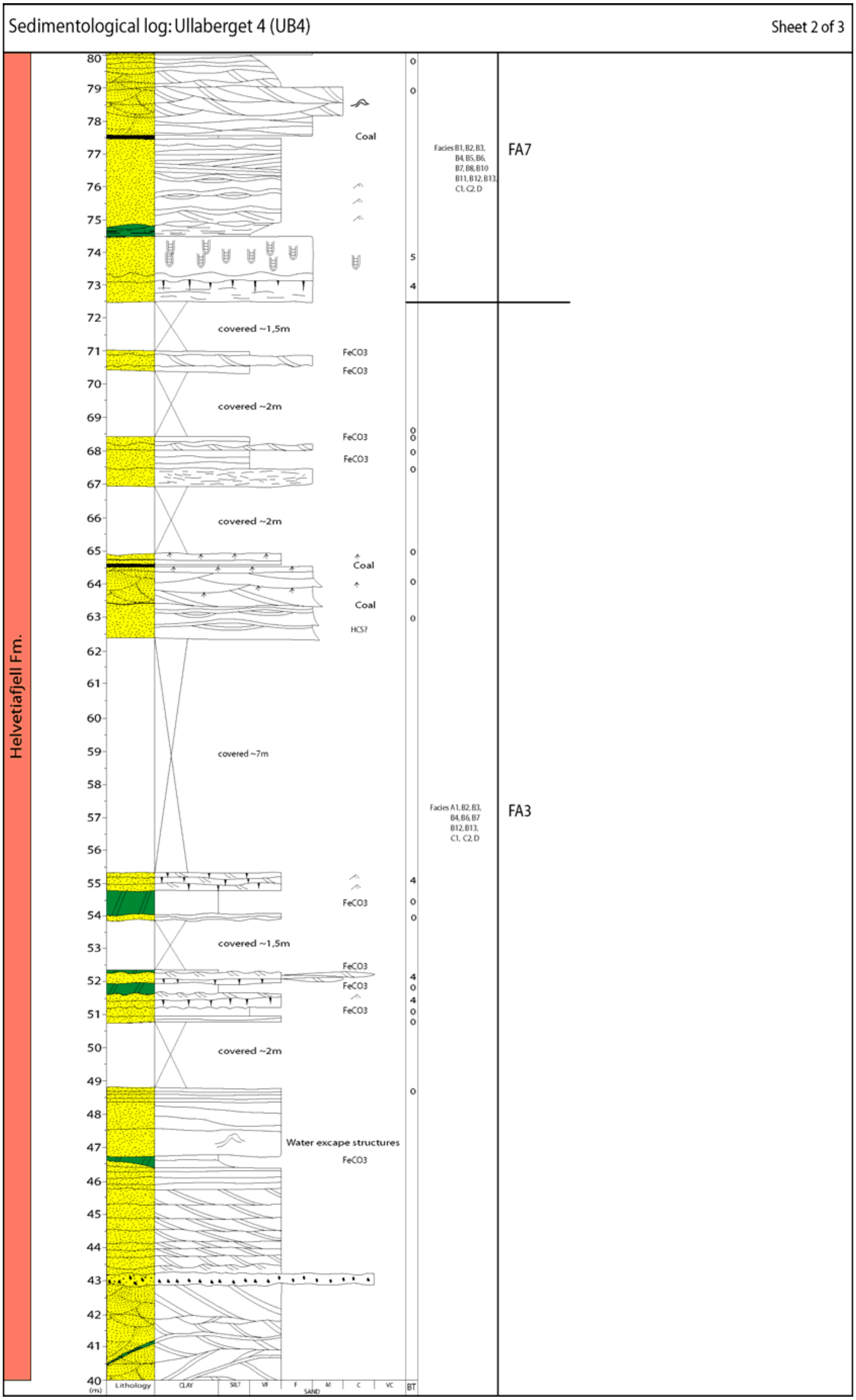


Sedimentological log: Ullaberget 2 (UB2)

