A COMPARATIVE STUDY OF BRAIDPLAIN DEPOSITS: SKAGERRAK FORMATION AT THE IVAR AASEN FIELD (Triassic) AND THE HORNELEN BASIN (Devonian) IN VESTLAND COUNTY

Master in Geodynamics and Basin Studies

Nora Fredheim

Department of Earth Science

University of Bergen

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Abstract

Braid plain deposits consist of large fractions of sandstone, with little to no mudstone and tend to be important reservoirs for hydrocarbons because of the high net-to-gross and low heterogeneity properties. The Triassic Braid Plain stratigraphical interval in the Skagerrak Formation, Ivar Aasen Field, located in the northern North Sea, contains deposits from fluvial braid plain systems. A more complex study of these deposits is conducted in this thesis. From the Devonian Hornelen Basin on the west coast of Norway, an outcrop analogue is described and studied to extract more information on ancient braid plain systems located offshore. Braid plain systems in the northern North Sea are understudied and this thesis contributes new insights into the Braid Plain stratigraphical interval.

This thesis compares an exposed onshore braid plain system to create a more extensive understanding of the Braid Plain stratigraphical interval in the North Sea. This study has found the Hornelen Basin to be a considerable analogue because it displays similar facies associations and architectural properties deposited in similar climatic conditions. Fieldwork was done in the Hornelen Basin, focusing on a well-exposed 150x100m outcrop. Virtual modeling of the outcrop was constructed. Data acquisition from the Braid Plain stratigraphical interval was conducted by sedimentological logging of two cores, drilled from the Ivar Aasen Field, provided by Aker BP. Facies associations and geometries of the two areas were identified and understood through interpretation of logs and virtual outcrops.

Results from studying the axial Devonian Hornelen Basin display a braided river system, with sandy fluvial channel deposits and thin lateral extending mudstone layers deposited in an arid climate with ephemeral streams and infrequent occasions of flooding. The Triassic Braid Plain system in the Ivar Aasen Field has not been described in earlier published work. Comparisons from the Devonian analogue shows that Braid Plain can be a high quality hydrocarbon reservoir and the lateral extension of the mudstone layers can contribute to reducing the possibilities of water coning and preserve integrity of the water front during hydrocarbon production.

Acknowledgements

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1.0 Introduction

1.1 Rationale

Modern braid plain deposits are deposits from multiple rivers that are active at the same time which creates a large area that displays multiple sand-rich channels, with a relatively small floodplain. At The Ivar Aasen Field there is an informal member in the Skagerrak Formation, called Braid Plain (Aker BP, unpublished). Large amounts of sand deposits, with sedimentary structures indicating unidirectional flow, deposited in a dry environment with channel flooding and a sparse amount of floodplain deposits. Following these observations, the interpretation that Aker BP has concluded that this system is a sand dominated fluvial system containing braid plain deposits (Aker BP, unpublished).

Fluvial deposits that contain large amounts of sand can stem from two different scenarios (Boggs, 2014). Sand dominated deposits can either stem from a braid plain fluvial system, or from a system with one or few active channels where the migration of channels has been higher than the rate of the basin subsidence. Aker BP has characterized the sandy deposits as braid plain deposits, but it is still difficult to determine if they are braid plain or a result from a low rate basin subsidence. This thesis will therefore study sand dominated fluvial deposits to further understand reservoir characteristics.

Sand dominated fluvial deposits are important to understand when studying hydrocarbon reservoirs, water migration and Co2 storage (Bridge, 2006). A study of braid plain systems in general is important to create a deeper understanding of how a potential reservoir of hydrocarbons would operate. The fluvial systems in the Triassic interval in the North sea, display a channel architecture that can be potential fluvial reservoirs.

Limited research has been done on the studies of braid plain systems in the subsurface and which kind of lateral and chemical heterogeneities that can be found in these systems. Depositional facies, models and outcrop analogues can help in the prediction of mapping subsurface deposits in areas where data like cores, seismic and well logs is limited (Bridge, 2006). This thesis focuses on finding an outcrop analogue to better understand processes that have been responsible for creating the facies associations and deposits that are observed in the Braid Plain stratigraphic interval in the Ivar Aasen Field.

Weissmann et al, 2015, uses a database of over 700 modern sedimentary basins to study their potential reservoir preservation in relation to tectonic subsidence of the sedimentary basins and long term facies preservation. More work is needed to interpret and understand the geometry of modern sedimentary basins to present additional facies models for the continental sedimentary records. In addition to modern analogues for hydrocarbon reservoirs, studies of fluvial systems in sedimentary basins are important for studying groundwater distributions and flood patterns. The fluvial-dominated Otter Sandstone Formation of the Wessex Basin, from the Triassic, has been studied to highlight the importance of outcrop-to-subsurface correlation in stratigraphic studies (Newell, 2017).

Creating an outcrop analogue to the Braid Plain stratigraphical interval in the Ivar Aasen Field is particularly important because Aker BP plans to develop the interval further, but there is little knowledge on the heterogeneity of the interval. Studying an outcrop analogue can provide information on geometries similar to those found in Braid Plain. Aker BP has provided cores and log data from two wells, 16/1-11 and 16/1-21S for this thesis.

There are relatively sparse data in the subsurface on braid plain systems and because the heterogeneities are small they are not visible when studying seismic from 2,5 km depth. A field analogue is therefore needed to understand the heterogeneities in these systems. The Hornelen Basin is a good analogue because of the large, steep exposures with little vegetation and a relatively well described large sandy fluvial system that is interpreted to be a braid plain fluvial system (Steel et al., 1977 & Anderson and Cross, 2001).

1.2 Aims and objectives

This thesis combines sedimentological field and core logging, virtual outcrop mapping, petrographic analyses, and establishing lithofacies and facies associations to further understand the Braid Plain stratigraphic interval in the Ivar Aasen Field. The following objectives were set to achieve the aims of this study:

1. Describe and improve the understanding of the deposits from the Braid Plain stratigraphical interval in the Ivar Aasen Field.
2. Investigate the sedimentary environment, channel and baffle geometries of the similar sandstones in the axial Hornelen Basin, using closely spaced logs and drone data.
3. Compare deposits in The Ivar Aasen Field- Braid Plain to the Hornelen Basin deposits to see similarities and differences between these stratigraphic units.
4. Investigate how insights from the Devonian sandstones in the Hornelen Basin can be used to improve understanding of the "braid plain" deposits in the Ivar Aasen Field, which might be important for field development.

2.0 Geological Setting

The main objective of this chapter is 1) to give the reader an overview of the tectonics and sedimentary processes that have been essential to making today's Hornelen Basin and The Ivar Aasen Field- Skagerrak Formation- Braid Plain stratigraphical interval, and 2) explain and introduce terms and concepts of fluvial processes and depositions that are used in this thesis.

2.1 Study Areas

In this thesis, two areas around the west coast of Norway are studied. The offshore study area The Ivar Aasen Field, and the onshore study area, The Hornelen Basin. Figure 2.1 shows an overview of the two study areas and where they are in relation to one another.

The Ivar Aasen field is located in the northern North Sea, specifically in block 16/1 on the Gudrun Terrace (Aker BP, unpublished). 200 km west of Stavanger, the field reaches 7x7 km in size and a water depth of 112 m. The Skagerrak Formation is one of the main reservoirs operated by Aker BP and is located in the Triassic interval (Aker BP, unpublished) (Fig 2.6). The cores that were studied in this thesis were drilled from the Braid Plain stratigraphical interval, located furthest down in the Skagerrak Formation (upper Triassic). Throughout this thesis the Braid Plain stratigraphical interval will be referred to as Braid Plain as it is not approved as an official member.

The Hornelen Basin is a Devonian sandstone-basin located on the west coast of Norway (Fig 2.1). The area where the exposed rocks were studied are located in the center of the Devonian basin, in Bremanger Norway (Fig 2.2).

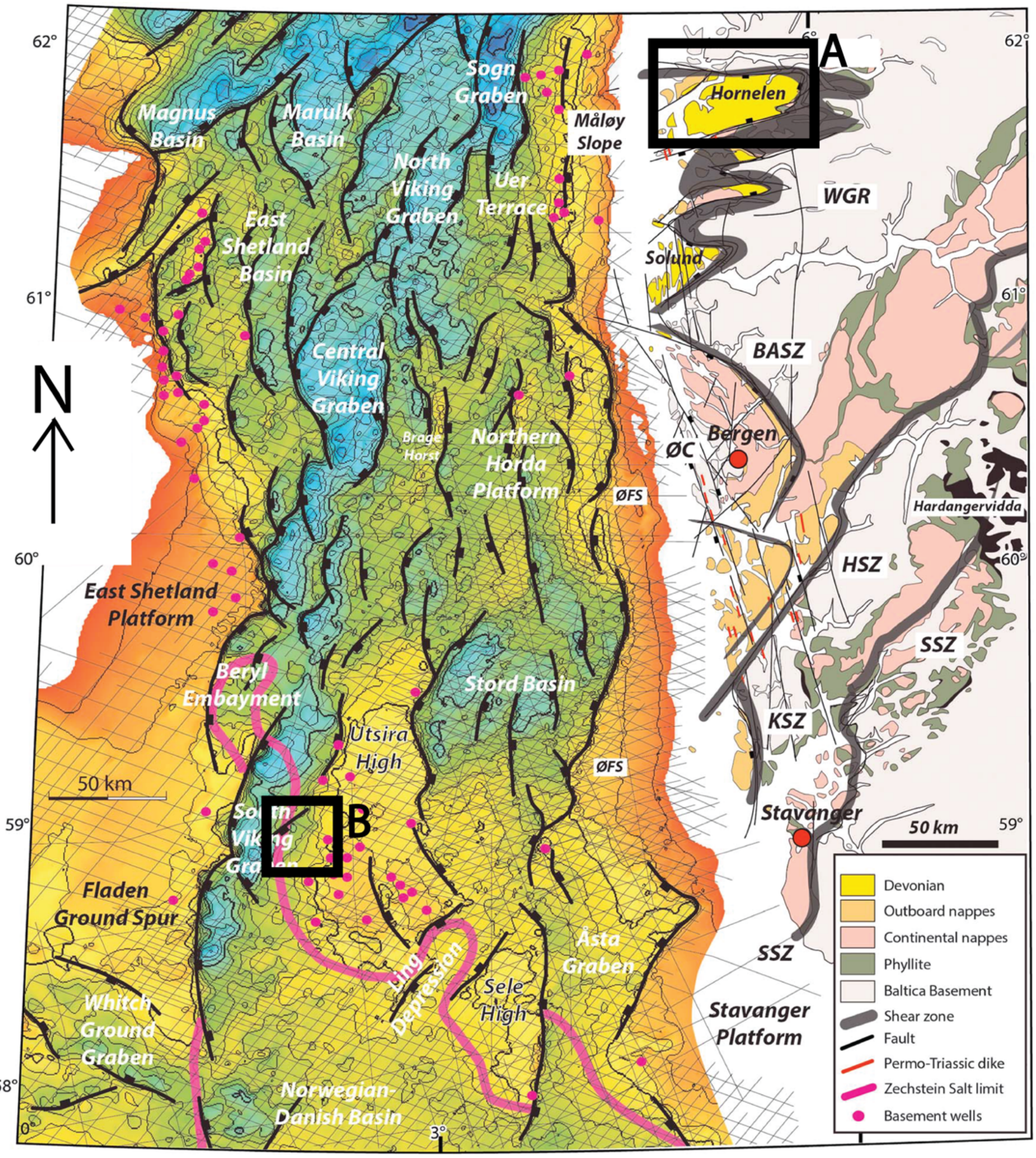


Figure 2.1: Location of the Study Areas. The map shows Western Norway on the right side, together with an overview of the general offshore structural configurations in the Northern North Sea. A) Devonian Hornelen Basin located in Bremanger County in Western Norway and B) Location of The Ivar Aasen Field in the North Sea. The Braid Plain stratigraphical interval is located in the Skagerrak Formation, in The Ivar Aasen Field. Figure collected and modified from (Fazlikhani et al., 2017).

2.2 Overall Setting - Caledonian Orogeny

The formation of the Caledonian orogeny started in the late Cambrian/early Ordovician and, put simple, formed on top of the Precambrian basement (Gee, 1975; Fossen, 2010; Roberts, 2003). The present day basement, underlying the North Sea and Western Norway, formed during the Sveconorwegian orogeny in Proterozoic. It was deformed and reworked during the

Caledonian orogeny (Phillips et al., 2019, Andersen, & Jamtveit, 1990). Baltica and Laurentia collided, and the Iapetus Ocean closed. This happened during the Scandian phase of the Caledonian orogeny (McClay et al., 1986; Phillips et al., 2016).

Thrust-nappe structures were transported and thrusted onto the western margin of Baltica, which consisted of continental terranes from Baltica and Laurentia, including oceanic terranes from the Iapetus Ocean (Phillips et al, 2019; Roberts, 2003). Transportation of allochthons happened along a basal de´collement zone (detachment zone) which consisted of weak shales and phyllites (Hossack & Cooper, 1986; Gee, 1975). The 1800 km long and 500 km wide orogenic wedge that formed from the accumulation of Caledonian allochthons (thrust nappes) caused a high grade of metamorphism and deformation to many of the nappes involved (Fossen, 2010; Fossen et al., 2017). The Nappe stratigraphy that has been assigned ranges from the short transported Lower and Middle Allochthon that originates from the pre-collisional Baltica continental margin, via the Upper Allochthon from the Iapetus ocean, and into the long travelled Uppermost Allochthon. The latter may be derived from the Laurentian plate (Fossen, 2010; Fossen et al., 2017).

2.2.1 Devonian extension

The cessation of the Caledonian orogeny in The North Atlantic region is characterized by rapid exhumation of high to ultrahigh-pressure rocks prior to and during the formation of supradetachment basins (Vetti et al., 2012). Supradetachment basins are basins that form in the hanging wall of low-angle normal faults (Friedmann & Burbank, 1995) The formation is closely tied to tectonic processes and are associated with extensional tectonics (Vetti et al., 2012). Supradetachment basins originating from the collapse of the Caledonian orogeny have accumulated clastic sequences with large stratigraphic thickness, and the basins in Southwest Norway are mainly composed of sandstone, conglomerates and a small amount of siltstone (Steel et al., 1985). The sediments that accumulated in the Devonian basins originate from the Caledonian allochthonous units. As of now the main theory is that the four individual Devonian basins, Hornelen, Håsteinen, Kvamshesten and Solund, are individual, but closely connected supradetachment Devonian basins, originating from the Caledonian extensional process (Cuthbert, 1991; Vetti et al., 2012). This thesis focuses on the Hornelen Basin and its sedimentary properties.

Some of the basin fill in the Hornelen Basin has been removed by erosion over time, but the Devonian sediments are preserved because the Nordfjord-Sogn Detachment Zone, which occurred during Mode II extension (Fig 2.2), was folded upright during the deposition of sediments (Fossen & Rotevatn, 2016). The sediment package is more than 25km thick (Steel et al., 1977; Bryhni, 1978; Fossen & Rotevatn, 2016).

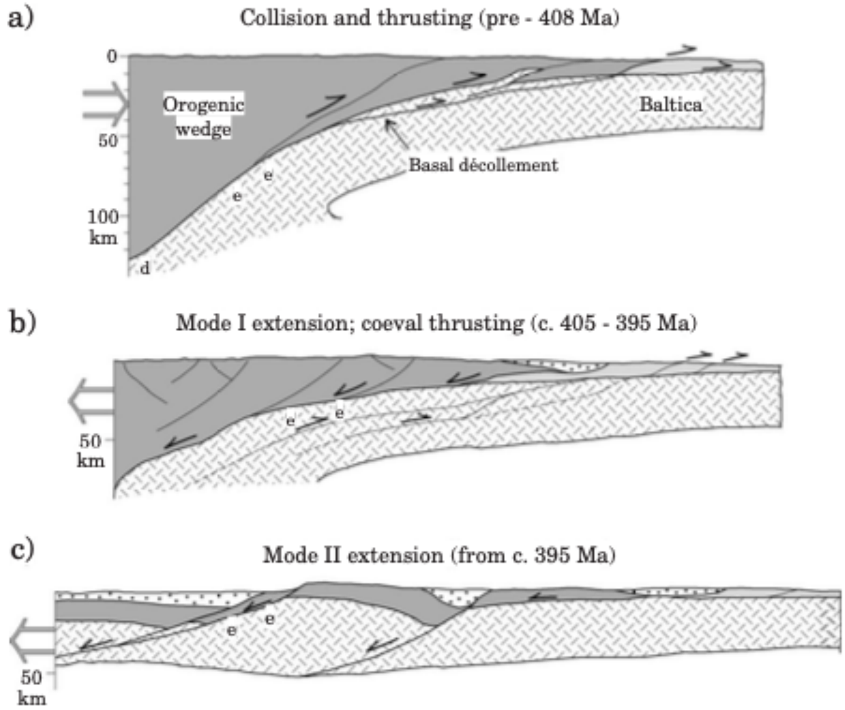


Figure 2.2: Arrows show movement direction of plates. Scandian phase of the Caledonian Orogeny (a). Mode I and II extension (b) and (c). In c the Devonian sediments are accumulating in the extensional basin, shown as dots in part (c). (Modified from Roberts, 2003)

2.2.2 Rift Phases in the Paleozoic and Mesozoic

Devonian times consisted of orogenic extension and basin formation in. Following these events, Western Norway, specifically the North Sea, was subjected to further tectonic activity. The Late Paleozoic and the Mesozoic was characterized by extension and compression which affected the North Sea (Ziegler, 1992; Phillips et al., 2016). Following the orogenic collapse and the following thermal subsidence, extension in the Carboniferous to Early Permian lead to a formation of many significant faults and development of the South and North Permian basins (Fazlikhani et al., 2017, Phillips et al., 2016, Phillips et al., 2019).

The southern and northern Permian sandstone basins of the Rotiegend Group (Fig 2.4) were overlain by the Late Permian Zechstein evaporite-dominated deposits, known as the Zechstein Supergroup (Fig 2.4) (Ziegler, 1992, Phillips et al., 2016). Because of the salts' mobility, the Zechstein Supergroup deposition varied in thickness in the Permian basins (Jackson & Lasren, 2009), and influenced the later structural style associated to the Jurassic extensional and compressional events (Thomas & Coward, 1996).

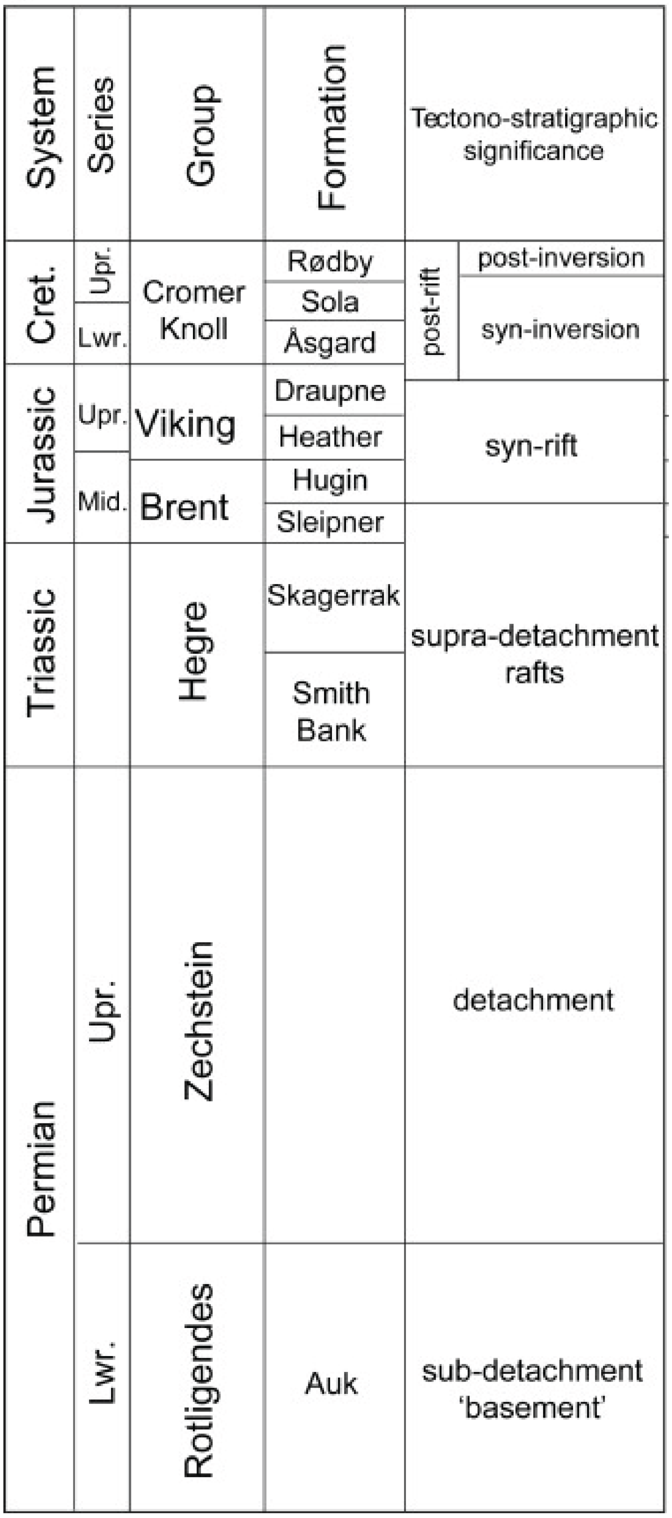


Figure 2.3: Stratigraphical column of the Norwegian sector , South Viking Graben. Indicated is also the regional tectono-stratigraphic presence of different significant stratigraphic units. Figure modified from Jackson & Larsen, 2009.

Mesozoic Rift Phases

Rift Phase 1

During the Mesozoic, the North Sea underwent two main rift phases. Rift Phase 1 (RP1) occurred during the Late Permian- Early Triassic in an E-W extensional direction (Osagiede et al., 2020; Phillips et al., 2019). The Triassic period was dominated by shale deposits from a marginal lacustrine environment, called the Smith Bank Formation (Fig 2.3), deposited in the then continental South Viking Graben (Lervik, 2006; Fazlikhani et al., 2017). Following the Smith Bank deposits, higher energy depositions from alluvial fans and alluvial plains were deposited, which lead to the Skagerrak Formation (Fig 2.3). High heterogeneity and conglomerates, shales, mudstones and sandstones frame the Skagerrak Formation (Aker BP, unpublished; Lervik, 2006; Jackson & Larsen, 2009). The Skagerrak Formation was later in the Triassic affected by a dry climate which led to finer material being re-distributed into channel sands (Lervik, 2006). The Viking Graben developed as a dominant graben structure in the North Sea during phase one (Færseth, 1996; Odinsen et al., 2000).

Inter Rift and Rift Phase 2 (RP2)

A period of uplift and erosion following RP1 led to the formation of the Mid-North Sea Dome. During the Early-Middle Jurassic, the dome removed the stratigraphic units from the Early-Jurassic in the North Sea, which resulted in the Mid-Cimmerian Unconformity. This unconformity is recognized as the characteristic boundary between the Triassic and the younger Jurassic units (Ziegler, 1992., Phillips et al., 2019). The Middle Jurassic is characterized by delta deposits, from the Mid-North Sea Doming known as the Sleipner Formation (Fig 2.4) (Helland-Hansen et al., 1992; Wei et al., 2018).

The overlying Hugin Formation (Fig 2.3) is characterized by shallow marine sandstones, deposited during the collapse of the Mid-North Sea Dome (Thomas & Coward, 1996). The Heather Formation (shelf deposits) followed by the Draupne Formation (deep marine deposits; Fig 2.4) are deposited after the Hugin Formation during the Inter Rift phase. The Triassic and Jurassic successions are faulted during the reactivation of the Graben Boundary Fault (Thomas & Coward, 1996; Jackson & Larsen, 2009; Osageide et al., 2020).

Rift Phase 2 stems from the Mid-North Sea Dome collapsing and inducing major rifting which created the trilete North Sea rift system; Viking Graben, Moray Firth and Central Graben (Badley et al., 1988; Phillips et al., 2016, Phillips et al., 2019, Osageide et al., 2020). There are several suggestions to the direction of the extensions that induced RP2, which is highly debated. In this thesis the relevance of the extension direction is minimal and will therefore not be further discussed.

Following the ending of RP2, the boundary between syn-rift and post-rifting stage is marked by the Base Cretaceous Unconformity (Gabrielsen et al., 2001).

2.2 Small scale setting

2.2.1 The Hornelen Basin

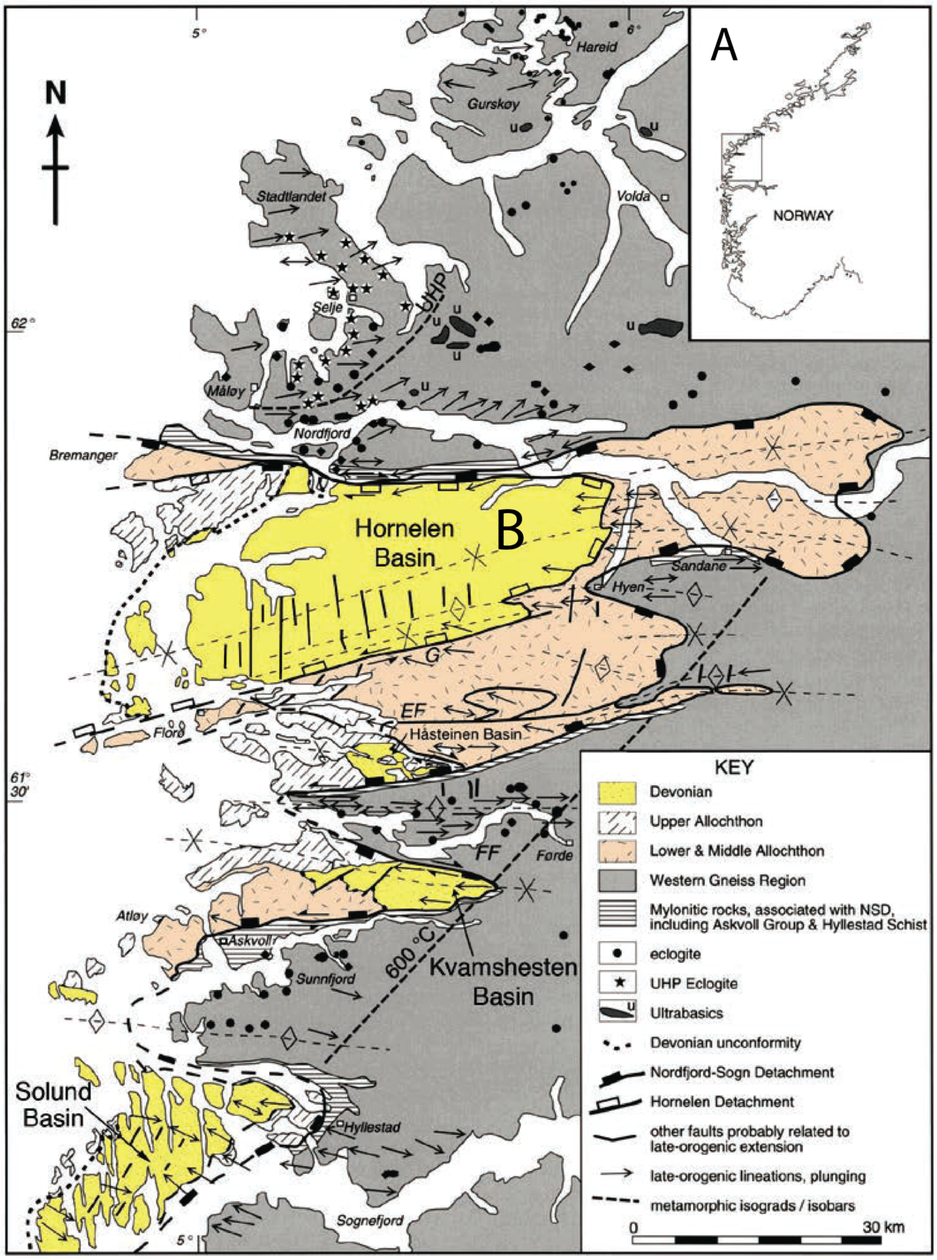


Figure 2.4: Location of study area Hornelen Basin in North Western Norway. An overview map of North Western Norway(A) and (B) shows the location of the first study area in this thesis, located furthest north, The Hornelen Basin (colored in yellow). The figure shows all four Devonian Basins' location in Norway and the surrounding geology of the area.