Sheet 3 of 3

Sedimentological log: Ullaberget 3 and 4 interpolated (UB3 /UB4) Sheet 1 of 3




Sedimentological log: Ullaberget 4 (UB4)
Sheet 2 of 3
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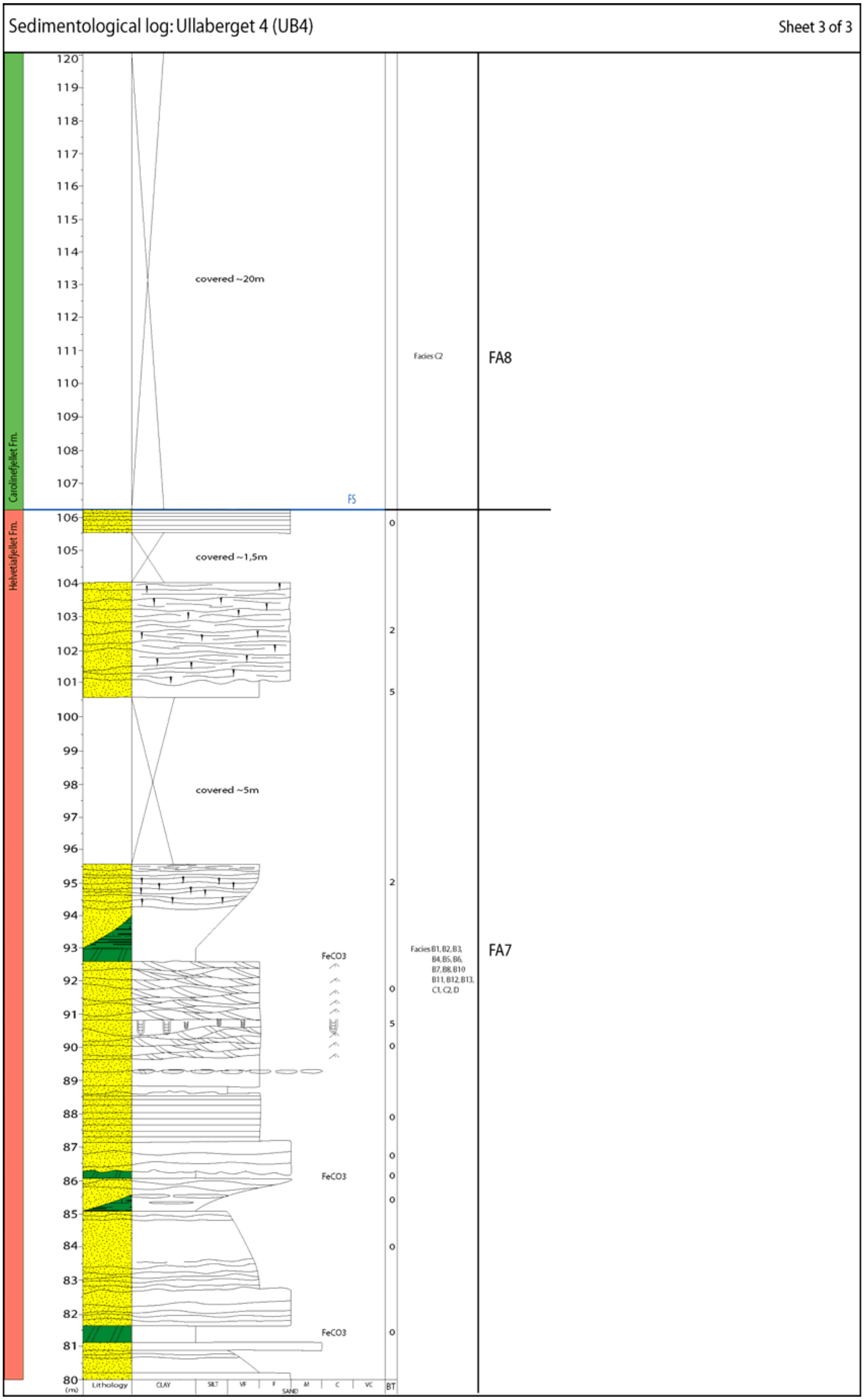
(m)
Lithology
CLAY
SILT
VF
F
M
C
VC
SAND
BT
Coal
covered ~1,5m
FeCO3
FeCO3
covered ~2m
FeCO3
FeCO3
covered ~2m
Coal
Coal
HCS?
covered ~7m
FeCO3
covered ~1,5m
FeCO3
FeCO3
FeCO3
covered ~2m
Water excape structures
FeCO3
Facies B1, B2, B3, B4, B5, B6, B7, B8, B10 B11, B12, B13, C1, C2, D
FA7
Facies A1, B2, B3, B4, B6, B7 B12, B13, C1, C2, D
FA3


Sedimentological log: Ullaberget 4 (UB4)
Sheet 3 of 3
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(m)
Carolinefjellet Fm.
Helvetiafjellet Fm.
covered ~20m
Facies C2
FA8
FS
covered ~1,5m
covered ~5m
FeCO3
FeCO3
FeCO3
Facies B1, B2, B3, B4, B5, B6, B7, B8, B10 B11, B12, B13, C1, C2, D
FA7
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Lithology
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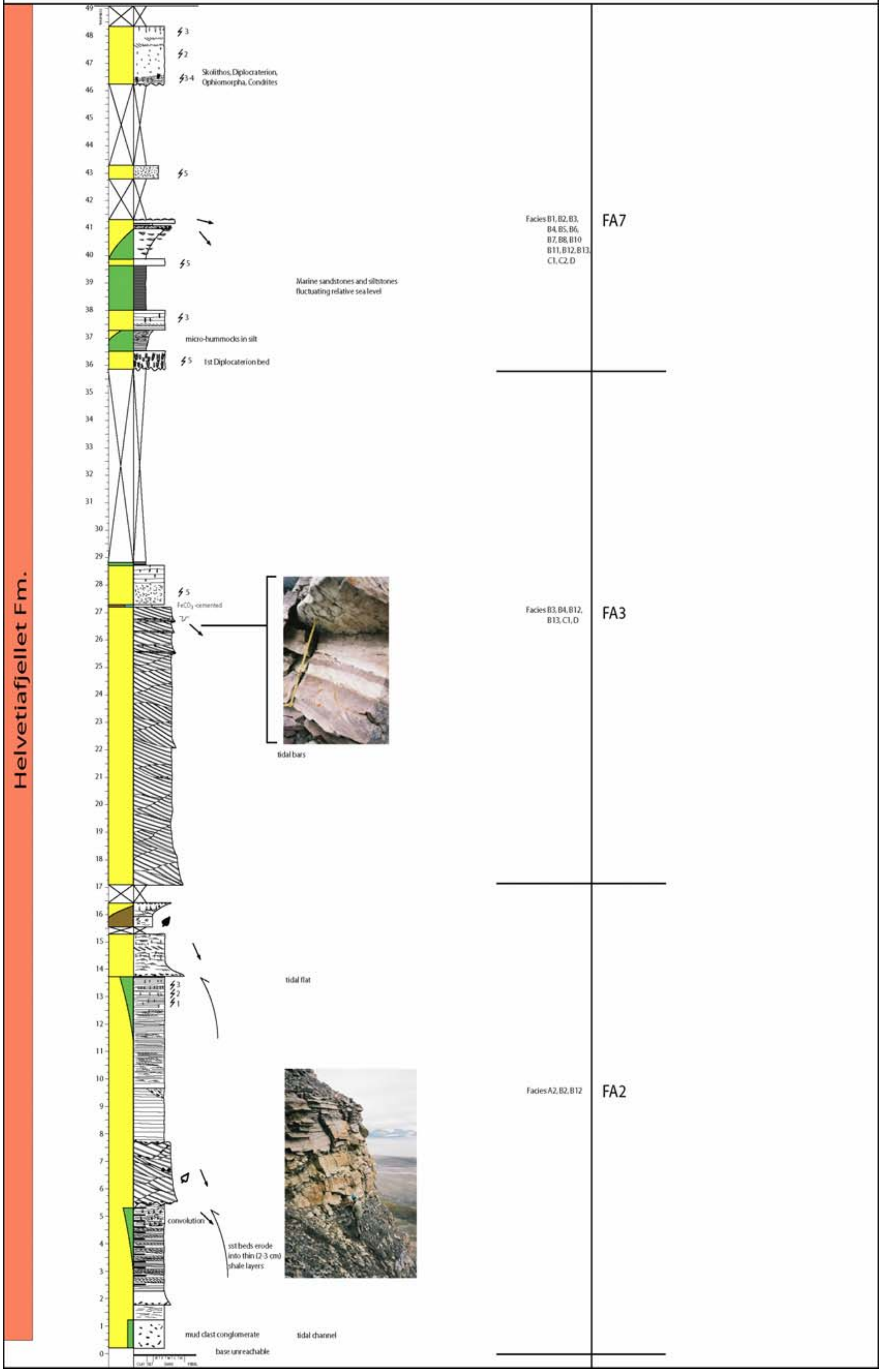
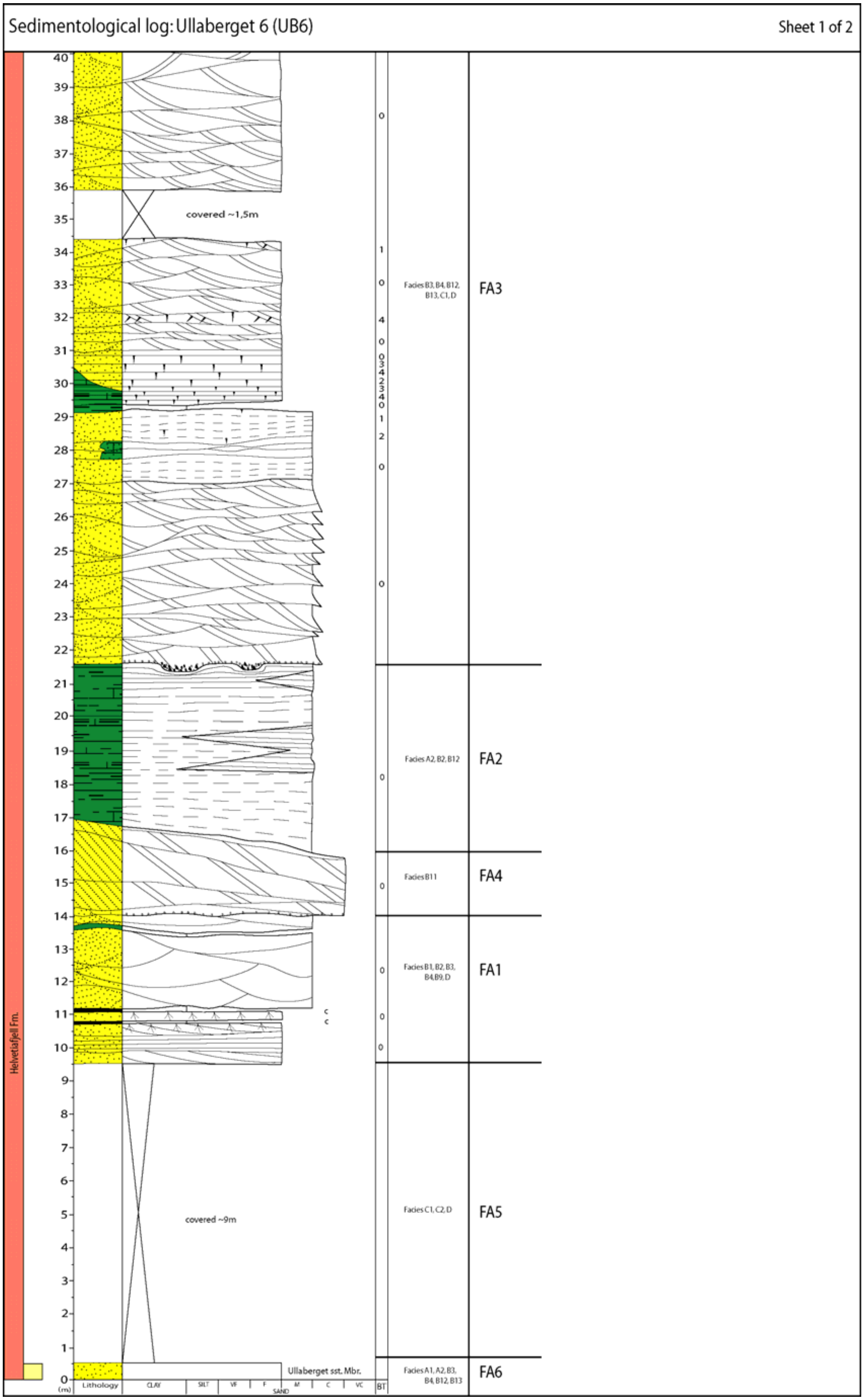
SAND
BT