The formation of the Hornelen Basin formed as a result of the orogenic collapse of the Caledonides. The Basin is located on the western coast of Norway, along with three other Devonian basins formed around the same time (Fig 2.4). The orogenic collapse of the caledonides created an extensional basin, and along with tectonics and sedimentation the Hornelen Basin was formed. The tectonic activity happened in stages and the extension of the orogeny allowed westward flowing rivers to transport sediments into the basin (Steel et al.,1977 & 1985; Vetti et al., 2012; Anders et al., 2022). The Hornelen Basin is filled in with approximately 25km of sedimentary rocks, primarily sandstones and conglomerates from Devonian, Middle Devonian (Pollard et al, 1982; Steel et al., 1985). Figure 2.5 shows where the fieldwork in the Hornelen Basin was conducted for this thesis.

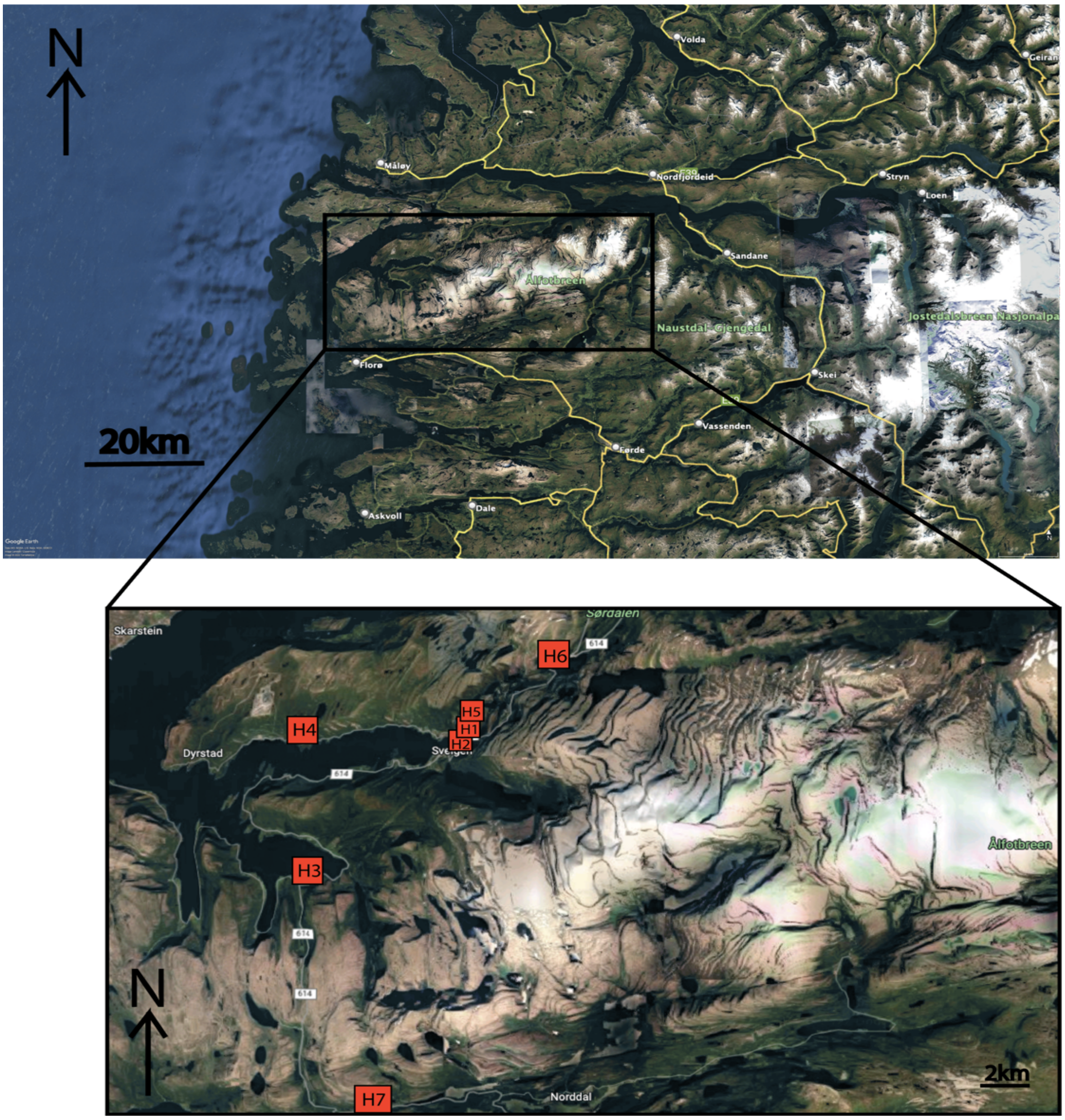


Figure 2.5: Satellite image of the Hornelen Basin location. A) Location of the Devonian sandstone basin outlined. Visible is part of Ålfotbreen (in white) lying on top of the sandstone shelves that distinguishes the basin. B) Close-up satellite image of the seven locations the logs were taken in (H1-H7). H1and H2 also represent where the virtual outcrop UAV images were taken from (Photos from Google Earth).

2.2.2 Skagerrak Formation

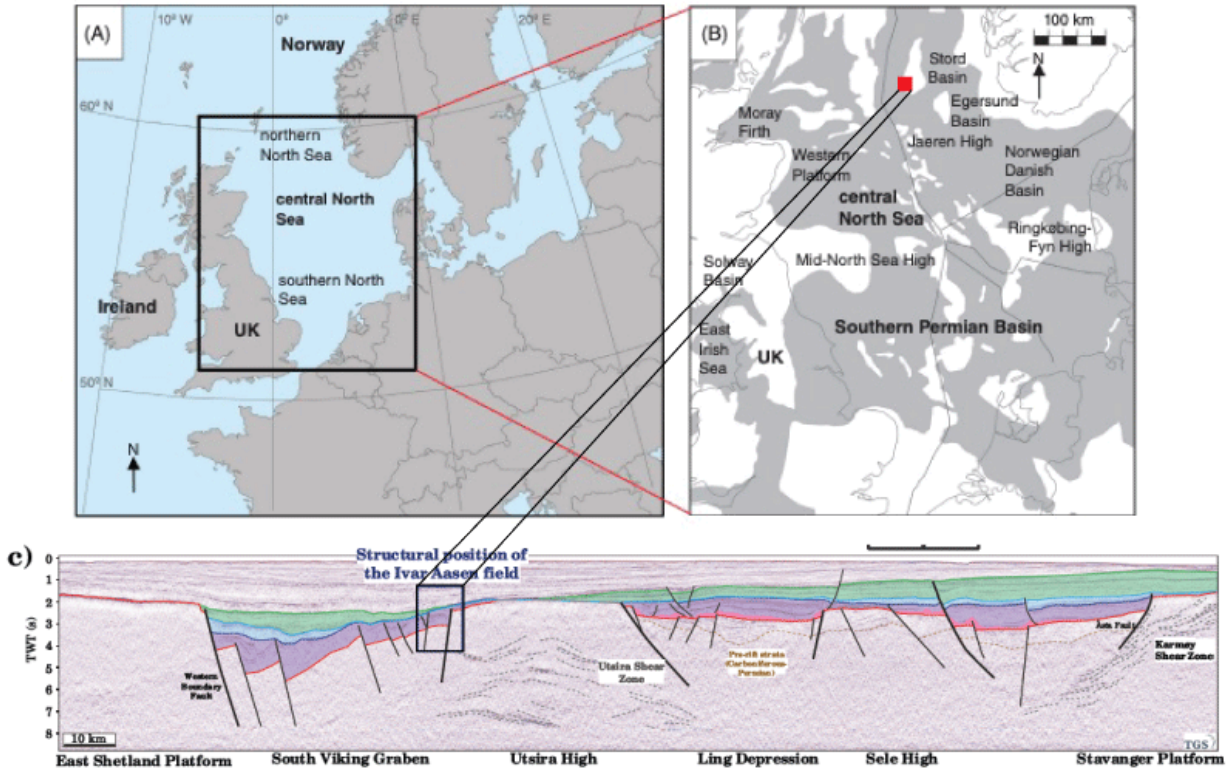


Figure 2.6: A) Overview of the study area offshore Western Norway, highlighting the North Sea. B) Regional setting of the Ivar Aasen Field (marked in red) (Fig A & B modified from McKie, 2014). C) From Phillips et al. (2019) shows a seismic section of the regional subsurface, stretching from the East Shetland Platform to the Stavanger Platform. The Ivar Aasen position is marked in the blue box on figure c.

The northern North Sea rift developed through several rift phases. During the rifting episodes that initiated the break-up of Pangea, deposition of Triassic sediments occurred in the north-west European region. There were two main extensional pulses that occurred in the North Sea during the late Early Triassic and the early Late Triassic. These can be identified from the southern North Sea Basin to mid- Norway. The basin fills from Permo-Triassic show a half-graben form, infiltrated by Jurassic rifting later on, and contain fills that show extensional episodes across migrating fault arrays (McKie, 2014).

The dryland basins formed in Triassic were, in the Central North Sea, dominated by fluvial, floodplain, and playa deposits. The Central North Sea succession is dominated by these deposits and divided into the Smith Bank Formation and the Skagerrak Formation (McKie, 2011).

The Smith Bank Formation is dominated by mud-rich playa (lake) deposits from early Triassic and is up to 500m thick. In middle-late Triassic the Skagerrak formation was formed, which consists of sand-rich fluvial sections (up to 500m) (McKie, 2011). The Skagerrak formation is divided further into members, with different names in the northern North Sea and the Central North Sea.

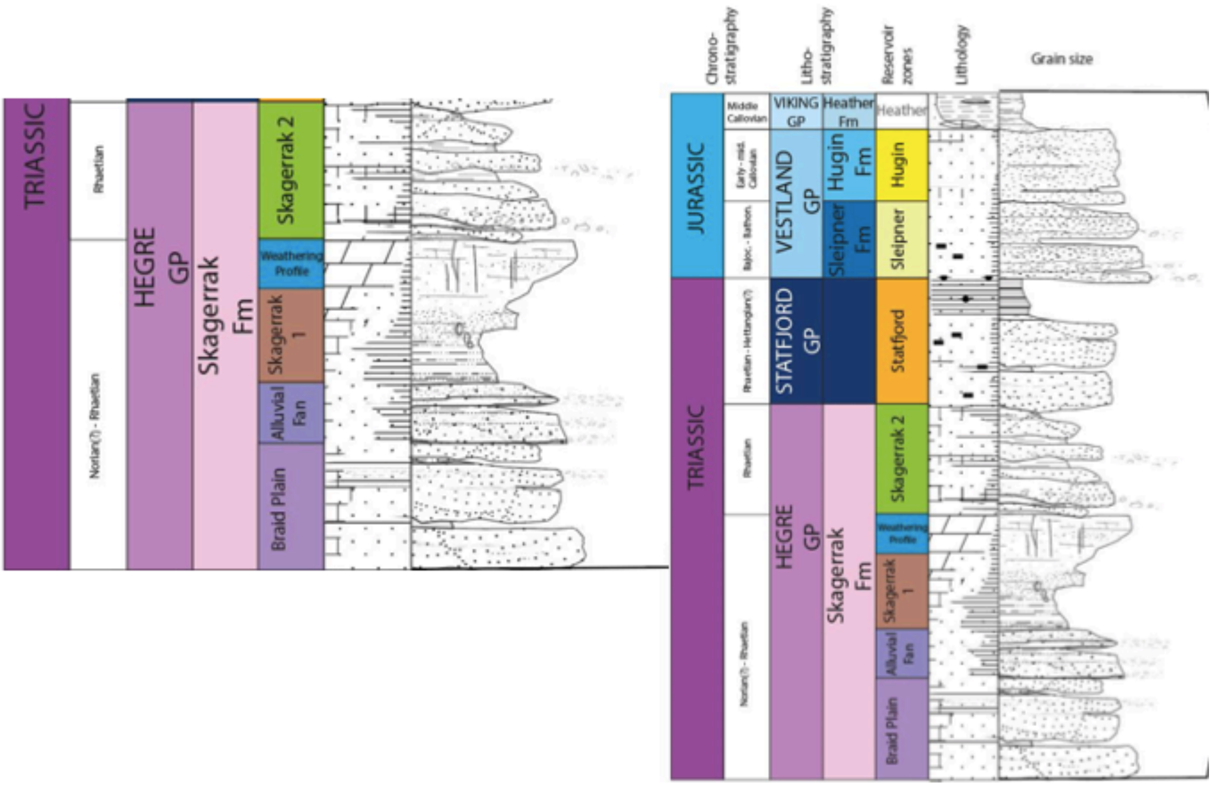


Figure 2.7:. Shows the litho- and tectonostratigraphy of the northern North Sea Ivar Aasen Field division. From Aker BP Reservoir Characterization Report 2020, unpublished.

The Skagerrak formation in the northern North Sea is divided into five members. From the oldest Braid Plain (informal member), to Alluvial Fan, Skagerrak 1, Weathering Profile and into the youngest Skagerrak 2 (Fig 2.7; Aker BP, unpublished). Further in this thesis the Braid Plain informal member is the one that will be studied. Presented below are the main characteristics of the members that make up the Skagerrak Formation (from Aker Bp, unpublished).

Skagerrak 2 – Very fine- to medium grained sandstones interbedded with mudstones, partly calcite cemented. Moderate net-to-gross alluvial deposits.
Weathering Profile – Karstified paleosol with high carbonate content.
Skagerrak 1- Greenish-grey mud dominated heteroliths.
Alluvial Fan- Arcosic sandstone (6-40% K-feldspar) and pebbly conglomerate
Braid Plain – Dark red to light greenish grey amalgamated cross-stratified sandstones.

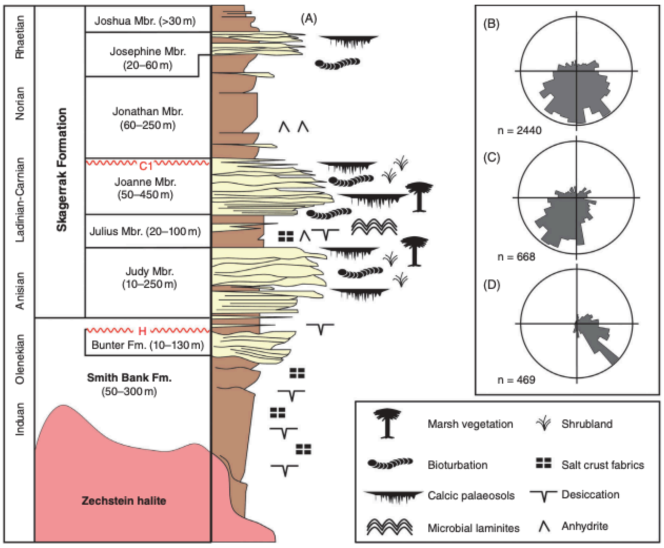


Figure 2.8 shows the Skagerrak Formation Central North Sea, divided into different members than in the northern North Sea.

Figure 2.8 displays the members of the Central North Sea Skagerrak formation. It is divided into six members, from the oldest Judy, into Julius, Joanne, Jonathan, Josephine and to the youngest Joshua.

2.3 Paleogeography and climate

The Devonian Period

The Devonian period is characterized as hot, with seasonally restricted rainfall (Woodrow et al., 1973). The landmass affected by this climate was made up of continental blocks, and was located around the equator, straddling 20 degrees north and south (Woodrow et al., 1973; Bryhni, 1978). The rainfall was limited in the south, but the north was characterized by greater, evenly distributed rainfall year around. Sedimentary records indicate coastal plain, basin, and continental shelf deposits (Woodrow et al., 1973). In the North Sea, due to a position of 15-30 degrees south of the equator at that time, the climate during the Devonian period was semi-arid (Witzke, 1990). From the knowledge of the North Sea position, it is reasonable to conclude that the Devonian basins onshore were affected by the same climate. Lundmark et al., 2012 describes the semi-arid continental sediments, called the Old Red Sandstone, to be interrupted by marine incursions. The Old Red Sandstone has been detected in drilled wells in the North Sea dominated by alluvial fan, braid plain, fluvial, and lacustrine beds (Lundmark et al., 2012).

The Triassic Period

The Triassic period in northwest Europe was characterized by dryland conditions, wide spread fluvial systems and ephemeral systems (McKie, 2014; McKie & Williams, 2009). The Triassic was prone to rifting in the early period, and post rifting and thermal subsidence following into the late Triassic (McKie, 2014). This tectonic activity characterized the style of which the fluvial and eolian dominated systems deposited sediments during this period.

2.4 Theoretical background

Frequently used terms are clarified and explained in this chapter. They are used throughout the thesis and are important for the understanding of the results. The terms used are for fluvial systems, both meandering and braided systems.

Fluvial deposits are gathered by the activities of rivers and streams, and the deposits are a wide spectrum of sediments. To recognize the ancient deposits from fluvial systems, it is useful to understand the channel shapes, transport of sediment and the characteristics of modern rivers. This chapter will go through the most common deposits and geometries of modern rivers.
The classification of rivers has been discussed and reviewed and some thoughts on this is that the classification cannot simply be divided into three different river types. Geologists use meandering (single channel), braided (multiple channels) and anastomosing (combination) as the classification. Some believe the classification is oversimplified but in this thesis this is what will be used.

2.4.1 Sediment Transport Processes in Rivers

Channel Transport:

The transport of sediments and erosion occur mainly in the river channels when located in a higher gradient. When the water flows downstream around channel bends it leads to a helical flow spiraling out towards the surface of the river and inward at the bed of the river (Boogs, 2014).

Point bars (side bars or lateral bars) are attached to the river bank. The outside parts of the bends of the river channel are being eroded because of the helicoidal river flow and this leads to a downward motion of water at the outer bend. The inner bend is formed by an upward motion of water together with a decreasing velocity of flow. The flow deposits sediments eroded from the cut bank along the bottom of the channel, on the point bar. The depositional pattern in a point bar is constructed by lateral accretion with upwards fining deposits and cross bedding. Lateral accretion surfaces are often spotted in the field and recognized as point bars (Boggs, 2014).

Braid bars are found in braided river channels and are located between channel pathways (midchannel). When the flow reaches the upstream end of the bar, lateral accretion is formed on both sides of the braid bar. At the downstream end of the bar, scouring and deposition resembling a delta happens because the braid bars can move downstream (Boggs, 2014).

Floodplain Deposition:

During seasonal floods, the surrounding land around a river channel floods of water and the river breaches its banks and natural levees. Deposition on a floodplain happens at these events and is most common along single channel rivers. Floodplains are present around both meandering and braided rivers but most likely preserved best around a meandering river. The fine sediments that are deposited from the floods are located in natural levees and crevasse splays (Boggs, 2014).

Crevasse splay deposits occur when the floodwaters breach the natural levees and is deposited onto the plain. The deposits consist of both coarse and fine grained sediments, and because the sedimentation occurs rapidly after the breach, they are deposited in a Bouma-like turbidite sequence (graded) (Boggs, 2014). Crevasse splays can be kilometers long and wide, and are deposited in a lobe shaped mound, stretching far onto the plain (Bridge, 2003).

Vertical accretion takes place when the river overflows its channel banks and sediments accumulate on the floodplain. The upbuilding of the sediment surface is the opposite of what happens with lateral accretion on point bars. Deposition of sediments during a stream overflow can be deposited in adjoining floodbasins, oxbox lakes and natural levees (Figure 2.9) (Boggs, 2014).

Natural levee deposits differ from crevasse splay deposits as they primarily form on the steep bank side(outside) of meandering river channels. Levees contain horizontally stratified fine sands, with mud on top. This is a result of a sudden loss of competence (Boggs, 2014).

The structures that form when fluvial sediments are deposited are planar and trough cross bedding, plane parallel stratification (lamination), and ripple structures. Sedimentary structures from rivers are more variable from meandering rivers than from braided rivers. The velocity and downstream paleocurrent directions change more in meandering rivers (Boggs, 2014).

Distributary Fluvial Systems (DFS):

The term DFS is used to describe the deposition pattern of channel and floodplain deposits when they are distributed from an apex into where the river enters the sedimentary basin. This is also known as an alluvial fan and this is commonly used in this thesis. Alluvial fans are created where the river becomes unconfined as it leaves the valley or plain and due to the energy loss from flow expansion it deposits a sediment wedge (Weissmann et al., 2010). Alluvial fans can range from 1 – 700 km depending on the size and flow power of the river, and the size and type of basin. There are often several DFSs present in one basin, and according to the study presented in Weissmann et al., DFSs dominate the fluvial deposit area in all studied modern sedimentary basins (724 basins) (Weissmann et al., 2010).

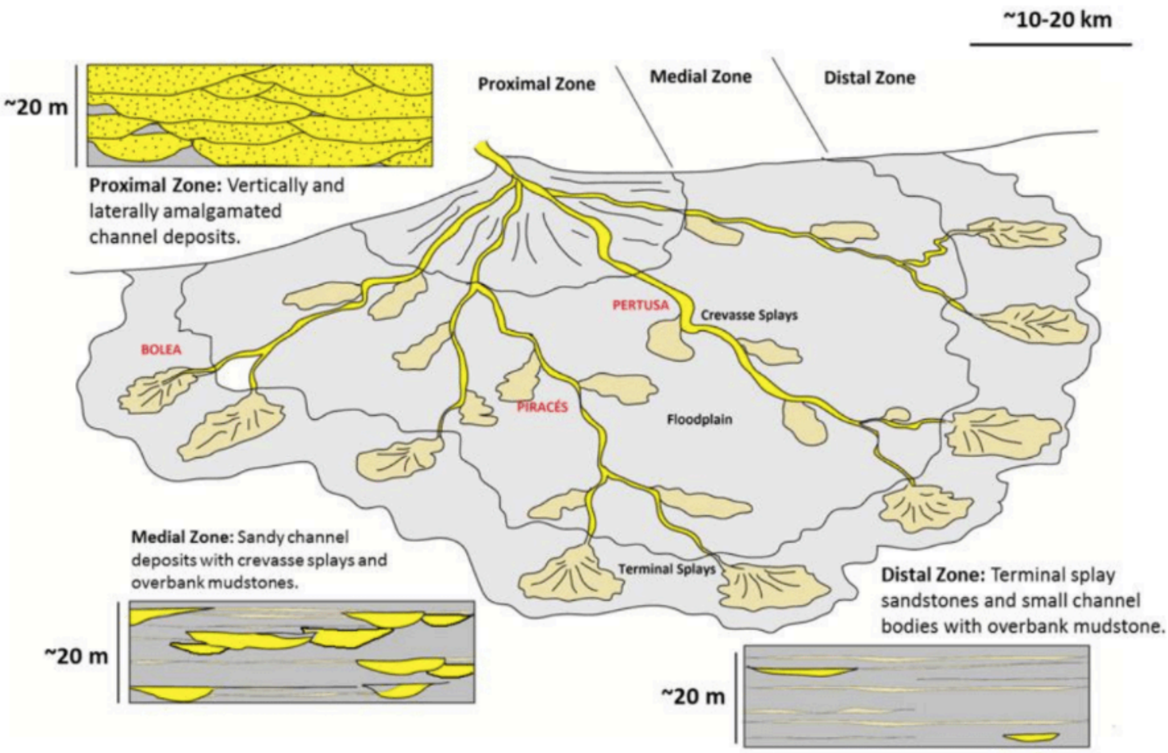


Figure 2.9: Figure of a typical distributary fluvial system**.** Figure from Nichols and Fisher, 2007

3.0 Methodology

Workflow:

- Synthesising (reading, preparing) research papers and already published data from the field areas.
- Field work. Logging, sampling rocks, pictures, UAV photographing
- Virtual outcrop models
- Digitalization of logs from Hornelen and Braid Plain
- Thin section descriptions
- SEM work on thin section- see chemical composition?
- Comparing data from Hornelen and Braid Plain. Interpretation of logs and petrographic data.
- Drone data from the Hornelen Basin.

3.1 Data acquisition

The data collected for this thesis is from field trips to the Hornelen Basin in Vestland County in June 2021 and September 2021. In addition to these trips there was data collected from Aker BP's cores from the Skagerrak Formation in the Ivar Aasen Field. The studied cores are taken from the Braid Plain Member, which is located in the lowermost part of the Skagerrak Formation.

Data from the two locations were collected through traditional sedimentological logging, drone mapping and field work.

3.2 Sedimentary logging

3.2.1 Fieldwork Hornelen Basin

To be able to interpret and recognize environments and processes, constructing sedimentary logs are necessary. Logs create a fundament to interpret depositional and biogenic structures. The key purpose was to observe and record grain size, lithology, structures (both biogenic and sedimentary), degree of bioturbation and sand/mud ratio.