Sedimentological log: Ullaberget 5 (UB5)

Sheet 1 of 1




Sedimentological log: Ullaberget 6 (UB6)
Sheet 1 of 2
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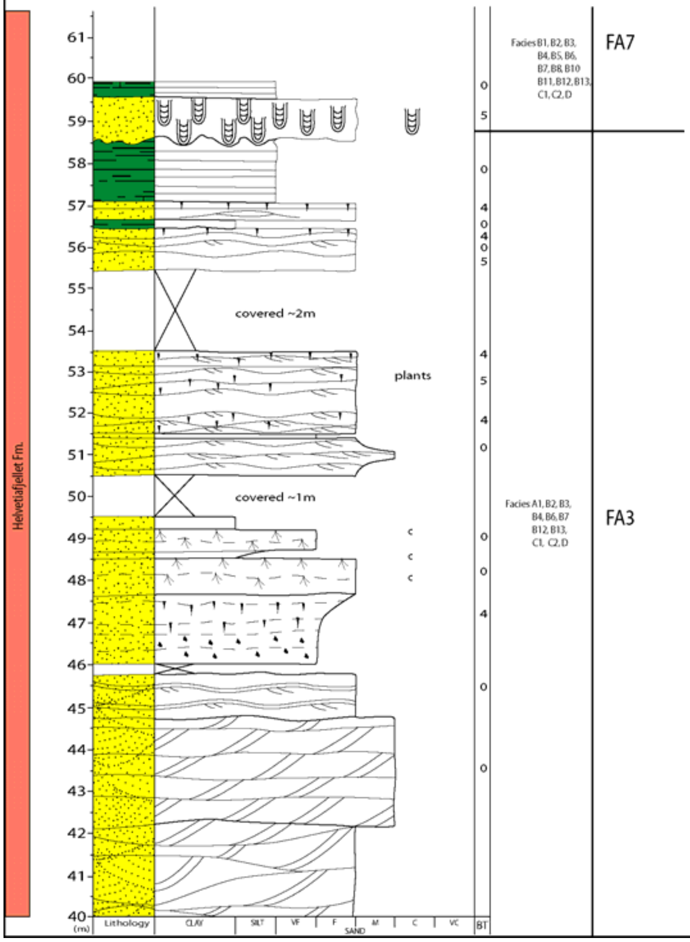
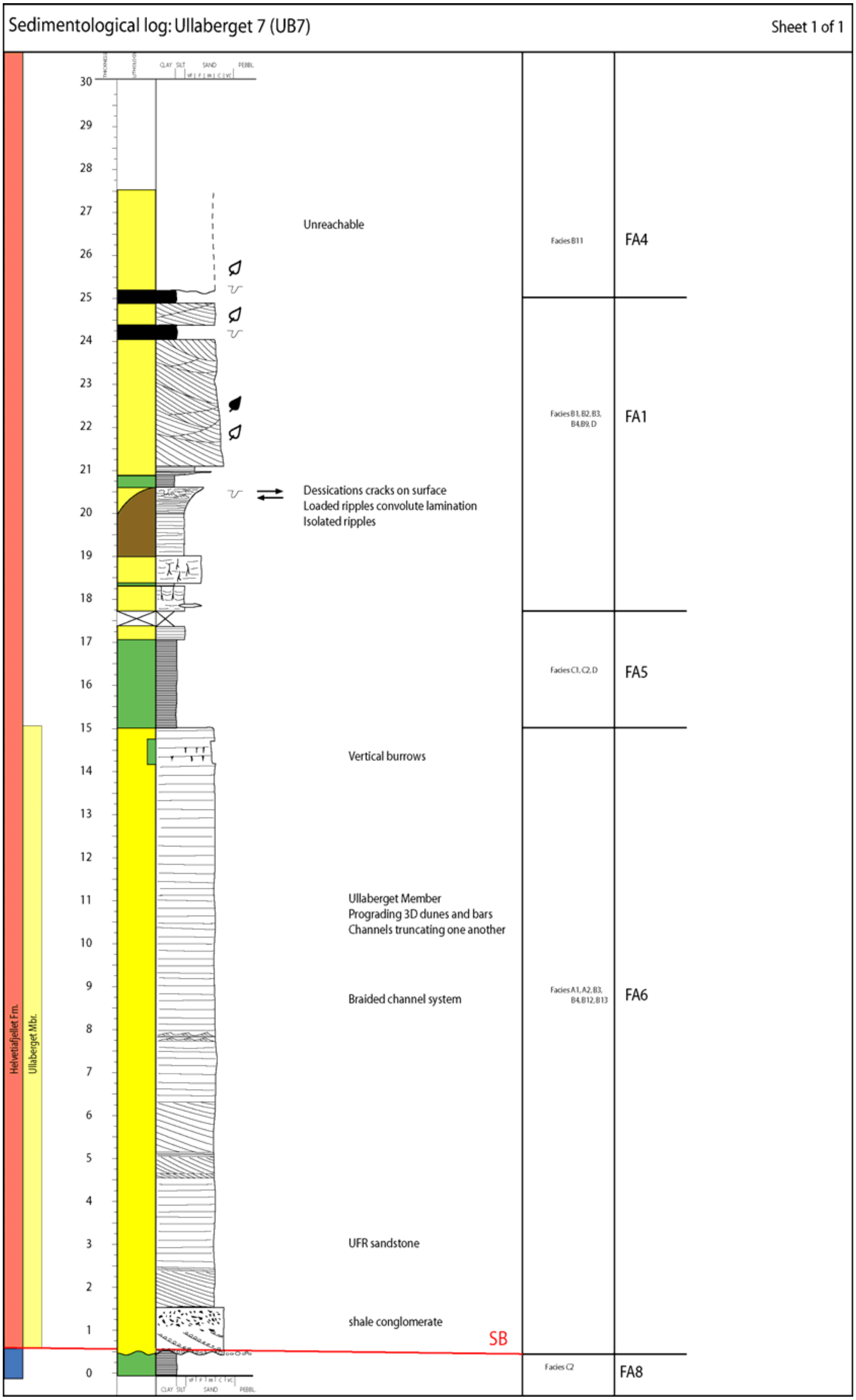
5
4
3
2
1
0
(m)
covered ~1,5m
covered ~9m
c
c
0
1
0
4
0
0
3
4
2
3
4
0
1
2
0
0
0
0
0
0
0
Facies B3, B4, B12, B13, C1, D
FA3
Facies A2, B2, B12
FA2
Facies B11
FA4
Facies B1, B2, B3, B4, B9, D
FA1
Facies C1, C2, D
FA5
Facies A1, A2, B3, B4, B12, B13
FA6
Helvetiafjell Fm.
Ullaberget sst. Mbr.
Lithology
CLAY
SILT
VF
F
M
C
VC
SAND
BT

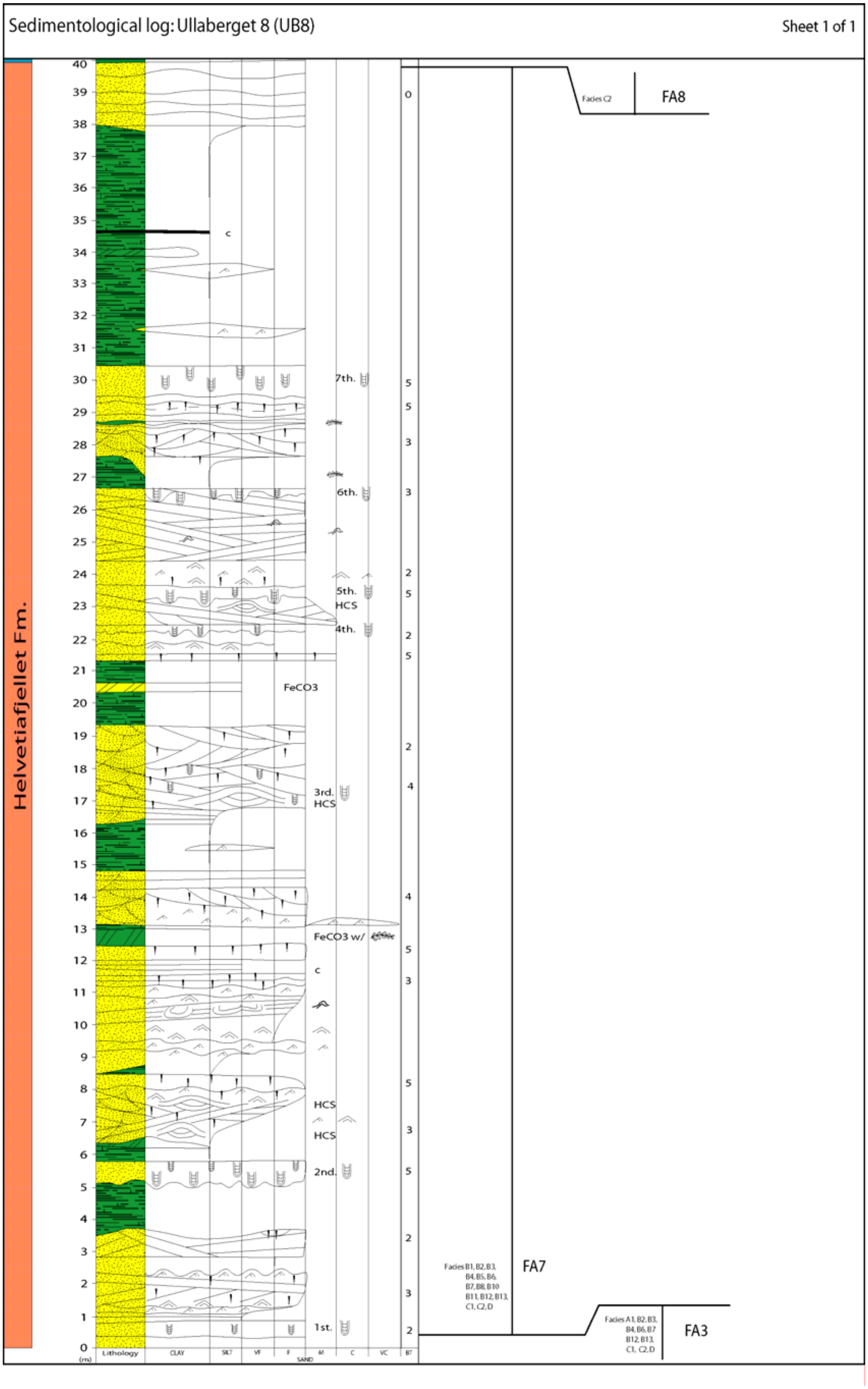
Sedimentological log: Ullaberget 6 (UB6)