To determine grain size in the field, a grain-size chart and a hand lens was used A meter stick was used to measure the thickness of the sedimentary and biogenic layers. Bioturbation was divided into grades, from 0-6. The logs were drawn on millimeter paper, including sedimentary structures and preliminary lithofacies interpretations. In the digitalization process of the logs, colors were used to distinguish between the different lithologies. Sandstone (yellow), mudstone (dark grey), oxidized siltstone (red), reduced siltstone (green), conglomerate (purple). The logs were made in a 1:25 scale and later merged into continuous logs covering the entire units.

3.2.2 The Ivar Aasen Field

The logs from the Braid Plain member of the Skagerrak formation at the Ivar Aasen field were logged in 1:25 scale and made the same way as the Hornelen Basin logs. The logs were interpreted from cores taken from the Ivar Aasen Field and because of this there were no samples taken, but petrographic data was sent from AkerBP to be used for interpreting mineral content.

3.3 Fieldwork – sampling

In the field, a total of 12 rock samples were taken using a geological hammer. The samples were taken from places where the surfaces were minimally weathered. Rock samples were taken from several locations in the Hornelen basin (make figure of this). Thin sections of the samples were made at UiB and described in terms of mineral content, grain size, sorting, and grain roundness.

3.4 Digitalization

The sedimentary logs from the field work and core storage were redrawn and rescaled from 1:25 in Adobe Illustrator.

3.5 Virtual outcrop

A second field trip to the Hornelen Basin was necessary to conduct UAV photographing by drone (DJI Mavic Air 2). A remote control connected to an iPhone was used to capture the images, and a total of 440 images were taken. *Agisoft Metashape Professional 1.7.3* was used to make a 3D-model of the outcrops by stitching photos together and georeferencing them.

After the 3D-model was constructed,, LIME v2.3 was used to make interpretations on the virtual model. Mudstone layers were interpreted, as well as correlation with logs, to give a larger understanding of net-to-gross values and the general geometry of the studied areas. Figure X.X shows the workflow that was used to make the virtual outcrops.

Workflow	**Explanation**
Go through pictures	Unclear pictures, identical, and pictures of structures or sky are not useable.
Open Agisoft	
Add photos	
Align photos	Makes a point cloud that appears like the terrain the pictures were focused on. Locates camera position and orients photos using GPS. Remove all points located outside the main point cloud.
Build dense cloud	From the point cloud, a dense cloud is created. Depth information is extracted from the photos to create a more dimensional model. Remove erroneous points and make sure the model has sharp edges (no noise).
Build mesh	From the dense cloud, a 3D mesh is constructed so that texture can be added. Face count of 1 200 000 was used.
Build texture	Generic mapping, mosaic blend, and texture size 4096x30 are the parameters used to add texture to the geometrical mesh model.
Export model to LIME	Export model as Local Coordinates with texture.
Export model from LIME to Adobe Illustrator	Interpret geometries and layers.

4.0 Results

4.1 Lithofacies and Facies associations

The purpose of this chapter is to give an understanding of how the fluvial processes in the Hornelen Basin and in the Braid Plain Member have impacted the geometry of both fields. Sedimentary facies and outcrop models are used to understand the field from smaller to larger scale. To understand different sedimentary processes and their significance it is useful to divide them into lithofacies. Lithofacies represent different building blocks in a sedimentary succession. To understand how the different processes work together and how they have taken place is a vital part of this thesis. Lithology, and chemical, physical and biogenic structures make up the different lithofacies. This is later used to distinguish between the different facies associations.

The following chapters contain a description of the different lithofacies which is later interpreted into the different sedimentary processes in which they were deposited.
Mud composition is vital in interpreting the energy levels during deposition and is therefore considered important.

Fifteen lithofacies and eight facies associations are presented based on the logging of the Hornelen Basin and The Braid Plain member. The table below is divided into lithofacies and description the Devonian Hornelen Basin and the Braid Plain member from the Skagerrak Formation. Facies from Braid Plain are listed as “S” as they are located in the Skagerrak Formation. Facies from the Hornelen Basin are listed as “H” .

4.1.1 Lithofacies descriptions

Hornelen Basin Facies	Lithofacies	Sub-facies	Description	Process Interpretation
FH1	Cross-bedded sandstone		Very fine to medium-grained sandstone with tabular cross-stratification, and trough cross-stratification.	Foresets dripping in one direction, height over 7 cm suggest a unidirectional current. Trough and planar cross-stratification are developed in a lower flow regime by dunes migrating in response to a unidirectional current. Lower flow regime in fluvial channel.
FH2	Planar-parallel stratified sandstone		Very fine to medium-grained sandstone with planar-parallel stratification	Planar foresets in mainly very fine to fine sandstone indicate upper stage plane bed in an upper flow regime. Upper flow regime in fluvial channel.
FH3	Current-rippled sandstone		Fine-grained sandstone with current ripples in directions east and west. Occur often in the same interval as FH1.	Height below 7 cm and internal cross laminae is dipping in one direction. Current ripples are formed by unidirectional currents, similar to cross stratification but the flow velocity and water column is lower. Lower flow regime in fluvial channel.
FH4	Sandstone with clasts of different lithology	FH3A- Sandstone with pink and white clasts	Fine to medium sandstone with rounded clasts of quartz and feldspar. Occurs rarely, and more often in logs taken further south in the Hornelen Basin. No contact between clasts.	Channel lag deposits
		FH3B- Sandstone with rip-up mud clasts	Fine to medium sandstone with elongated angular-squared mud-chips. Fluid-escape structures occur in some intervals.	

FH5	Homogenous sandstone		Fine structureless sandstone. Occurs mainly in between FH1 facies. Massive, some clasts of quartz or feldspar occur south in the basin.	Stable flow in fluvial channel
FH6	Laminated mudstone with little to no structures		Laminated siltstone with current ripples, loading structures, or no structures. Occurs mainly at the top of channel belts and is in general up to 20cm thick. Degree 1 bioturbation.	Floodplain/ floodplain lake/ overbank deposits
FH7	Mudstone with rip-up mud clasts		Siltstone layers with pink and white rip-up mud chips surrounded by F1. Occur randomly throughout Lithofacies F1. Mud chips are angular and vary in size from 2-6cm. Mud chip layers are matrix-poor, clasts are dominating.	Channel base/channel lag deposits
FH8	Matrix-poor conglomerate with clasts		Poorly sorted, matrix-poor conglomerate. Various non-rounded clasts, some rounded occur in between. Clasts are intraformational, and range from pebble to cobbles. The matrix around is medium-grained sandstone.	Alluvial fan (Steel et al, 1977)
FH9	Matrix-poor breccia with angular clasts		Poorly sorted breccia, with immature angular clasts. Fine-grained sandstone around the fragments. Medium-grained massive and pps-sandstone patches occur. At the top of the interval the clasts are cobble-sized, with pebble-sized clasts forming the rest of the interval. The matrix around clasts is fine-grained sandstone.	Alluvial fan (Steel et al, 1977)

Skagerrak Formation Facies	Lithofacies	Sub-facies	Description	Process Interpretation
FS1	Cross stratified sandstone		Fine to course-grained sandstone set in foresets that vary from low- to high-dipping. Foresets are tangential. Bioturbation is absent. Trough cross-stratification is present but rarely occurs. Color varies from brown to red(oxidized) to green (reduced). Moderately sorted.	Foresets dripping in one direction, height over 7 cm suggest a unidirectional current. Trough and planar cross-stratification are developed in a lower flow regime by dunes migrating in response to a unidirectional current. Lower flow regime in fluvial channel.
FS2	Sandstone with current ripples		Fine to medium-grained sandstone with current ripples in different directions. Current ripples range from low dipping(?) to regular. Color varies from brown to red(oxidized) to green (reduced).	Height below 7 cm and internal cross laminae is dipping in one direction. Current ripples are formed by unidirectional currents, similar to cross stratification but the flow velocity and water column is lower. Lower flow regime in fluvial channel.
FS3	Planar-parallel stratified		Very fine to medium-grained sandstone with planar parallel stratification. Color varies from brown to red(oxidized) to green (reduced). FS3 often occurs with FS1 and FS2. Bioturbation is absent. Lithofacies FS3 generally occurs in alternating intervals with massive sandstone (FS4)	Planar foresets in mainly very fine to fine, rarely medium grain-sized sandstone, indicate upper stage plane bed in an upper flow regime. Upper flow regime in fluvial channel.
FS4	Planar-parallel laminated sandstone		Course-grained sandstone. Planar parallel structure is planar parallel lamination.	Plane bed, lower stage in lower flow regime of unidirectional current. Due to the mean grain size being over 0.7mm it is interpreted as lower stage plane bed (Allen, 1982).

FS5	Homogenous sandstone		Fine to coarse-grained sandstone with no structures. Massive and moderately sorted. Occurs throughout both cores, most often in intervals with FS1,2 and 3. Color varies from brown to red(oxidized) to green (reduced).	Stable flow in fluvial channel
FS6	Sandstone with rip-up mud clasts and mud-drapes		Very fine to course-grained sandstone. Both sandstone and clasts vary in color from brown to red (oxidized) to green (reduced) to grey (calcite). Visible in both cores. Little bioturbation.	Channel base/ channel lag deposits
FS7	Mudstone with rip-up mud clasts and desiccation cracks		Silt-grained mudstone with elongated angular mud clasts and current ripples or desiccation cracks. Varying in color from grey to red (oxidized) to green (reduced).	Floodplain/dried floodplain lake deposits
FS8	Structureless mudstone		Silt-grained mudstone with no structures. Varying in color from grey to red (oxidized) to green (reduced). Occur in intervals between sandstone lithofacies. Erosional contact between the sandstone lithofacies. Weak laminae is visible in some of FS8.	Abandoned channel fill/mud plug on floodplain

4.2 Facies Associations – Hornelen Basin

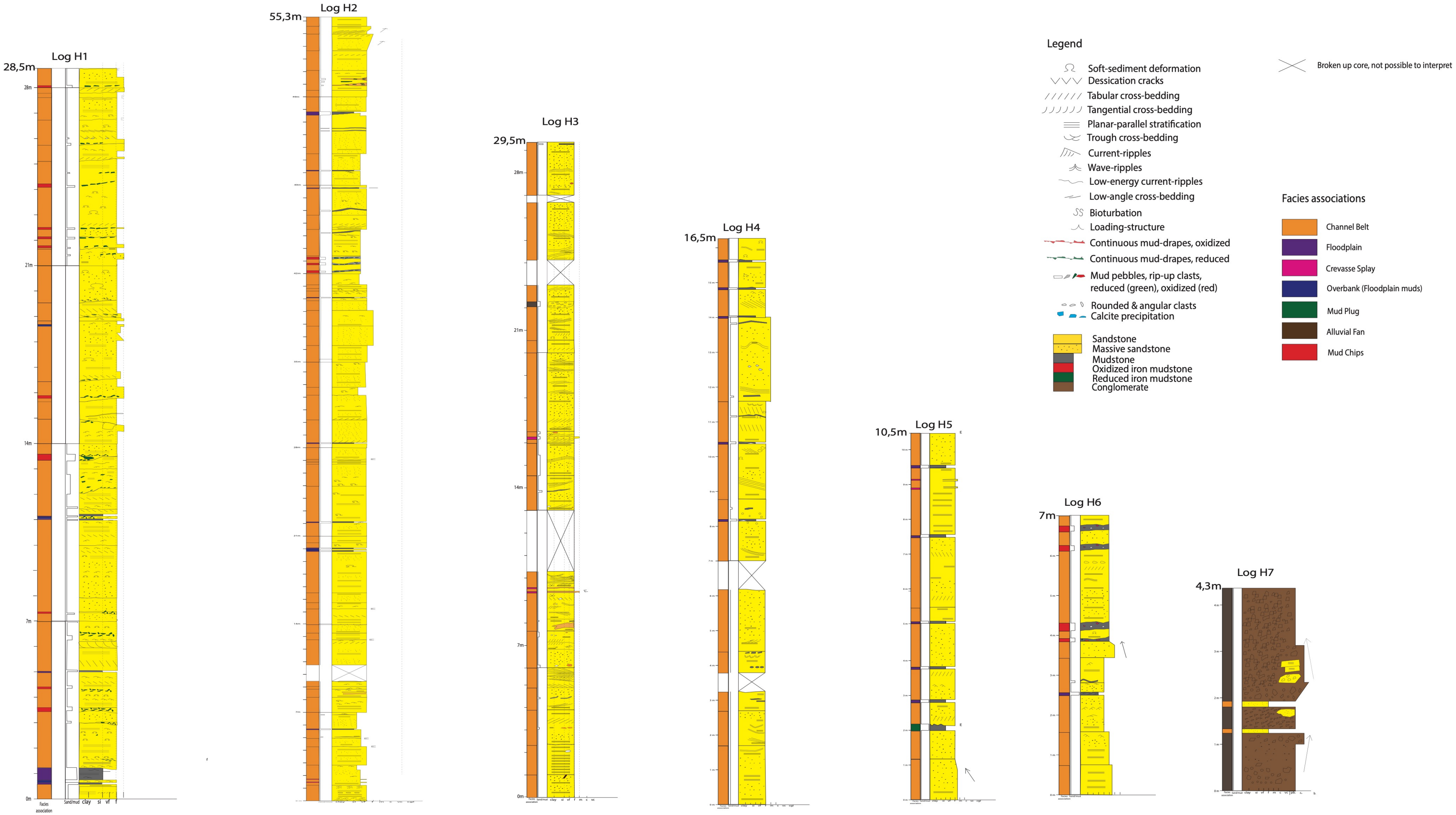


Figure 4.1: Shows all logs taken in the Hornelen Basin. Logs H1-H7 are used to identify facies association in the Hornelen Basin. The logs range 158m in total and from

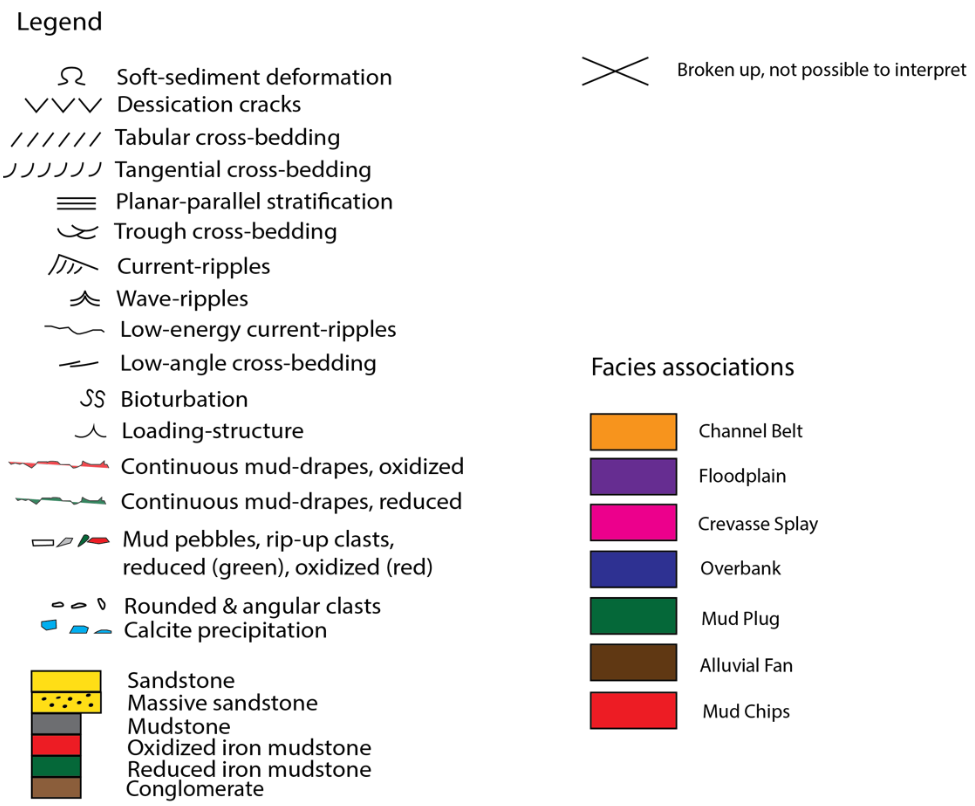
4.2.1 Facies Association HCB – Channel Belt

This facies association predominantly consists of very fine to medium grained sandstone (Fig 4.2). Fine grained sandstone is the dominating grain size through logs H1-H7 within this facies association. In a few places there are distinguished belts that contain rip up mud clasts and mud chips. The Mud chips often occur in the foresets of the cross stratification

Soft sediment deformation is visible throughout all the sandstone beds. Planar parallel stratification, together with current ripples in both western and eastern directions are visible. SSD and fluid escape structures appear to be local and not in context with fluvial deposition. Layers with medium sand create erosive bases into the layers with fine sand.

Thickness varies from 10 cm up to 3 meters. This facies is dominant in all the studied logs in this thesis.

The channel belts observed in Facies Association HCB are complex and display multiple structures to different flow regimes. All structures present evidence of unidirectional current flow and are interpreted as deposits from a braided fluvial system (Steel et al, 1977). The channel belts are stacked in a systematic matter (Fig 4.X) and little evidence is found of isolated channels outside the braided river system. The legend below is presented in all chapters of facies associations.



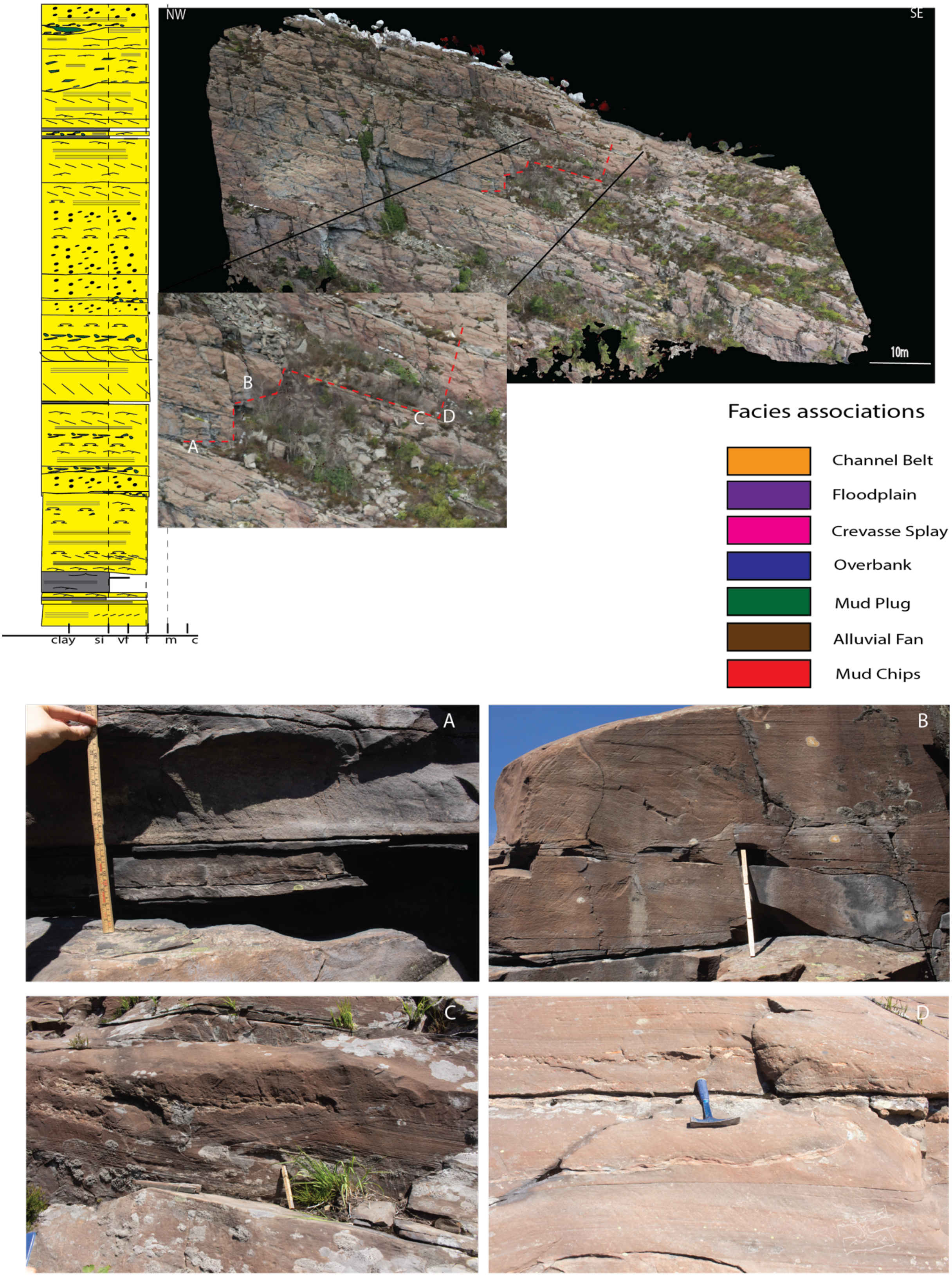


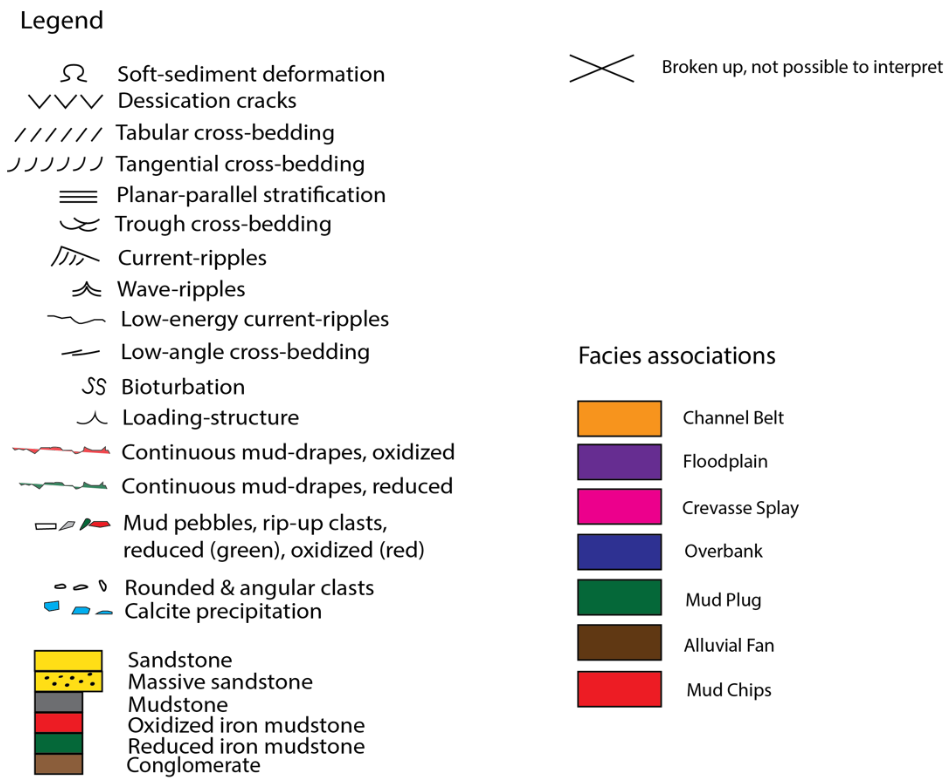
Figure 4.2: Hornelen Channel Belt Facies. A) thin mudstone layer with ruler for scale. B) plane parallel stratification and massive sandstone. C) cross-stratified sandstone in surrounding massive sandstone with mud-chips. D) Layers of mud-chips in massive sandstone and cross-stratification.

4.2.2 Facies Association HFM1 – Hornelen Floodplain Muds - Floodplain

This facies association consists of dark colored mudstone layers that vary in size from 1 cm to 40cm and is visible between the channel belt facies associations. In the virtual outcrops (figure X.X and X.X) the mudstone layers are traced in blue. Mudstone is the least abundant facies association represented in figure X.X and X.X. Little structures are visible in most mudstone layers, although current ripples, plane parallel stratification and loading structures are visible at 2m in figure B (Fig 4.3). Two types of mudstone intervals dominate the succession; silt-grained mudstone with no structures and thinner silt-grained mudstone with current ripples and plane parallel stratification. No bioturbation was visible in the logged successions. Some mudstone layers are deformed by soft sediment deformation, and therefore have a slightly different dip in some places in Figure 4.3.

The thickness of the mudstone layers varies from 1 cm-thin layers to 40 cm thick packages located between very fine to medium grained sandstone packages. Erosive bases where the sandstone package has eroded down into the mudstone layers are present in the succession. The boundaries between the mudstone and sandstone are undulating as the sandstone has eroded into the mudstone.

The mudstones in Facies Association HFM are interpreted as floodplain deposits associated with the flooding of braided river channels on the alluvial plain (axial) in the Hornelen Basin (Steel et al, 1977).



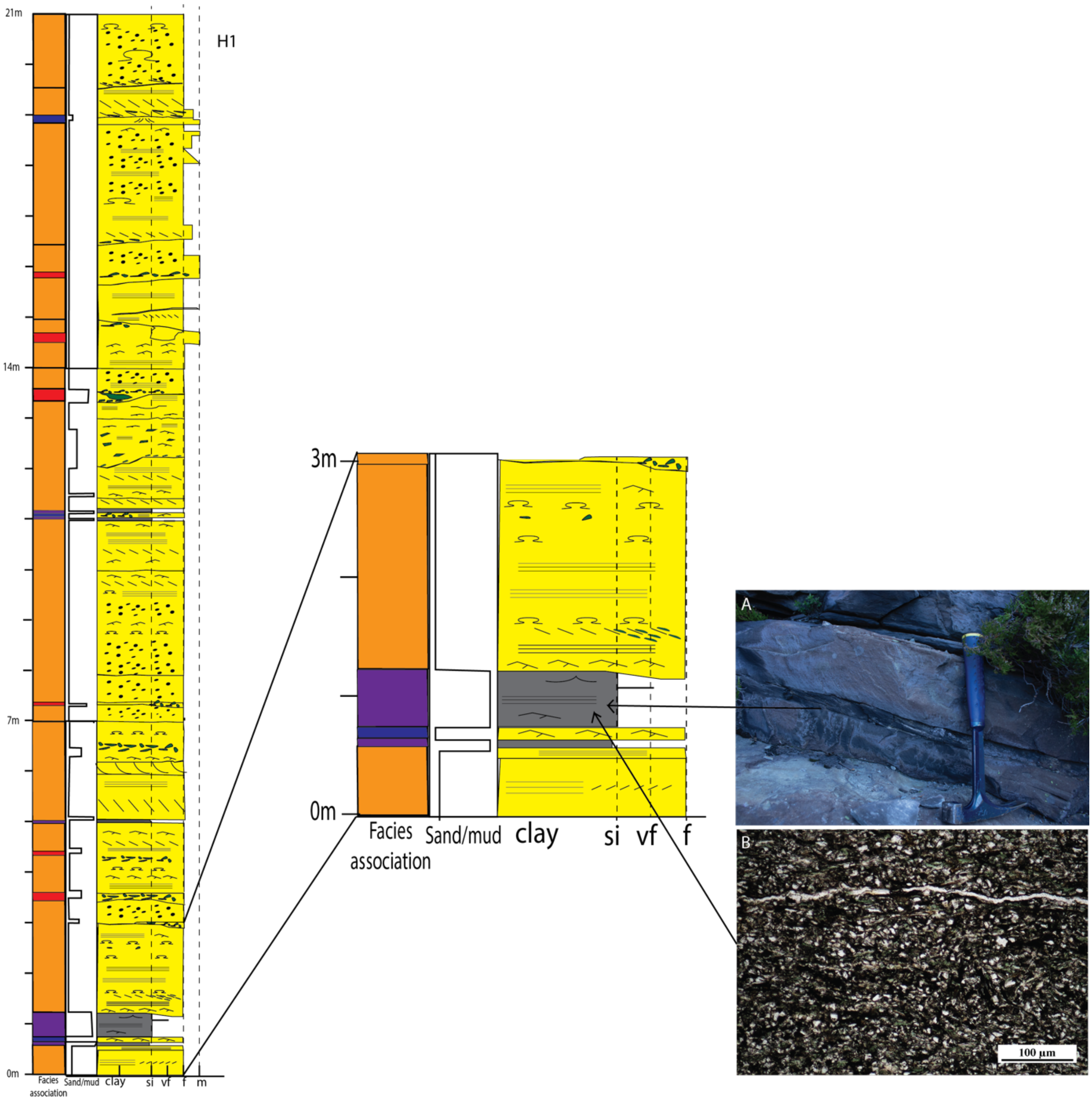
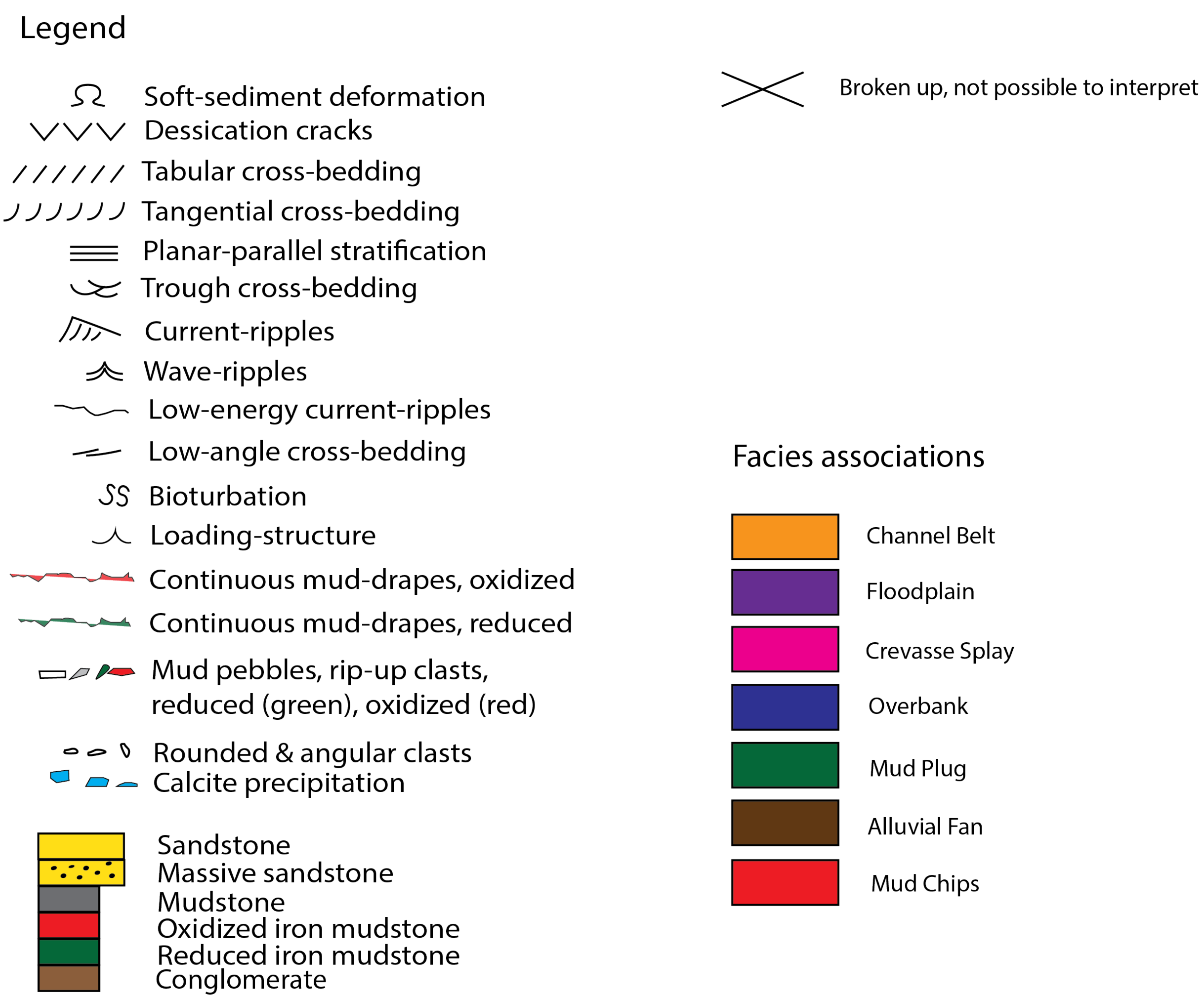


Figure 4.3: Log from H1 (Fig 4.1)displaying floodplain deposits (in grey) with picture of a thin mudstone layer interbedded in fine sandstone, from fieldwork in the Hornelen Basin. Picture in left corner shows a thin section image of the mudstone grainsize.

4.2.3 Facies Association HFM2- Hornelen Floodplain Muds – Mud-chips

This facies association consists of elongated red and white mud clasts in a concentrated sphere, surrounded by fine grained sandstone (Figure 4.4). The mud clasts appear along the channel belts' lower boundaries. The thickness of the mud chips layers vary from 10cm up to 50cm. No visible structures are visible throughout the layers. The size of the mud chips vary from 0,5 cm up to 3 cm in length and approx.. 0,5 cm in width. The surrounding matrix is fine grained sandstone, with the clasts connecting to each other in about 70% of the layer.

The mud chips appear in a lense-shaped form, surrounded by fine grained sandstone with cross stratification. This suggests a unidirectional current flow and the mud chips layers occurring at the base of the fluvial channel. Mud chips layers disrupt the heterogeneity of the succession and is an important factor in the interpretation.



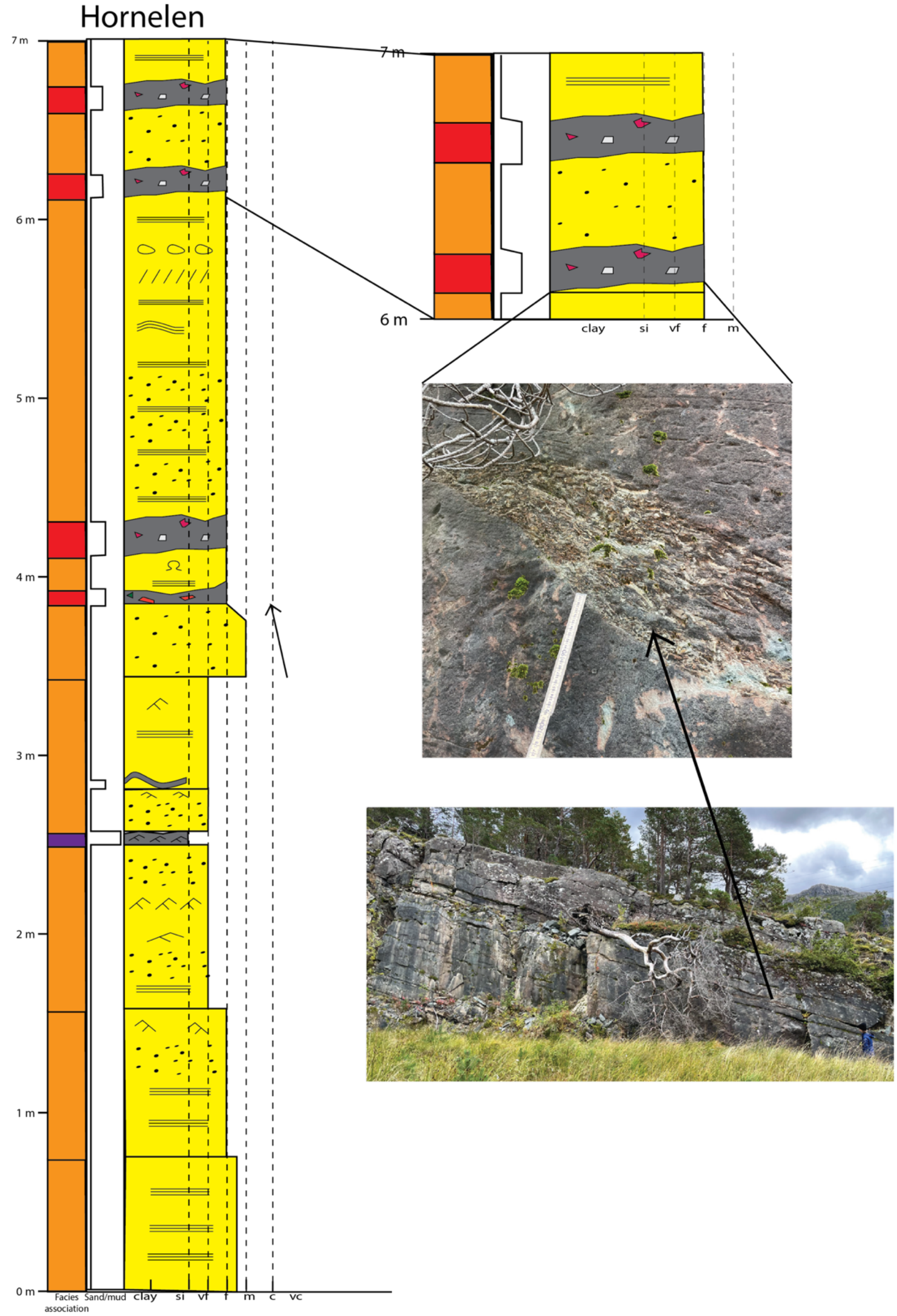
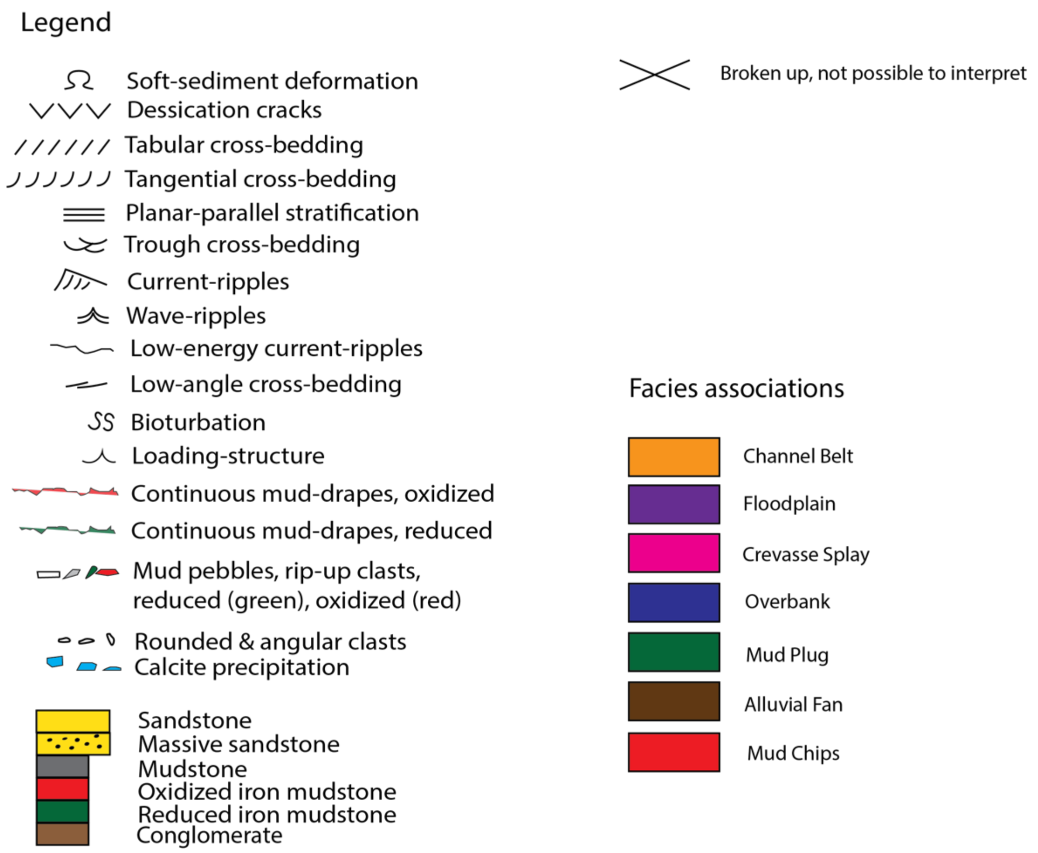


Figure 4.4: Log from Log H6 (Fig 4.1) in the Hornelen Basin. Picture showing the lense shaped mud-chips layer, with surrounding fine sandstone. Mud clasts in the mud-chips layer are red and white.

4.2.4 Facies Association HFS – Floodplain Sands

Facies Association HFS consists of sandstone beds varying in thickness from 2 to 15cm. These sandstone beds are located in between mudstone layers and are formed over and below facies association HCB and HFM, channel belts and floodplain deposits. The grain size in these sandstones vary from fine to course sand and mud-chips are present in the majority of the bodies. Current ripples, as well as plane parallel stratification is present (Fig 4.5). There is no bioturbation present, but soft sediment deformation is strongly present. The thickness of layers in this facies association is significantly smaller than the thickness of the sandstone bodies in HCB.

The grain sized represented in this facies association is larger than the grain size of the HCB channel belts that surround the facies association. Because of the mud chips, current ripples and cross stratification, and the out-standing grain size, this facies association is interpreted to be overbank deposits, more precise crevasse splays. When the channel breaks over the levees of the current channel flow, sediments are deposited on the floodplain as crevasse splays (Bridge, 2003).



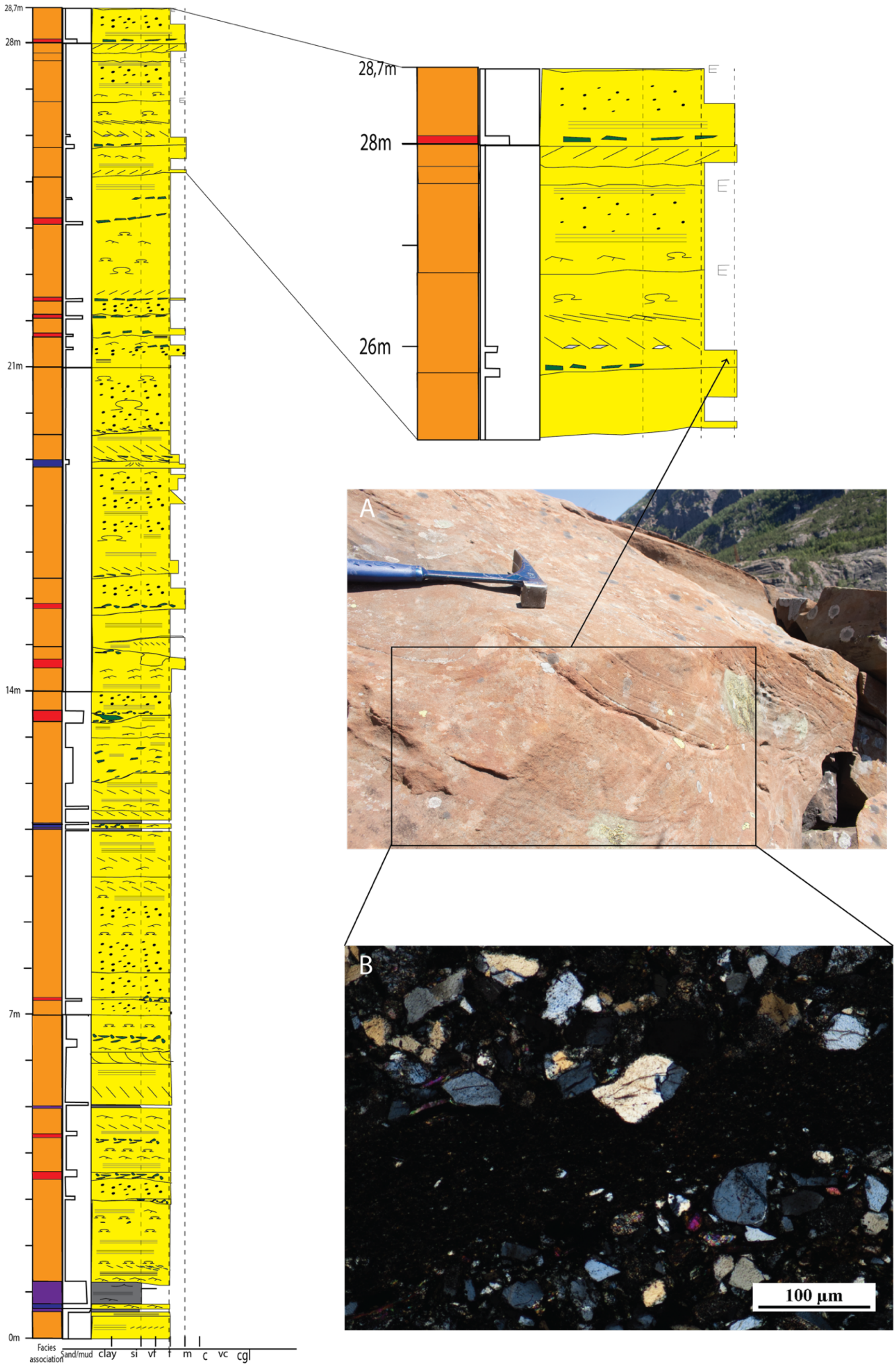


Figure 4.5: Log H1 (Fig 4.1) with detailed showing of the Floodplain Sands. A) Image from fieldwork in the Hornelen Basin, displaying medium grainsized sandstone in surrounding fine grained sandstone. B) Image of thin section taken from the location of the floodplain sands, verifying the interpreted grainsize.

4.2.5 Facies Association HAF - Hornelen Alluvial Fan

Facies Association HAF displays two types of mass flows. The lowermost part of the log, from 0 to 1,2 m (Fig 4.6) consists of matrix rich, unsorted, pebble to cobble sized clasts that are rounded to subangular. The matrix surrounds the clasts, and the clasts are rarely in contact. A fine sandstone makes up the matrix and is also found on top of the pebble-rich layer. Clasts are elongated and show a small sign of inverse grading. The thickness of the bed is 1,2 m.

From 1,2 m up to 4,5 m the succession consists of angular, mostly pebble sized clasts that are in contact with each other. The layers are clast supported, and some patches of fine sandstone with plane parallel stratification and clasts are found at 1,7 m and from 2-3m (Fig 4.6). The uppermost layer has a normal grading as it goes from cobble sized clasts to pebble sized clasts. The clasts are elongated and more rounded at the lowermost part of the interval and in the upper the clasts are non-elongated and very angular. Figure B displays a thin section from a sample taken from log H7. The pebble sized clast is surrounded by a matrix dominated by quartz crystals indicating a sandstone matrix. Thickness of the beds vary from 50 cm to 2,5 m.

This Facies Association is interpreted to be alluvial fan. The lowermost bed displays rounded to sub rounded clasts surrounded by a sandy matrix in an inverse graded succession, this is therefore interpreted to be a conglomerate. The two uppermost beds contain angled, pebble sized clasts which are not matrix supported and have a normal gradation. This is therefore interpreted to be breccia. These two lithologies are found in alluvial fans and the breccia display clasts that have been less eroded than the conglomerates by fluvial systems (Steel et al, 1977).

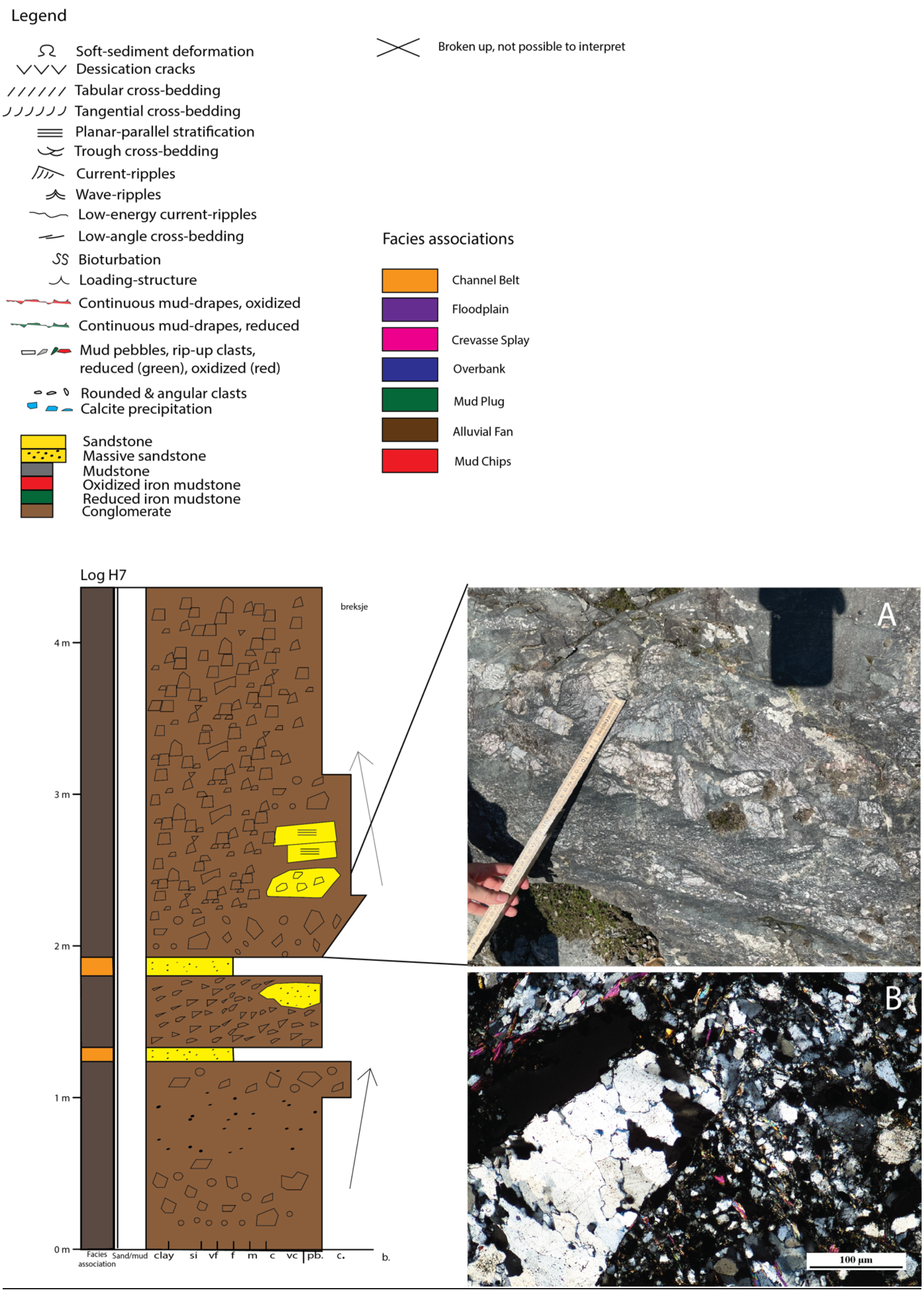


Figure 4.6: Log H7 with images of conglomerate sized clasts. A) Image from fieldwork in the Hornelen Basin showing the pebble sized clasts with an underlying fine grained sandstone. B) Image of thin section located in the Alluvial Fan, verifying the interpreted grain size.

4.3 Facies Associations – Skagerrak Formation - Braid Plain

The following chapters will describe the facies associations interpreted from cores 16/1-11 and 16/1-21 S drilled from Braid Plain in the Skagerrak Formation in the Ivar Aasen Field. Figure 4.7 gives a first look on the grain size variations in the cores, and more detailed sections of the logs are displayed in the following chapters.

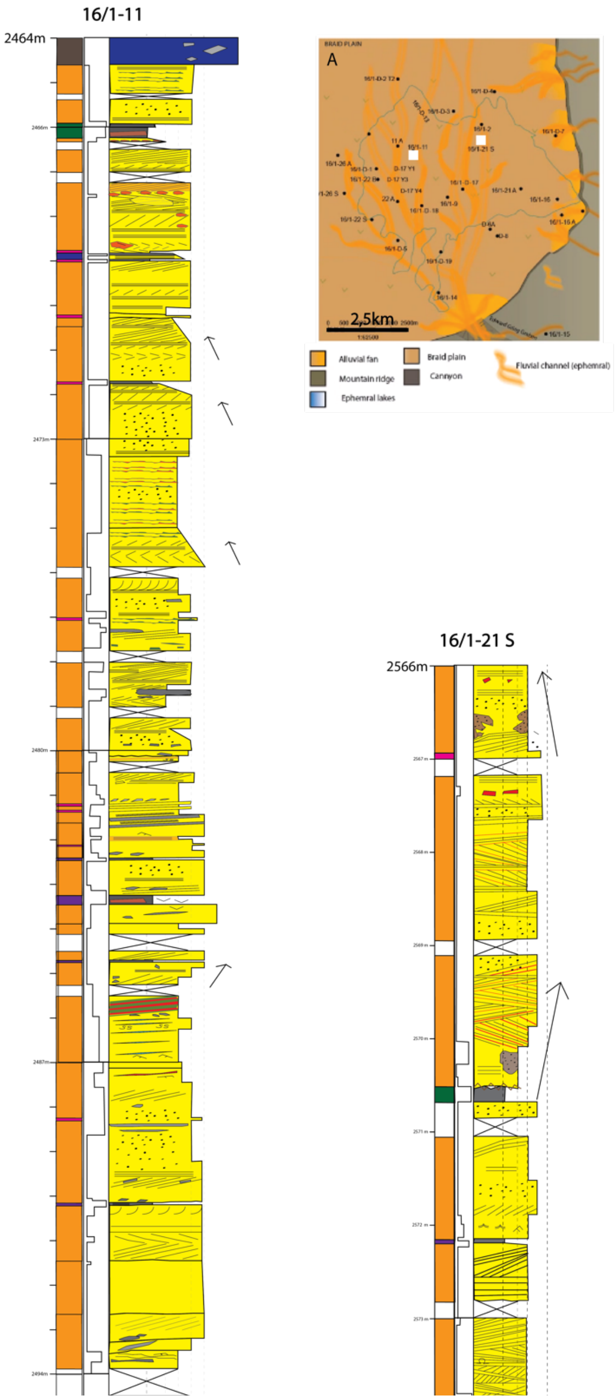
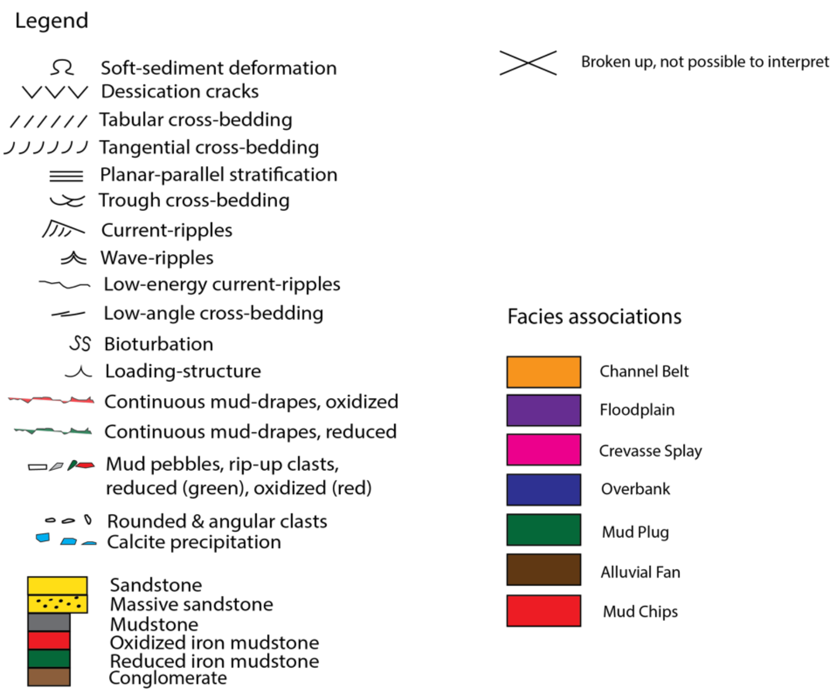


Figure 4.7: Cropped logs from cores 16/1-11 and 16/1-21S. Complete logs from cores are found in appendix. A) Model from Aker BP (unpublished), displaying the interpreted location of where in the Braid Plain system the cores are drilled from.

4.3.1 Facies Association SCB – Skagerrak Channel Belt

This facies association is dominated by very fine to medium sandstone with plane parallel stratification, current ripples, non-stratified massive sandstone, and scattered mud clasts. The facies association is dominant through both of the studied cores in this thesis. The color of the sand packages vary from green, red and grey/brown through cores 16/1-11 and 16/1-21S. There is no relevant correlation between the color of the sandstone and the grain size in which the colors appear and therefore not specified in the facies association table in the figures. Cross stratification is the dominant structure throughout the whole facies. The cross stratification is simple and low angled, together with planar parallel stratification (Fig 4.8) these show signs of a unidirectional current flow. Scattered mud clasts appear through both cores and also display a color variation of red, green or grey. The enhanced log image in Figure 4.8 shows a two meter interval representing the average trend of how the structures are formed. The thickness of the sandstone packages vary from 20cm up to 2,5m and a fining upwards trend is found through some packages.
Current ripples, cross stratification, and planar cross stratification are evidence of a unidirectional flow, together with a fining upwards trend and a variance of grain sized this facies association is interpreted to be a channel belt and will be mentioned as this throughout this thesis. Channel belts from a braid plain fluvial system are represented in cores 16/1-11 and 16/1-21S, and act as the most dominant facies association in the Braid Plain- Skagerrak study area.



16/1-11

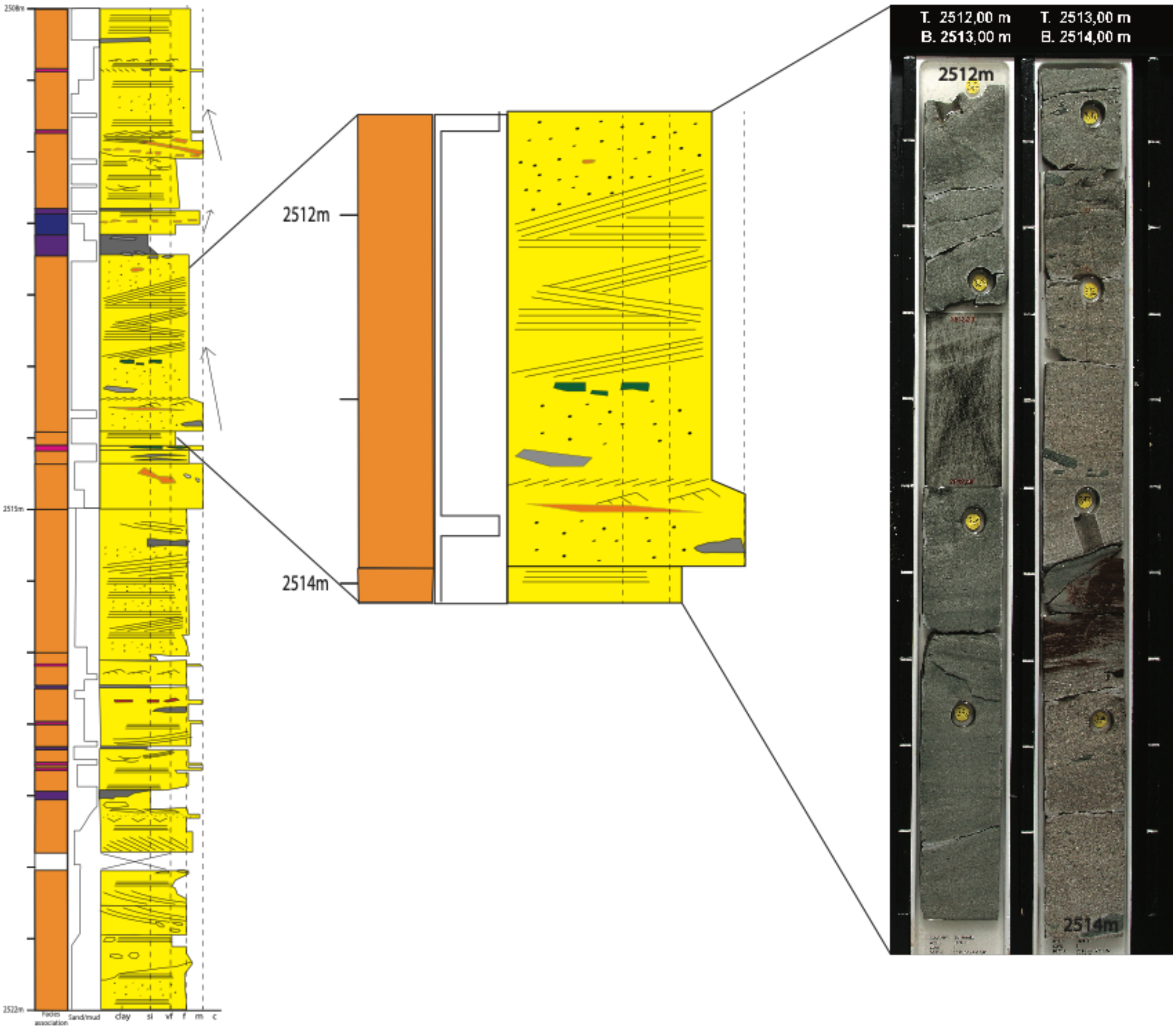
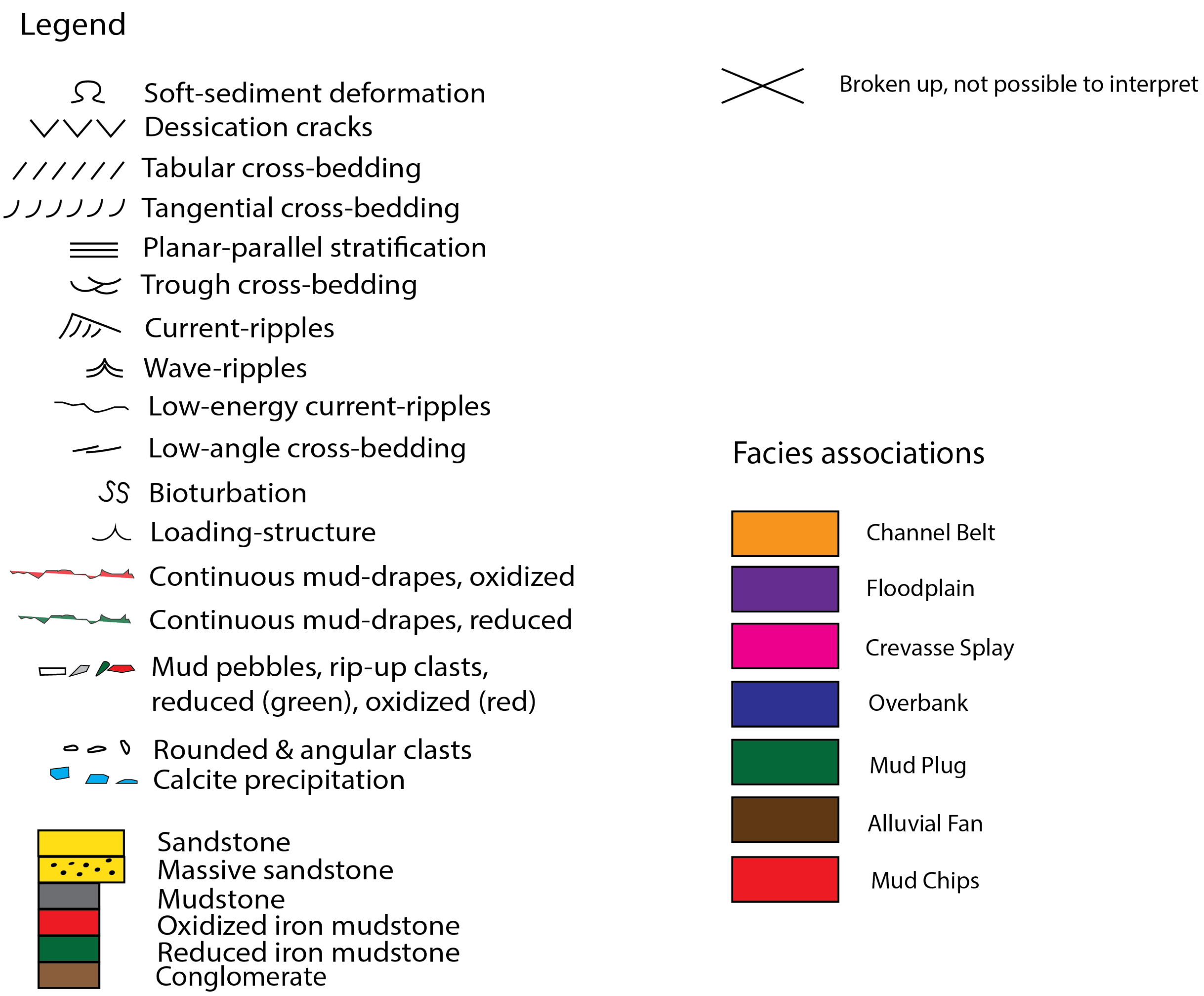


Figure 4.8: Log from 16/1-11 displaying the main structures of the Skagerrak Channel Belts. Cross stratification and plane parallel stratification are enhanced. Image showing the selected meters from the original cores.

4.3.2 Facies Association SFM1 - Skagerrak Floodplain Muds

Mud-drapes

This facies association is dominated by green and red colored drapes that contain mud sized grains which appear in a very fine to medium grain sized sand package. The log in Figure 4.9 shows a two meter interval with continuous appearances of mud sized 50mm thick layers. There are no structures observed in the mud-layers, but the main trend shows they tend to follow the angle of the surrounding beds' depositional trend.



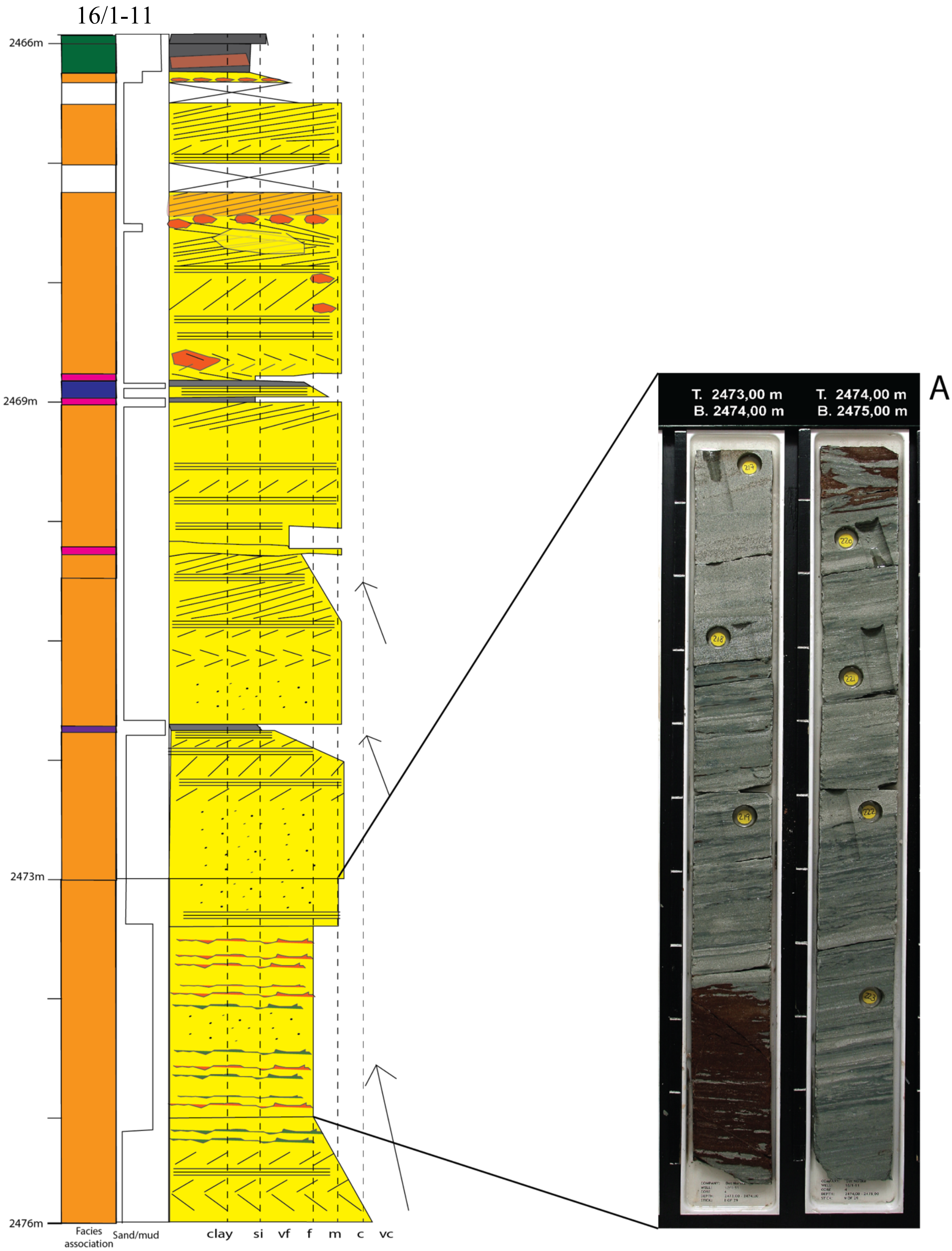
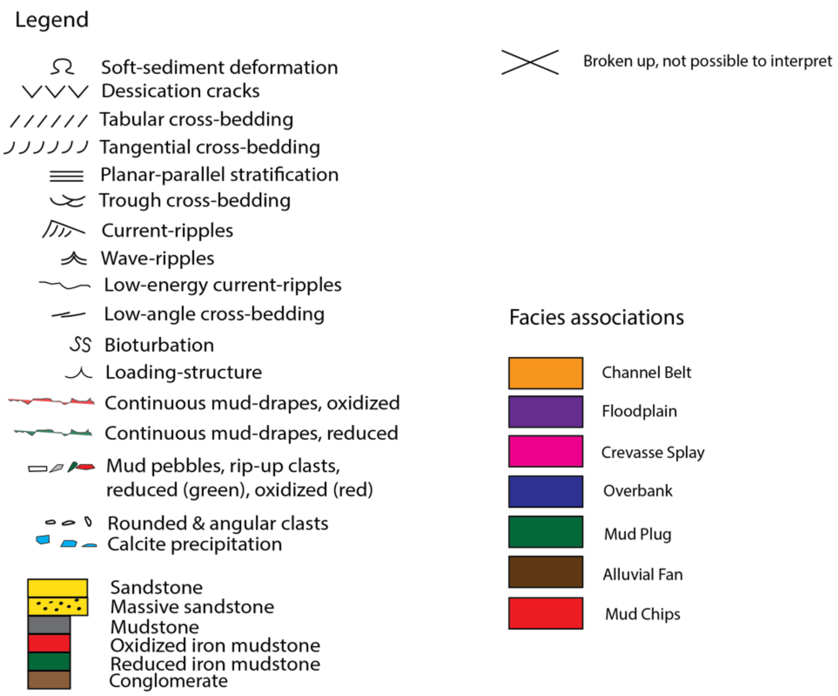


Figure 4.9: Log from 16/1-11 with image of the red and green colored mudstone depositions interpreted to be mud-drapes.

4.3.3 Facies Association SFM2 – Skagerrak Floodplain muds –Mud Plug or Floodplain

Figure A in Figure 4.10 shows red and green colored mud sized grains on top of a very fine grained sandstone with an erosive base. There is no internal lamination in the mudstone and the sandstone underneath contains red colored mud-chips (SFM- Mud chips). Bioturbation is present at the top of the layer, but is rare throughout the rest of the cored interval (degree 1). Interbedded within the mudstone are very thin layers of very fine grained sandstone. The thickness of the mudstone layer is 40 cm.
Figure B in Figure 4.10 contains scattered red colored mud clasts that are surrounded by a medium grain sized sandstone. The mud clasts show no internal lamination while the surrounding sandstone shows cross lamination and plane parallel stratification. There is no trend in where the mud clasts are placed, but they follow the angle of the structures of the surrounding sandstone in general.

This facies association is interpreted as floodplain deposits, possibly deposits from an avulsed channel during floods, formed in an abandoned channel making a mud-plug (Boggs, 2014) Thin sand layers within mudstone layers on top of an erosive base, together with bioturbation (Boggs, 2014), indicate spill-over deposits which are here interpreted to be deposited in an abandoned channel.



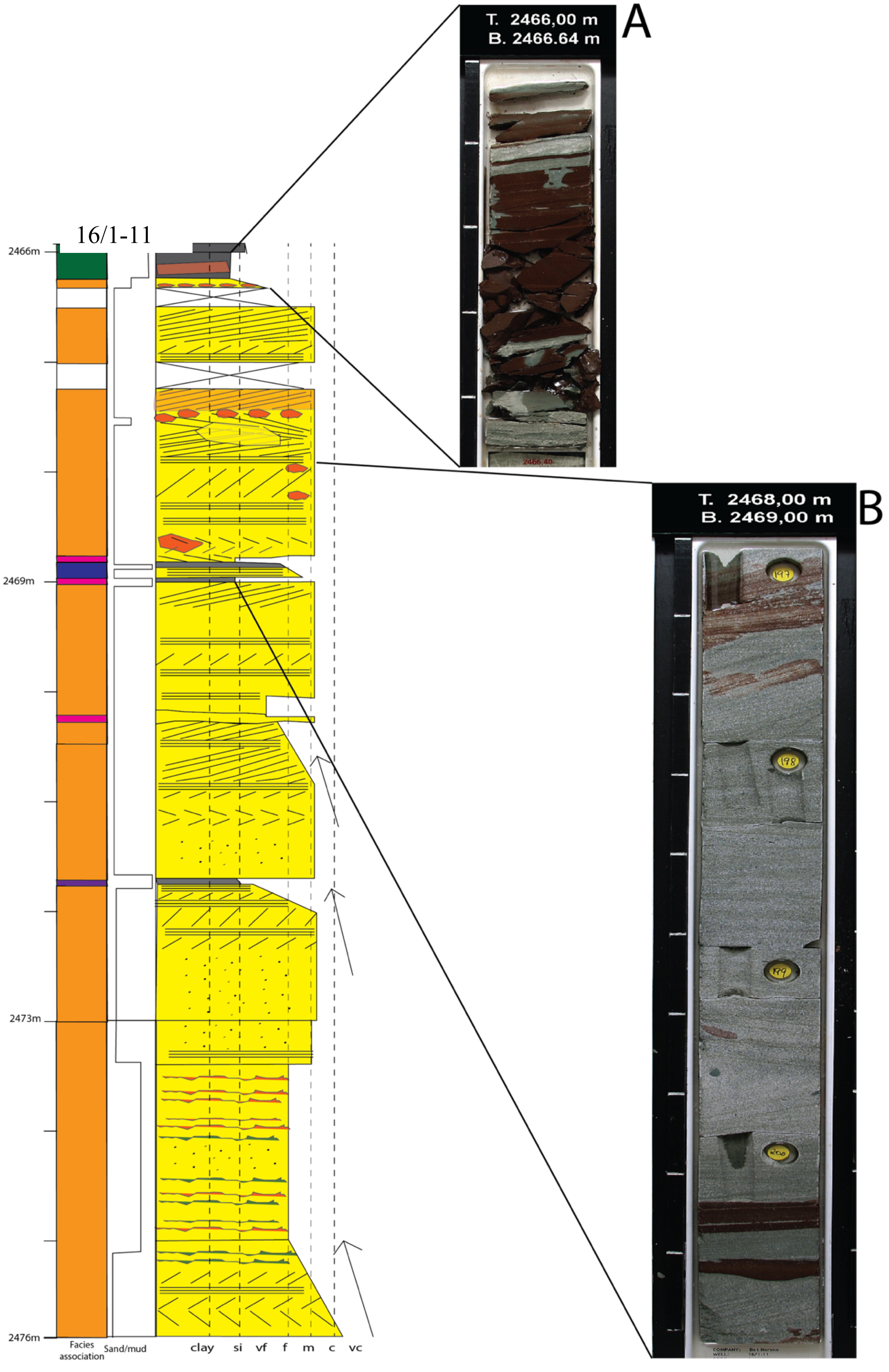
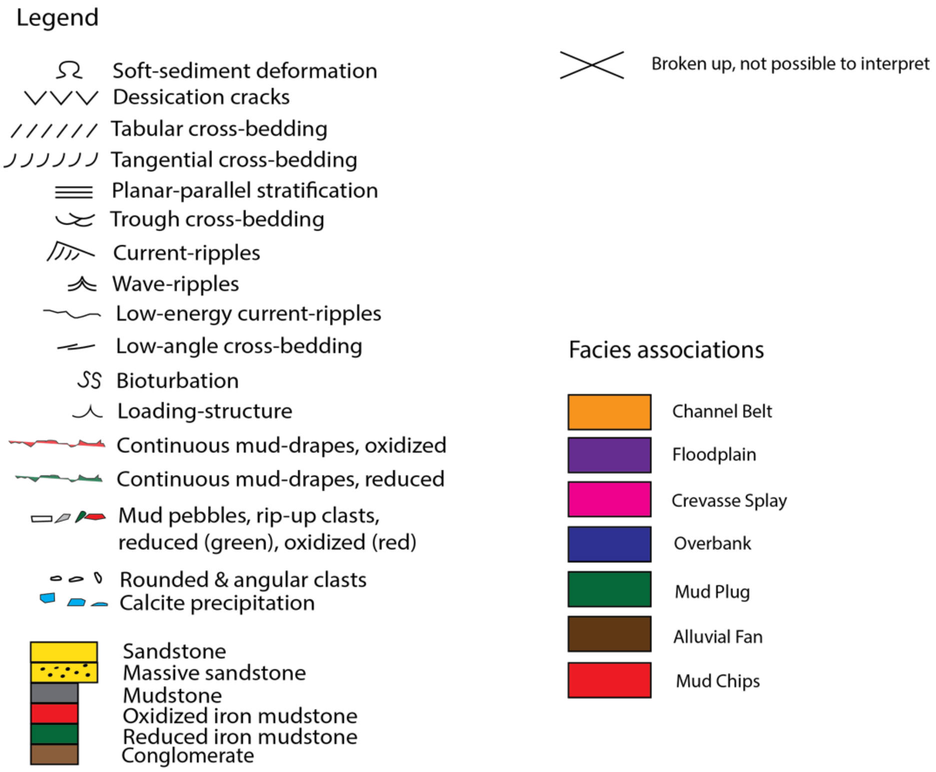


Figure 4.10: Log from 16/1-11. A) Image of possible mud-plug deposition with an erosive base at the bottom of the red mudstone layer. B)

4.3.4 Facies Association SFS - Skagerrak Floodplain Sands

This facies association consists of 3 cm to 40 cm thick medium grain-sized sandstone layers deposited between very fine to fine grained sandstone layers. Planar parallel stratification and current ripples are found in the surrounding sandstone layers and often occur at the top of the layers. The color of the medium grained sandstone is grey and this trend is displayed throughout the whole facies association (Fig 4.11). Lateral variation is not possible to see in the cores and the bioturbation value is 0. Related to the medium grained sandstone deposits, non-structured massive sandstone is often found in correlation to the larger grained deposits.

The limited extent of medium grain-sized sandstone, together with unidirectional current ripples and plane parallel stratification which indicates a uniform paleo-flow direction, lead to the interpretation that these deposits are from when the channel levees are flooded by the stream and deposits coarser grained material on the floodplain as overbank deposits and crevasse splays (Boggs, 2014).



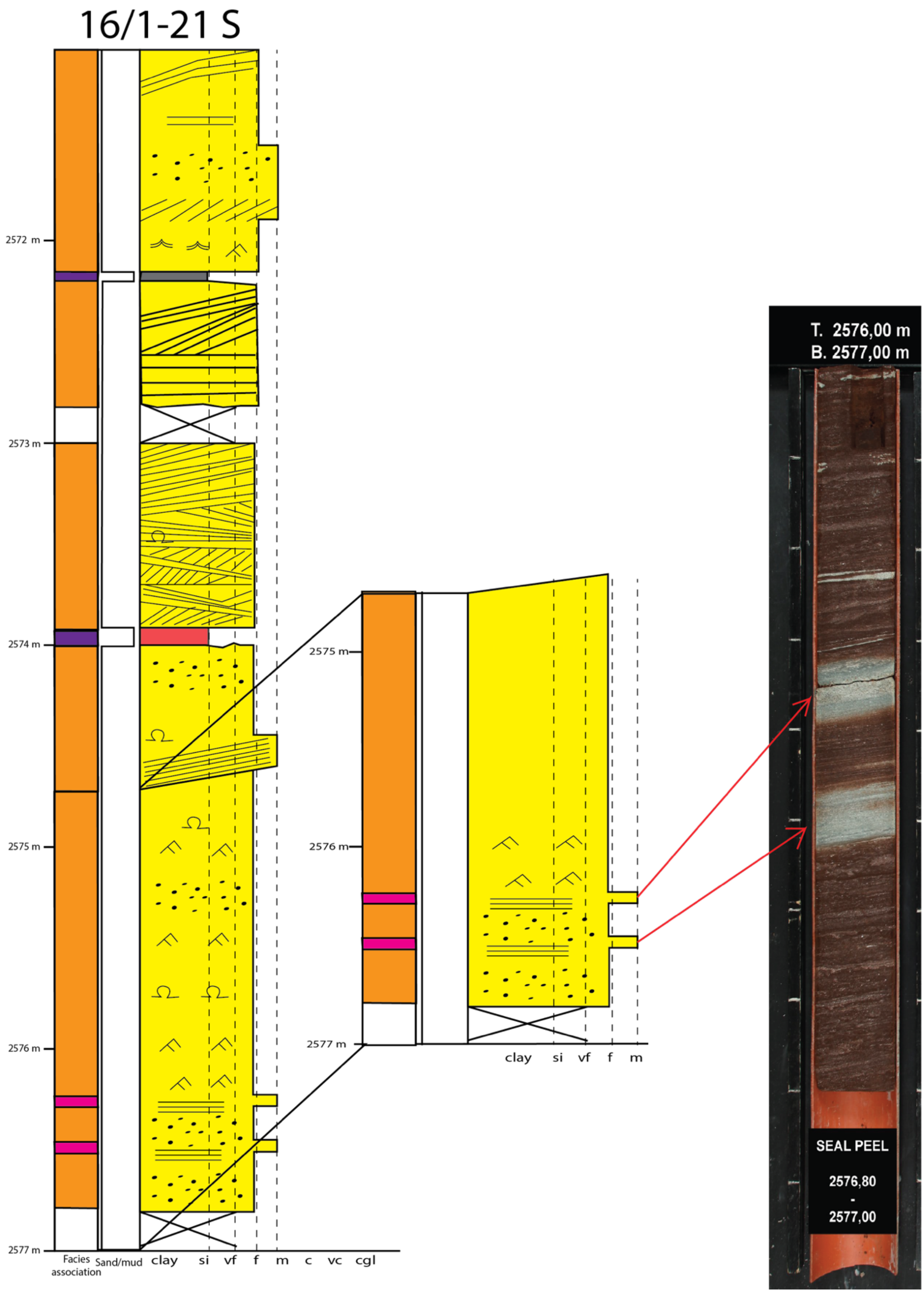


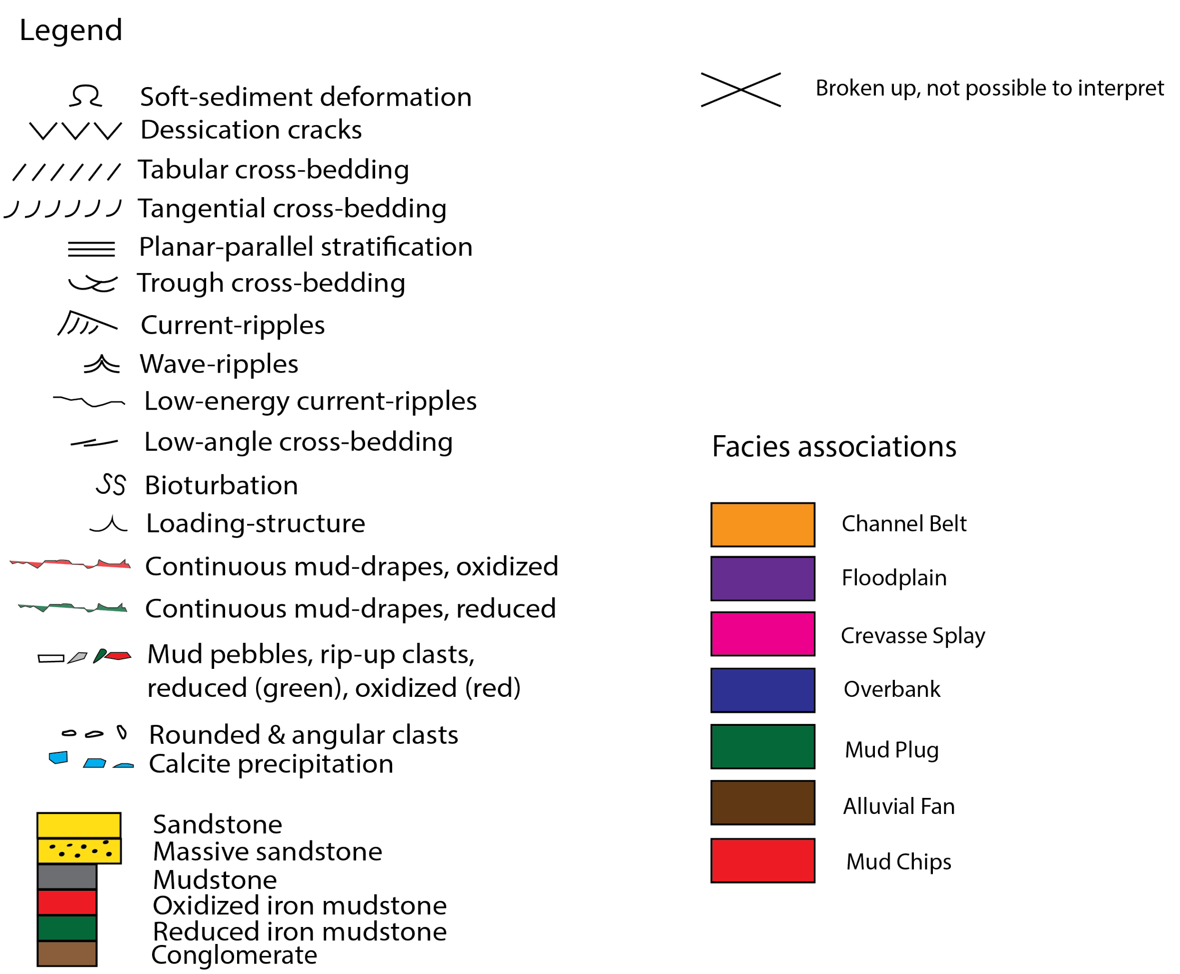
Figure 4.11: Log from 16/1-21 S. Enhanced two meter interval from the core-log displaying crevasse splay deposits. Image of medium grainsized crevasse splays from the core.

4.3.5 Facies Association SAF – Skagerrak Alluvial Fan

This facies association consists of sub-angular to rounded clasts that vary in size from granular (2-4mm) to cobble (64-256mm) sized clasts (Boggs, 2014). This facies association is not classified into the Braid Plain Formation by Aker BP but will be taken into account in this thesis because of the similarity in depositional environments to the Hornelen Basin.

The rocks fragments are granitic within a muddy matrix and some sparse large clasts. There is no sign of grading or bioturbation in this meter of the core (Fig 4.12).

Because of the rounded clasts in a size variation from granular to cobble-sized (Fig 4.12), with a muddy matrix this facies association is interpreted to be a conglomerate from an alluvial fan (Aker BP, unpublished).



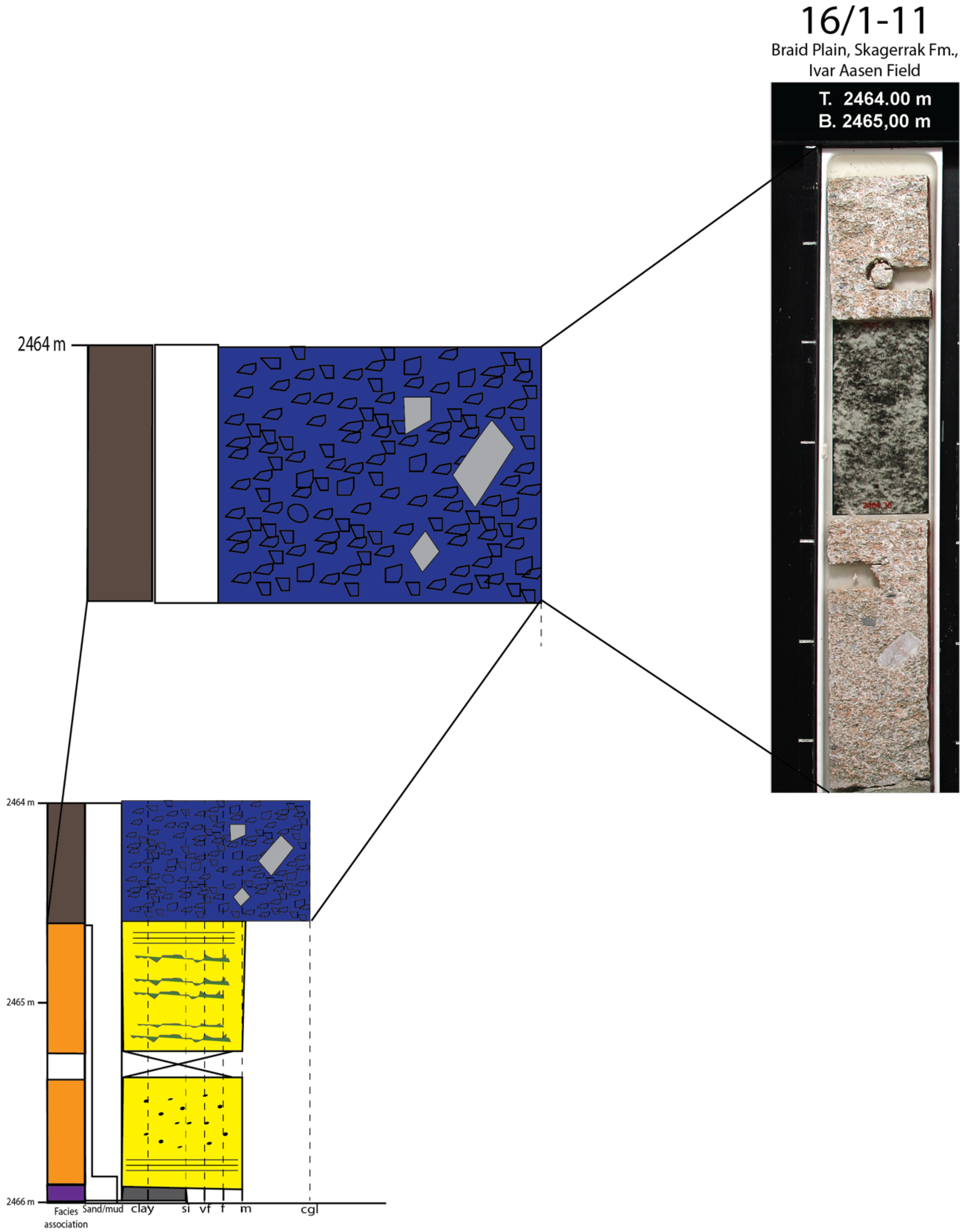


Figure 4.12: Log from 16/1-11. Enhanced section of the Alluvial Fan deposits with image showing the color variation of the clasts in the Alluvial Fan in the Skagerrak Formation.

4.4 Petrological data

The aim of studying thin sections from the Hornelen Basin is because the Devonian basin has undergone a lot of tectonic activity over a long period of time and therefore the grain size can be difficult to interpret by eye sight straight from the outcrops. Thin sections can help determine the grain size, especially when considering silt or mud sized grains.

A total of 12 thin sections, collected from the field work in The Hornelen Basin were analyzed for a more detailed interpretation of the lithological grain size. The samples were taken from interpreted silt-stone, sandstone and conglomerates in logs H1, H2, H4 and H7. A more detailed location and description is listed in table 4.1 and in the following chapter. The selected thin sections below represent the differences within the study area of the Hornelen Basin.

4.4.1 Mineralogical description

Thin sections of samples from the Hornelen basin were petrographically interpreted using an optical microscope. The microscope was connected to a computer to capture images of the thin sections. A selection of pictures from the results are presented in Table 4.1. A complete table of the images of thin section can be found in the appendix.

Three lithologies were studied in the thin sections. Sandstone, mudstone and conglomerate. The sandstones consist mainly of quartz, rock fragments, mica minerals and some traces of plagioclase.

In log H1, a total of six samples from 1m, 2m, 5m, 13m, 26m and 28m were taken using a geological hammer. From Table 4.1, five samples have small variations in grain size, grain shape and lithology. The sixth sample, from 26m, shows a larger grain size and a different lithology.

Sample H1.1 displays a mud grain size, where the grains are closely spaced and a low porosity. The fragments have a large color variation and the minerals are hard to distinguish in the microscope. The sample is therefore interpreted to be from a mudstone. In the cross polarized light the fragments that has a lack of color could be quartz minerals.

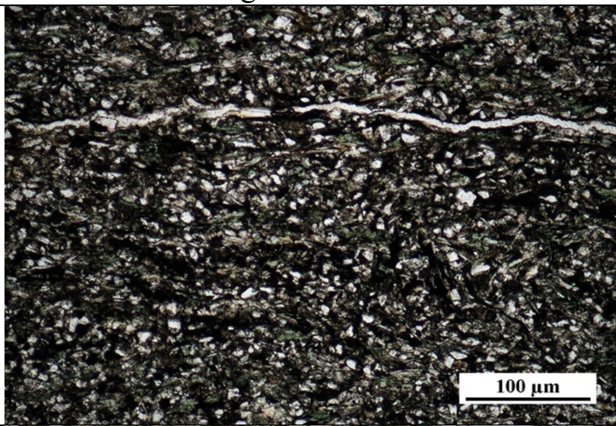
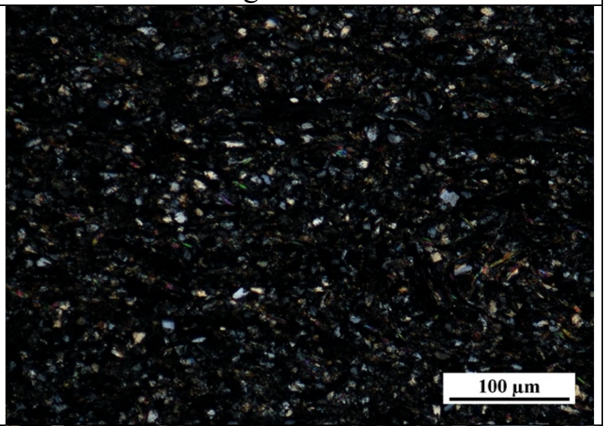
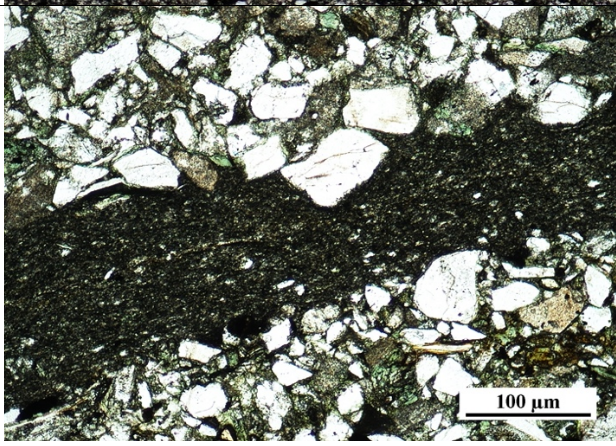
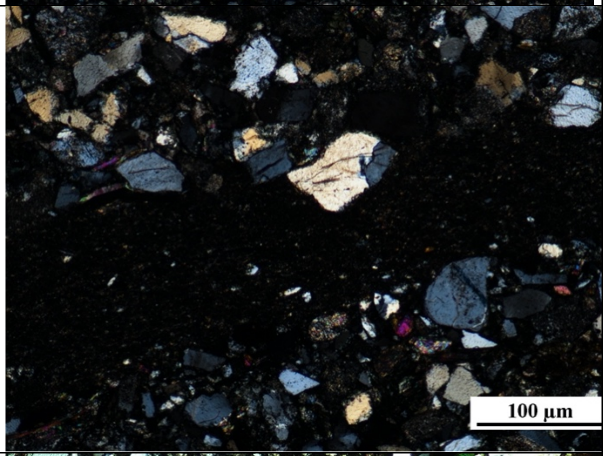
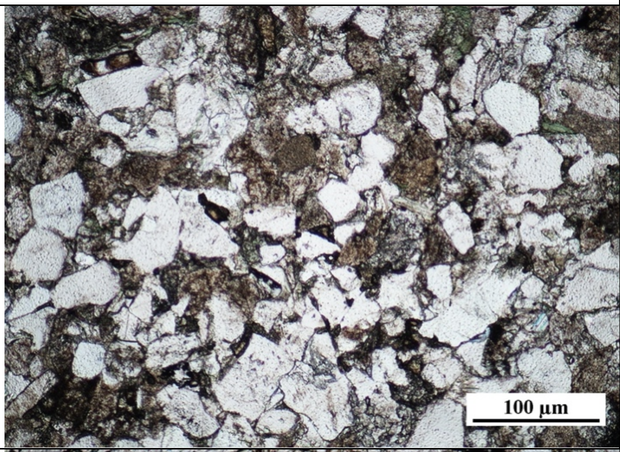
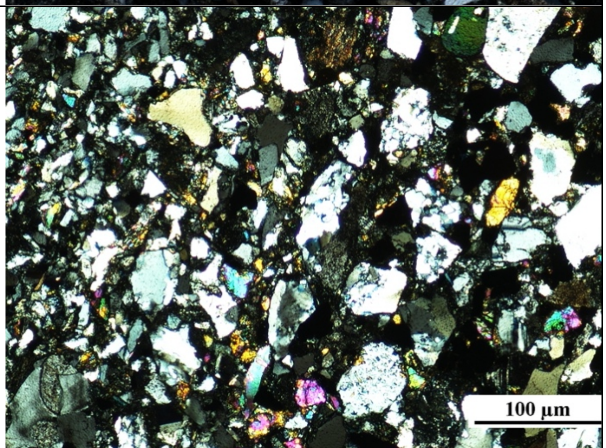
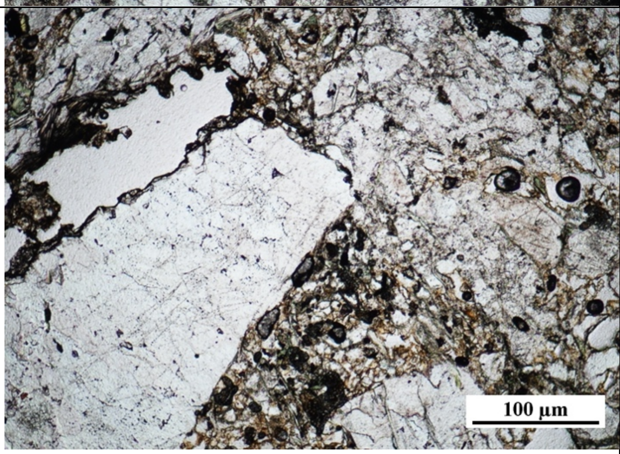
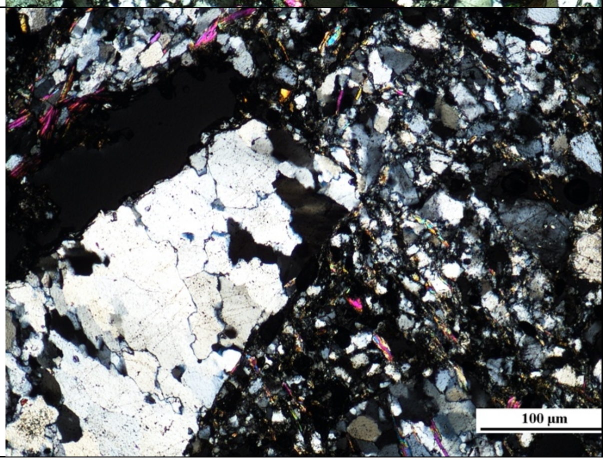
Sample H.1.5 shows rounded grains that vary in size from very fine to medium sized. Distributed around a patch of mud sized, darker fragments. Quartz, feldspar, and rock fragments are found in the sample and is therefore interpreted to be from a very fine to medium sandstone.

Sample H4.2 is taken from log H4 which is interpreted to be a very fine grained sandstone. Large proportions of quartz and plagioclase and rock fragments are present in the sample. Green secondary minerals are visible. Previous studies have shown that there is an abundance of chlorite minerals in this area because the basin has been affected largely by tectonics and therefore undergone a low grade metamorphism (Anders et al, 2022).

Sample H7 contains large fragments of quartz surrounded by a mass of undistinguishable minerals interpreted to be mudstone fragments. This sample is taken from log H7 which displays a large amount of conglomerates surrounded by silt and very fine sand.

Samples from sandstone and mudstone show a large difference in porosity. The high proportions and non-rounded fragments of quartz minerals indicate an immature sandstone.

Table 4.1: Images taken from the thin sections created from samples collected during fieldwork in the Hornelen Basin.

Log	m	Plane Polarized Light	Cross Polarized Light
H1.1 Mud (silt)	1m		
H1.5 Sand	26m		
H4.2 Sand	8m		
H7 Cong	1m		

4.5 Virtual Models of The Hornelen Basin

This chapter presents the virtual outcrops constructed from the UAV in the Hornelen Basin, based off of log H1 and log H2. The chapter focuses on two outcrops representing the trends found in the Hornelen Basin.

Both models (Fig 4.13 & Fig. 4.14) are presented without interpretations, and then blue lines are added where the interpreted mud-layers are located. The aim of this chapter is to give an understanding of the fluvial architecture, focusing on the geometries of the mud-layers, represented in the succession. How the virtual outcrops fit into the large scale architecture of the fluvial system, by focusing on small scale structures and the trend of the lateral and vertical variations of the mud-stone depositions. The interpretations in the virtual outcrop are correlated with the data collected in the field, and therefore the logs taken where the virtual outcrops are located, will be represented in the figures.

The two virtual outcrops are not divided into units because of the relative small size and no relevant depositional variation, so both models will each be represented as one unit. The virtual models are discussed in chapter 5.1.

4.5.1 Virtual Model A

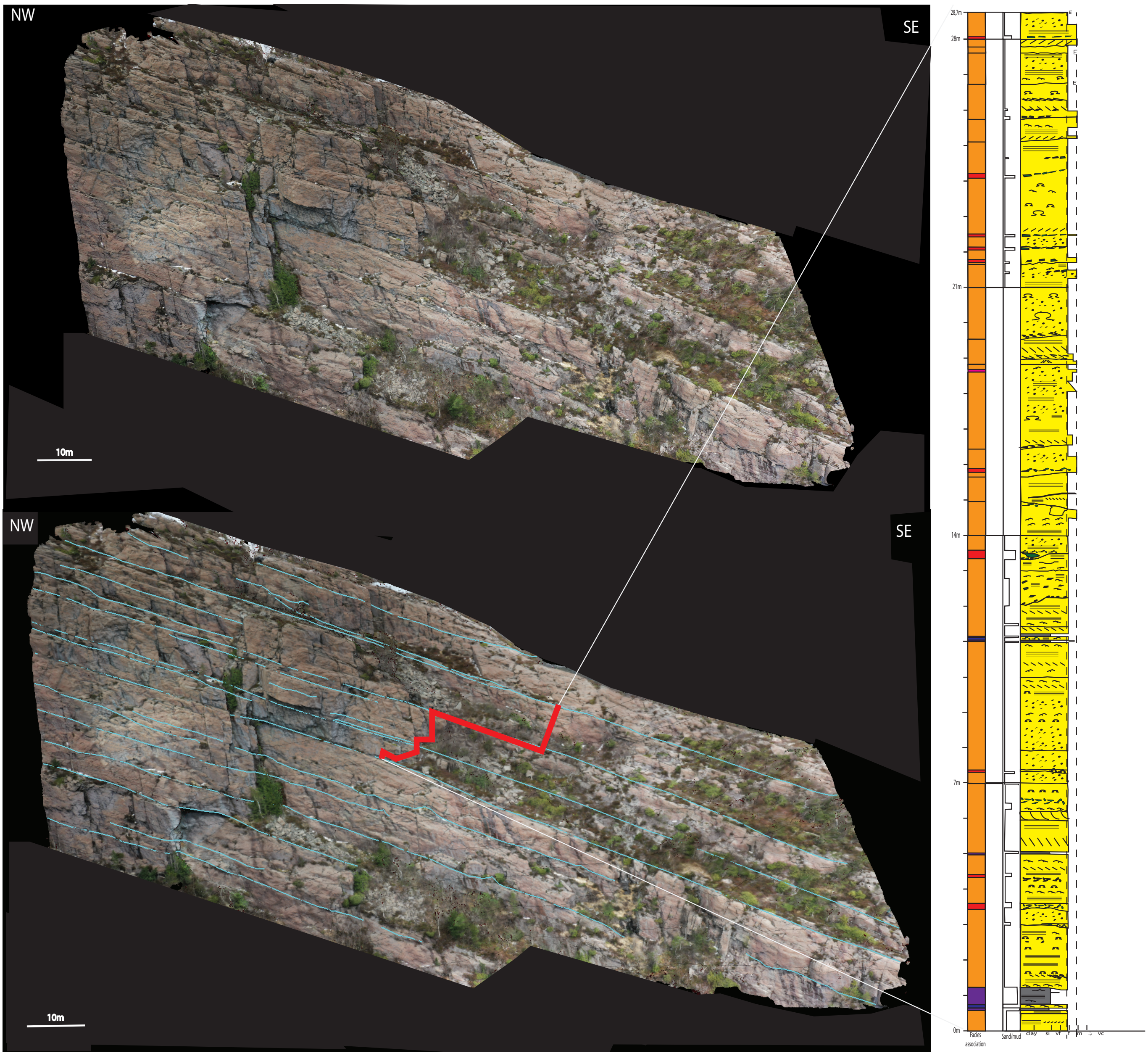


Figure 4.13: Virtual Model A with log H1 (Fig 4.1) taken from the fieldwork in the Hornelen Basin. Virtual outcrop A is 146mx80m. Blue lines are interpreted mudstone layers and red line show the out-trace of where log H1 was taken.

4.5.2 Virtual Model B

Figure 4.14 shows a 130 m x 22 m outcrop of the typical sandstone deposits of the Hornelen Basin. Model B is located approximately 100 m southwest of model A.

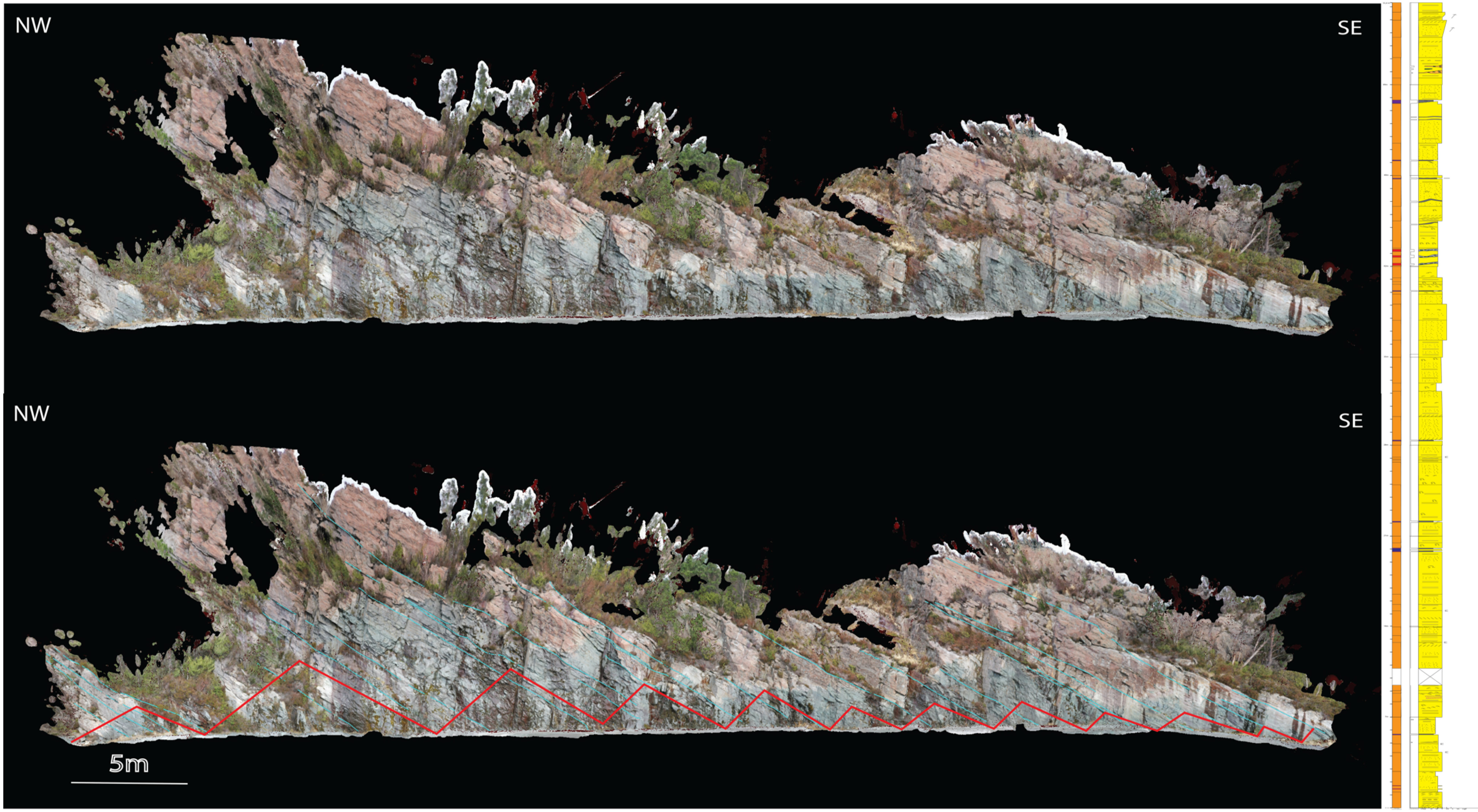


Figure 4.14: Virtual Model B with Log H2 taken from fieldwork in the Hornelen Basin. Virtual outcrop B is 130mx22m and the blue lines drawn on the lower picture presents the interpreted mudstone layers. Red trace is where log H2 (Fig 4.1) was taken.

5.0 Discussion

The purpose of this chapter is to elaborate and discuss the results presented in the previous chapter. This is done by 1) Elaborating and understanding the sedimentology and fluvial system and the Hornelen Basin and discussing the lateral and vertical variability of the system, 2) Comparing the Hornelen Basin with the Skagerrak "Braid Plain" Formation, focusing on lateral extending mud layers and fluvial deposition, 3) Findings on the Skagerrak "Braid Plain" Triassic Formation after studying outcrops and systems in the Devonian Hornelen Basin, and 4) Discussing the reservoir properties of the Braid Plain Formation from models and net to gross values.

5.1 What can be said about the sedimentology in the Hornelen Basin

Sediments logged in this thesis in the Hornelen Basin range from mudstone to conglomerates. The majority of the sediments are fine grained sandstone (Fig 4.1).

From chapter four, sedimentary unidirectional structures as high and low scaled cross-stratification and plane parallel stratification are dominating in the sandstone successions. The tabular cross stratification is around 20-30 cm, but sometimes range up to 1 m. Larger scale cross stratification is found towards the south of the basin where the conglomerate successions are present. Current ripples (low scale cross-stratification) are clearly developed and show evidence of strong currents because of their asymmetrical shape (Fig 5.1).

In the mudstone layers, desiccation cracks containing fine grained sandstone are sparse, but visible. Most mudstone layers contain no structures, but layers with structures contain current ripples in a western dominating direction. Mud clasts are present in mudstone layers towards the southern part of the basin (Log H6, Figure 4.1).
Soft sediment deformation is, in this study, strongly present throughout the study area, with an exception of the conglomerate succession in the southern part of the basin. The sandstone layers are thought to have different mechanical properties directly after or during deposition, and therefore responded differently to miscellaneous loading of sediments (Bryhni, 1963).

Transport direction of the sediment infill of the Hornelen Basin is from the eastern, western and southern margins (e.g.: Osmundsen & Andersen, 2001; Steel et al., 1977). From this thesis, the

current ripples display an east and west direction, the latter being the dominating direction. This observation agrees with earlier studies of the paleocurrent directions that are thought to be WSW (Steel et al., 1977; Steel and Aasheim, 1978; Steel et al., 1985; Anderson & Cross, 2001). Sediments entered the basin and were carried by fluvial channel belts from the east (Andersen & Cross, 2001) longitudinally following the axis of the Hornelen Basin (Bryhni et al., 1964). The fluvial channel belts, in this study, show braided streams depositing sandstones in the axial part of the basin. Floodplain deposits are found in intervals between the channel belts and display evidence of cycles of flooding in the basin.
From figure (geometry from chap.4) the geometry of the virtual outcrops display a pattern of thin (0,01 cm – 60cm) mudstone layers in between the dominating channel belts. The channel belts vary in thickness (Fig 4.1) and shown in the virtual outcrop, (geom from 4) relatively thin channel sequences that coincides with a braid plain fluvial system. Virtual outcrop A and B are located in the axial basin, and agrees with earlier studies that a braid plain fluvial system was the dominating depositional system in the axial Hornelen Basin (Steel et al., 1977 & 1985; Anderson & Cross, 2001; Anders et al., 2002).

The Hornelen Basin in North Western Norway displays several 100m thick, large-scale stratigraphic cycles, that record sediments deposited from alluvial fans, braid plain fluvial systems and lake deposits (Anderson &Cross, 2001, Steel et al, 1977, Wilks & Cuthbert, 1994). The preserved fill in the basin is derived from the erosion of the Caledonian highlands (Andersen & Jamtveit, 1990; Braathen et al., 2002; Andersen et al., 1991).

Evident from the virtual outcrops (Fig 4.13 and Fig 4.14) and summary of facies associations, the vertical and lateral observations show that the thickness of sandstone successions are constant and do not change throughout the successions.

Facies of the braid plain system in the Hornelen Basin, also described by previous workers (Steel and Aasheim 1977; Pollard et al. 1982; Nemec et al. 1984; Folkestad 1995), consist of dominantly trough cross-stratified medium sandstone representing channel-fill and bar deposits of braided rivers. Most floodplain facies from this study and by previous investigators (Steel et al., 1985) consist of thin-bedded mudstones.

It is reasonable to suggest that the studied deposits in this thesis stem from braid plain, and because of flood plain deposits found in Figure 4.3 from the axial part of the Hornelen Basin.

From the virtual models (Fig 4.13 & 4.14; and 5.1) sedimentary lithofacies and facies associations together with past studies it is reasonable to conclude that this system is a fluvial braid plain system, more precise the axial part of a braid plain system.

Virtual outcrop A and B (Fig 4.13& Fig 4.14; and Fig 5.1& 5.2) were constructed to show geometries and the lateral variations of mudstone layers. From calculations of the lateral extent of the mudstones vary and only a fraction of layers extend throughout the outcrops. Not all mudstone layers can be correlated with logs taken in the same outcrop due to thick vegetation and steep hill-sides in outcrop B. Log H2 in outcrop B (Fig 5.2) is affected by blasting from road work which made structures and layers hard to distinguish. Log H1 in outcrop A (Fig 5.1) is taken on a steep hill-side which may have affected the vertical context of the log. The mudstone layers are more abundant in the virtual outcrops than in logs H1 and H2 partly due to the difficulties when collecting the data. Heterogeneity of the studied deposits in this thesis is low, as sandstone is the clearly dominating grain size. There is no evidence of bioturbation in this study, but earlier studies (Steel et al., 1977; Pollard et al., 1981) have found traces of bioturbation in the basin. The lack of bioturbation, in this study may be due to the dominating soft sediment deformation affecting the sandstones.
How the lateral extent of mudstone layers affect the fluid flow and reservoir properties will be discussed in chapter 5.5.

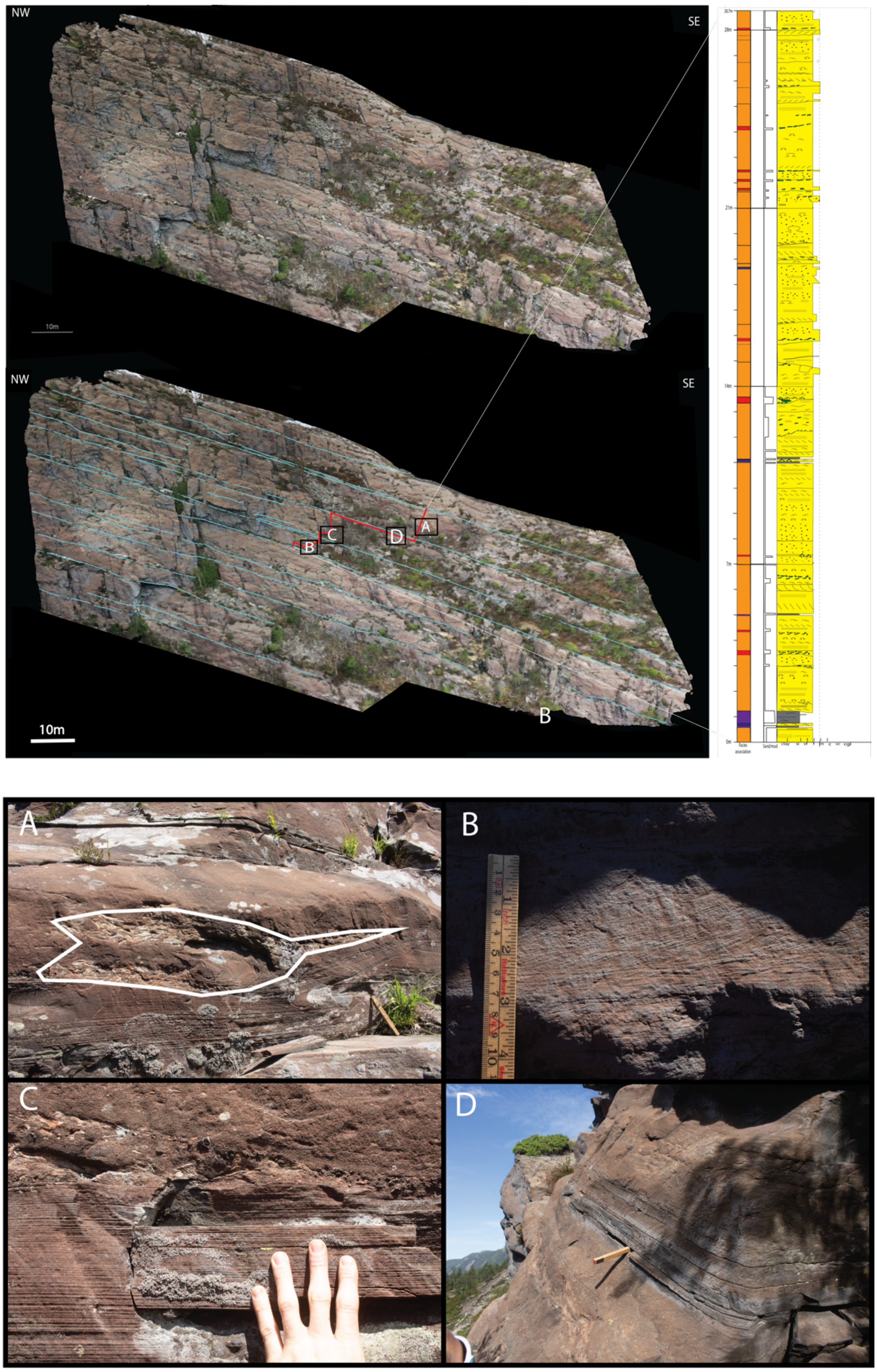


Figure 5.1: Virtual outcrop A (Fig 4.13) from chapter 4 with corresponding log (H1 traced in red). A) Mud-chips layer in surrounding massive sandstone in location A on outcrop, ruler for scale. B) current ripples in very fine grained sandstone with ruler for scale. C) Plane parallel stratification with overlain mud-chip layer, in fine grained to medium grained sandstone, with hand for scale. D) Large-scale plane parallel stratification where the ruler is located with over- and underlain massive sandstone.

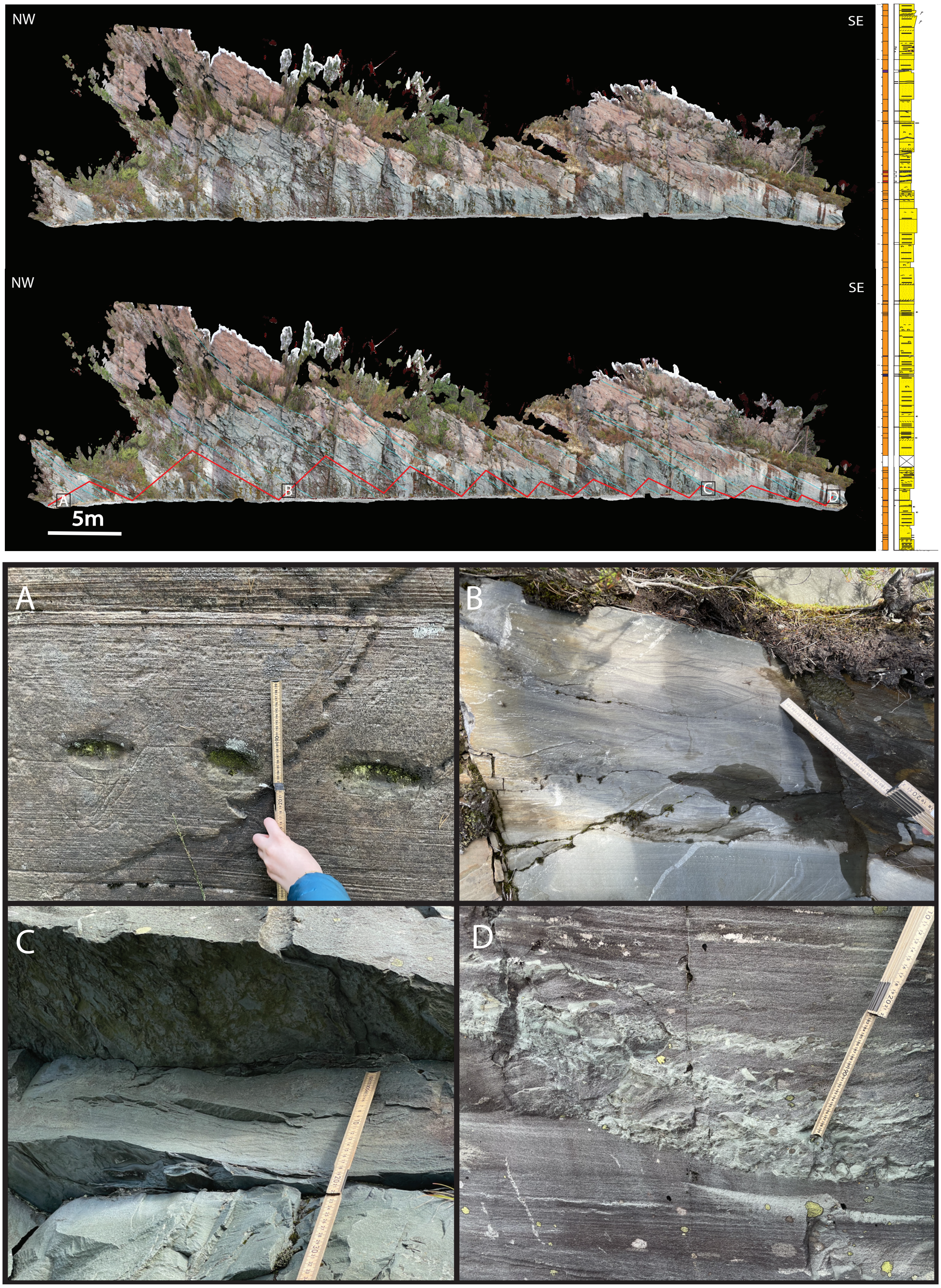


Figure 5.2: Virtual Outcrop B (Fig 4.14) with corresponding log (H2) traced in red. A) Plane parallel stratification in sandstone with evidence of eroded mud clasts. B) Climbing ripples. C) Thin mudstone layer in surrounding fine grained sandstone. D) Mud-chips layer in surrounding finer sandstone.

Sandy braided-river deposits are commonly described as sheetlike (high width-to-thickness ratios), with good porosity and permeability, and particularly high net-to-gross ratios (e.g., Miall, 1977, 1978; Martin, 1993; Collinson, 1996). These characteristics make them potentially excellent oil, gas, and groundwater reservoirs.

Interpreting and modeling braided-fluvial reservoirs rely on constraining the lateral dimensions of the reservoir, porosities and permeabilities as a function of grain size, and internal reservoir architecture (e.g., Bridge and Tye, 2000). Within an individual reservoir, some of these properties can be measured from cores, wire-line logs, two- and three-dimensional seismic data, and flow between injector and producer wells. However, it is difficult to confidently extrapolate such data to new reservoirs because individual reservoirs are as unique as the braided rivers that formed them, varying greatly in terms of scale, discharge, sediment load, and geologic history.

Within sandy braided-fluvial reservoirs, permeability variations caused by fine-grained intervals are particularly challenging complications for reservoir characterization and development. These low-permeability units can compartmentalize reservoirs and critically impede fluid flow and sweep efficiency (e.g., Weber, 1982; Martin, 1993; Brayshaw et al., 1996). Unlike deposits of single-thread rivers, which typically consist of channel-sandstone bodies encased in flood-plain mudstones (Allen, 1974), fine-grained material in braided-fluvial systems is commonly deposited within the active channel, generating sandstone-dominated successions with small mudstone intervals intercalated throughout the deposit. Furthermore, although braided-river deposits are typically considered sand dominated, the abundance of muddy material present in modern braided rivers and in ancient braided-river deposits can be high. Consequently, much work has focused on understanding the geometry and distribution of impermeable and low-permeability mudstone bodies in sandy braided-river deposits.

From chapter 4, virtual outcrop A (Fig 4.13) displays a total of 24 lateral extending mud layers in between channel belts (HCB).

Figure 5.3: Log H1 and Log 16/1-11 with lines extending from mudstone layers in H1 to similar mudstone layers in 16/1-11.

5.2 What can be said about the sedimentology in the Braid Plain informal member in the Ivar Aasen Field

The dominating sediments observed in the Braid Plain stratigraphical interval are very fine to coarse grained sandstone, with multiple phases of coarse- and fining-upwards sequences. The dominating structures in the sandstones are cross and trough cross stratification, along with plane parallel stratification. Current ripples are present, varying in two directions parallel to the evident unidirectional current shown from the cross stratification.

The color front variations change at impermeable beds in cores 16/1-11 and 16/1-21S were caused by interaction (reduction /oxidation), or dissolution percolating through the rocks after disposition (Fig 5.2).

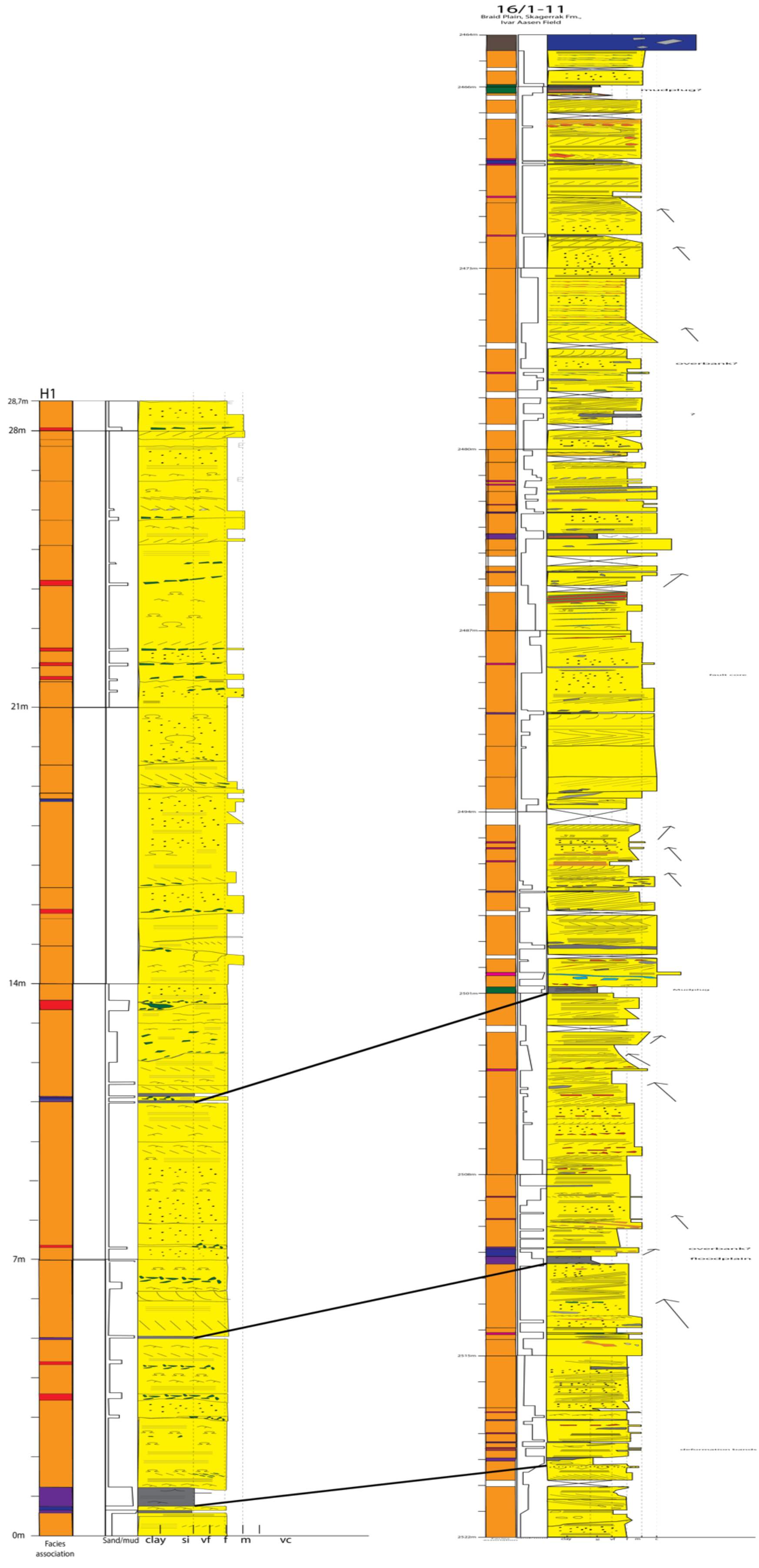
In chapter 4, the facies associations are dominated by unidirectional current structures as low and high scale cross stratification, and plane parallel stratification well preserved in the sandstones. The Channel Belt facies association is dominating in Braid Plain and makes up for over 90% of the studied deposits. This succession must have been exceptionally large or have had a very low preservation of floodplain mudstones. In this thesis, the Braid Plain informal member is interpreted to be from a system that displays large bodies of sandstone with a small percentage of mudstone. Together with sedimentary structures from unidirectional currents these observations coincide with a braided river system dominating a local area of the Ivar Aasen Field. Low and high scale cross stratification and planar parallel stratification, with sparsely preserved floodplain deposits are found in braided river systems (Boggs, 2014).

5.3 Comparison of the Hornelen Basin and Skagerrak- Braid Plain stratigraphical interval

The Hornelen Basin and Braid Plain display the same facies associations. Channel Belt, Floodplain Muds, Floodplain Sands, Mud Chips, and Alluvial Fan. The deposits in these two fluvial systems are very similar and display similar facies lithologies. To compare these systems, focusing on facies associations and data from field and core logs will be the main source of comparison.

Similar:

Bioturbation is in mudstone layers is sparse in both systems. In the Braid Plain stratigraphical interval, a higher level of bioturbation is observed throughout the mudstone layers. This can indicate that there have been longer periods of flooding with a more standstill body of water than in the Hornelen Basin.



H1
28,7m
28m
21m
14m
7m
0m
Facies association
Sand/mud
clay
si
vf
f
m
vc
16/1-11
Braid Plain, Skagerrak Fm.,
Ivar Aasen Field
2464m
2466m
mudplug?
overbank?
overbank?
floodplain

Both systems display characteristics of a braided river system, with minimal preservation of floodplain mudstones (Fig 5.3). The axial Hornelen Basin was dominated by braided fluvial channels in the Devonian period, in which the climate was affected by more rainfall over longer periods of time than in the Triassic period. The Triassic period, in the North Sea, displayed more events of ephemeral streams and flash floods in a semi-arid climate (McKie, 2014; Aker BP, unpublished). Alluvial fan deposits are thought to be washed down from nearby hills, possibly from the Utsira High. Alluvial fan deposits are also present in the Hornelen Basin, located at the southern margin of the basin in this study. These deposits are concluded, from earlier studies (e.g. Steel et al., 1977;1985, Anders et al., 2022) to be deposited when tectonic processes pushed the basin westward.

The studied deposits in this thesis coincide with the climate in the two periods. McKie, 2014, explains that the Triassic period in the southern North Sea displays little evidence of fluvial activity and that standing bodies of water were not a dominant feature of the Triassic landscape in the area. Towards the central North Sea, there is evidence of a decrease in paleoflow termination of the fluvial systems. This is explained from a decrease in sandbody thickness and an increase in splay facies related to the channel-confined deposits. Although there are studies on fluvial systems from the Triassic period in the North Sea, very few mention braid plain systems as a source of fluvial deposits. A question that arises from the findings in this thesis may be that some of these fluvial systems could possibly be braid plain systems but are not concluded as such. From this knowledge, the system studied in this thesis, the Braid Plain stratigraphical unit is thought to be a local braid plain fluvial system, located in the Triassic interval of the Skagerrak Formation in the Ivar Aasen Field.

The geometry of the Hornelen Basin channel belts is more difficult to see and study than Braid Plain geometries, because outcrop studies displayed less visible details, such as erosion surfaces and channel thicknesses, than core logging. There are more visible erosion surfaces that help separate and measure channel thickness in the cores from Braid Plain than found in the outcrops in the Hornelen Basin (Fig 5.3).

Channel

5.4 Geometries in reservoir properties in the Skagerrak Formation in the Braid Plain stratigraphical interval

Fluvial reservoirs are inherently heterogeneous and they typically have a complex connectivity between sand bodies of limited predictability and have highly variable reservoir properties (McKie, 2011). Braid Plain reservoirs on the contrary display a low heterogeneity and a lesser complex connectivity between the sand bodies and mudstone layers (Lynds & Hajek, 2006). Sandy braided-river deposits with high net-to-gross ratios are attractive reservoirs but internal lithologic heterogeneities such as mudstone deposits displaying low permeability, can act as barriers when predicting flow in such reservoirs (Lynds & Hajek, 2006; Jones & Hartley, 1993). Potential permeability barriers in the Skagerrak - Braid Plain can be floodplain deposits or dense mud-chips layers.

The net to gross value, calculated from the sedimentological cores in this study are 94% in the Hornelen Basin outcrops while the values for Braid Plain are 91%. Well 16/D-4 was drilled in 2020 and the observations and studies (Aker BP, unpublished) show that the core was less permeable than first assumed because of clay mineralization. This is an important factor to consider when drilling wells and cores in the subsurface. The sandstones are predicted to have a high permeable and porosity value, but because of the clay mineralization it is not the case. It is a factor to keep in mind when using the Hornelen Basin fluvial system as an analogue to the Braid Plain stratigraphical interval in the Ivar Aasen Field.

Lateral mudstone layers can possibly contribute to better flow in a reservoir by reducing the possibilities of thief zones and improve the water pressure flow when producing in a hydrocarbon field. In figure 5.3 a conceptual model of reservoir flow is constructed from outcrop A in the Hornelen Basin. Thief zones are uneven scouring of the reservoir from the injected water, which can result in a higher possibility of flooding of highly permeable layers. Identifying and understanding thief zones is crucial to reservoir descriptions and production performance (Su et al., 2021). The lateral extending mudstone layers in the Hornelen Basin are studied to help understand the mudstone layers in Braid Plain. It is concluded in this thesis that the mudstone layers in Braid Plain are similar in thickness and lateral extent and therefore may display the same characteristics of thief zones possibilities in a reservoir.

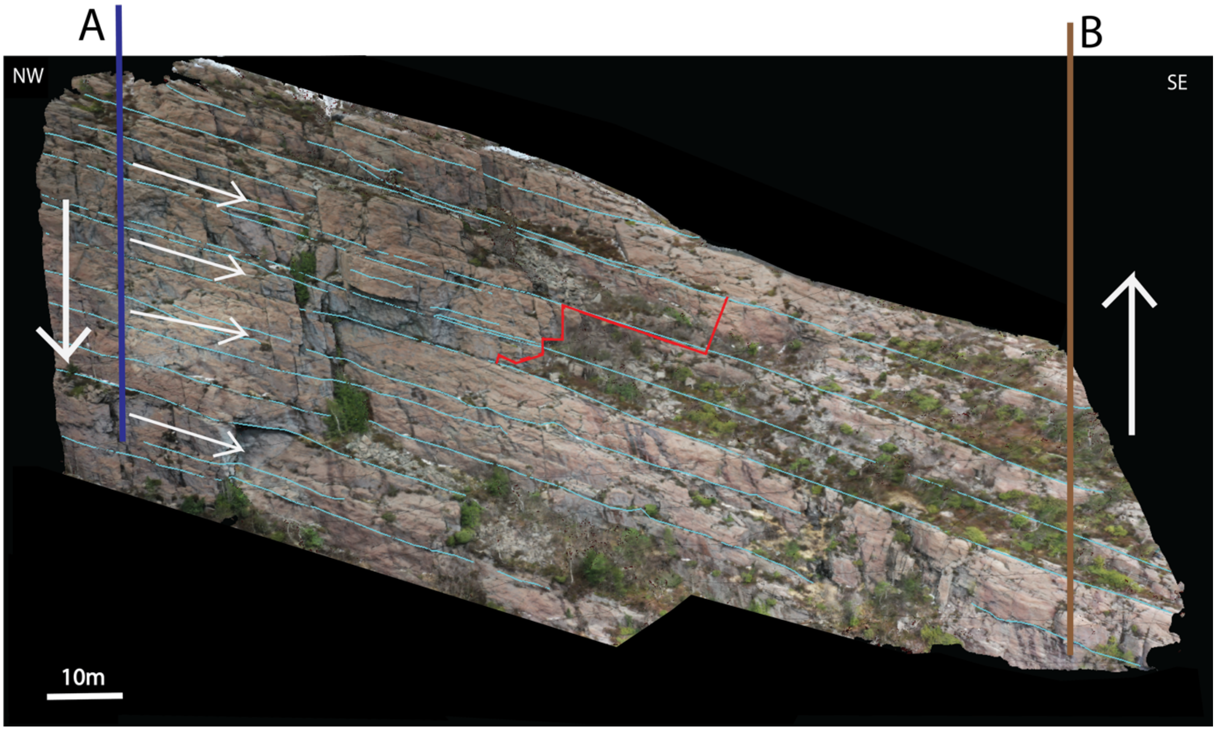


Figure 5.4: Conceptual model of a reservoir with injection and production wells in the outcrop from the Hornelen Basin. A) water injection well and B) production well. White arrows indicate the direction of fluid flow in the reservoir.

The overall study of sedimentological aspects from the axial Hornelen Basin display a low heterogeneity system, with a high net-to-gross value. The Hornelen basin is a great analogue for the Braid Plain stratigraphical interval in the Skagerrak Formation. Heterogeneity in Braid Plain is low and with a high net-to-gross value this system should be a great reservoir for hydrocarbon production.

Fluvial deposits from braid plain systems typically form less heterogeneous reservoirs than most other depositional settings (Lynds & Hajek, 2006). Connectivity of fluvial channels is focused on because this primarily determines the level of hydrocarbon recovery. In sandy fluvial reservoirs, connectivity is a smaller issue and therefore the focus shifts to the internal heterogeneity related to deposition and preservation of the fluvial deposits. The Triassic Braid Plain is an example of a sand-rich, dryland fluvial reservoir that would, prior to production, be regarded as having no issues relating to depositional architecture (McKie, 2011).

6.0 Summary and Conclusions

By investigating the Hornelen Basin in Western Norway, this thesis has characterized facies and architectural elements of a braid plain fluvial system. The Braid Plain stratigraphical interval in the Skagerrak Formation from the Ivar Aasen Field has been investigated in the same manner and is concluded to be a braid plain system, similar to the axial Hornelen Basin. The axial Hornelen Basin is therefore concluded to be a great analogue to Braid Plain. Sedimentological hydrocarbon properties in Braid Plain have been studied based on the outcrop analogue. From the results and discussions displayed in this thesis, the following conclusions are made:

- The Hornelen Basin consists of sandy fluvial channels and thin floodplain deposits that display low degree of internal and architectural variations. The lateral occurrence of mudstone layers is continuous throughout the study area and the fraction of mudstone does not change upwards in the succession.
- The Braid Plain stratigraphical interval deposits are similar to the Hornelen Basin deposits. The fluvial sandstones display a higher occurrence of cross stratification and the floodplain deposits occur in thicker intervals. Sandy fluvial channels and floodplain deposits in this system display similar architecture and internal variations.
- Comparing the two similar braid plain systems and extracting information from the virtual outcrop in the Hornelen Basin, implies that the Braid Plain stratigraphical interval can act as a high quality hydrocarbon reservoir. The lateral extension of mudstone layers can contribute to reducing the possibilities of thief zones during field production.
- Comparisons from the Devonian analogue from the Hornelen basin shows that Braid Plain can be a high quality hydrocarbon reservoir and the lateral extension of the mudstone layers can contribute to reducing the possibilities of thief zones during hydrocarbon production.
- Sand dominated systems as fluvial deposits from a braid plain system typically form low heterogeneity reservoirs and are assumed to be associated with limited production issues.

6.1 Future research

This study suggests these points for a further detailed investigation:

- A more detailed sedimentological study of braid plain systems in the northern North Sea, not just the local system in the Ivar Aasen Field. This would contribute to better understand the local braid plain system in the Skagerrak Formation.
- Further investigation of the geological setting in the northern North Sea.
- Create a production simulation of the results from this thesis.
- Investigate Triassic fluvial systems in other fields in the North Sea and compare to Braid Plain to understand the lateral extent of Braid Plain.

References

Fossen, H. (2010). Extensional tectonics in the North Atlantic Caledonides: a regional view. *Geological Society,* 335, 767-793.

J.E. Pollard, R.J. Steel, E. Undersrud, (1982). Facies sequences and trace fossils in lacustrine/fan delta deposits, Hornelen Basin (M. Devonian), Western Norway, *Sedimentary Geology,Volume 32,* (1–2) 1 63-87.

Phillips, T. B., Fazlikhani, H., Gawthorpe, R. L., Fossen, H., Jackson, C. A.-L., Bell, R. E., Faleide, J. I., & Rotevatn, A. (2019). The influence of structural in- heritance and multiphase extension on rift development, the Northern North Sea. *Tectonics, 38*(12), 4099–4126.

R. J., Steel, S, Næhle, H, Nilsen, S. L. røe, A. Spinnangr. Coarsening-upward cycles in the alluvium of Hornelen Basin (Devonian) Norway: Sedimentary response to tectonic events. *GSA Bulletin* 1977;; 88 (8): 1124–1134.

Vegard V. Vetti, Haakon Fossen. (2012) Origin of contrasting Devonian supradetachment basin types in the Scandinavian Caledonides. *Geology* ;; 40 (6): 571–574.
Steel, R., Siedlecka, A., and Roberts, D., 1985, The Old Red Sandstone basins of Norway and their deformation: A review, inGee, D.G., and Sturt, B.A.,eds., The Caledonide orogen—Scandinavia and related areas: John Wileyand Sons, p. 293–315

Nichols, G. and Fisher, J. 2007. Processes, facies and architecture of fluvial distributary systemdeposits. Sedimentary Geology, 195(1-2),75-90

McKie, T. 2014. Climatic and tectonic controls on Triassic dryland terminal fluvial system architecture, central North Sea. In *From Depositional Systems to Sedimentary Successions on the Norwegian Continental* Margin (eds Martinius, A. W., Ravn, R., Howell, J. A., Steel, R. J. & Wonham, J. P.), pp. 19–58. International Association of Sedimentologists, Special Publication 46.

S.K. Davidson, S. Leleu, C.P. North, (2011). Architecture and behavior of dryland fluvial reservoirs, Triassic Skagerrak Formation, Central North Sea. From River to Rock Record, *SEPM Special Publication, 97* 189-214

Weissmann, G.S., Hartley, A.J., Nichols, G.J., SCuderi, L.A., Olsen, M., Buehler, H., AND Banteah, R., 2010, Fluvialform in modern continental sedimentary basins: distributive fluvial systems: Geology, v. 38, p. 39–42.

Andersen, & Jamtveit, B. (1990). Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord Region of western Norway. *Tectonics.*, *9*(5), 1097–1111.

McClay, Norton, M., Coney, P. *et al.* Collapse of the Caledonian orogen and the Old Red Sandstone. *Nature 323,* 147–149 (1986).

Anders, M.H., Christie-Blick, N., and Templeton, J.A., 2022, Tectonic evolution of the Devonian Hornelen basin of western Norway, in Koeberl, C., Claeys, P., and Montanari, A., eds., From the Guajira Desert to the Apennines, and from Mediterranean Microplates to the Mexican Killer Asteroid: Honoring the Career of Walter Alvarez: Geological Society of America Special Paper 557, 223–238.

Allen, J. R. L., (1982). Sedimentary Structures: Their Character and Physical Basis: Developments in Sedimentology, 30A. Elsevier, Amsterdam, 593 p.

Fazlikhani, H., H. Fossen, R. L. Gawthorpe, J. I. Faleide, and R. E. Bell (2017). Basement structure and its influence on the structural configuration of the northern North Sea rift, *Tectonics, (36),* 1151–1177,

Gee, D. G. (1975). A tectonic model for the central part of the Scandinavian Caledonides. *American Journal of Science, 275*(A), 468-515.

Fossen, H. (1992). The role of extensional tectonics in the Caledonides of south Norway, *Journal of Structural Geology*, *14* (8-9), 1033-1046.

Hossack, J. R., & Cooper, M. A. (1986). Collision tectonics in the Scandinavian Caledonides. *Geological Society, London, Special Publications, 19*(1), 285-304.

Roberts, D. (2003). The Scandinavian Caledonides: Event chronology, paleogeographic settings and likely modern analogues. *Tectonophysics, 365* (1-4), 283-299.

Fossen, H., Khani, H. F., Faleide, J. I., Ksienzyk, A. K., & Dunlap, W.J. (2017). Post-Caledonian extension in the West Norway-northern North Sea region: The role of structural inheritance. *Geological Society, London, Special Publications, 439*(1), 465-486.

Gee, D. G., Fossen,, H., Henriksen, N., & Higgins, A.K. (2008). From the early paleozoic platforms of Baltica and Laurentia to the Caledonide Orogen of Scandinavia and Greenland, *Episodes, 31*(1), 44-51.

Friedmann, S.J. and Burbank, D.W. (1995). Rift basins and supradetachment basins: intracontinental extensional end-members. *Basin Research, 7*, 109-127

Cuthbert, S. J., (1991). Evolution of the Devonian Hornelen Basin, west Norway: new constraints from petrological studies of metamorphic clasts. *Geological Society, London, Special Publications, 57,* 343-360.

Phillips, T. B., Jackson, C. A.-L., Bell, R. E., Duffy, O. B., & Fossen, H. (2016). Reactivation of intrabasement structures during rifting: A case study from offshore southern Norway. *Journal of Structural Geology, 91*, 54–73.

Bryhni, I. (1978). Flood deposits in the Hornelen Basin, west Norway (Old Red Sandstone). Norsk Geologisk Tidsskrift Vol. 58, 273-300.

Osagiede, E.E, Rotevatn, A, Gawthorpe, R, Kristensen, T. B., Jackson, C, Marsh, N (2020). Pre-existing intra-basement shear zones influence growth and geometry of non-colinear normal faults, western Utsira High–Heimdal Terrace, North Sea, *Journal of Structural Geology, Volume 130,* 103908

Ziegler, P. A. (1992). North Sea rift system. *Tectonophysics, 208* (1-3), 55–75.

Badley, M., Price, J., Dahl, C. & Agdestein, T. (1988). The structural evolution of the north Viking Graben and its bearing upon extensional modes of basin formation (North Sea). *Journal of the Geological Society.145*(3)

Jackson, C. A.-L., & Larsen, E. (2009). Temporal and spatial development of a gravity-driven normal fault array: Middle–Upper Jurassic, South Viking Graben, northern North Sea. *Journal of Structural Geology,* 31 (4), 388–402.

Thomas, D.W. & Coward, M.P.. (1996) Mesozoic regional tectonics and South Viking Graben formation: evidence for localized thin-skinned detachments during rift development and inversion, *Marine and Petroleum* Geology, 13 (2) 149-177.

Lervik, K. (2006). Triassic lithostratigraphy of the northern North Sea Basin. *Norsk geologisk tidsskrift, 86* (2), 93.

Helland-Hansen, W., Ashton, M., Lømo, L., & Steel, R. (1992). Advance and retreat of the Brent delta: Recent contributions to the depositional model. *Geological Society, London, Special Publications, 61* (1), 109–127.

Xiaojie Wei, Ronald J. Steel, Rodmar Ravnås, Zaixing Jiang, Cornel Olariu, Yinsheng Ma, 2018, Anatomy of anomalously thick sandstone units in the Brent Delta of the northern North Sea, *Sedimentary Geology, 367,* 114-134.

Færseth, R. B. (1996), Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea, Geol. Soc. London Spec. Publ., 153, 931–944.

Odinsen, T., P. Christiansson, R. H. Gabrielsen, J. I. Faleide, and A. M. Berge (2000), The geometries and deep structure of the northern North Sea rift system, in Dynamics of the Norwegian Margin, edited by A. Nøttvedt, et al., Geol. Soc. London Spec. Publ., 167, 41–57.

Gabrielsen, R. H., Kyrkjebø, R., Faleide, J. I., Fjeldskaar, W., & Kjennerud, T. (2001). The cretaceous post-rift basin configuration of the northern north sea. Petroleum Geoscience, 7 (2), 137–154.

Bryhni, I., 1964. Relasjonen mellom senkaledonsk tektonikk og sedimentasjon ved Hornelens og Håsteinens devon: Norges Geologiske Undersøkelse, v. 223, p. 10–25.

Braathen, A., Osmundsen, P.T., Nordgulen, Ø., Roberts, D, & Meyer, G. (2002). Orogen-parallel, extension of the Caledonides in northern Central Norway: an overview. Norwegian Journal of Geology, Vol. 82, pp. 225-241

Andersen, T.B., Jamtveit, B., Dewey, J.F. and Swensson, E. (1991), Subduction and eduction of continental crust: major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. Terra Nova, 3: 303-310

Woodrow, D. L., Fletcher, F. W. & Ahmsbrak, W. F. 1973: Paleogeography and paleoclimate at the deposition sites of the Devonian Catskill and Old Red Facies. Bull. Geo/. Soc. Am. 84, 3051-3064.

Mckie, t., and Williams, b., 2009, Triassic palaeogeography and fluvial dispersal across the northwest European Basins: Geological Journal v. 44, p. 711–741. MCKIE, T., AGGET

Würtzen, C. L., Osmond, J. L., Faleide, J. I., Nystuen, J. P., Anell, I. M., & Midtkandal, I. (2022). Syn- to post-rift alluvial basin fill: Seismic stratigraphic analysis of Permian-Triassic deposition in the Horda Platform, Norway. *Basin Research*, 34, 883– 912.

Osmundsen, P. T., & Andersen, T. B. (2001). The Middle Devonian basins of western Norway: Sedimentary response to large-scale transtensional tectonics? Tectonophysics, 332 (1-2), 51-68

Steel, R. J., & Aasheim, S. (1978). Alluvial sand deposition in a rapidly sudsiding basin (Devonian, Norway). *A.D. Miall (Ed.), Fluvial Sedimentology, Mem. Can. Soc. Pet. Geol.,* 5385-413.

A.M. Lundmark, R.H. Gabrielsen, H. Austrheim, K. Flaat, T. Strand, S.E. Ohm. (2012). Late Devonian rifting in the central North Sea: Evidence from altered felsic volcanic rocks in the Embla oil field, *Marine and Petroleum Geology*, 29 (1). 204-218.

J. Witzke. (1990). Palaeoclimatic constraints for palaeozoic palaeolatitudes of Laurentia and Euramerica Brian. *Geological Society, London, Memoirs, 12,* 57-73.

Lynds, R & Hajek, E. (2006). Conceptual model for predicting mudstone dimensions in sandy braided-river reservoirs. *AAPG Bulletin*,90 (8): 1273–1288.

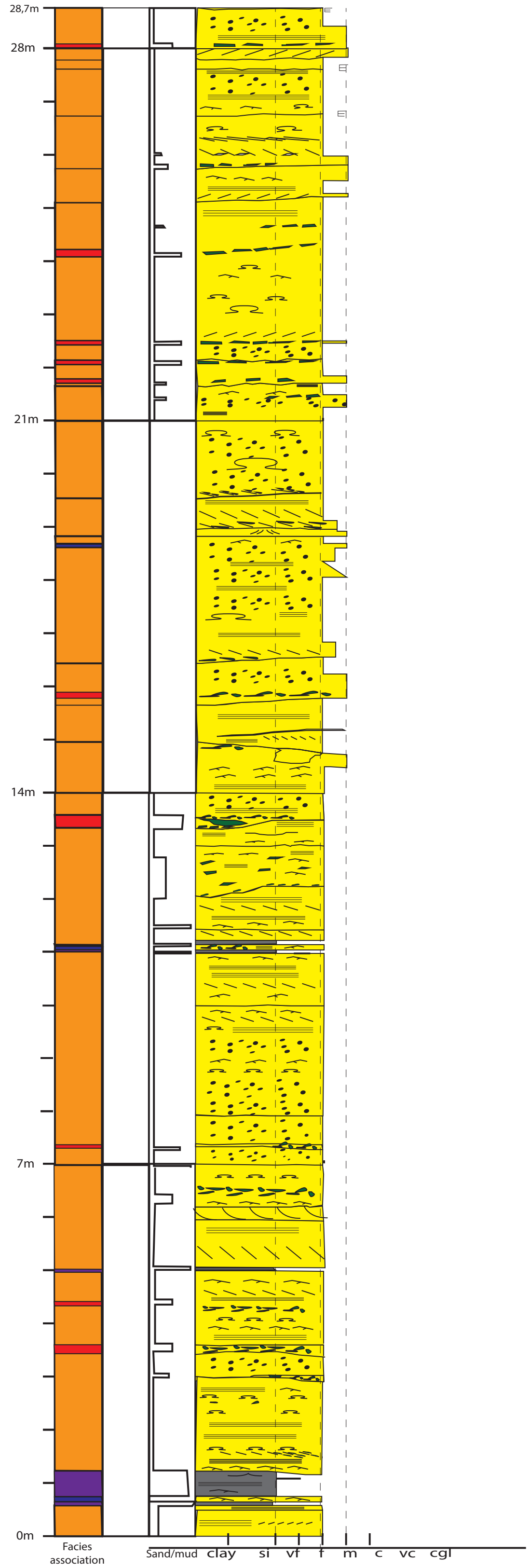
Hartley, A. J., Jones, J. J. (1993). Reservoir characteristics of a braid-plain depositional system: the Upper Carboniferous Pennant Sandstone of South Wales. *Geological Society, London, Special Publications, 73*, 143-156.

Su, C., Xu, H., Zhong, D. et al. (2021). Genetic mechanism and prediction of the distribution of thief zones in the Donghe sandstone reservoir in the Hade Oilfield. *Arabian Journal of Geoscience, 14,* 1099.

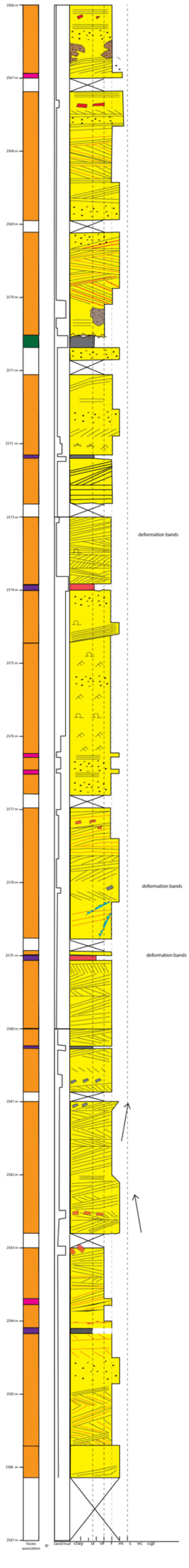
McKie, T. (2011). Architecture and behavior of dryland fluvial reservoirs, Triassic Skagerrak Formation, central North Sea. From River To Rock Record: The Preservation Of Fluvial Sediments And Their Subsequent Interpretation *SEPM Special Publication, 97.*

Appendix

Log H1-H7:



Log 16/1-11 and Log 16-1-21 S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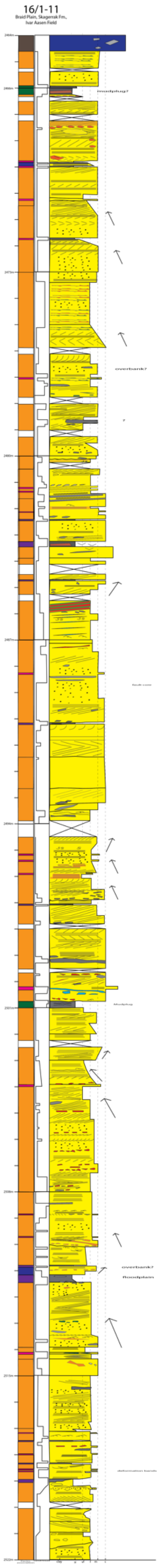
16/1-21 S


16/1-11
Braid Plain, Skagerrak Fm.,
Ivar Aasen Field