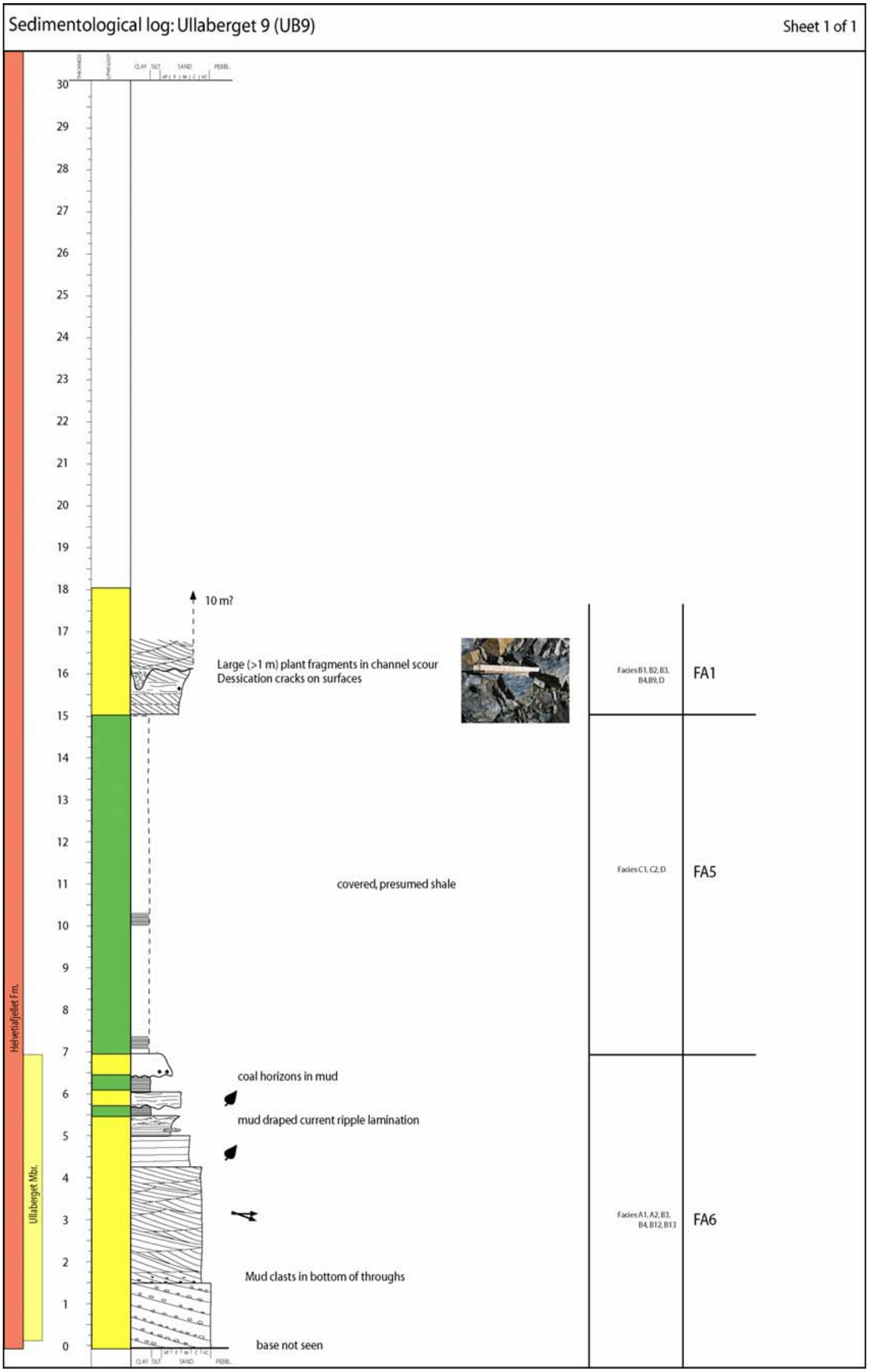
Sheet 2 of 2

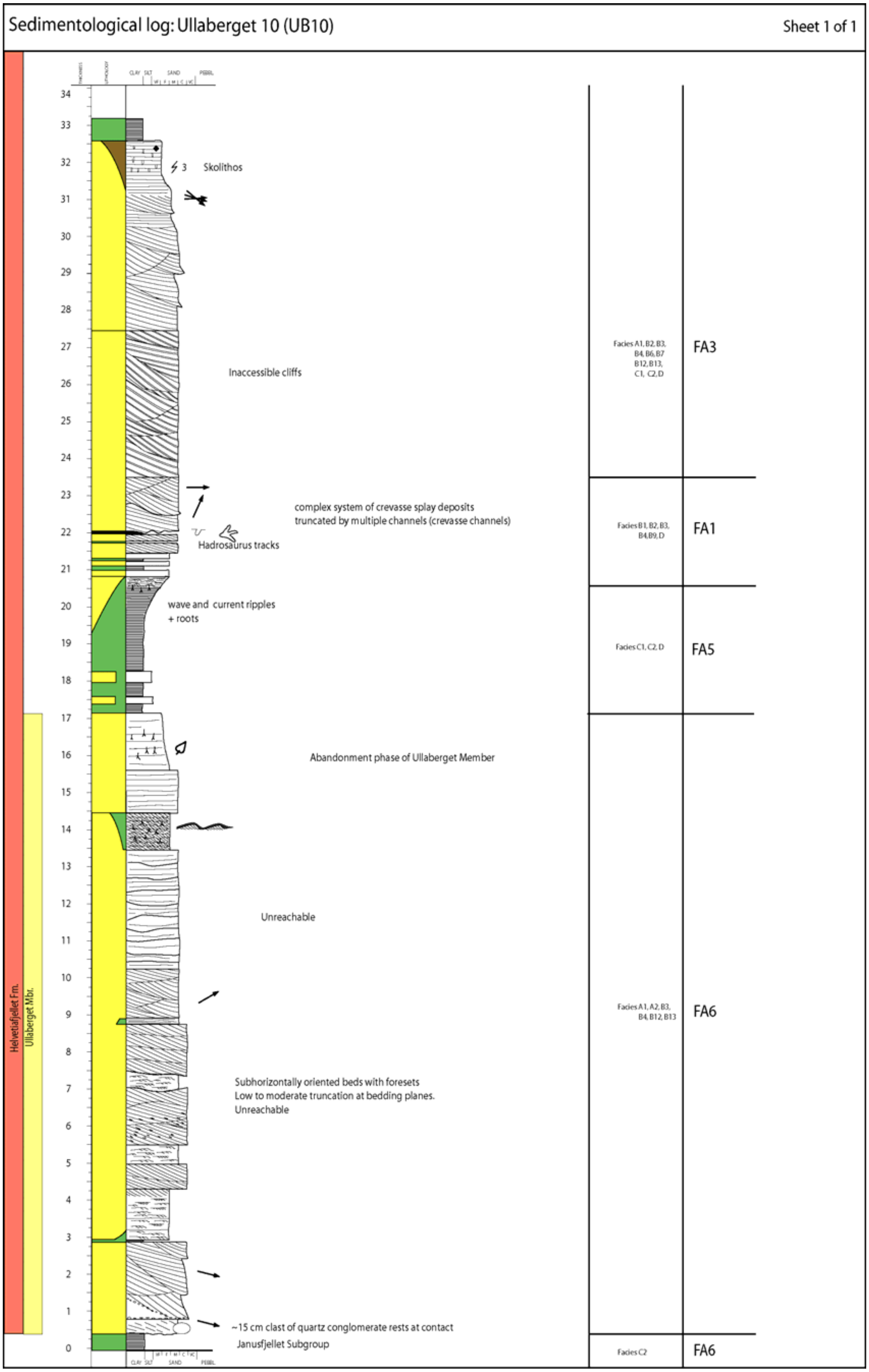



Sedimentological log: Ullaberget 7 (UB7)

Sheet 1 of 1


Sedimentological log: Ullaberget 8 (UB8)
Sheet 1 of 1
Helvetiafjellet Fm.
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
(m)
Lithology
CLAY
SILT
VF
F
M
C
VC
SAND
BT
c
7th.
6th.
5th.
HCS
4th.
FeCO3
3rd.
HCS
FeCO3 w/
c
HCS
HCS
2nd.
1st.
0
5
5
3
3
2
5
2
5
2
4
4
5
3
5
3
5
2
3
2
Facies C2
FA8
Facies B1, B2, B3, B4, B5, B6, B7, B8, B10 B11, B12, B13, C1, C2, D
FA7
Facies A1, B2, B3, B4, B6, B7 B12, B13, C1, C2, D
FA3


Sedimentological log: Ullaberget 9 (UB9)
Sheet 1 of 1
THICKNESS
LITHOLOGY
CLAY
SILT
SAND
PEBBL.
vf
f
m
c
vc
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
10 m?
Large (>1 m) plant fragments in channel scour
Dessication cracks on surfaces
covered, presumed shale
coal horizons in mud
mud draped current ripple lamination
Mud clasts in bottom of throughs
base not seen
Facies B1, B2, B3, B4, B9, D
FA1
Facies C1, C2, D
FA5
Facies A1, A2, B3, B4, B12, B13
FA6
Helvetiafjellet Fm.
Ullaberget Mbr.



Sedimentological log: Ullaberget 10 (UB10)

Sheet 1 of 1

Errata

Please observe some misprints and omissions of text used in this thesis. The correct texts are given below: