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Visualize and interpret the geometry, heterogeneity and lateral continuation of channel bodies in the De Geerdalen Formation at Hopen.

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Abstract

A digital 3D-model of Hopen has been created, using high-resolution photos taken along the coastline of the entire island. By merging these photos together in PhotoModeler software it has been possible to produce a workable PhotoModeler-model of major parts of the island.

Detailed sedimentological logs, provided by many different geologists, are representative of specific locations, mostly along the eastern side of the island. All the sediments at Hopen are part of the Upper Triassic succession and include the De Geerdalen, Flatsalen and Svenskøya formations.

Large fluvial channel bodies, up to 36 m thick, are observed in the steep, near vertical cliffs of the island. The model makes it possible to map seismic scale channel bodies, as well as smaller channel bodies, and interpret them with measured sedimentological logs. Based on position of exposed sandstones, visible on both sides of the island, the development of the river system can be suggested.

The model combined with additional photos has made it possible to recognize a potentially new member on the island, referred to as Hopen member. This member marks a possible transgressive system tract, from fluvial dominated delta plain sediments to shallow marine deposits. This member is about 70 meters below the well-known Slottet Bed, which marks the transition from the De Geerdalen Formation to Flatsalen Formation. The Hopen member has also been used to place the different channel bodies at the right stratigraphic level relative to each other.

The Hopen member might be deposited due to the same flooding event as the Isfjorden Member on Spitsbergen and might be correlatable with a 3rd global sequence boundary, which can be correlated between deposits found in northern Himalaya, Sverdrup Basin and the southwestern USA.

This thesis has also made it possible to map where to expect to find Slottet Bed, which may help updating the geological map of the island.

Sammendrag

En digital 3D-modell av Hopen har blitt konstruert ved hjelp av høyoppløselige bilder tatt langs øyas kystlinje. Ved å fusjonere disse bildene sammen i programvaren PhotoModeler har det vært mulig å konstruere en drivverdig 3D modell av store deler av øyen.

Detaljerte sedimentologiske logger, hentet inn av mange forskjellige geologer, representerer mange lokaliteter langs den østlige siden av øyen. Alle sedimentene funnet på Hopen er en del av Øvre Trias og består av De Geerdalen, Flatsalen og Svenskøya formasjonene.

Store fluviale kanalkropper, opp mot 36 meter tykke, er observert i de bratte nesten vertikale klippene på øyen. Modellen gjør det mulig å kartlegge disse kanalkroppene, så vel som mindre kanalkropper, og tolke de ved hjelp av sedimentologiske logger. Basert på posisjonen til de eksponerte kanalkroppene, synlig på begge sider av øyen, kan utviklingen av elvesystemet foreslås.

Modellen kombinert med supplerende bilder har gjort det mulig å foreslå et nytt ledd på øyen, foreslått navn er Hopen leddet. Dette leddet markerer en mulig transgressiv systemrekke, fra delta slette sedimenter til mer grunnmarine avsetninger. Dette leddet starter ca. 70 meter under og stopper ved Slottet laget, som markerer overgangen fra De Geerdalen formasjonen til Flatsalen formasjonen. Hopen leddet har også blitt brukt til å plassere de forskjellige kanalkroppene i riktig stratigrafisk rekkefølge, i forhold til hverandre.

Hopen leddet kan ha blitt avsatt av den samme transgresjonen som Isfjorden leddet på Spitsbergen og den kan være korrelerbar med en 3ordens global sekvensgrense. Denne sekvensgrensen er mulig å korrelere mellom sedimenter funnet i nordlige deler av Himalaya, Sverdrup bassenget i Barentshavet og sedimenter funnet sørvest i USA og nå også på Svalbard.

Denne oppgaven har også gjort det mulig å kartlegge Slottet laget i områder der den ikke er observert tidligere.

Contents

1. Introduction

1.1 Preface

This master`s thesis aim to study the distribution, heterogeneity and geometry of channel bodies of Upper Triassic age at the island Hopen on Svalbard (Figure 1.1). Former studies (Riis et al., 2008; Glørstad-Clark, 2010; Glørstad-Clark, 2011) show that the Upper Triassic sediments at Svalbard represent a continuation of the same depositional environment as the Upper Triassic sediments in the Barents Sea. The deposits at Hopen thus represent possible reservoir sandstones in the Barents Sea. The thesis is part of a larger project facilitated by Sintef Petroleum Research where the main aim is to reconstruct the palaeoenvironment of the Triassic succession of Northern Barents Shelf and Svalbard. Several companies support the project (see Subsection 1.1.1). The data that are used in this thesis, including photo material and logs, are collected by several workers of this project team. PhD student Tore Klausen (University of Bergen) has recently submitted a manuscript focusing on the sedimentology of the seismic scaled channel bodies (channel bodies 1, 3, 4, 11 and 14) at Hopen and comparing that with seismic collected in the south-western Barents Sea. His work overlap with the present work and will be referred to where relevant.

The present study started as an engagement work for Sintef Petroleum Research by author, and included using the software PhotoModeler to prepare a model of the island by use of high- resolution photos. The model makes the foundation for this thesis and the work with the model has been continued into this thesis, trying to develop it into a more detailed geological model. The model can help us visualize and therefore improve our understanding of the distribution of channel bodies at Hopen, as well as marker horizons. The high-resolution photos used to make this model were collected by Terje Hellem during the fieldwork on Hopen in 2011.

1.1.1 *Acknowledgement*

First, I would like to thank my supervisor Atle Mørk for giving me the opportunity to do this study, and for always being there for me when I needed someone to discuss my challenges with. I also want to thank him for his valuable support and for giving me the chance to take a closer look at Hopen.

Secondly, I wish to thank my co-supervisor Terje Hellem for taking the pictures that are used in my PhotoModeler-model, and for his valuable help with constructing the PhotoModeler-model.

I also want to thank Tore Klausen for valuable discussions concerning the large channel bodies found on the island and all the geologists taking part on the 1995 and 2007-2012 expeditions to Hopen. Without their expertise and detailed logging this thesis wouldn't be possible to complete.

The companies and geologist contributing to this thesis are summarized below:

The following license groups and organizations have supported the project:
PL609: Lundin, RWE Dea, Idemitsu
PL438: Lundin, Det norske, Talisman, Spring, Petoro, RWE Deea
PL492: Lundin, Talisman, Det norske, RWE Dea
PL533: Eni Norge A/S, Det norske, Lundin, RWE Dea
PL611: Wintershall Norge AS (operator), Faroe Petroleum Norge AS and Petoro AS
Norwegian Petroleum Directorate and Norwegian Polar Institute

Sedimentological sections logged at Hopen
1995: Geir Elvebakk, Roger I. Johansen, Geir Birger Larssen, Tor Nedkvitne, Arvid Nøttvedt, Atle Mørk, Anne Mari Østvedt-Gahzi.
2009: Alvar Braathen, Ingrid B. Hynne, Turid Anita Knudsen, Bjørn Anders Lundschien Atle Mørk, Rita S. Rød.
2011: Marianne Ask, Morten Bergan, Håvard Buran, Mike Charnock, Geir Elvebakk, Andrey Fedyaevskiy, Terje Hellem, Frode Karlsen, Tore Klausen, Trond Kristensen, Audun Kjemperud, Hilde Krogh, Bjørn Anders Lundschien, Gunn Mangerud, Atle Mørk, Ales Rusinovich, Terje Solbakk, Marina Tugarova, Marta S. Woldengen.
2012: Frode Karlsen, Gareth S. Lord, Atle Mørk, Espen Simonstad, Kristoffer Solvi.

Last but not least I want to thank my family for being so supportive and understanding.

1.2 Study Area

Hopen is part of the Svalbard archipelago, situated on the north- western margin of the Barents Sea, covering less than 5 % of the total area of the Barents Sea (Worsley, 2008)(Figure 1.2). The island rises out of the sea and is located on the south-eastern margin of the archipelago, bounded by the Edgeøya Basin in the west and the Olga Basin in the east (Doré, 1995). The island is about 37 km long and between 0.5 and 2.5 km wide, stretching in a NNE direction (Figure 1.1). The island has latitude and longitude coordinates of 76°42'52"N, 25°29'39"E on the northern and 76°26'37"N, 24°55'39"E on the southern tip of the island (Norwegian Polar Institute (online), 2013).

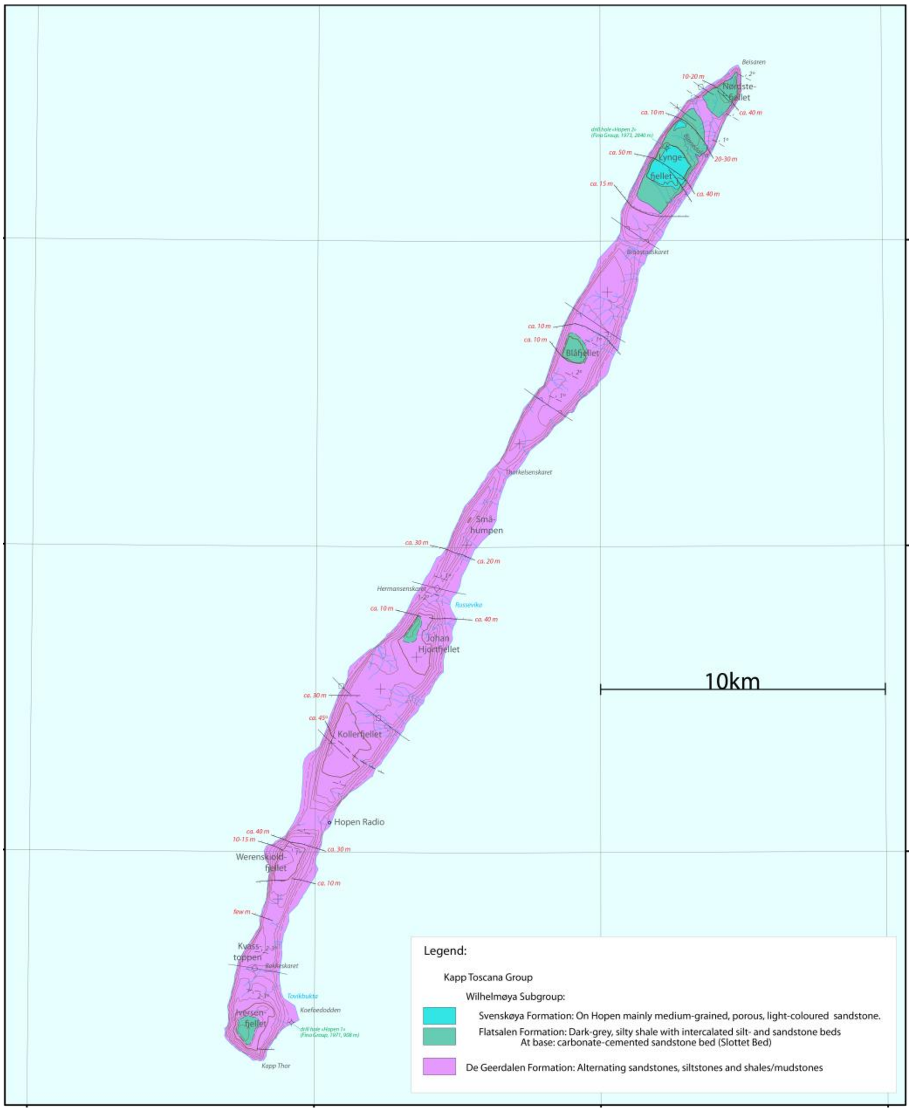


Figure 1.1: Geological map of Hopen. Mapped by W.K. Dallmann, Norwegian Polar Institute, during cruise with the vessel M/S Kongsøy, organized by the Norwegian Petroleum Directorate, August 2009. Based on a previous map by Smith et al., (1975).

1.3 Regional geological setting

The Svalbard archipelago was uplifted during tectonic activity in the Mesozoic and the Cenozoic. The varying geology at Svalbard is a consequence of the northwards drift of the plate, from 30° south to the present 81° north. The age of the rocks ranges from Precambrian to sediments deposited today (Worsley, 2008).

The Precambrian –Silurian basement rocks at Svalbard consist of sediments, metasediments and igneous rocks, ranging in age from Riphean (1275 Ma) to Silurian. The entire succession consists of 20 lithostratigraphical groups, collectively referred to as Hecla Hock (Worsley, 2008) (Pre-old Red basement in Fig. 1.2).

The strata deposited during post -Caledonian time can be divided into different regimes depending on several important factors like tectonic activity, depositional climate and sediment sources (Stemmerik and Worsley, 1995, 2005; Worsley, 2008).

During Early- mid Devonian the degradation of the Caledonian orogeny formed the Old red sandstone. The late Devonian to early Carboniferous Billefjorden Group consist mostly of fluvial and lacustrine sediments that where deposited in a humid climate. Half–grabens situated on the western shelf margin show a generally upward coarsening trend, from meandering river sandstones, into braided river streams, alluvial sandstones and conglomerates (Worsley, 2008).

The Mid-Carboniferous – Lower Permian Gipsdalen Group is dominated by shallow marine carbonates, sabkha evaporates and halite, deposited in large and deep isolated basins. The climate is warm and arid during this phase, with frequent changes in sea-level, due to glaciation of Gondwanaland. During high glacioeustatic sea-levels, the deposition was characterised by shallow-marine carbonates, while during low sea levels, sabkhas as well as sub aerially karst and fossil soils were developed (Worsley, 2008).

The base of the Bjarmeland Group is marked by a major flooding event and marks the end of the Gipsdalen Group with shallow warm waters, to deeper and more temperate conditions during deposition of Bjarmeland Group in Sakmarian and Artinskian (Worsley, 2008). This transgression is probably due to the final disappearance of the Gondwanian ice cap, as well as major plate reorganization, which formed the Urals at the east and closed the Tethys seaway (Worsley, 2008). The Bjarmeland Group is only exposed at Bjørnøya. At the rest of the

Svalbard archipelago the Gipsdalen Group is overlain by the Tempelfjorden Group (Dallmann et al., 1999a).

The middle-upper Permian Tempelfjorden Group marks a dramatic depositional change, from carbonate environments to deep-water spiculitic shale deposition with minor units of sandstone and limestone (Worsley, 2008).

In the Mesozoic, Svalbard was situated on the northern rim of the Pangaea supercontinent, 50°-70°N of equator. Except some movement along existing lineaments, most of the Mesozoic was a tectonically quiet period and the Svalbard archipelago was situated on a depositional platform. Svalbard continued to be a depositional platform until late-Cretaceous, when a crustal uplift caused the plate margin to tilt southwards. (Steel and Worsley, 1984; Mørk et al., 1982; Riis et al., 2008; Midtkandal, 2009). The Mesozoic stratigraphic record consists mainly of repeated delta-related and shallow shelf sediments in Triassic – Early Jurassic and again in later part of Early Cretaceous periods.During middle Jurassic – earliest Cretaceous deeper shelf sediments were deposited (Dallmann, 1999).

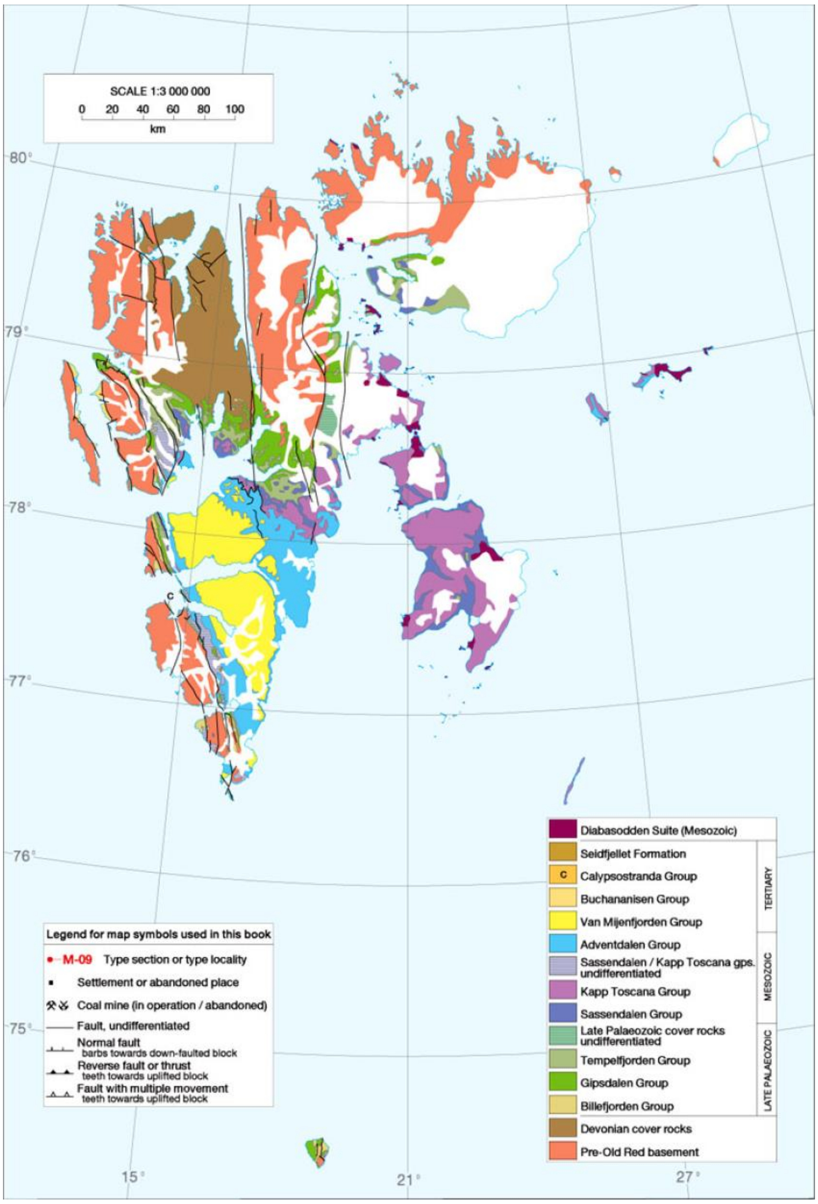


Figure 1.2: Geological map of Svalbard from Dallmann, 1999. The purple area represents the Mesozoic Kapp Toscana Group.

The Triassic of Svalbard consists of two lithostratigraphic groups. The dominant lithologies in the Sassendalen Group are of Early to Middle Triassic age and consist of shales and siltstones with minor amounts of sandstone and carbonates (Mørk et al., 1999). Mørk et al. (1982) suggested that the sandstone units exposed on the western coast of Svalbard are related to coastal progradation from Greenland in the west. The Sassendalen Group has coastal to deltaic sediments exposed on the western Spitsbergen, which grade into organic-rich shelf mudstones eastwards in Svalbard and southwards into the Barents Sea Shelf (Mørk et al., 1999).

The Kapp Toscana Group is deposited during the Middle Triassic to Middle Jurassic in a deltaic environment. There is still some local deltas prograding from the west, affecting the western coast of Svalbard (Worsley, 2008), while Riis et al. (2008) suggests that the Urals provide the major part of the sediment input, leading to a delta-plain environment over much of the northern Barents Shelf (For more detailed information about the Triassic succession at Svalbard see subsection 1.4).

The Adventdalen Group represents the sediments deposited on Svalbard during the latest Middle Jurassic to Early Cretaceous. The Group contains claystones, shales and sandstones deposited in shelf settings (Mørk et al., 1999). During the Barremian, Helvetiafjellet Formation was deposited on Svalbard. This significant sandstone unit was deposited as a result of the Cretaceous regional uplift, as well as deltaic progradation and relative sea level fall. For the period of latest Jurassic to earliest Cretaceous dolerite sills and dikes intruded older rocks all across Svalbard (Gjelberg and Steel, 1995). These intrusions were a result of the break-up between Greenland and Europe (Burov et al., 1977; Birkenmajer et al., 2010).

The Late Cretaceous uplift exposed Svalbard and subjected the northwestern rim of the Barents Shelf to erosion, preferentially in the north because the erosion cuts deeper into the Carolinefjellet Formation strata here than in the south and northwest (Steel and Worsley, 1984). This uplift of the northwestern edge of the Barents Shelf was probably part of a doming related to development of the Artic Basin to the north (Steel and Worsley, 1984).

The Tertiary basins of Svalbard developed in a period of considerable tectonic activity, in contrast to the Mesozoic depositional platform (Steel and Worsley, 1984). The Central Tertiary basin is situated in the southern and central parts of the island Spitsbergen. This basin forms a NNW-SSE trending synclinorium, infilled with clastic sediments (Dallmann et al., 1999b).

During the glaciation cycles in the Neogene, large amounts of sediments were redeposited on the shelf edge. Repeated shelf depression and uplift took place causing erosion, and shaped the topography that we can see on Svalbard today (Worsley, 2008).

1.4 The Triassic succession on Svalbard

Triassic rocks crop out extensively on the Svalbard archipelago. On the eastern side of the archipelago the exposed rocks are fairly horizontal, while on western Svalbard the sediments are folded and thrusted as a result of the Tertiary deformation (Mørk et al., 1982; Bergh et al., 1997; Braathen et al., 1999). As mentioned in Subsection 1.3 the Triassic of Svalbard consists of two lithostratigraphic groups; the Sassendalen Group and the Kapp Toscana Group. On Hopen the sediments are of Late Triassic age, and belong to the Kapp Toscana Group.

The Kapp Toscana Group is deposited during late Middle Triassic to Middle Jurassic time and consists of sandstones and mudstones. During the deposition of the Late Triassic Storfjorden Subgroup (Figure 1.3) deltaic and floodplain environments were established over much of the Svalbard Platform (Worsley, 2008), and in the upper part of Storfjorden Subgroup the De Geerdalen Formation was deposited on Svalbard.

The Carnian to early Norian De Geerdalen Formation is underlain by the grey shales of the Tschermakfjellet Formation and overlain by the Wilhelmøya Subgroup (Figure 1.3). The formation is suggested to be diachronous and to have more proximal facies to the southeast (Lock et al., 1978; Mørk et al., 1982; Riis et al., 2008). The De Geerdalen Formation thickens to the east and southeastwards, from 200-300 meters on central and eastern Spitsbergen (Mørk et al., 1999; Mørk and Worsley, 2006) to about 700 meters on Hopen (Riis et al. 2008). The lower boundary is defined at the base of the first pronounced sandstone bed above the Tschermakfjellet Formation (Mørk et al., 1999). The De Geerdalen Formation is the dominant formation on Hopen and consists of shales, silts and sandstones. This island is situated on the south-eastern border of the Svalbard archipelago, hence the outcrops on Hopen are most likely illustrating the most proximal part of the De Geerdalen Formation. Larger sandstone bodies, some even in seismic scale can be seen several places at Hopen (e.g. Subsection 4.1.1: Channel body 1). On some of the higher mountains, like Lyngefjellet (Figure 1.4), the De

Geerdalen Formation is overlain by the Slottet Bed, which marks the beginning of the Flatsalen Formation. The bed is typically 1.5 m thick and consists of calcareous sand- and siltstone. It is easily recognised because of its distinct orange-brown colour (Mørk et al., 1999) and might be deposited due to a global 2order sequence boundary (Embry, 1997; Egorov and Mørk, 2000). The overlying part of the Flatsalen Formation consists of coarsening upward units with marine shales transitioning into more silty- sand towards the top (Mørk et al., 1999). Above the Flatsalen Formation the Svenskøya Formation is dominated by fluvial sandstones (Mørk. et al., 1999). This formation is only visible on Lyngefjellet (Figure 1.4). Both Flatsalen and Svenskøya formations are part of the Willhelmøya Subgroup (Figure 1.3).

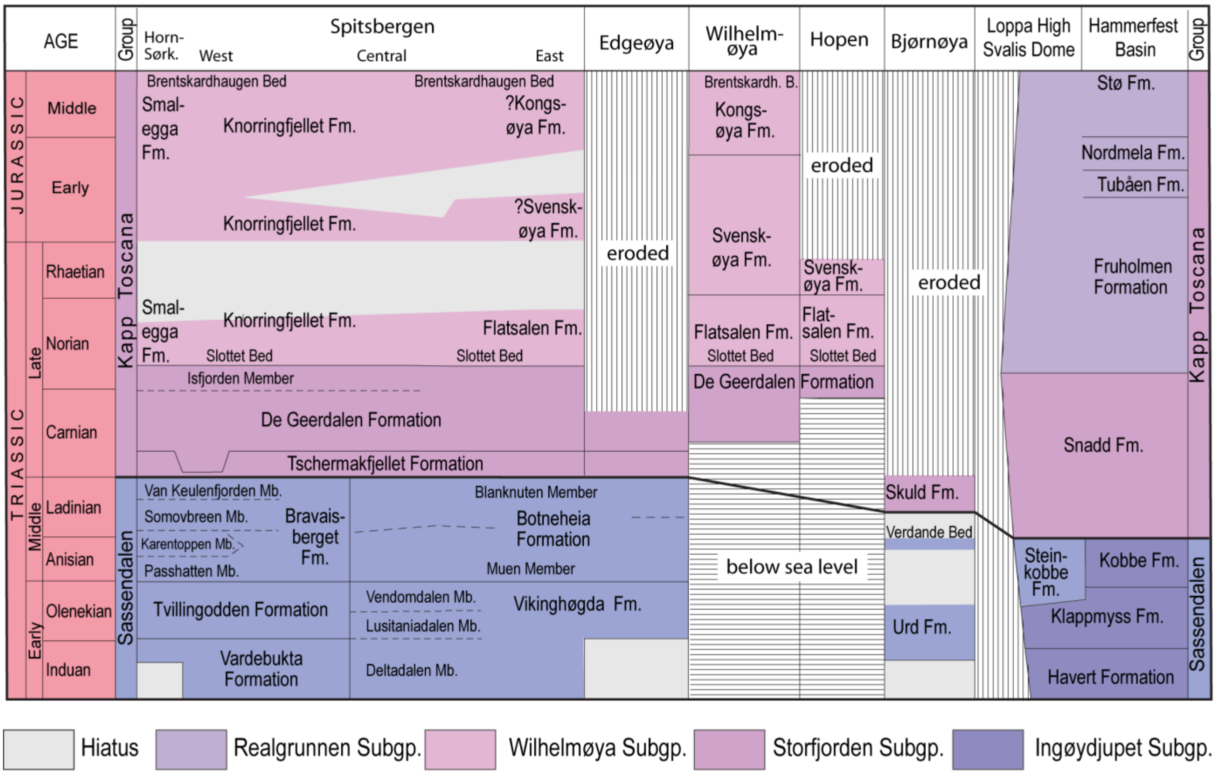


Figure 1.3: Overview of the Triassic lithostratigraphy of Svalbard and the Barents Sea. Modified from Mørk et al., 1999.

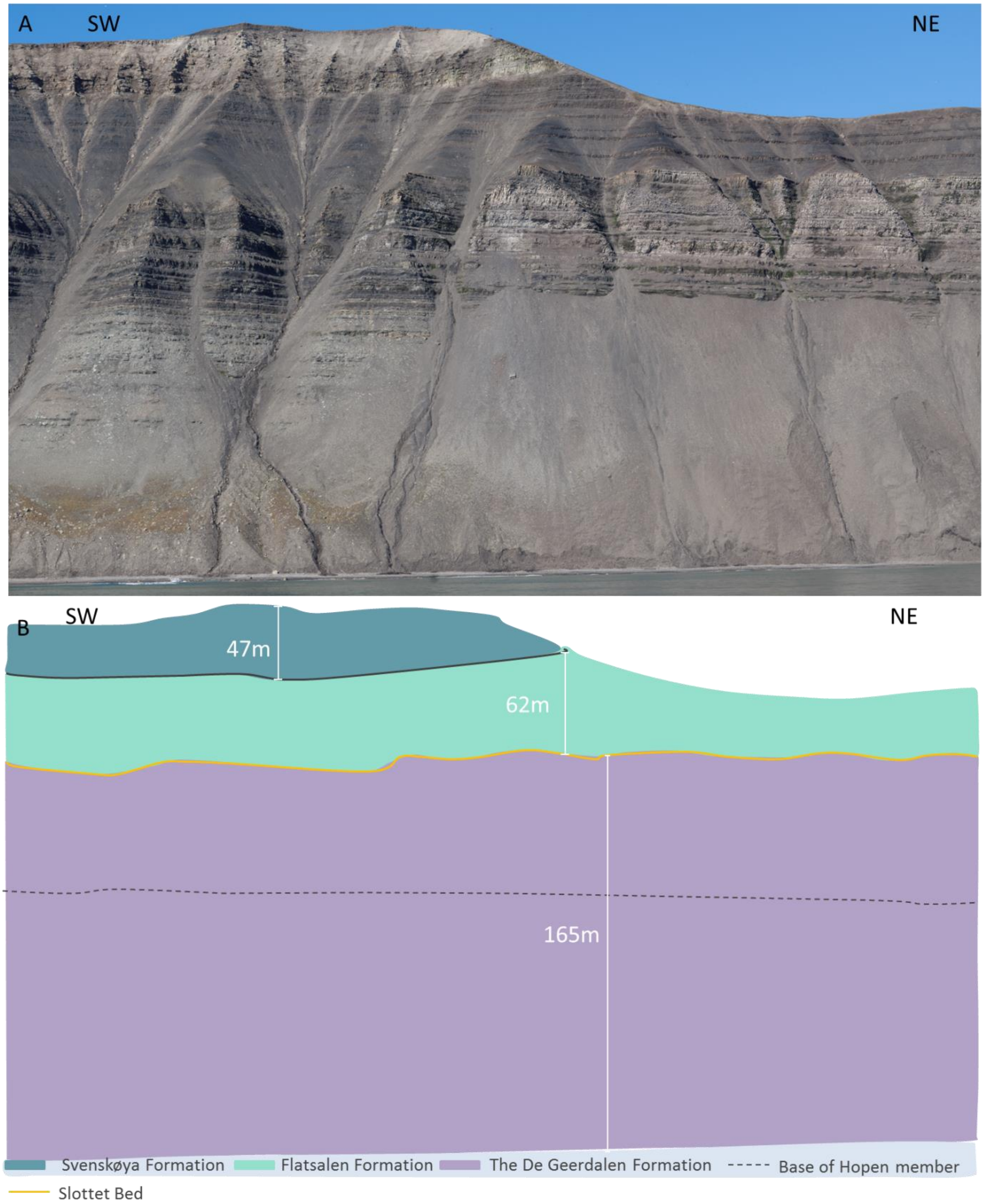


Figure 1.4: Part of Lyngefjellet, which is the only mountain that displays all the formations on Hopen.

1.5 Previous work at Hopen

The Swedish polar explorer and geologist Alfred Gabriel Nathorst published in 1894 the first paper with a geological map of Hopen. He interpreted the deposits to be of Triassic age, but the paper did not include any explanation. As Nathorst never got the chance to go on land on Hopen, all his observations were done from offshore meaning that his interpretations, most likely, are based on the cliff sections seen from the sea.

Several expeditions from the beginning of 1920- 1960's tried to establish the geological age of Hopen. Publication by Iversen (1926), Werenskiold (1926) and Bodylewsky (1926) suggested early Cretaceous age based on their topographical map, geological notes and notes on fossil plants. An expedition in 1930 also suggested early Cretaceous age based on the occurrence of loose pieces of coal.

Norwegian Polar Institute collected in 1969, plants, bivalves and ammonites that were examined and in 1971, Flood, Nagy and Winsnes published an article suggesting a late Triassic age and a possible correlation to the De Geerdalen Formation of Edgeøya and Barentsøya. Pčelina participated on two Russian expeditions (1966 and 1971) and published in 1972 a paper with a complex stratigraphic section with lithological details of the sequence exposed in the southern parts of the island. She divided the island into Carnian and Norian age, mostly grounded on lithological division, but also based on evidence from fossil plants and bivalves. She claimed that the lowest part was of Carnian age while the top was of Norian age. Without visiting the northern part of the island, Pčelina suggested that the island had a gentle dip towards the north and therefore would contain younger rocks, perhaps even of Jurassic age. Worsley (1973) based on his work in the northern part of Hopen and suggested like Pčelina that the rocks in the northern part was younger, but instead of explaining it with a regional gentle dip he explained it with faulting. The paper by Smith et al. (1975) states that several of the faults found at Hopen do not have a dip direction to the NE and thereby they do not believe that the sediments situated at the northern part of the island is younger than the ones in south strictly because of faulting, but that there might be a combination of gentle dip and to some extent faulting.

During the last 40 years several expeditions has taken place, but in general little work has been published.

Because of regenerated belief in the Barents Sea as a petroleum play, Norwegian Petroleum Directorate (NPD) and SINTEF Petroleum Research organized studies from 2007-2012 with the aim to reconstruct the palaeoenvironment of the Upper Triassic as an analogue to the Barents Sea Region. Several logs shown in this thesis were also collected on an expedition to Hopen in 1995, organized by NPD and Norwegian oil companies.

2. Methods

The work of this thesis is mainly based on photo material, which has been used to try establish a geological model of the island. The data and software used for this purpose will be discussed below.

2.1 Data collection

Photo collection took place at Hopen and was done by Terje Hellem during the 2011 field work. Some supplementary photos were also taken in areas with low coverage during the 2012 field season by Kristoffer Solvi and Atle Mørk. The photos were collected in a systematic manner by sailing with M/S *Stålbas* around the island. In some areas, mostly on the eastern side of the island, a rubber boat was used to get closer to shore in order to obtain more detailed photos.

Terje Hellem used a Nikon D3X camera with an 85 mm or a 300 mm lens during collection of photos on the field trip in 2011. The 300 mm lens was only used in areas were the boat could not get close enough to the shore. On the 2012 expedition a Canon EOS 60D with a 150 mm lens was used for photo collection. Most of the PhotoModeler-model has been constructed by using the photos taken with the 85 mm lens. These photos have a high quality and make it possible to pick the same pixel on different photos. The photos taken with an 85 mm lens are also best calibrated in the model. Photos taken with a 300 mm lens are used from Blåfjellet and down to Johan Hjortfjellet on the western side of the island. Since these photos are taken with a higher zoom, the photos are more blurry, hence it is difficult to pick out the same spot on different photos. The photos taken on the 2012 expedition are not used in the PhotoModeler-model, but are used as a supplement in order to get a better understanding of the different channel bodies.

During the Hopen expedition in 2011 Terje Hellem took 4700 photos covering the entire island. Close to 1500 of these were taken with the 300 lens, while the rest were taken with the 85 mm lens. In 2012 approximately 200 pictures were shot in areas where the photos from the 2011 expedition had low coverage or low quality due to fog.

The logs that are used in this thesis were collected during expeditions to Hopen in 1995 and in the time period 2007- 2012. The geologists contributing to the data collection are shown in Subsection 1.1.1. Data collected during field work have been used to get a better understanding of the geology of some of the channel bodies in De Geerdalen Formation at Hopen. The sedimentological data have mainly been collected from the eastern side of the island, as a consequence of limited accessibility on the westerns side. The photo material and PhotoModeler-model will be used to understand the channel bodies and will also be supplemented with logged sections where it is suitable.

Klausen and Mørk (submitted) obtained palaeocurrent measurements and detailed sedimentological analysis of some of the most important channel bodies on the island. These measurements and interpretations have been used in the discussions to confirm or disprove the interpretations based on geometrical indicators found on the different channel bodies as seen on the photos.

To interpret the different channel bodies described in this thesis the high-resolution photos have been used. Programs like Photoshop, Light Room and PhotoModeler combined with the use of two high-resolution widescreens and a custom-made computer made it possible to zoom in on features related to the channel bodies and be able to do detailed interpretation of them. The most detailed interpretations are difficult to see on the photos presented in this thesis. This is because the thesis is printed in B5 size, about 16% smaller than A4 and because the photos presented in the thesis are PNG-files or JPEG-files, while the detailed interpretation is done on photos saved as Tiff-files, which have a higher resolution than PNG and JPEG files.

2.2 PhotoModeler-model

The program PhotoModeler was used to make a PhotoModeler-model of the photos taken of Hopen. This was done by combining photos from different camera positions and different angels (Figure 2.1). In principle this is done by laboriously orienting two photos. When these two photos are oriented you can add one photo at the time, connecting them with the photos that are already oriented.

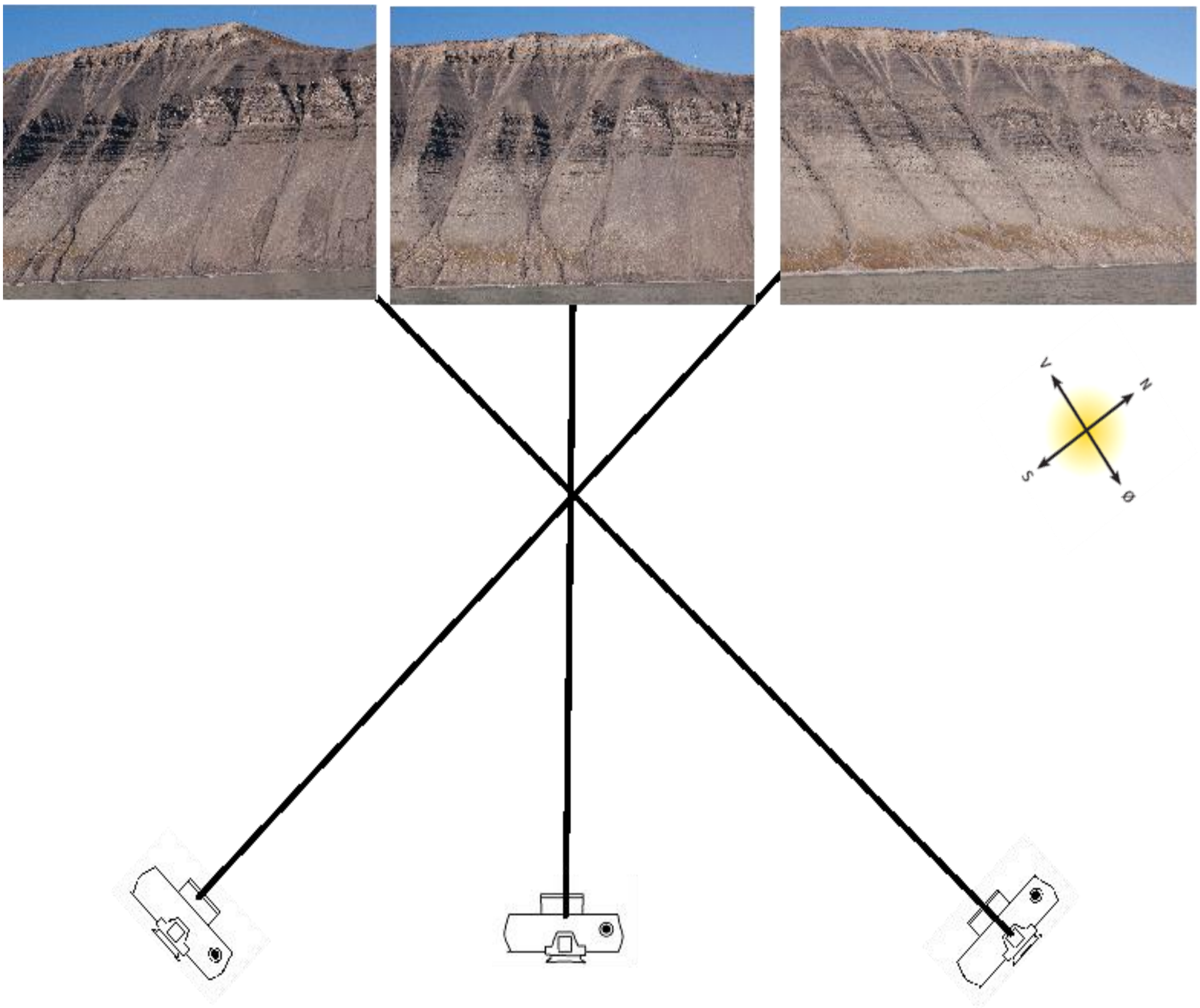


Figure 2.1: Illustration of how to combine the different photos with different angels to create points with correct X, Y and Z values.

To get the correct position of the photos and the spatial position of each individual point, you need to pick out the exact same spot on all the photos. When this is done to a sufficient number of points it is possible to process the model. If this is done correctly the new photo is oriented and the PhotoModeler-model will be updated. The X, Y and Z coordinates of each individual point should now be accurate compared to the other points. To place the model of Hopen at its true geographical position, a geographical coordinate system had to be created. This was done by giving the key points around the island their exact geographical coordinates. Some of the coordinates were collected during logging, and these give the possibility to correct the height of the island, as well as correcting the model in the northern and eastern direction. The numbers of points were not sufficient to get the true geographical position of the model, and map data and vertical plane photos from the Norwegian Polar Institute were therefore integrated into the software MapInfo Professional in order to get the resisting coordinates. The elevation on the maps is therefore not precise, as points were picked at sea level and then the northern and eastern coordinates were extracted and the resulting values were given to a point at the exact same place in the model. To even out the island at sea level, all the points at sea level were constrained to be coplanar.

After orienting the model correctly it was possible to take out the correct thickness and length of the different channel bodies on the Northern (Nørstefjellet and Lyngefjellet) and southern part (Johan Hjortfjellet, Kollerfjellet, Werenskioldfjellet and Iversenfjellet) of the island, as well as on the eastern side of Blåfjellet. The PhotoModeler-model for Småhumpane and the western side of Blåfjellet is not correctly oriented in either X, Y or Z direction. As a reason for this there will be some errors regarding thickness and length of the channel bodies in this area. This will be further discussed in the next subsection.

Some of the channel bodies in this thesis are illustrated with the help of the PhotoModeler – model (e.g. Figure 4.1A and Figure 4.2A). In these photos only the actual channel body and some key horizons are highlighted. In some cases (e.g. Figure 4.1A and Figure 4.30A) the photo illustrates the channel body on both sides of the mountain, which might be a bit confusing. For instant the white coloured part of Channel body 14 (Figure 4.30A) is situated on the eastern side of the island. At the same side as Figure 4.30B and C illustrates. While the darker part of the channel body is on the opposite side of the island.

2.3 Sources of error

There are no known examples of attempts to make a geological model of this size based on high – resolution photos in PhotoModeler, meaning that the work has been time- consuming and that a lot of the work has been done by the principle learning by doing. This also opens for several sources of errors and the most important possible errors will be discussed below.

The PhotoModeler-model can contain errors related to poor overlapping of the photos. In some areas the difference in angle between the oriented photos is too high or too low. When this is the case the software has some difficulties creating a correct PhotoModeler-model.

Another problem is pictures disturbed by fog. On the eastern side of the island, between Johan Hjortfjellet and Hopen radio, a lot of the photos are taken when the fog is covering the upper part of the mountain. This leads to problems with observing possible channel features in that area.

For PhotoModeler to handle a model of this size some of the points had to be frozen. That means that the program gave them fixed X, Y and Z values. After finishing the model a problem regarding the frozen points occurred. Nearly all the frozen points had inaccurate X, Y and Z values and the X, Y and Z values of the points which were not frozen, were given their X, Y and Z values based on these frozen points and hence were also inaccurate. So to orient the model correctly one needed to construct a model without frozen points. The problem was then that the model was depending on the frozen points, and without these points the program crashed. A possible solution to the problem was to divide the model into a few separate parts and unfreeze the points in each of them. By using this method it was possible to get rid of all the frozen point in most of the areas (Nørstefjellet, Lyngefjellet, Johan Hjortfjellet, Kollerfjellet, Werenskioldfjellet, Iversenfjellet and eastern side of Blåfjellet). With help of GPS coordinates and constrains, the points got the right X, Y and Z coordinates. The two remaining areas (Småhumpane and Blåfjellet west) still have frozen points, and there are therefore still problems regarding correct coordinates. This can be a source of error when it comes to thickness and width measurements, as well as comparing cross-sections of the channels on both sides of the island.

A different issue is that the model was made in two separate parts that in the end were merged together. This was not successful and the model got twisted, meaning that points at sea-level on the western side of the island could have a height value of -200 m, while the point at sea-level on the opposite side had a Z value of 100 m. Since this is not entirely corrected on Småhumpane and Blåfjellet it is an important source of error.

The PhotoModeler-model can contain errors related to quality of the photos, hence there has been some problems with orienting photos taken with the 300 mm lens. The 300mm lens photos are only used on the western side of the island, from Blåfjellet down to Johan Hjortfjellet (See Figure 1.1). As discussed above, the western side of Blåfjellet and Småhumpane still have frozen points controlling the model. This might be due to the photos taken with the 300mm lens. A frozen point is a point with fixed X, Y and Z values and is used while processing the model. To orient a photo one needs to pick out at least 10 points on the photo you want to orient and connect these with points placed at the exact same place on photos that have already been oriented (Figure 2.1). If than these 10 points are frozen and have inaccurate X, Y and Z values, the model is only processing due to these values. The model will orient, but not correctly since all the points that the newly oriented photo is based on are inaccurate. If we than unfreeze these points, all the X, Y and Z values that the program thought was correct are gone, and the program will crash. This is the case for some of the photos taken with the 300mm lens, hence these photos are part of the reason for inaccurate X, Y and Z values in this area.

3. Lateral distribution of possible marker horizons

3.1 Lateral distribution of the black interval at the uppermost part of the De Geerdalen Formation (Hopen member)

To pin point the exact location of this horizon is difficult, because it is not possible to follow this layer throughout the island. One can however see this prominent black belt at several places at the island (e.g. Figure 3.1, Figure 3.2). The layer is quite characteristic that possible measuring errors are most likely not more than 10 meters. To find out if this assumption is correct, I measured the distance from the base of this black belt up to the Slottet Bed in all areas where that was possible (Figure 3.1), to see if the thicknesses are more or less the same in all the areas. The thickness of the black interval is easy to find on Iversenfjellet, as well as on the southern part of Lyngefjellet, at the southern and northern part of the island respectively. The distance between Slottet Bed and base Hopen member is measured to be 66 meters at Lyngefjellet South (Figure 3.1), while the distance between the same two layers at Iversenfjellet is 68 meters (Figure 3.2), indicating that the black interval is the same stratigraphical interval on both of the mountains.

(1) Discussion

The measured logs are used to interpret if there is any change in depositional environment that has caused the transition from the lighter coloured sediments deposited below the black member to the black interval. The log "Lyngefjellet south" was logged during the 1995 expedition and in this area the transition to the black interval is clear (Figure 3.1). This log shows a clear shift from fluvial dominated delta plain sediments below to shallow marine sediments in the black interval (Figure 3.1A). The log indicates shallow marine environment for the entire black interval, which in the log, as well as in the PhotoModeler-model is about 70 meters thick (Figure 3.1C). This log is defined as the type section for these black coloured, shallow marine sediments and will in this thesis be referred to as the Hopen member. A bit further north, on the northern side of Lyngefjellet, Binnedalen is situated. This location is easily accessible and is therefore thoroughly logged. This log and the associated photo of Binnedalen (Figure 3.3) is verifying the Hopen member, since one can see that there is a switch to more shallow marine sedimentation at about 60-70 meters below the Slottet Bed (Figure 3.3C).

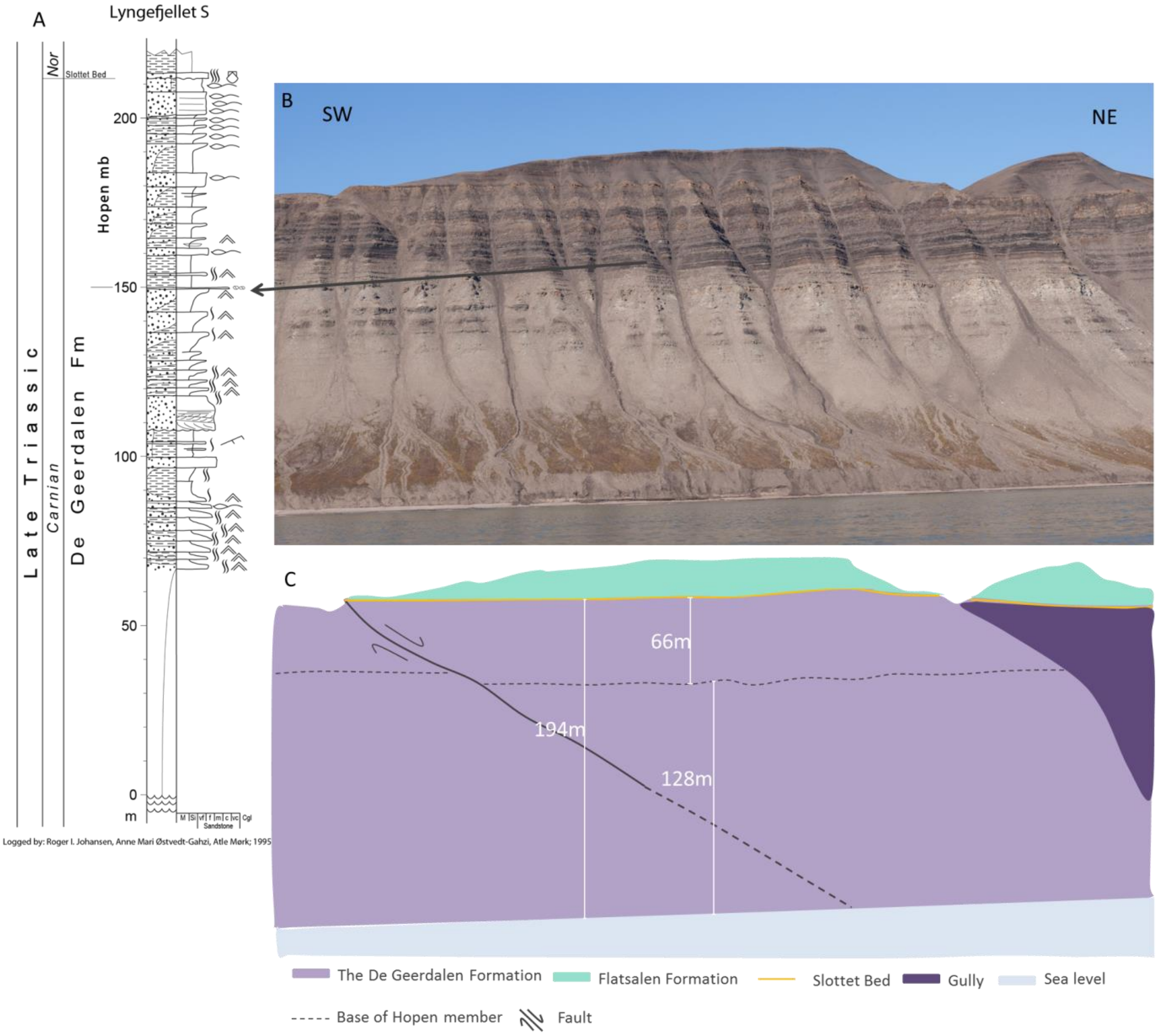


Figure 3.1: This figure illustrates the photo interpretation and the associated log taken at Lyngefjellet south. (A) A log collected by Roger I. Johansen, Anne Mari Østvedt-Gahzi and Atle Mørk during the 1995 expedition to Hopen. (B) A photo of Lyngefjellet south. (C) Interpretation of the photo shown in B, with the aim of finding the thickness of Hopen member.

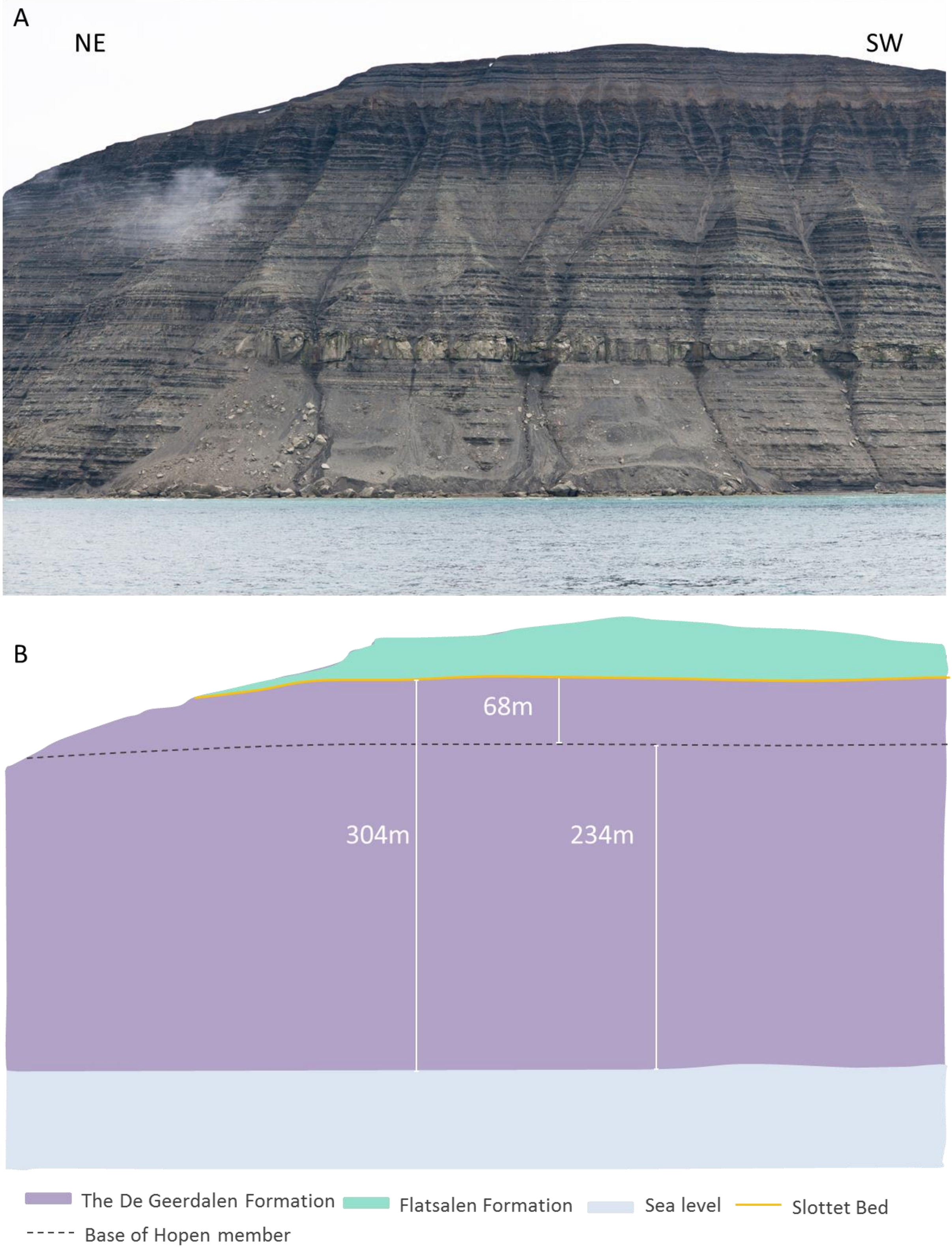
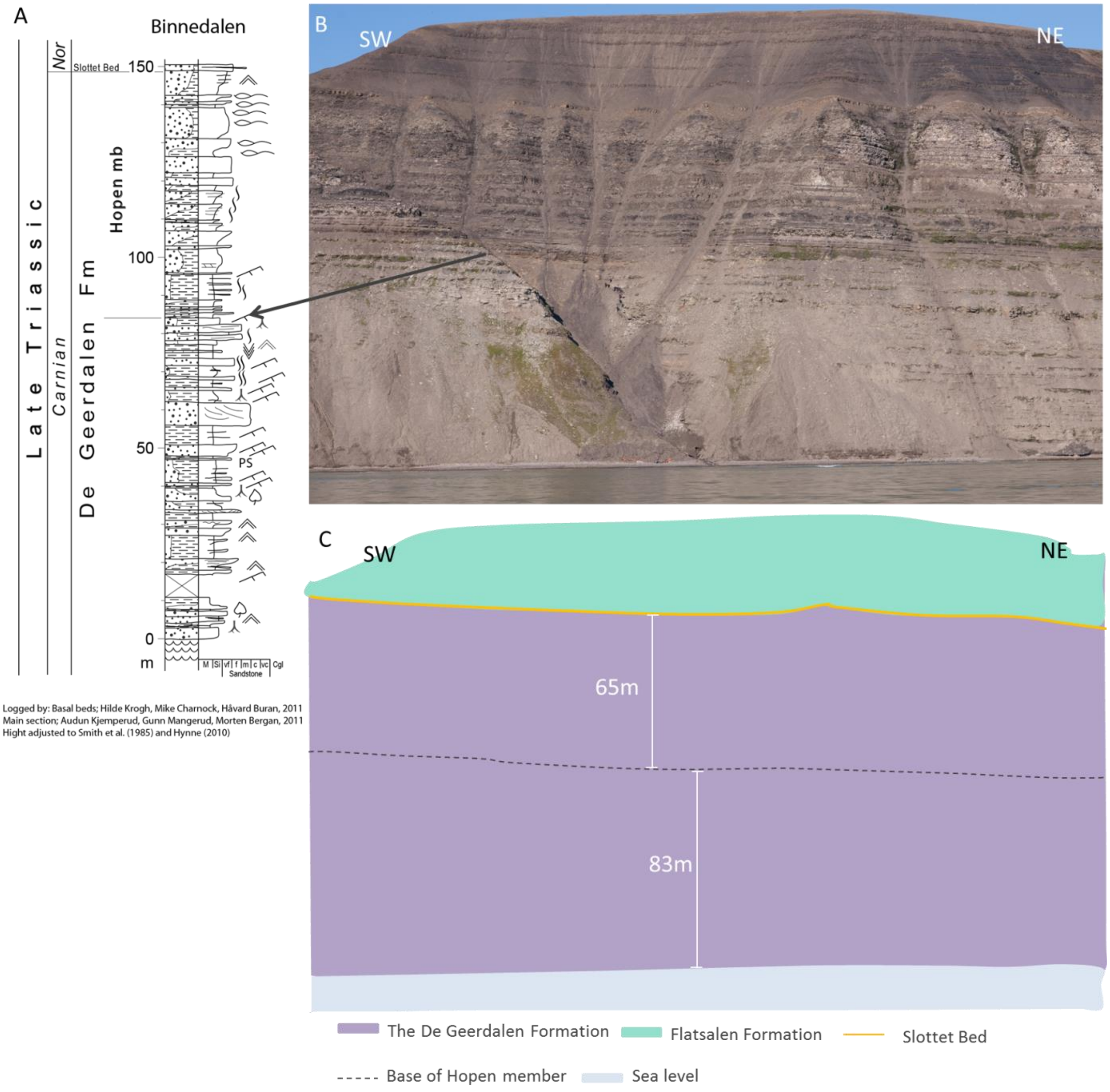


Figure 3.2: This photo and drawing illustrates the interpretation of Iversenfjellet. (A) A photo Iversenfjellet, situated at the southernmost tip of Hopen. (B) Interpretation of the photo shown in A.



Logged by: Basal beds; Hilde Krogh, Mike Charnock, Håvard Buran, 2011
Main section; Audun Kjemperud, Gunn Mangerud, Morten Bergan, 2011
Hight adjusted to Smith et al. (1985) and Hynne (2010)

Figure 3.3: This figure illustrates the photo interpretation and the associated log taken in Binnedalen. (A) A log collected during the 2011 expedition to Hopen. (B) A photo of Binnedalen. (C) Interpretation of the photo shown in B, with the aim of finding the thickness of Hopen member.

3.2 Lateral distribution of Slottet Bed

In several areas where the Slottet Bed might be deposited towards the top of the mountain, erosion has made it difficult to spot the Bed, as well as the coarsening-upward successions characteristic for the rest of Flatsalen Formation. The thickness of the Hopen member can be used to locate the Slottet Bed and overlying parts of the Flatsalen Member. As explained in the subsection above, the Hopen member is no more than 70 meters thick. One can than take the distance to the top of the mountain in areas where Slottet Bed might be situated and subtract that thickness with the thickness between sea-level and the base of Hopen member. If this subtraction leads to a thickness of more than 70 meters one can assume that the Slottet Bed, and thereby the Flatsalen Formation is situated towards the top of the mountain. Below the different mountains where Slottet Bed might be situated, will be investigated by using this method. The descriptions will start by examining the northern most mountain and then continuing towards the southern tip of the island.

At Blåfjellet, on the western side of the mountain one can clearly see the Slottet Bed, but the precise thickness of Hopen member is unfortunately not possible to detect from the PhotoModeler-model. While on the eastern side of the mountain the PhotoModeler-model is correctly oriented. Towards the top of Blåfjellet East one can clearly see an orange coloured layer resembling Slottet Bed (Figure 3.4). By using the PhotoModeler-model the distance between the possible Slottet Bed and the base of Hopen member is estimated to be about 67 meters, indicating that this actually is Slottet Bed (Figure 3.4).

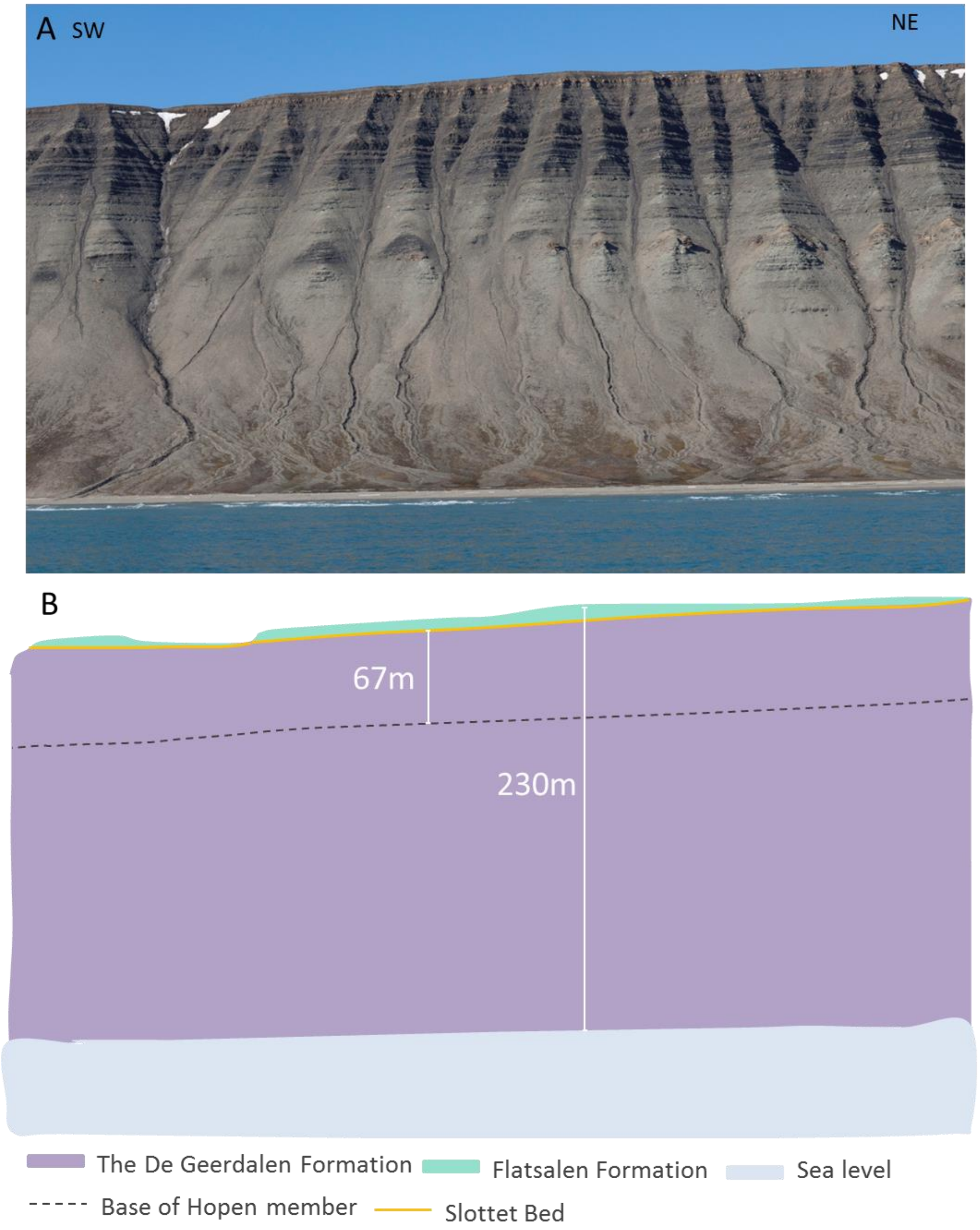


Figure 3.4: This figure illustrates the photo and interpretation of what might be the Slottet Bed at Blåfjellet east. (A) A photo of Blåfjellet east. (B) Interpretation of the photo shown in A.

At the western side of Johan Hjortfjellet the PhotoModeler-model estimated the top of the mountain to be approximately 306 meters above sea level, while the base of Hopen member is situated about 224 meters above sea level, giving a distance of 82 meters between the base of

Hopen member and the top of the mountain. This indicates that the Slottet Bed is situated at around 294 meters above sea level (See Figure 3.5A and B for illustration of the different thicknesses at Johan Hjortfjellet W). By measuring the distances at the eastern side of Johan Hjortfjellet, the thickness between the base of Hopen member and the top of the mountain is approximately 50 meters, indicating that the Slottet Bed is not present at this side of the mountain (Figure 3.5C and D).

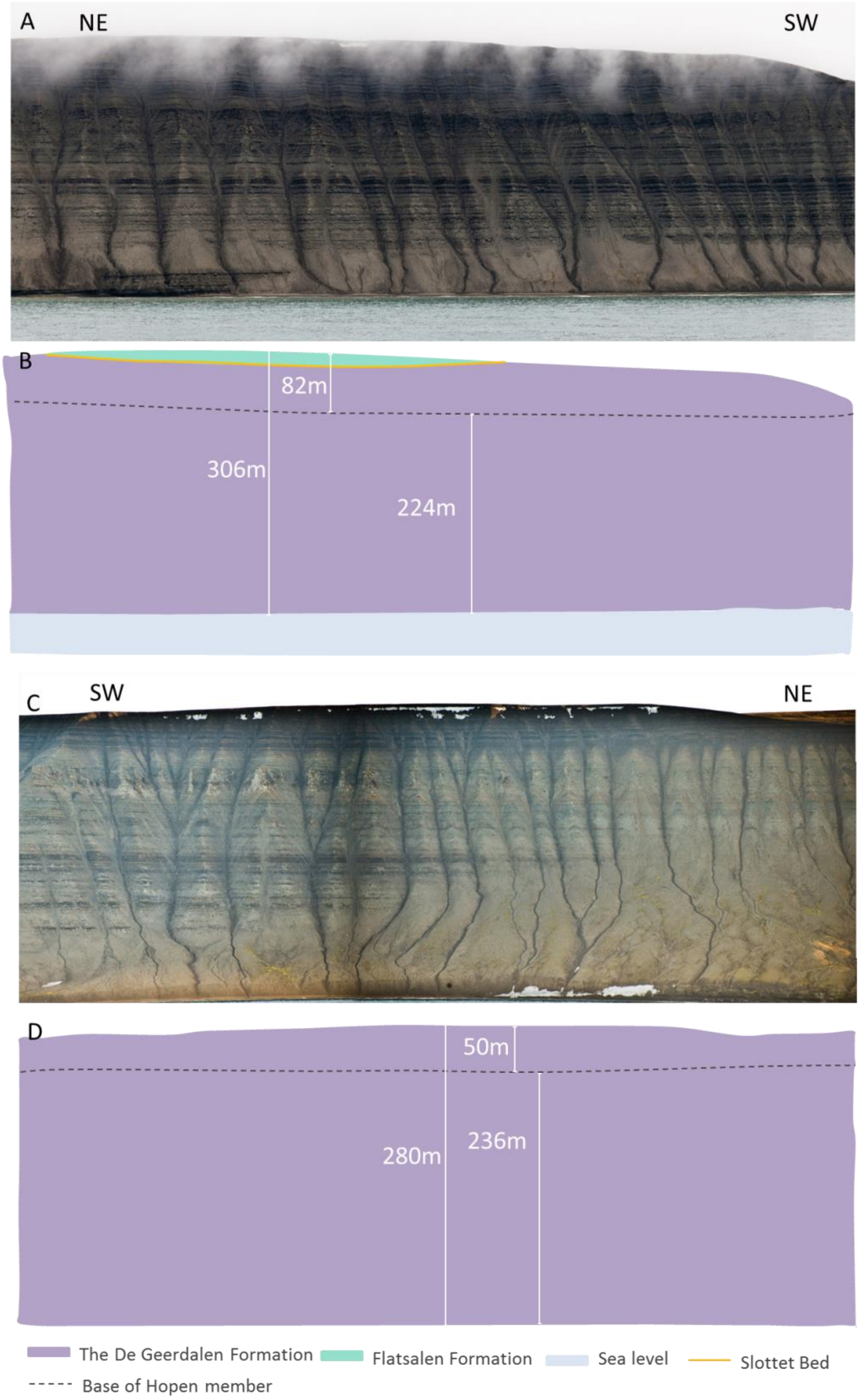


Figure 3.5: This Figure illustrates the photo and the interpretation of both the eastern and western side of Johan Hjortfjellet. (A) A photo taken at the western side of Johan Hjortfjellet. (B) An interpretation of Photo A. (C) A photo taken at the eastern side of Johan Hjortfjellet. (D) An interpretation of Photo C.

Werenskioldfjellet is situated just south of Hopen radio. The model calculates this mountain to be about 314 meters high, while the base of Hopen member is situated around 236 meters above sea level. This can indicate that the top of Werenskioldfjellet actually consists of sediments from the Flatsalen Formation (Figure 3.6).

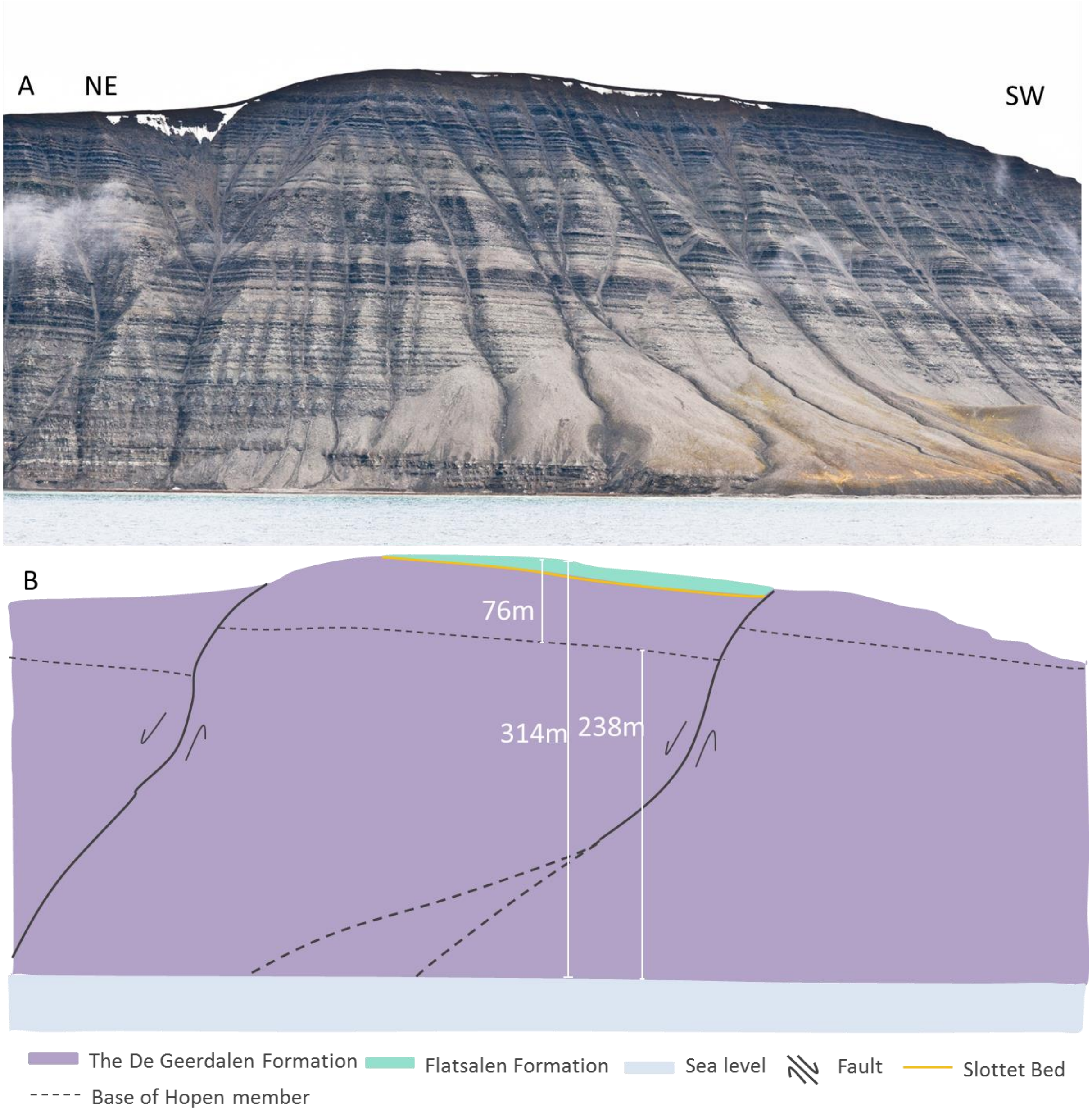


Figure 3.6: This figure illustrates the photo and interpretation of what might be the Slottet Bed at Werenskioldfjellet. (A) A photo of Werenskioldfjellet. (B) Interpretation of the photo shown in

4. Channel bodies

In this chapter observations of the geometry, heterogeneity and distribution of some of the channel bodies in the Upper Triassic succession at Hopen will be described and discussed. The only area where there will be an interpretation of channel bodies that do not have an oriented PhotoModeler-model to confirm the thickness and width of the channel bodies, is on the western side of Blåfjellet (channel bodies 3, 9 and 16).

At Hopen different types of channel bodies can be seen. The channel bodies can be distinguished on the basis of geometrical indications visible on photos and in the PhotoModeler-model, and these observations are compared with logs provided from field-work. Some of the logs are situated at the location of the channels (e.g. Channel Body 4), while in some cases the sand bodies are only explained by comparing geometrical indications with lateral continuation of logged sections towards outcrops of channel bodies.

18 different channel bodies will be described and discussed in this chapter. Some more thoroughly than others.

The channel bodies have been put into three groups based on size (thickness, width), if the channel body is logged or not, and probability for channel body (Table 4.1, 4.2 and 4.3). Each channel body group starts with interpretation of the northern most channels in that particular subsection and continues towards the southern tip of the island.

4.1 Channel body Group 1

Channel body group 1 consists of four different channel bodies with visible thicknesses of 15-36 meters and widths between 400 and 1000 meters. All of these channels are logged and therefore the channel bodies can be explained on the basis of both geometrical indicators and facies found by logging. This means that these channel bodies have the highest degree of certainty, since the interpretation is based on sedimentological logs, distance found by using the PhotoModeler-model and geometrical indicators found on photos.

Table 4.1: Overview of the channel bodies described in subsection 4.1: Channel body group 1.

Channel body	Size (thickness, width)	Logged	Probability for channel body
1	36 m thick, 1000 m wide.	Yes	High
2	15 m thick, width depends on interpretation of the channel body.	Yes	High
3	The PhotoModeler-model is not oriented correctly on the western side in this area, but on the eastern side it is approximately 30m thick and 415 m wide.	Yes	High
4	32 m thick and 950 m wide.	Yes	High

4.1.1 *Channel body 1 (Northern channel)*

Channel body 1 is situated on the northern most part of the island (Figure 4.1 and Figure 4.2). It has a maximum thickness of around 36 meters and is approximately 1 km wide in the exposure. The channel body can easily be spotted on both sides of the island. The channel body is displaced by a steeply dipping normal fault, with a displacement of about 50 meters on the eastern side and only 18 meters on the western side of the island (Figure 4.1 and Figure 4.2). The channel body is clearly cutting into the underlying sediments, with a maximum down cutting of about 17-20 meters. By studying the pinch outs seen on this channel body one can clearly see that they are pinching out into fine- grained sediments (Figure 4.1D-G and Figure 4.2 D-G). By looking at the photos, the channel body appears massive and without any erosional scours. However, as marked on Figure 4.1C, some layers are dipping towards the south.

In this area it is not easy to see the clear black interval that marks the Hopen member, but as shown in Figure 4.1 and Figure 4.2, the Hopen member is most likely situated between the dotted black line and the solid black line, which marks the beginning of the Hopen member and the Slottet Bed respectively. This indicates that Channel body 1 is deposited approximately 60 meters below Hopen member.

(1) Discussion

The massive character of the channel body indicates deposition by a single channel, hence the channel body is single-story, where the dipping surfaces are indications of lateral accretion. This interpretation is supported by Klausen and Mørk (submitted).

The log from this section only covers the lower portion of the channel body, but it is still valuable for explaining some of the dominating processes responsible for creation of the channel body. The sedimentological log is indicating fine- medium grained sandstone, with a high sand/shale ratio. The channel body cuts into and rest on overbank fines characterized by shaly coal and carbonaceous shale, with abundant plant fragments (Klausen and Mørk, submitted).

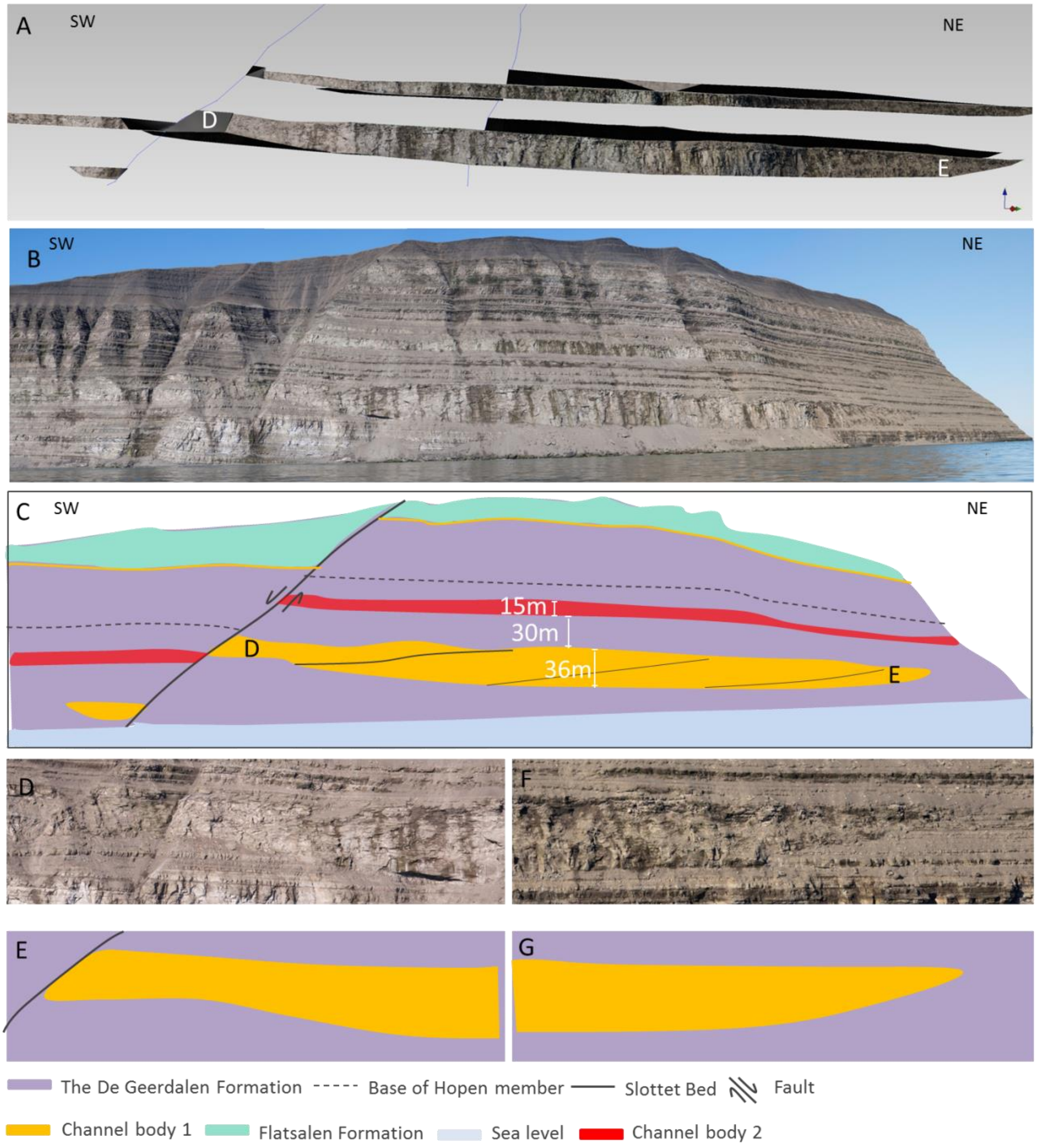


Figure 4.1: Photos and illustrations of the interpretation of the northern most part of the stratigraphic interval with Channel body 2, and the entire Channel body 1 on the eastern side of the island. (A) The PhotoModeler-model illustration of channel bodies 1 and 2 on the eastern side of the island. (B) Photo of the eastern side of the island. (C) Interpretation of the photo in A. (D) A close-up photo of the area where Channel body 1 is displaced by the northern most fault. (E) Interpretation of the photo in C. (F) A close-up photo of the northern pinch out of Channel body 1. (G) Interpretation of the photo in E.

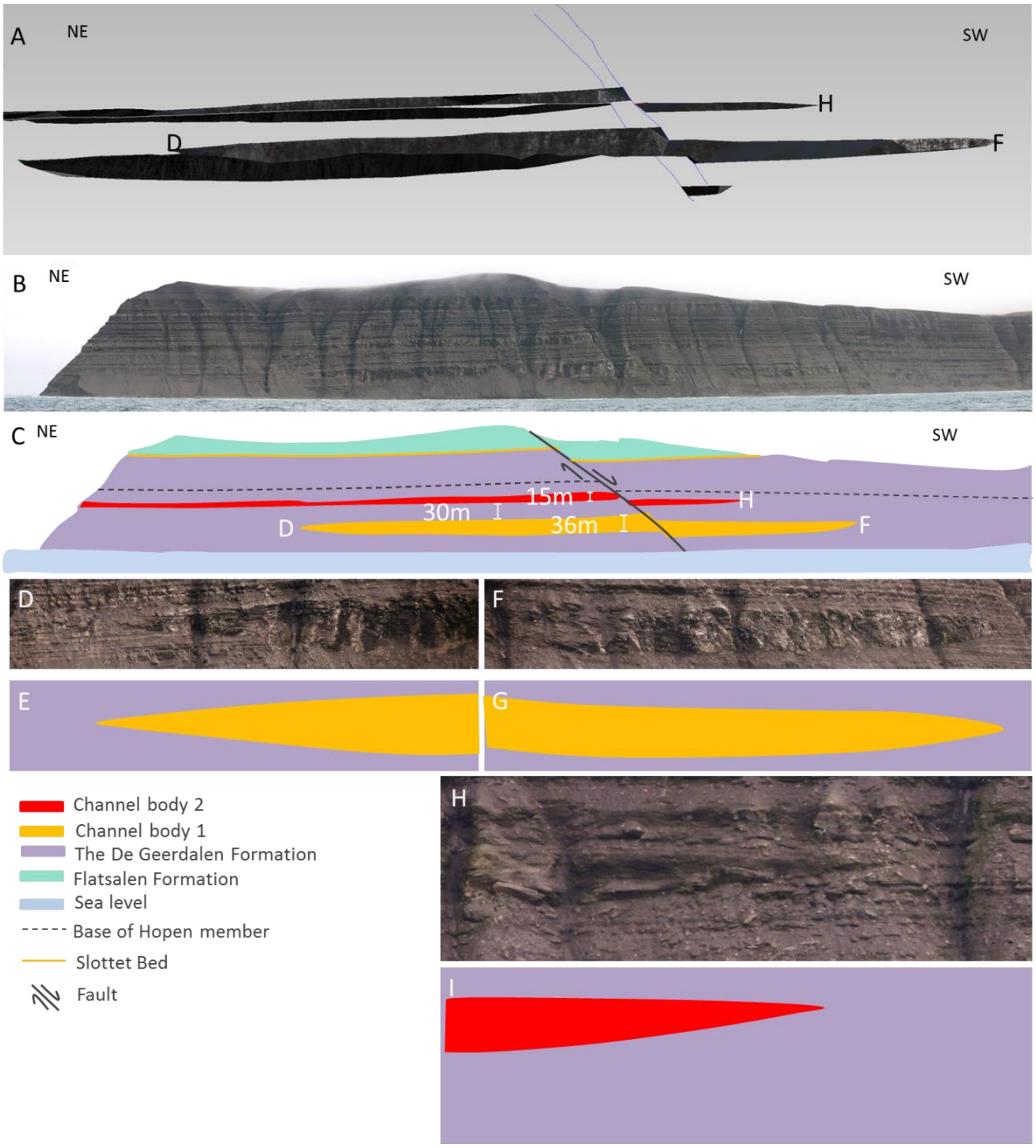


Figure 4.2: Photos and illustrations of the interpretation of the northern most part of the stratigraphic interval with Channel body 2 and the entire Channel body 1 on the western side of the island. (A) The PhotoModeler-model illustration of channel bodies 1 and 2 on the western side of the island. (B) Photo of the western side of the island. (C) Interpretation of the photo in A. (D) A close up photo of the northern most pinch out of Channel body 1. (E) Interpretation of the photo in C. (F) A close up photo of the southernmost pinch out of Channel body 1. (G) Interpretation of the photo in D. (H) A close up photo of the southernmost pinch out on Channel body 2. (I) Interpretation of the photo in H.

The log shows that the channel body consists of large scale trough cross-stratification. Trough cross-stratified sandstone can be formed by waves in the upper shoreface or by fluvial-generated currents in a channel (MacEachern and Bann, 2008; Ainsworth et al., 2011). Due to no indication of ichnofauna and that the channel body is clearly cutting into the underlying deposits, it is most likely a fluvial-dominated channel.

Palaeocurrent measurements are indicating a more or less NW-SE direction of the channel (Klausen and Mørk, submitted). This fits well with what can be seen on the PhotoModeler-model (Figure 4.1), meaning that the cross section is more or less perpendicular to the flow direction. Due to this, it is possible to compare the thickness/width ratio on the channel body with the channel body types shown in the study by Reynolds (1999). A general assumption described in the literature is that fluvial channels often have higher thickness/length ratios than distributary channels (Reading and Collinson, 2006). Typical thickness/width ratios of fluvial channels are about 1:100, while for distributary channels typical ratios are between 1:40 and 1:70. By using the maximum thickness on this channel, the thickness/width ratio is about 1:28 and therefore lower than what has been predicted for both fluvial and distributary channels. What needs to be taken into consideration is that Reynolds (1999) study is using thickness from well logs and not field observations and the theory thus might need more correction before it is applied to maximum thicknesses in the field. It is also important to recognise that the cross-sections might be partly along the channel body, giving a higher width than if the cross-sections are perfectly perpendicular to the flow-direction. Even if it is not fitting the predicted dimensions of a distributary channel perfectly, Reynolds (1999) study, clearly favours the interpretation of a distributary channel before fluvial.

There are also indications of this being a trunk channel. A trunk channel is the upstream equivalent of a fluvial distributary channel (Olariu and Bhattacharya, 2006; Blum et al., 2013). Klausen and Mørk (submitted) suggested this theory because the channel body shows indications of fluvial influence, like the lack of marine bioturbation, relatively coarse grain sizes and abundant plant fragments. This combined with its size and internal beds associated with a large river system and lateral accretion surfaces, indicates that the river stayed active and relatively stable over a prolonged period with somewhat restricted accommodation. All this together can indicate that the channel body is deposited closer to the source area than the interpreted distributary channels, hence it might represent the principle routing for major parts of the De Geerdalen Formation on Hopen.

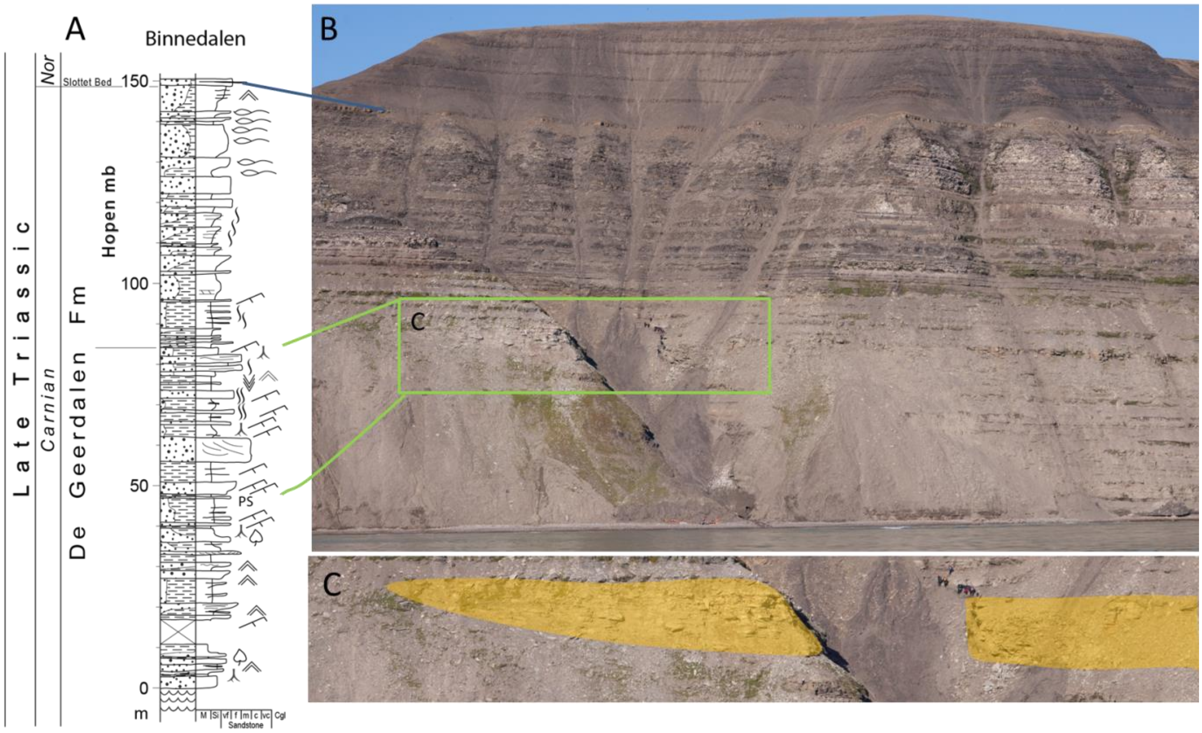
4.1.2 *Channel body 2 (Binnedalen)*

Channel body 2 is situated in Binnedalen and by using the PhotoModeler-model it is estimated to be found around 55 meters above sea level and around 90 meters below Slottet Bed. The channel body is found at approximately the same height above sea level on the logged section (Figure 4.3) and in the model, while the Slottet Bed is about 6 meters lower in the model (144 meters) than on the logged section (150 meters). This can be explained by the model having problems with orienting correctly inside this gully and some wrong height measurements while logging. Both the logged section and the PhotoModeler-model estimate the channel body to be 7 meters high. The width is difficult to estimate, because it is lacking clear pinch outs. A pinch out might be found to the left on Figure 4.3, but it is difficult to pin point the exact location due to scree covering parts of the channel body. It is not possible to see a pinch out on the right side of the same figure. On the other side of the island, NW of Binnedalen, Channel body 2 cannot be seen.

Channel body 2 is situated about 20 meters below what is interpreted to be the base of Hopen member in this area.

By following the stratigraphic unit of Channel body 2 towards the north it is possible that the sand more or less disappears (Figure 4.4 C and D). It is difficult to see if this is due to actual disappearing of the channel body or that it is only covered by scree. The reduction of the sand continues all the way to the fault seen on Figure 4.4 A and B. The fault has a displacement of around 70 meters, hence the stratigraphic unit of channel body 2 is almost at the top of the mountain on the northern side of the fault (Figure 4.4 A and B). When following the unit even further north it is possible to see that the sandstone part of it varies in thickness. In some areas it almost disappears (Figure 4.5B), while in other parts it can be up to 15 meters thick (Figure 4.5D and E). This continues all the way up to the northern most fault. As mentioned in the previous subsection the northern most fault displace the sediments with about 50 meters on the eastern side and around 18 meters on the western side of the island (Figure 4.1 and Figure 4.2). In this area it is possible to see the sandy interval of this stratigraphic unit on both sides of the island (Figure 4.1 and Figure 4.2) and Slottet Bed is once again visible and is still around 90 meters from the bottom of the interpreted stratigraphic unit.

On the western side of the island one can clearly see that the sandy unit has a pinch out towards SE (Figure 4.2 H and I), indicating a possible channel feature. The sandstone continues on the other side of the fault on both sides of the island and has a maximum thickness of around 15 meters (Figure 4.1 and Figure 4.2). On this part of the island the stratigraphic unit of Channel body 2 is approximately 30 meters above Channel body 1 (Figure 4.1 and Figure 4.2). One can also see that the sand units look similar in colour.



Logged by: Basal beds; Hilde Krogh, Mike Charnock, Håvard Buran, 2011
Main section; Audun Kjemperud, Gunn Mangerud, Morten Bergan, 2011
Hight adjusted to Smith et al. (1985) and Hynne (2010)

Figure 4.3: This figure illustrates Binnedalen with its associated log. (A) A illustration of the log taken of Binnedalen. (B) An overview photo of Binnedalen. The right part of this photo is of the same area as the left part of picture 4.4. (C) Zooming in on Channel body 2, with the interpretation of the pinch out seen to the left of the picture.

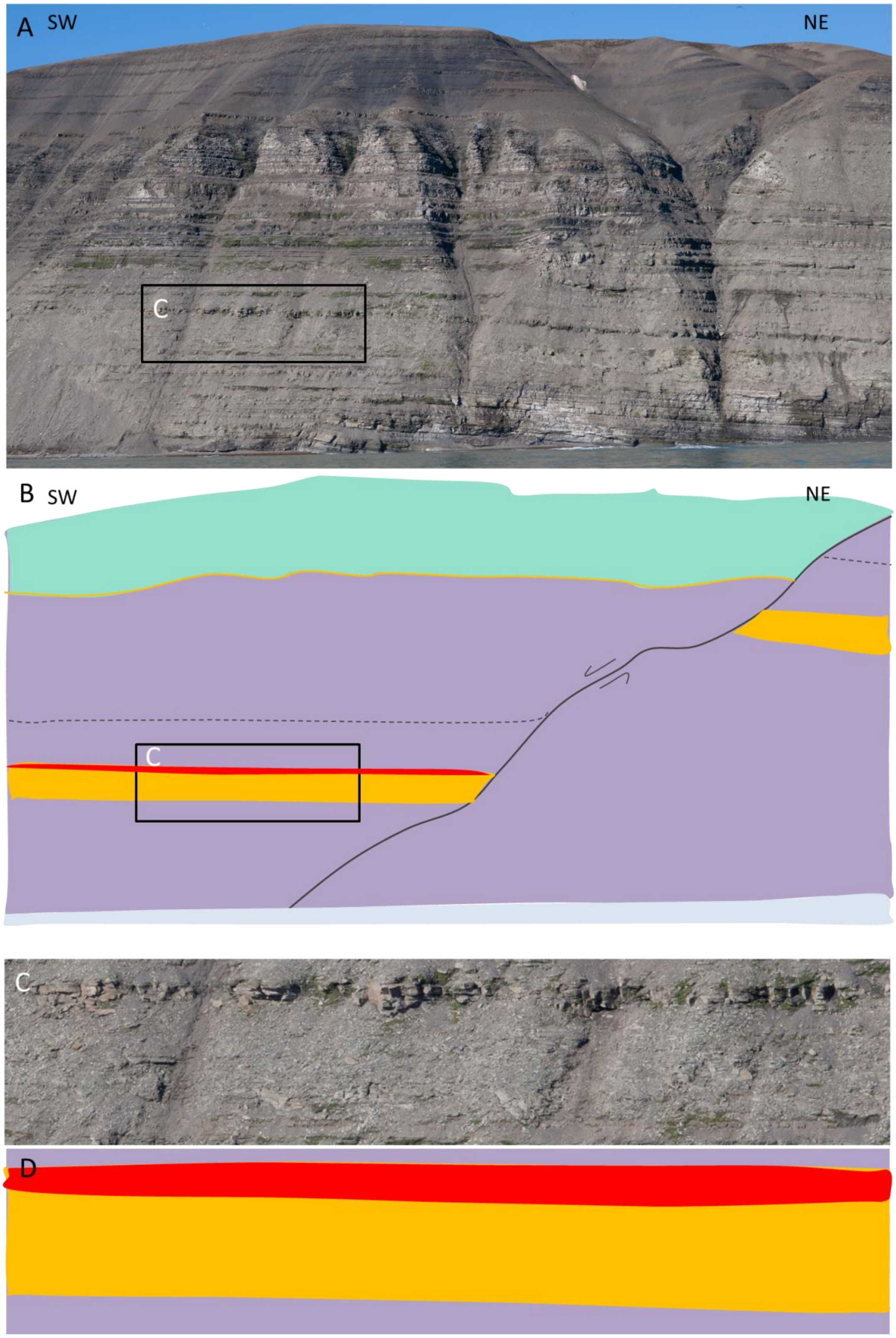


Figure 4.4: This figure illustrates the outcrop north of Binnedalen. (A) A photo of the area. (B) Interpretation of the fault displacing the sandstone unit and Slottet Bed. (C) A photo zooming in on the sandstone unit south of the fault. (D) Interpretation of the sandstone unit (orange and red), south of the fault. Red is the visible sand content and the orange colour marks a finer grained interval, possibly the channel body covered with scree.

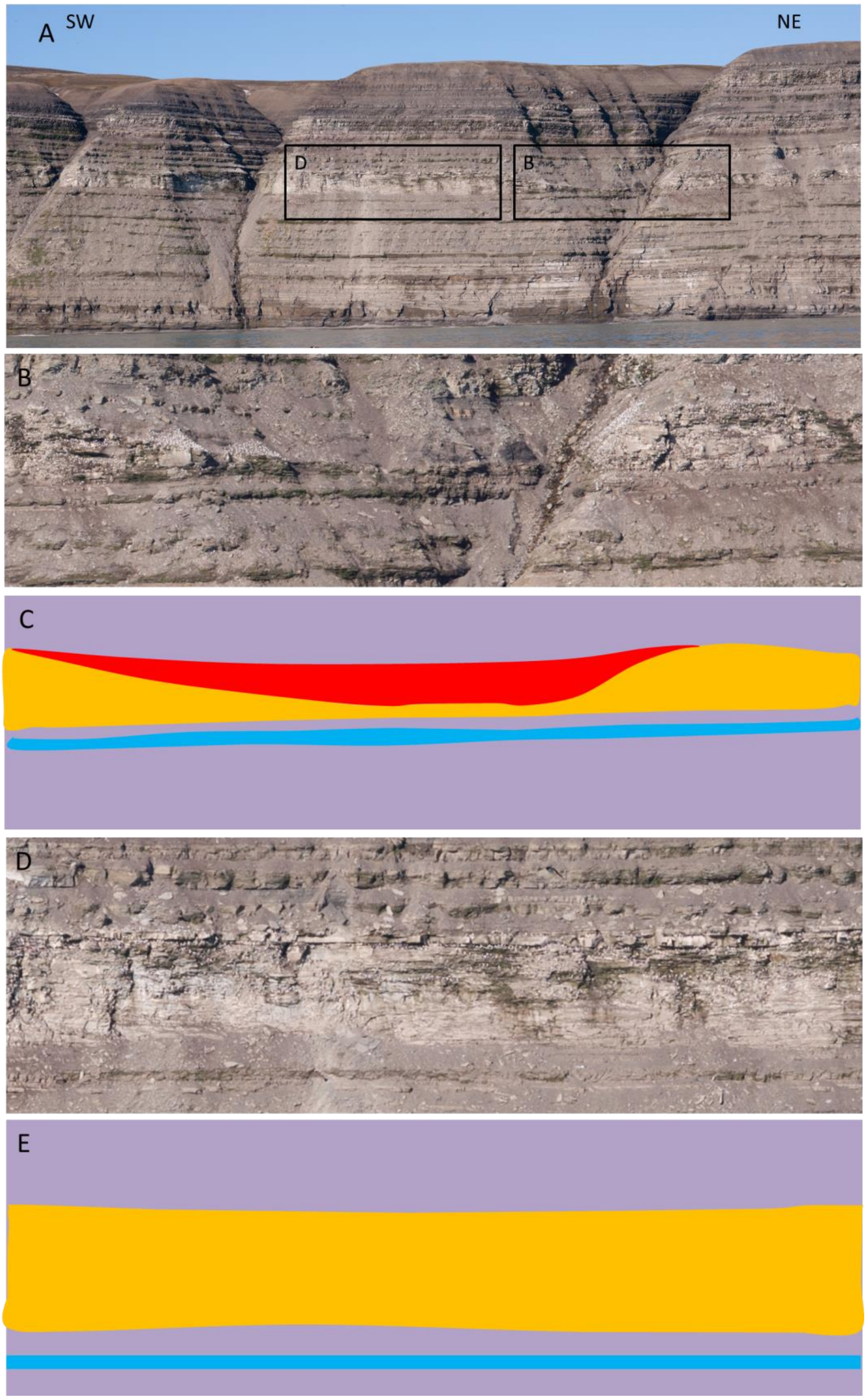


Figure 4.5: This figure displays the thickness variations found in the stratigraphical unit of Channel body 2. (A) An overview photo of the area between Binnedalen and the northern most fault. (B) Zooming in on the actual thickness variation.
(C) An interpretation of Photo B. (D) Zooming in on the on a thick sandstone interval.
(E) An interpretation of Photo D. The blue is the underlying sand layer. Orange displays the actual sandstone unit and how it thins out in the present gully. Red is the finer material covering or replacing the sandstone.

(1) Discussion

Facies occurring in the sandy interval in the logged section of Binnedalen are through cross stratified and current rippled sandstone, with indications of rip-up mud clasts. The grain size is fine- medium sandstone (Figure 4.3). These types of facies are often found in channels (Reading and Collinson, 2006), hence it supports the interpretation of this being a channel body.
The underlying layer consists of silt with root and loading structures. These facies types can be found in the interdistributary areas of a delta plain (Reading and Collinson, 2006). The overlying layer has a silty grain size as well, with indications of desiccation cracks, which corresponds to facies deposited in interdistributary areas (Bridge, 2006).

The through cross stratified and current rippled sandstone contributes to the interpretation of this being a channel. Since the channel body is placed between two layers that probably are deposited on the delta plain the channel is most likely deposited there as well, hence it is a distributary channel situated at the delta plain. The channel also lack features indicating tidal influence. The upper delta plains are essentially unaffected by tidal processes (Reading and Collinson, 2006), which leads to an interpretation of this channel body being a fluvial dominated distributary channel deposited on the upper delta plain.

Another interesting feature is the differences in distribution of the sand body on the different sides of the island. On the eastern side, the sandstone unit is found all the way from Binnedalen to the northern most part of the island, while on the western the sandstone body stops much further north. One explanation is that the sandstone body represents two channels; one in the north, found on both sides of the island, and one on the eastern side, in Binnedalen. The sandstone between them than probably consists of crevasse splay deposits. Crevasse splays are deposited by scouring through the channel levees and lobes of fine sand are deposited where these debouch into the flood basin (Selley, 2000). If this is the case the direction of these channels fits well with what is found other places on the island, going in a SE-NW direction (Klausen and Mørk, submitted) (Figure 4.1). One observation that works against this interpretation is the thickness of the crevasse splay deposits. By using the PhotoModeler-model the maximum thickness of the sandstone unit, possibly representing crevasse splay deposits, was found to be 15 meters. Reynolds (1999) found out, by studying 84 different crevasse splays that the maximum thickness was 12 meters and that the mean thickness was only 1.4 meters. This weakens the interpretation of this being two channels with one associated crevasse splay deposits. On the other hand it can have several levee-breakthroughs creating an amalgamated sandstone unit consisting of several crevasse splays. As mentioned by Mjøs et al. (2009), a single crevasse-splay is commonly less than 2.5 meters, hence thicker crevasse splay sandstones are most likely composite. If this is the case a thickness of 15 meters is perhaps not likely, but possible.

Another explanation is that the entire sandstone unit represents one channel body. For this to be valid the flow-direction of the channel must be different than what is found on other channels on the island. There are three findings that can support this explanation.

1. No pinch outs are seen between Binnedalen and the northern most fault (Figure 4.1, Figure 4.4 and Figure 4.5) on the eastern side of the island.
2. The clear pinch out on the western side of the island, close to the northern most fault (Figure 4.2 H and I).
3. A thick sandstone unit is seen on the eastern side of the island, between the northern most fault and Binnedalen, while on the western side no sand is observed in this stratigraphic interval.

A possible explanation is a channel that goes more or less parallel to the island from Binnedalen towards the northern most fault. The channel is not wide enough to be seen on both sides of the island. Around the northern most fault the channel body is shown on both sides. This can be explained by a decrease in island width towards the northern tip, combined with the channel having a direction change, getting more perpendicular to the island towards the end of the island (Figure 4.6A). This can indicate a shift in sediment supply, from the normal SE-NW trend (Klausen and Mørk submitted) to an N-S or even NNE-SSW trend. Another explanation is that this is a distributary channel with an oblique flow-direction to the overall trend.

Both the interpretation of two channels with a connected crevasse splays and the interpretation of a single channel are plausible explanations, but with the dataset collected at the island it is difficult to determine either one of them.

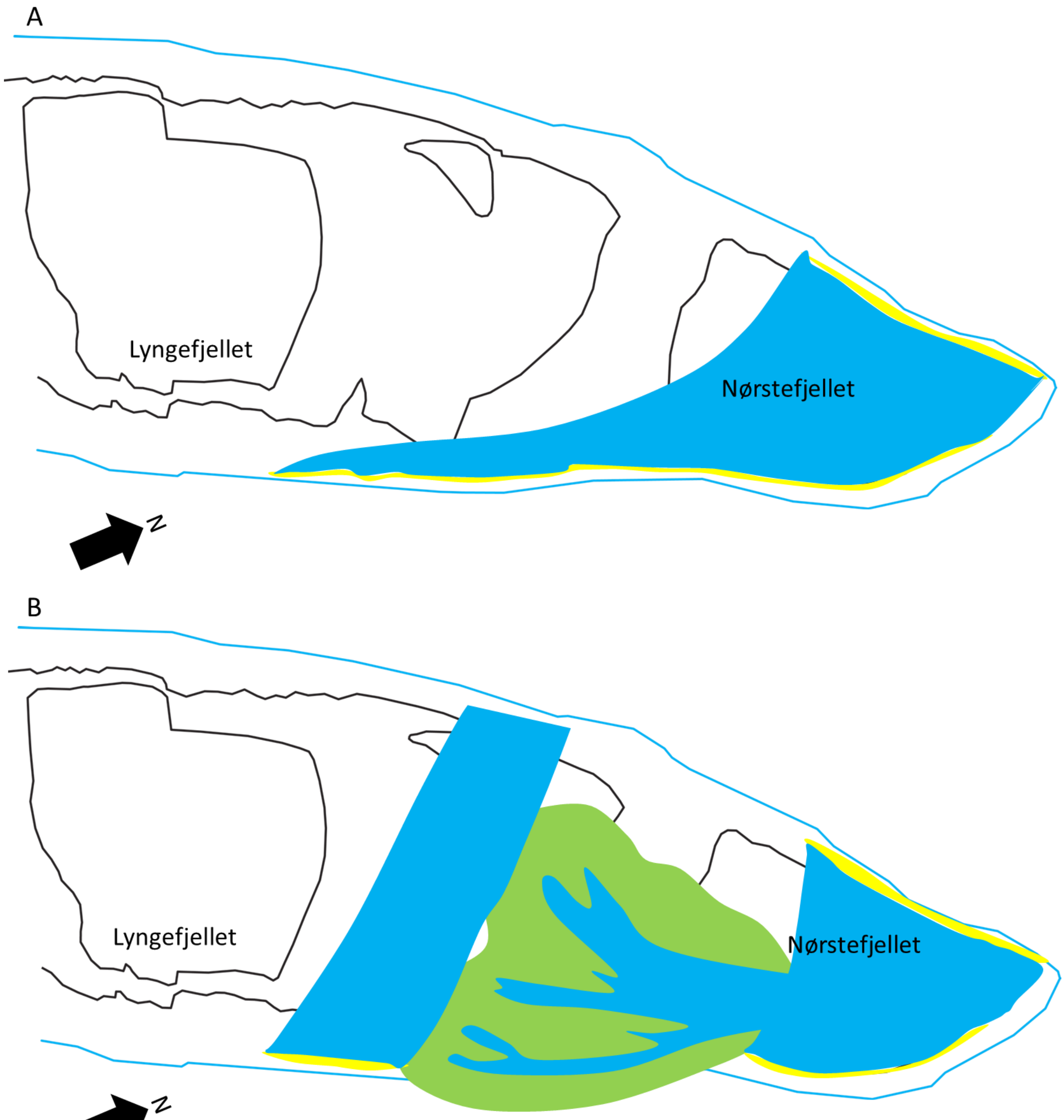


Figure 4.6: This figure illustrates river paths that can explain the sandstone unit found in the stratigraphical unit of Channel body 2. (A) Illustrates the interpretation of the sandstone unit being deposited by one channel. (B) Illustrates the interpretation of the sandstone unit being deposited by two channels and associated crevasse splay. The areas marked with yellow are illustrating outcrops, while blue illustrates possible river-path.

4.1.3 *Channel body 3 (Blåfjellet Channel complex)*

Since the PhotoModeler-model is only accurate in terms of thickness and width of the channel bodies on the eastern part of the island, the measurements described here are only done on one side of the island. On the eastern side, Channel body 3 is measured to be approximately 30 meters thick and about 415 meters long. The width of this channel body can possibly be larger, because the sandstone unit seen left of what is interpreted as Channel body 3 can actually be part of the same channel body. If this is the case, the width will be approximately 810 meters. The channel body erodes into what looks like another channel body towards the south.

This channel complex is situated just south of Blåfjellet, more or less at sea-level. The distance to Hopen member is difficult to estimate on the western side of the mountain, but the channel body is located approximately 140 meters above the top of Channel body 3 on the eastern side of the island.

By looking at the channel body on the eastern side, as well as on the western side of the island, it is possible to see several erosional surfaces (Figure 4.7). It will be too detailed to interpret every single one of them, but some of the key factors will be discussed.

The area marked with orange colour (Figure 4.7) is clearly cutting into the underlying deposits, as defined by a clear erosional base. Inside this channel body there are several erosional scours along the bed boundaries. It is also possible to see that the channel body has a light grey colour, but when zooming in on the erosional contact, darker layers, possibly finer grained, appear in the underlying sequence (Figure 4.7). One can also see that the channel body is eroding into sandstone bodies on both sides. The sandstone body towards the south shows clear indications of having an erosional base, and hence might be a channel body (Figure 4.7).

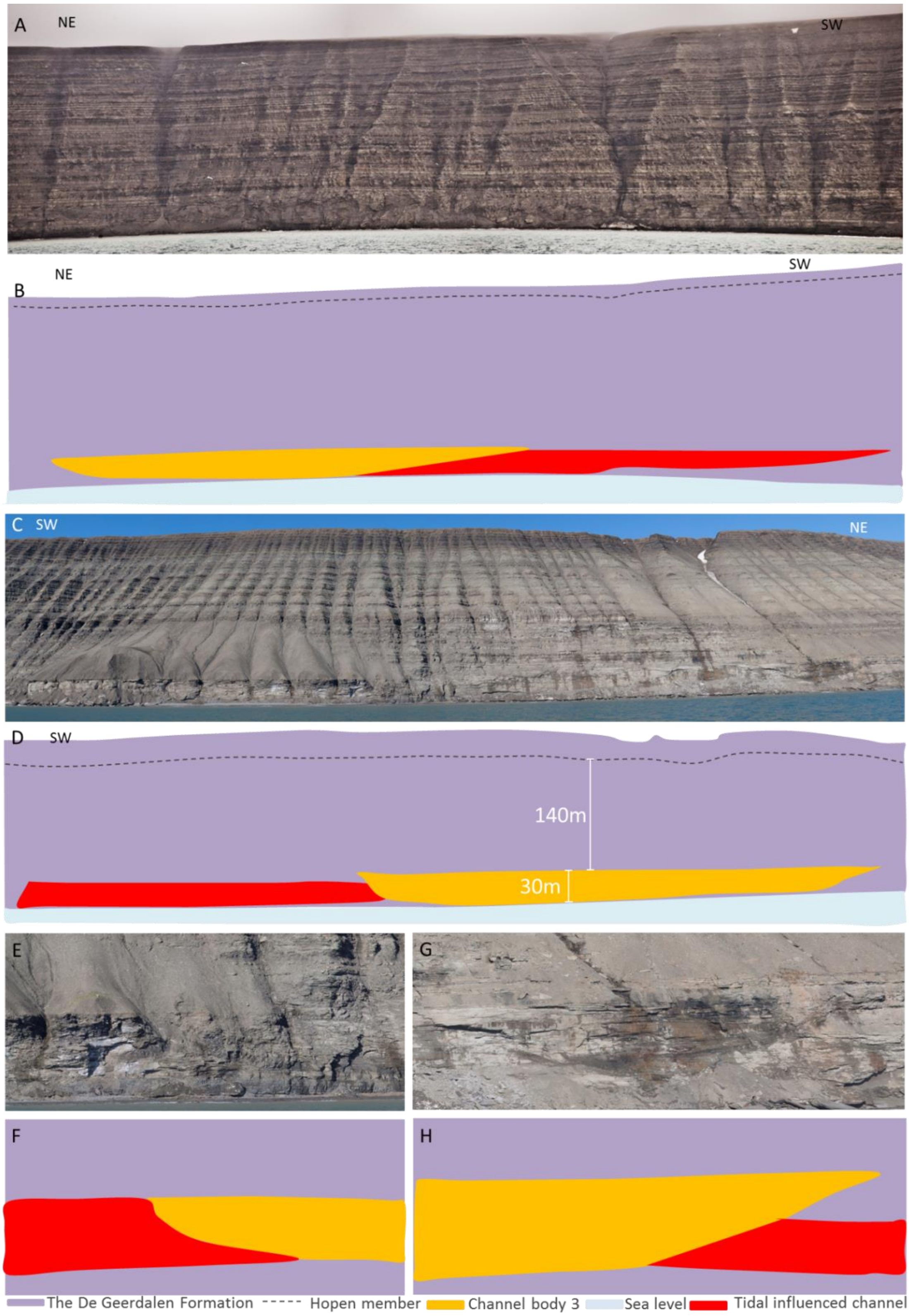


Figure 4.7: This figure illustrates an overview of Blåfjellet channel-complex. (A) A panorama of the channel complex seen from the western side of the island. (B) Interpretation of the panorama shown in A. (C) A panorama of the channels seen from the eastern side of the island. (D) Interpretation of the panorama shown in C. (E) A close up photo of the southern pinch out of Channel body 3. (F) Interpretation of the photo shown in E. (G) A close up photo of the northern pinch out of Channel body 3. (H) Interpretation of the photo shown in G.

(1) Discussion

Some of the features found in this channel body indicate a different depositional environment than all the other channel bodies that have been logged. During the following section the observations described above will be discussed, with emphasize on the differences between this channel body and the rest.

The most striking feature found on Channel body 3 is that it has several erosional scours. This indicates that the channel body is multi-story, where each of the channel body is less than 5 meters thick. This means that the channel body is deposited in an environment where relatively thin, multiple amalgamated bodies that pinch out within 10-15 meters, are plausible to find. The logged section of Channel body 3 also indicates that this channel body has signs of tidal influence, where tidal bundles and mud drapes are the main indicators. These indications are strikingly different from what is found in the other channels of this size. For instant, in Channel body 1, indications of tidal influence is totally absent and the channel body is most likely representing one channel in a restricted area. The features of channel body 3 however, are most likely indicating an estuarine channel body, where the amalgamating channel bodies are thought to be deposits of migrating dunes (Klausen and Mørk, submitted).

The channel body to the south, eroded by Channel body 3, is also partly logged. The photos indicate that this channel body consists of amalgamated channels; hence this channel body is also multi-story. The logged section shows that the channel body consists of fine to very fine arenitic sandstone with an upward fining trend, through-cross stratification and common mud drapes. Through-cross stratification in sandstone bodies with erosional bases, indicates channel deposition (Reading and Collinson, 2006), while mud drapes are often associated with tidal influenced deposition (Bhattacharya, 2006). The similarities to the facies found in a distributary channel are striking, but due to the indications of tidal influence, this channel body is most likely a tidal influenced fluvial channel.

It was not possible to log the erosional scours due to a nearly vertical outcrop, as well as rock falls, which makes it dangerous to log in that area. The assumption of these channel bodies being multi-story is only based on what is visible on the photos.

4.1.4 *Channel Body 4 (Johan Hjortfjellet)*

Channel body 4 is situated on Johan Hjortfjellet and is most likely found on both sides of the mountain (Figure 4.8, Figure 4.9 and Figure 4.10). By using the PhotoModeler-model, the maximum thickness on both sides of the mountain is estimated to be approximately 32 meters and the width around 950 meters. The width is challenging to estimate since it is difficult to see a clear pinch out towards the south on the outcrop on the eastern side of the island (Figure 4.9C). On the western side the pinch out towards the south can be seen, while the pinch out towards the north is more difficult to pinpoint (Figure 4.10C). Just by a quick look on the channel body, one can see that Channel body 4 appears much more fractured than the channel bodies found closer to sea-level, for instant Channel body 1. The widespread fracturing makes it difficult to see any large-scale structures and make it difficult to pinpoint the location of pinch outs.

This channel body is most likely situated 18 meters from what is interpreted as Hopen member (Figure 4.8).

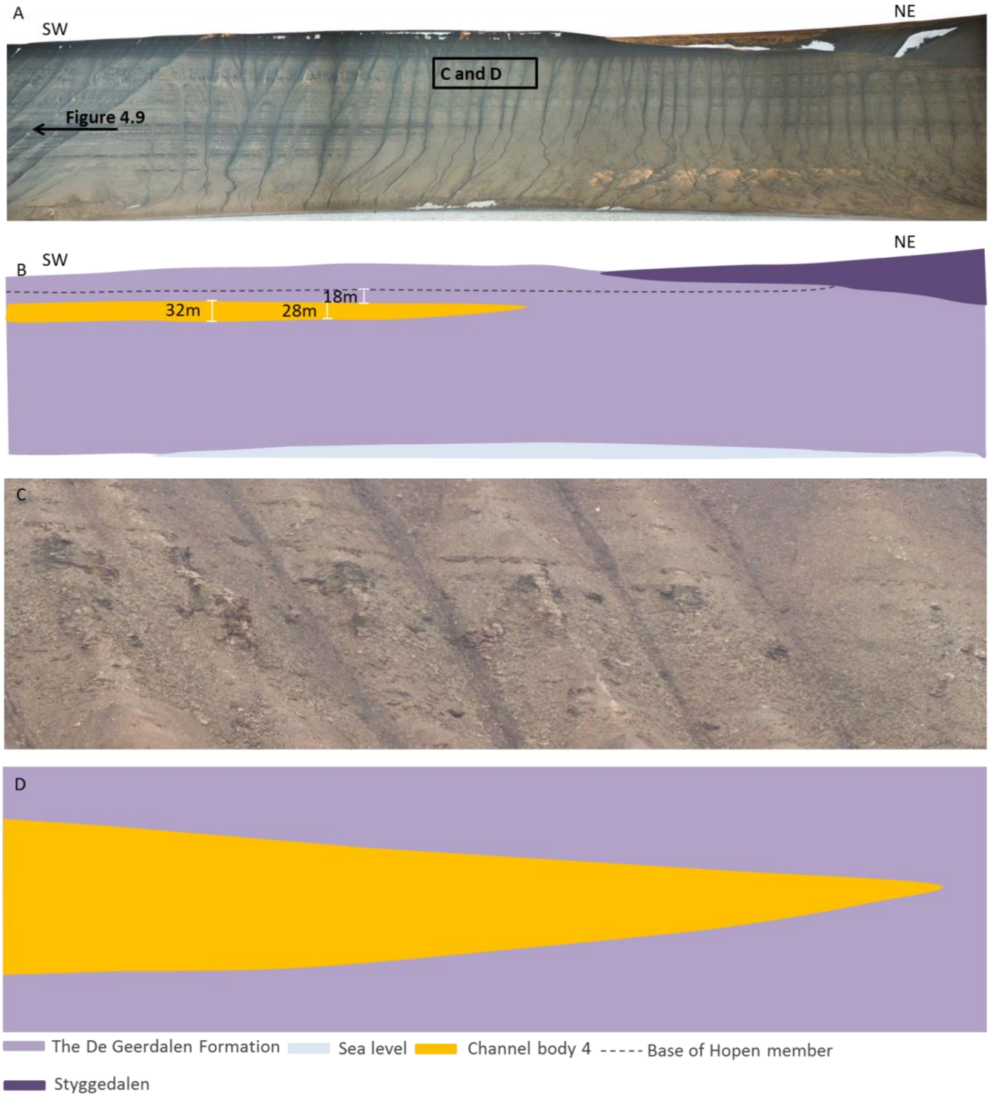


Figure 4.8: Photos and illustrations of Channel body 4 on the eastern side of the island, northern most part. (A) Photo of the eastern side of the island. (B) Interpretation of the photo in A. (C) A close-up photo of the northern pinch out of Channel body 4. (D) Interpretation of the photo in C.

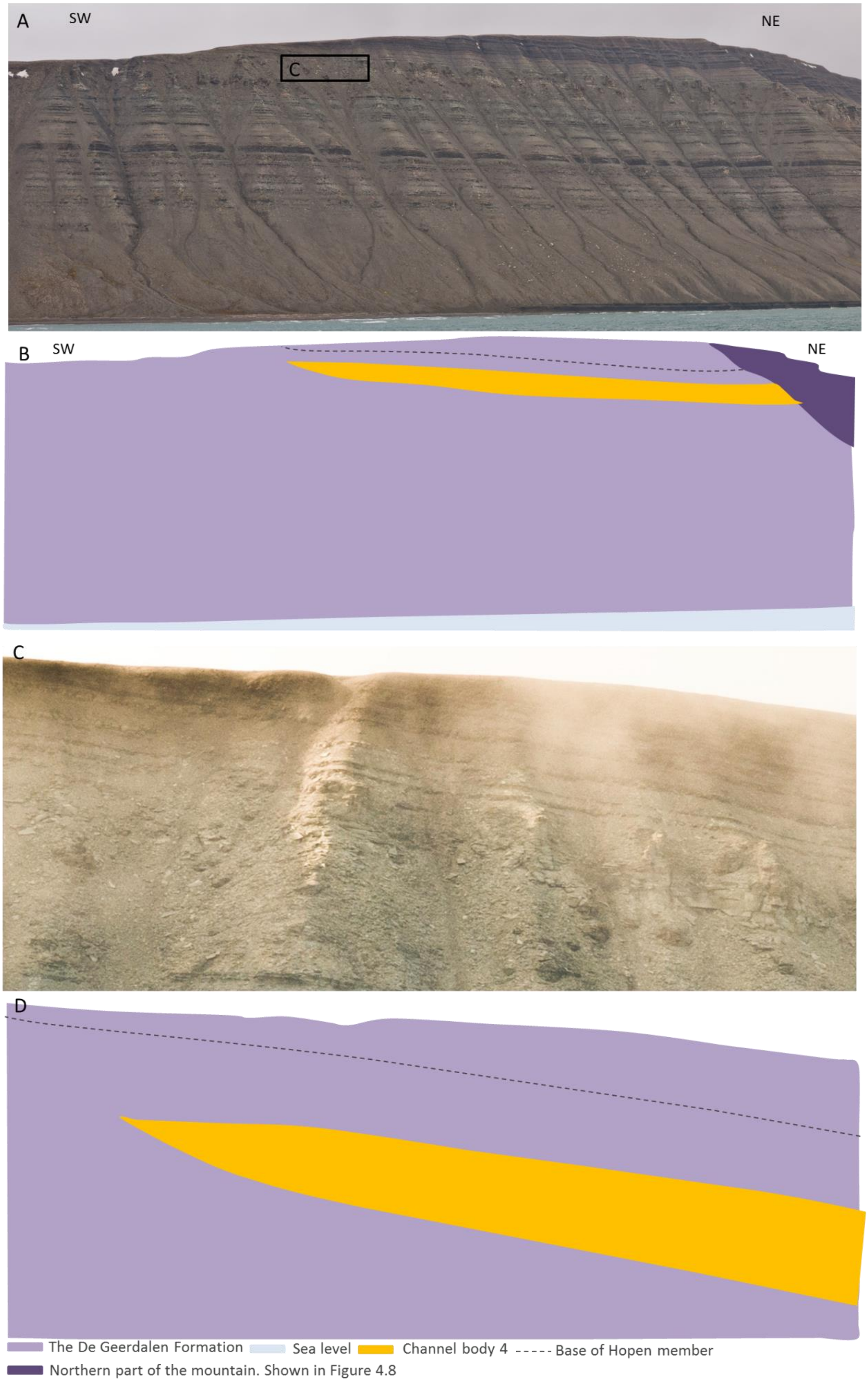


Figure 4.9: Photos and illustrations of Channel body 4 on the eastern side of the island, southern most part (A) Photo of the eastern side of the island. (B) Interpretation of the photo in A. (C) A close-up photo of the southern pinch out of Channel body 4. (D) Interpretation of the photo in C.

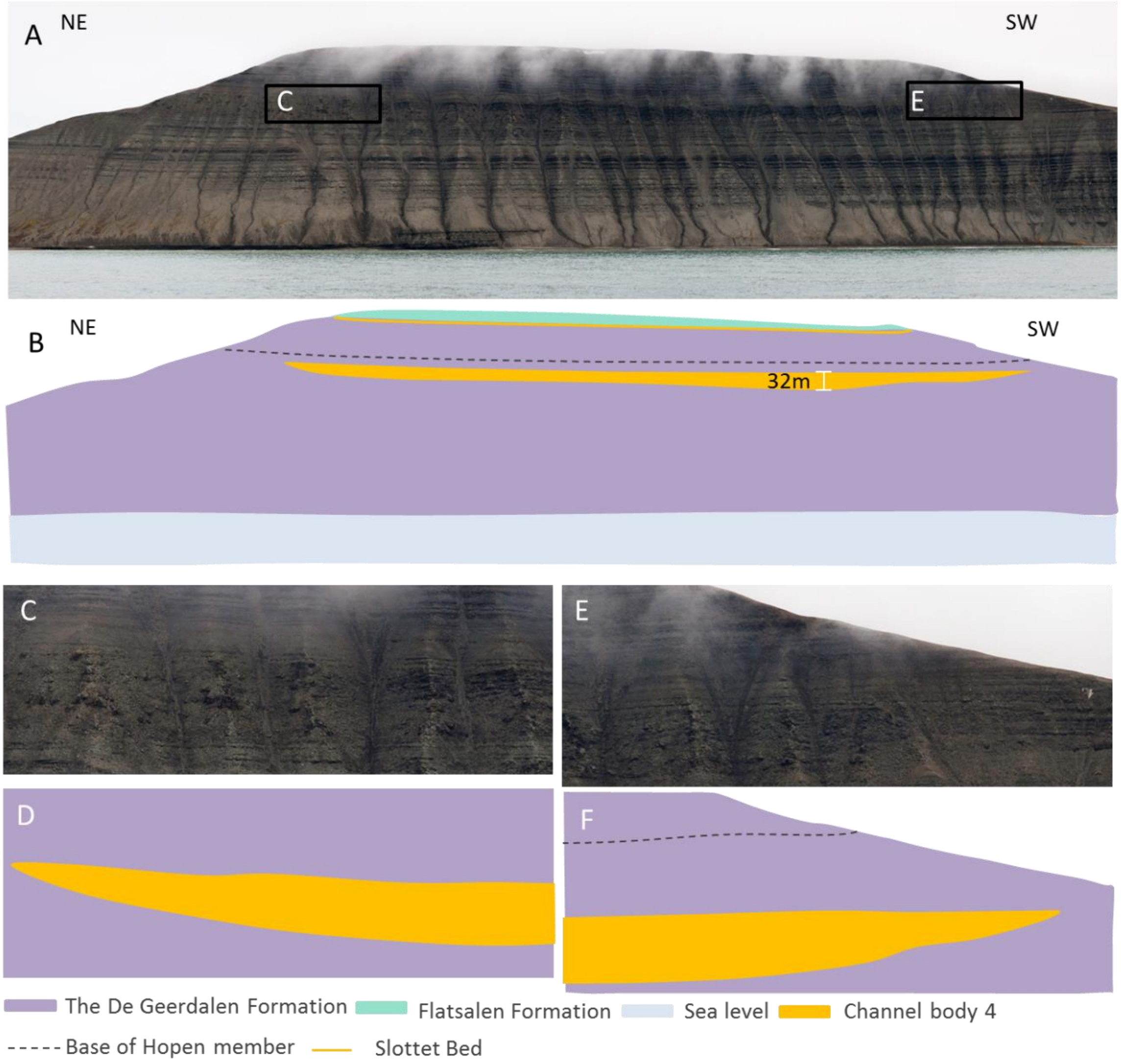


Figure 4.10: Photos and illustrations of Channel body 4 on the western side of the island (A) Photo of the western side of the island. (B) Interpretation of the photo in A. (C) A close-up photo of the northern pinch out of Channel body 4. (D) Interpretation of the photo in C. (E) A close-up photo of the southern pinch out of Channel body 4. (F) Interpretation of the photo in E.

(1) Discussion

This is one of the few channel bodies on the island where the entire thickness of the channel body has been logged (Figure 4.11). The thickness that is measured by logging is approximately 28 meters, while the thickness in the PhotoModeler-model is 32 meters. The difference can be caused by a small error in the model, but most likely it is caused by the lateral change in channel body thickness, since the GPS suggests that the section was logged a bit further north, where the channel body starts to thin out (Figure 4.8B).

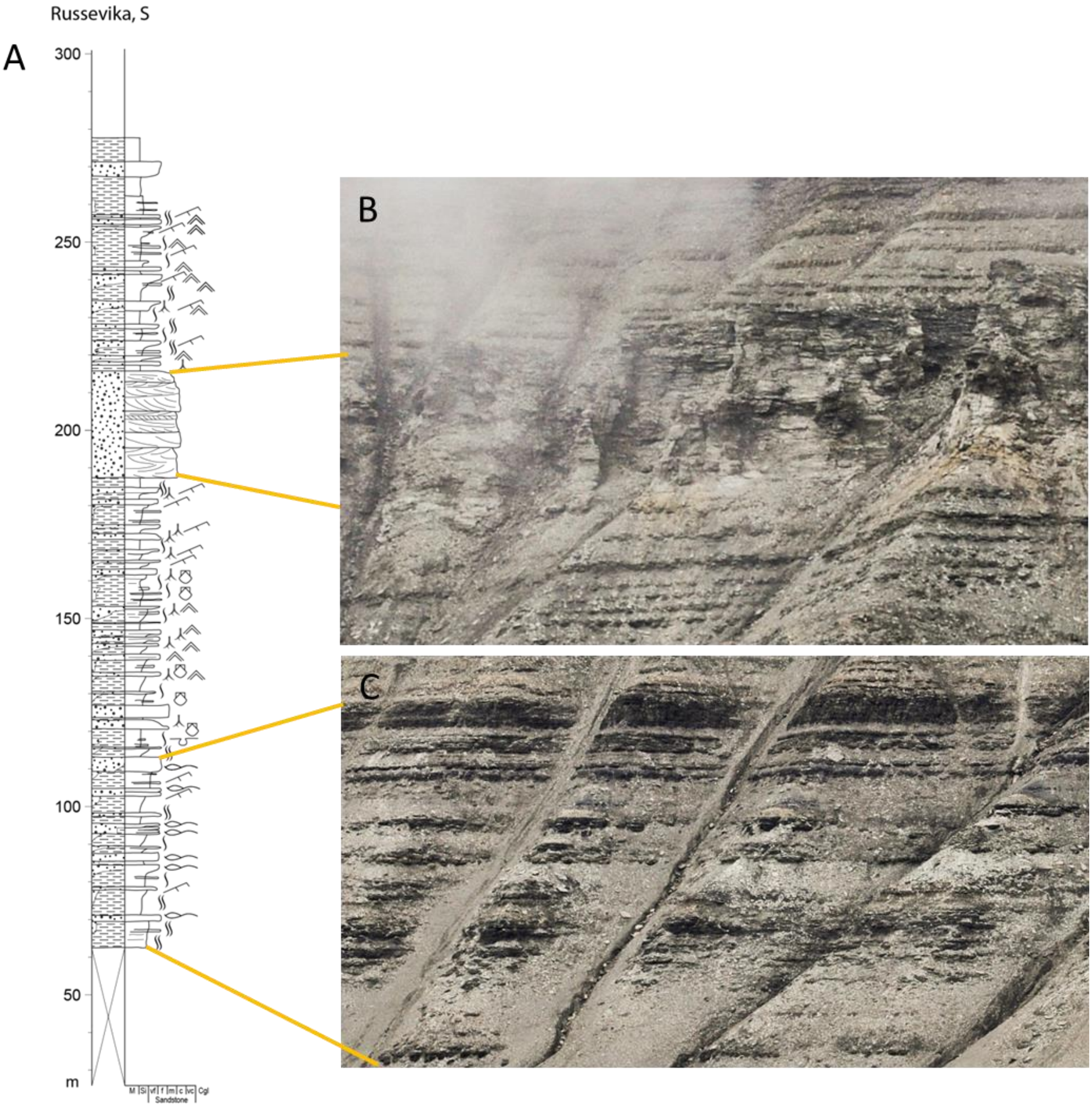


Figure 4.11: This figure illustrates the log done at Russevika south in 1995 by Geir Elvebakk, Leif Bjørnar Henriksen and Per Emil Eliassen, and two photos of key areas in the log. (A) An illustration of the log. (B) A close up photo of Channel body 4. (C) A close up photo of the lower part of the log, where one can clearly see marine influence indicating shallow marine environment.

The log shows that the channel body consists of fine to medium grained sand with through cross-stratification forming large beds and no indication of tidal influence. Hence it resembles Channel body 1, both in size and in dominating sedimentological structures. As mentioned by Klausen and Mørk (submitted), the difference is that there are no signs of lateral accretion surfaces on Channel body 4, as oppose to Channel body 1. This can be caused by this outcrop being a lot more fractured due to its elevation and distance to the sea, or it is reflecting a different migration direction relative to the outcrop direction than what is found on Channel body 1. Either way this channel body is assumed to be a trunk channel by Klausen and Mørk (submitted) for the same reasons as explained in subsection 4.1.1: Channel body 1.

As described above it is possible to see this channel body on both sides of the island. The outcrop on the western side of the mountain is situated NW of the logged section on the eastern side of the island. This fits well with the palaeocurrent measurements done by Klausen and Mørk (submitted).

Another interesting feature is found by looking at the lateral continuation of this stratigraphical interval. By examining Figure 4.9 one can see that even though the channel pinches out there is still a sandstone unit continuing towards the north, possibly representing crevasse splays and levee complexes with a direct link to the channel body. This theory is supported by Klausen and Mørk (submitted).

The difficulties with pinpointing the location of the pinch outs can be due to crevasse splays and levee complexes with a direct link to the channel body. The reason for that is that crevasse splays can comprise depositional elements such as channel bars and channel-fill which are hard to distinguish from the main channel on the floodplain. Crevasse splays can also be difficult to distinguish from levee deposits. (Bridge, 2006), making it difficult to state if this sandstone interval consists of either crevasse splays or levee complexes, or perhaps a combination.

It is also important to recognize that the lower portion of the log (Figure 4.11A and 4.11C) indicates that this stratigraphical interval experienced marine influence, partly interpreted on the base of abundant hummocky cross-stratification dominating the sediments. Hummocky cross- stratification is typically found in connection with storm influenced deposits in a shallow marine environment (Reading and Collinson, 2006).

4.2 Channel body Group 2

Channel body group 2 consists of 10 different channel bodies. As mentioned in the introduction, some of these channels bodies are discussed by comparing the geometrical indications with the lateral continuation of logged sections from outcrops of channel bodies. This gives an indication of what environment the channel body was deposited in. Where there are no logged sections available, the channels are interpreted by use of geometrical indicators found on the photos and in the PhotoModeler-model only, and hence are more briefly discussed.

Table 4.2: Overview of the channel bodies described in Chapter 4.2: channel body group 2.

Channel body	**Size (thickness, width)**	**Logged**	**Probability for channel body**
5	15 m thick and 200 m wide	No	Medium->High
6	11 m thick and 210 m wide	No	Medium
7	6 m thick and 145 m wide	No	Medium
8	8 m thick and 240 m wide	No	Medium
9	The PhotoModeler-model is not oriented properly, hence it is difficult to evaluate its thickness on the western side of the island, but on the eastern side it is approximately 19 m thick and 475 m wide.	Compared with a log nearby	High
10	25 m thick and 815 m wide	Yes	High
11	15 m thick and 232 m wide	No	Medium
12	20 m thick and 917 m wide	No	Medium
13	22 m thick and 210 m wide	Compared with a log nearby	Medium->High
14	15 m thick, while the width cannot be calculated	Compared with a log nearby	High

4.2.1 *Channel body 5 (SW of Nørstefjellet)*

Channel body 5 is situated a bit south of Nørstefjellet (Figure 4.12) and is only observed on the western side of the island. The channel body is situated around 40 meters below Hopen member. As marked by the stippled line in Figure 4.12C. The stratigraphic unit including Channel body 1 has its base 1.5 meter bellow the base of this channel body (Marked with yellow in Figure 4.12). By using the PhotoModeler-model, the maximum thickness was estimated to be around 15 meters and the width to be approximately 200 meters. The Slottet Bed is marked with an orange line in Figure 4.12C. It is also possible to see a fault approximately 100 meters away from the channel body (Figure 4.12B and C).

By examining the channel body it looks like the body is cutting down into the underlying layers for roughly 8 meters. The channel body also has a convex-upward shape with the overlying layers bending over. Another interesting feature seen both in the model and on the photos, is that while the overlying mud layer is approximately 2 meters thick on both sides of the sand body, the mud layer is no more than 0.5 meters thick above the actual sandstone. It is also possible to see that the apparent folding of the overlying layers seems to disappear further up in the stratigraphy (Figure 4.12).

The natural dips in the area were calculated by using the height above sea level on different levels in order to examine the extent of the apparent anti-form. First dips where measured on a layer located beneath the channel body, and thereby not influenced by overlying deposits. Three different height measurements were taken. Results show that the layer below the sandstone unit has a steady dip of 1.7 degrees towards the south. By using the same method on a layer located right above the channel body, the calculations shows that this layer has a dip of 0.3 degrees towards the north between measurements 1(47.5m) and 2(48.3m), while the dip is 3.2 degrees towards the south between point 2(48.3m) and 3(42.4m). To be certain that the layers further up in the stratigraphy actually do not have an anti-form, the dip of a layer towards the top of the mountain were found. In this upper layer the calculations found a steady dip of about 1.5 degrees towards the south, more or less the same as the one below the sandstone, indicating a local anti-form close to the channel body.

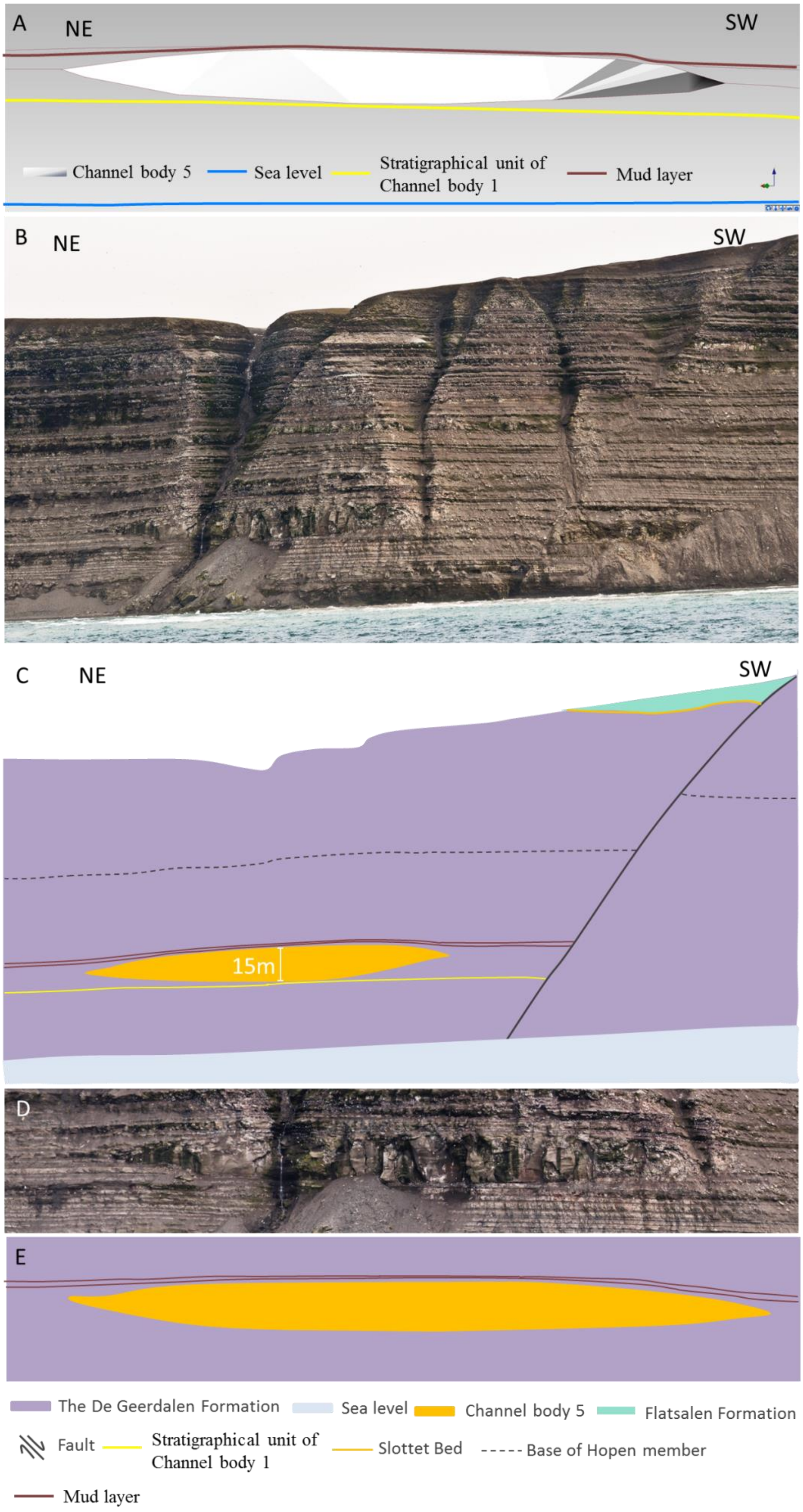


Figure 4.12: An illustration of the location of Channel body 5. (A)PhotoModeler-model of Channel body 5. (B) An overview photo of Channel body 5. (C) Interpretation of the photo shown in B. (D) A close up photo Channel body 5. (E) Interpretation of the photo shown in D.

(1) Discussion

One of the interesting features found on this channel body, is that the top of the channel has a convex-upward shape as well as the thinning of the overlying muddy layer. This type of structures can be caused by differential compaction. Where there is a lateral change in sediment type, differential compaction can occur. That means that one part of a sediment pile compacts more than the part adjacent to it (Nichols et al., 2009). Differential compaction is typically not found in areas where fluvial channel bodies are surrounded by overbank mudstones (Nichols et al., 2009). This is because the fine sediments on a floodplain dry out between flood events and lose most of their pore waters at this stage. As a consequence the effect of overburden pressure on overbank muds and channel sands may be the same (Nichols et al., 2009). This can therefore contribute to an interpretation of Channel body 5 being a distributary channel located close to the delta front, in an area where overbank sediments do not have time to dry out.

Another possible interpretation is that the bending of the layers is caused by the fault (Figure 4.12B and C). Layers tend to bend down against faults, creating a possible anti-form. The anti-form typically weakens upwards as we move away from the fault. One observation that questions this interpretation is that the layers beneath the channel body are not affected. If this anti-form was caused by the fault, the layers underneath would most likely have been equally, or possibly even more effected than the layers above, as the layers below are located closer to the fault (Figure 4.12).

4.2.2 *Channel body 6 and 7 (Western side of Lyngefjellet)*

Channel body 6 shown on Figure 4.13 has a maximum thickness of 11 meters and is around 210 meters wide. While Channel body 7 (Figure 4.13) is 6 meters thick and 145 meters wide. These two channels are described in the same subsection partly because they are situated in the same area, but also because their geometry is similar. Channel body 6 is situated 29 meters below Hopen member, while Channel body 7 is situated around 50 meters below Hopen member.

Channel body 6 and 7 seem to have a higher portion of mud on the left side of the channel bodies, than on the right side (Figure 4.13). The colour also changes from light orange on the right side to more grey/black colour on the left side. It also seems to be finer material towards the top of the channel bodies (Figure 4.13). The channel bodies consist of several dipping layers (Figure 4.13).

By taking a closer look at Channel body 6, it seems like the layers at its southern most part appear to pinch out towards the overlying sandstone unit (Figure 4.13).

On Channel body 7 it is difficult to see any clear indications of dipping layers towards the north of the channel body, while on the southern side the dipping layers are clear (Figure 4.13).

(1) Discussion

The dipping layers which seem to pinch out towards the overlying sandstone unit can indicate presence of amalgamating channel bodies, which would mean that the channel body actually consists of at least two channels, where the youngest erode into the underlying channel. This can contribute to an interpretation of Channel body 6, as a channel body consisting of a younger channel with point bars and channel infill, possibly mud-plug, while the oldest channel only displays its point bars. This indicates a multilateral channel body, which is defined as laterally coalescent sand bodies (Potter, 1967; Gibling, 2006).

Channel body 7 seems to be single-story where the dipping layers to the south are point bars and the area marked with red in Figure 4.13 is channel infill, possibly mud-plugs.

Another explanation of the apparent fine-grained material could be that the sediments are covered by scree and therefore have nothing to do with the sediments deposited in that stratigraphical interval.

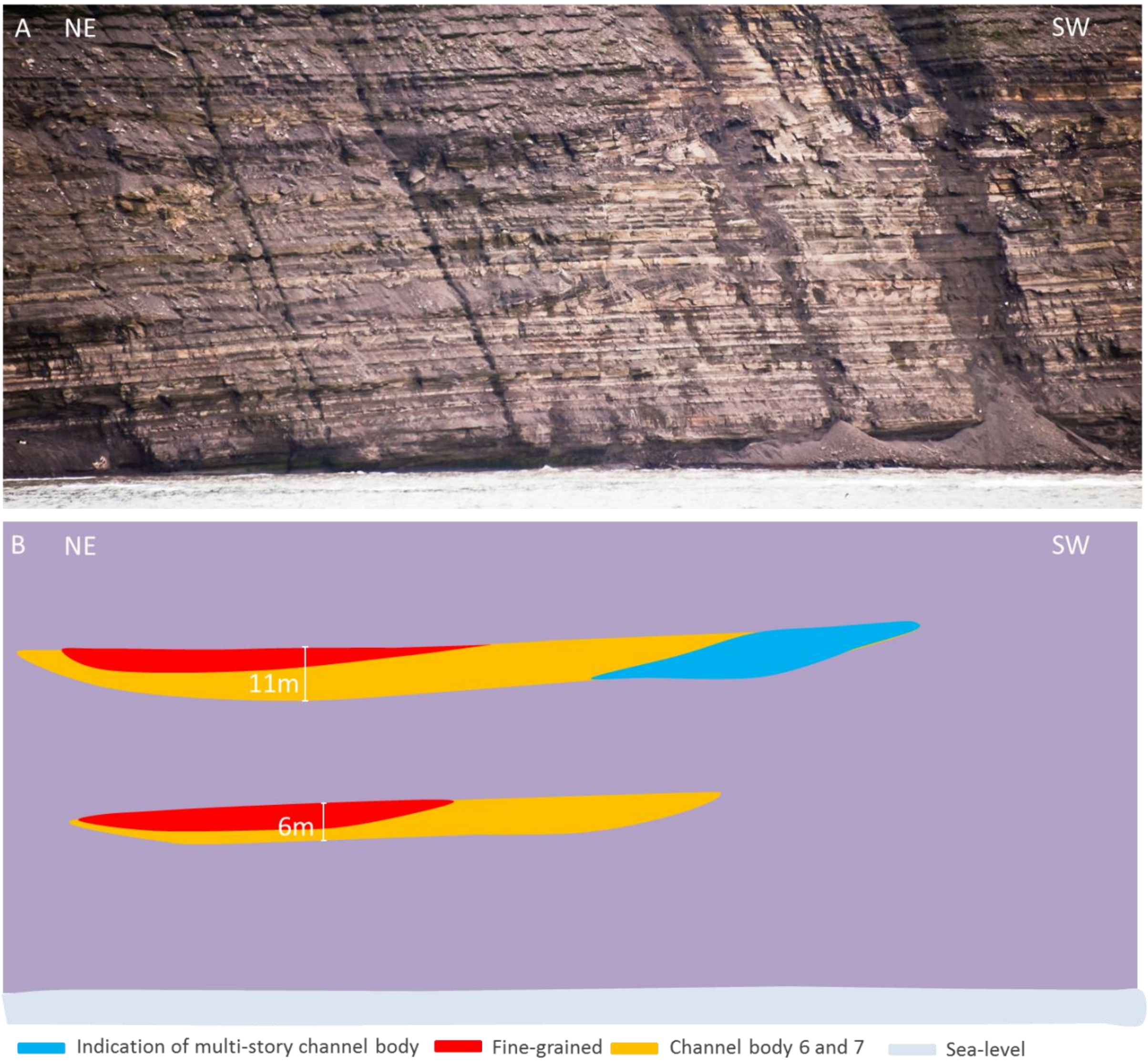


Figure 4.13: This Figure illustrate channel bodies 6 and 7 found on the western side of Lyngefjellet. (A) A photo of channel bodies 6 and 7. (B) An interpretation of the photo shown in A.

4.2.3 *Channel body 8 (SW of Lyngefjellet)*

Channel body 8 (Figure 4.14) has a maximum thickness of 8 meters (based on the interpretation shown in Figure 4.14) and a width of approximately 240 meters. The channel body has a white to orange colour. On the left side of Figure 4.14 it is possible to see that for about 90 meters the channel body thickness is constant. Towards both of the pinch outs, the channel body consists of darker coloured sediments (Figure 4.14) and especially on the right side of the channel body, towards the south, these darker coloured sediments seem to consist of finer grained material than the central body (Figure 4.14).

The channel body is situated only 4 meter below what is interpreted as the Hopen member, and is also the uppermost channel body found on the island.

(1) Discussion

The most important feature found on Channel body 8 is the wing seen on the left side in Figure 4.15. A wing is defined as a thin marginal part of a channel body, often distinguished from the central body where basal scour shows a distinct inflection point. It is usually composed of levee and/or crevasse-splay deposits (Bersier, 1958; Gibling, 2006) or in some cases, the wing can represent the upper part of the actual channel body, also called the topmost story (Gibling, 2006). In the case of Channel body 8, no clear erosional scours or other indications of that the wing is connected, but distinct from the channel fill are found. It is also important to have in mind (As described in Chapter2) that the interpretations are done with a much higher resolution, hence it might be difficult to see the interpretations on the photos shown in this thesis. It is difficult to conclude that the wing consists of crevasse-splay and/or levee complexes. This means that the most likely interpretation of Channel body 8 is that the wing only is a continuation of the upper part of the channel body and therefore represents the topmost story. However, since there is no logged section in this area, the interpretation is only based on the geometry seen on photos and therefore the theory about this being crevasse-splay and/or natural levees cannot be excluded.

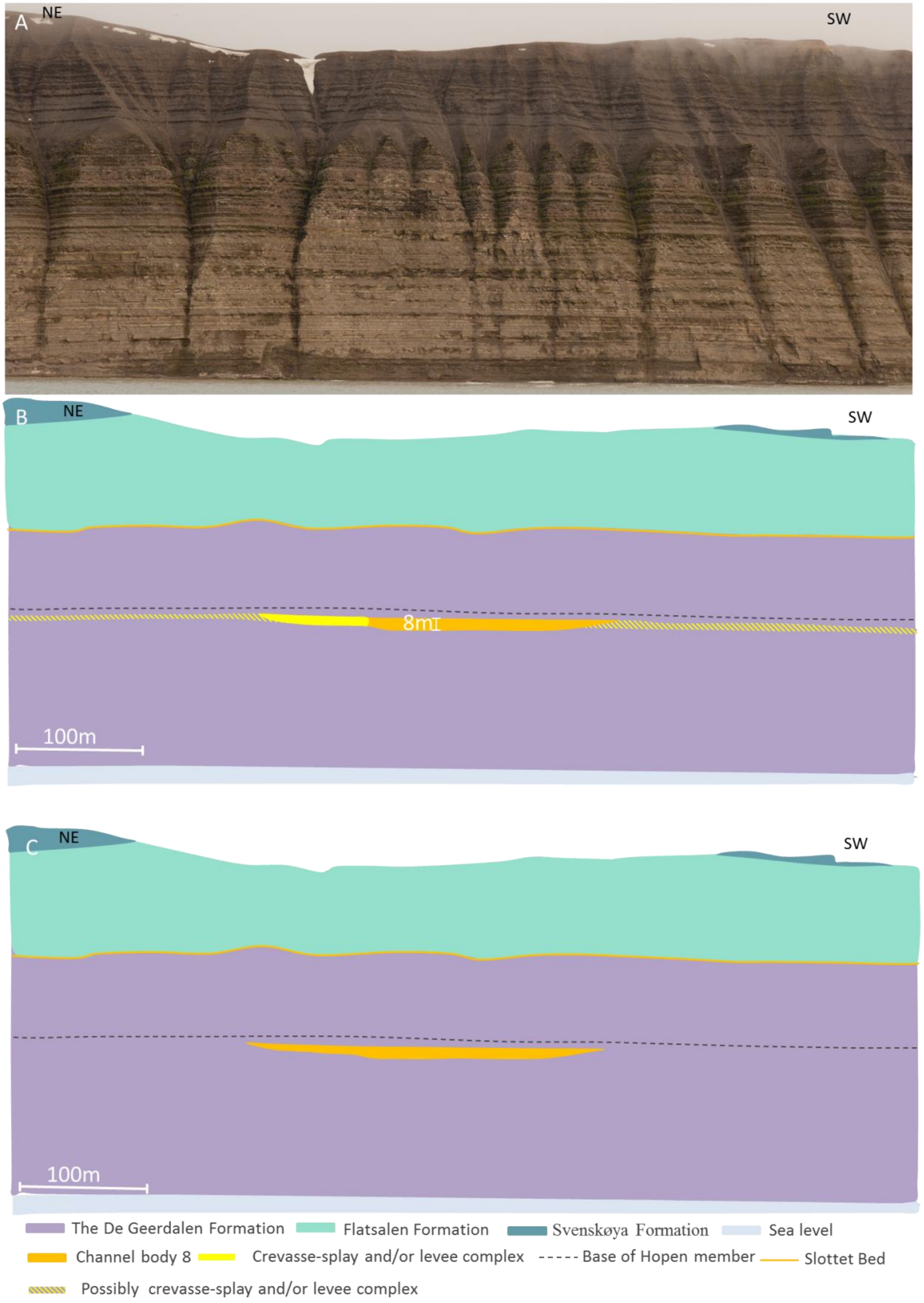


Figure 4.14: This figure illustrates the area where Channel body 8 is situated. (A) A overview photo of the outcrop where Channel body 8 is situated. (B) Interpretation of Channel body 8, where the wing consists of natural levee and/or crevasse splay. (C) Interpretation where the wing is the topmost part of the channel body.

Figure 4.15: This figure illustrates the wing found at Channel body 8. (A) A photo of the wing. (B) The wing consisting of natural levee and/or crevasse splay. (C) The wing is the topmost part of the channel body.

4.2.4 *Channel body 9 (Blåfjellet, Middle unit)*

Channel body 9, shown on Figure 4.16 and Figure 4.17 is situated on Blåfjellet. The orientation of the constructed model is not optimal on the western side of this mountain. This leads to uncertain thicknesses and width measurements on that side (Table 4.2). The PhotoModeler-model shows a maximum thickness of 13 meters and a width of around 325 meters on the western side, while the measurements, on what is interpreted as the channel body on the eastern side, give a maximum thickness of 19 meters and width of 475 meters. The channel body consists of dipping sand layers separated by, what looks like, more mud-rich layers (Figure 4.16A and 4.17A).

The channel body cross-section on the eastern side of Blåfjellet is positioned E-SE of the cross-section on the western side of the island (Figure 4.17). Both of the cross-sections are placed at the same stratigraphic level and show the same characteristic dipping layers. By comparing photos of the two outcrops, the dip appears similar. It is also possible to see that the layers are dipping towards north for about 2/3 of the channel body's width on the western side, while the layers dip south for about 2/3 of the channel body width on the eastern side (Figure 4.16 and 4.17)

One can see that layers close to each other have different dips and that the lower most layers seem to wedge out, indicating erosion into the layer beneath.

Another interesting observation is that towards the top of the investigated channel body more white-orange coloured sand lenses occur (red colour in Figure 4.16 and 4.17). The sand lenses clearly pinch out towards the south on the cross-section found on the western side of the island, while the location of the pinch outs on the eastern side is more difficult to pin point. On the western side, the colour of these sand lenses changes from white-orange to more grey-black towards the north. The layers are underlain by grey- coloured, possibly very fine-grained material to the south and more black coloured, most likely coarser material towards the north.

(1) Discussion

By comparing the pictures (Figure 4.16 and 4.17) and thickness/width measurements of the two outcrops, the cross-section on the eastern side of the island seems to be bigger than the one on the western side. It is also important to discuss possible explanations of why most of the layers are dipping towards the north (on the outcrop) on the western side of the island, while on the eastern side, 2/3 of the channel body layers have the opposite dip direction. During the next part of this subsection these two phenomena's will be discussed.

By studying the geometry of the channel body on both sides of the PhotoModeler-model, as well as on the photos, it is possible to see that the channel body on the western side of the island is situated on a really steep mountain side, while on the eastern side, the channel body is situated on a more gently dipping hillside. This can mean that what looks like a significant thickness difference actually is nothing more than an optical illusion due to variations in hillside dip. If this is the case, the thickness/width measurements from the model are uncertain, and the thickness variation may be smaller than first suggested (12 meters on the western side and 19 meters on the eastern side) by the model. However this interpretation cannot explain the total thickness difference, as the difference in width needs a different explanation.

The width difference of the two outcrops can be explained by different orientations of cross sections relative to the channel bodies (Figure 4.16 and 4.17). By assuming a moderate meandering channel, the outcrop on the western side is situated where the channel is more or less straight, while the cross-section on the eastern side is cutting through the channel path more oblique (Figure 4.16 and 4.17).

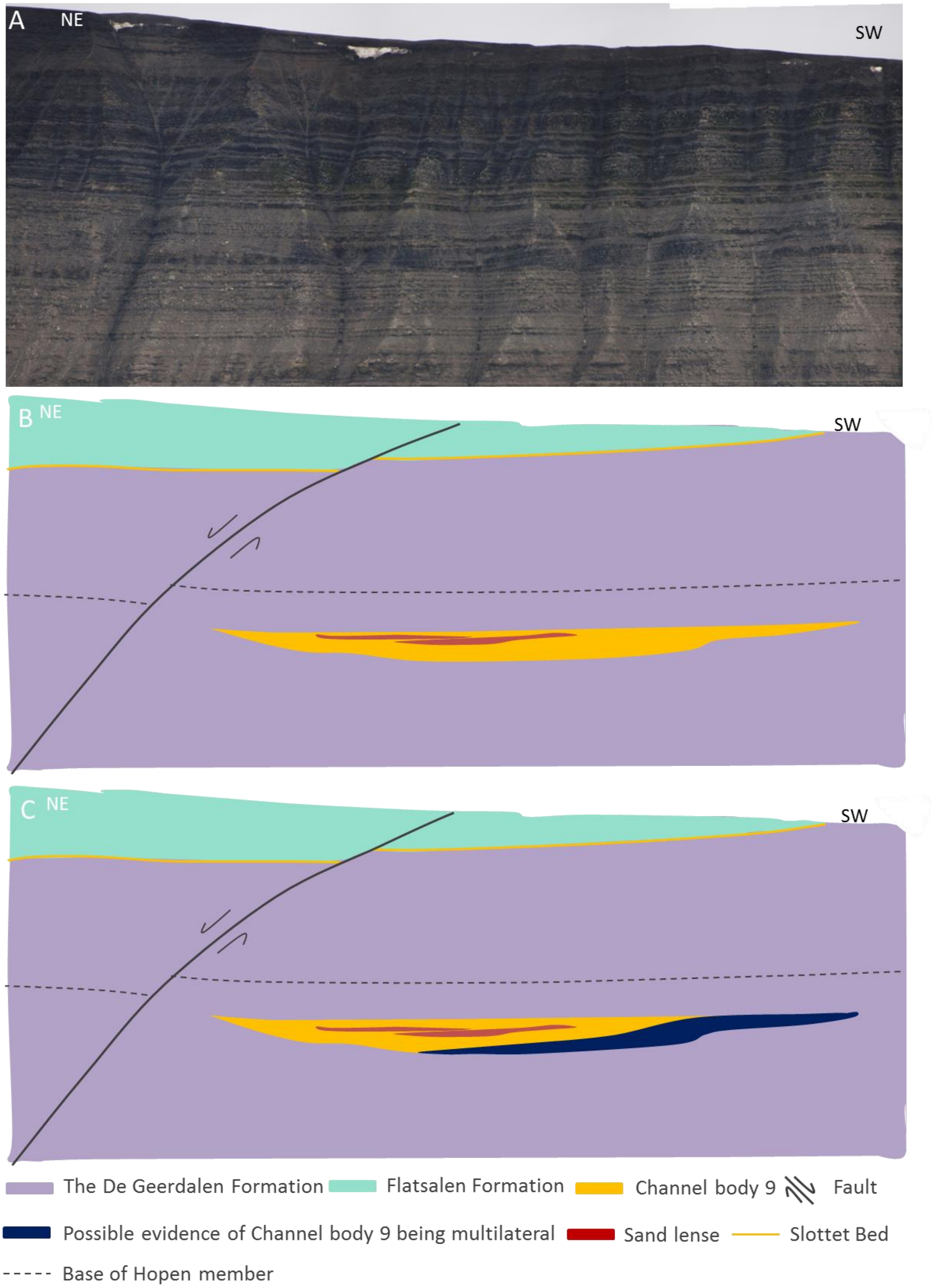


Figure 4.16: Illustrates Channel body 9 on the western side of the island. (A) Photo of the outcrop. (B) Interpretation of the channel body as single-story. (C) Interpretation of the channel body as multi-story.

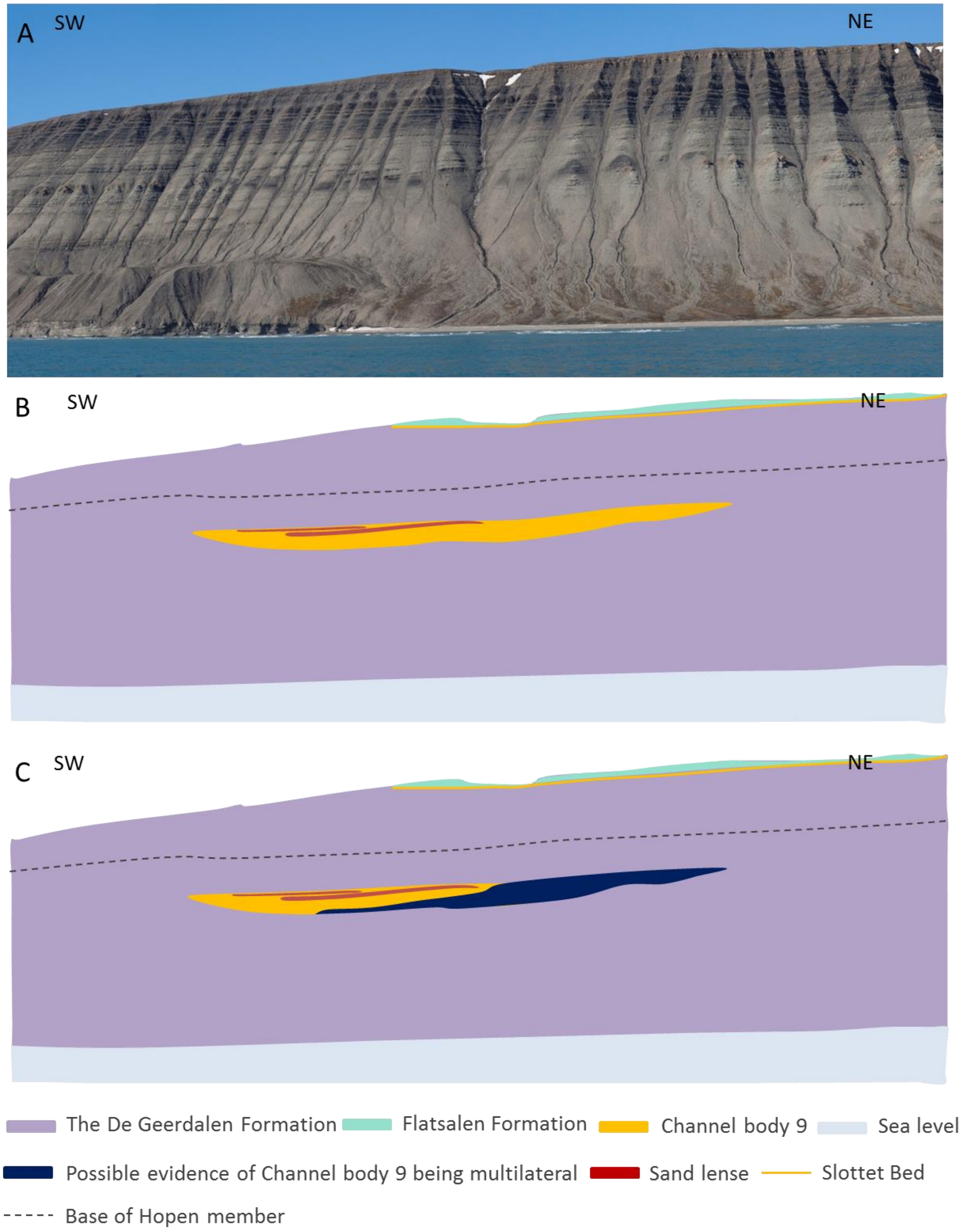


Figure 4.17: Illustrated Channel body 9 on the eastern side of the island. (A) Photo of the possible channel body. (B) The interpretation of the channel body as single story. (C) Interpretation of the channel body as multi-story.

The outcrop orientations and/or a natural thickness /width change can explain the changes in thickness and width, but they cannot explain why two connected layers have different dips. Different dips could however indicate presence of two channels, which could mean that Channel body 9 is a multilateral channel (Potter, 1967; Gibling, 2006) (Figure 4.16C and Figure 4.17C). If this is the case the two outcrops of the first channel have slightly different orientations (Figure 3B), while the channel eroding into it (Figure 4.18A), has less sinuosity, and hence the cross-sections of the last channel body are more or less the same in both outcrops (Figure 4.18).

The latest deposited channel is eroding into the underlying channel to the north on the western side of the island, while on the eastern side, the channel is eroding into the underlying channel to the south (Figure 4.16 and 4.17). This can be explained by the difference in orientation between the two channels. The second one is straighter and has a more NNW-SSE trend than the underlying channel body (Figure 4.18C).

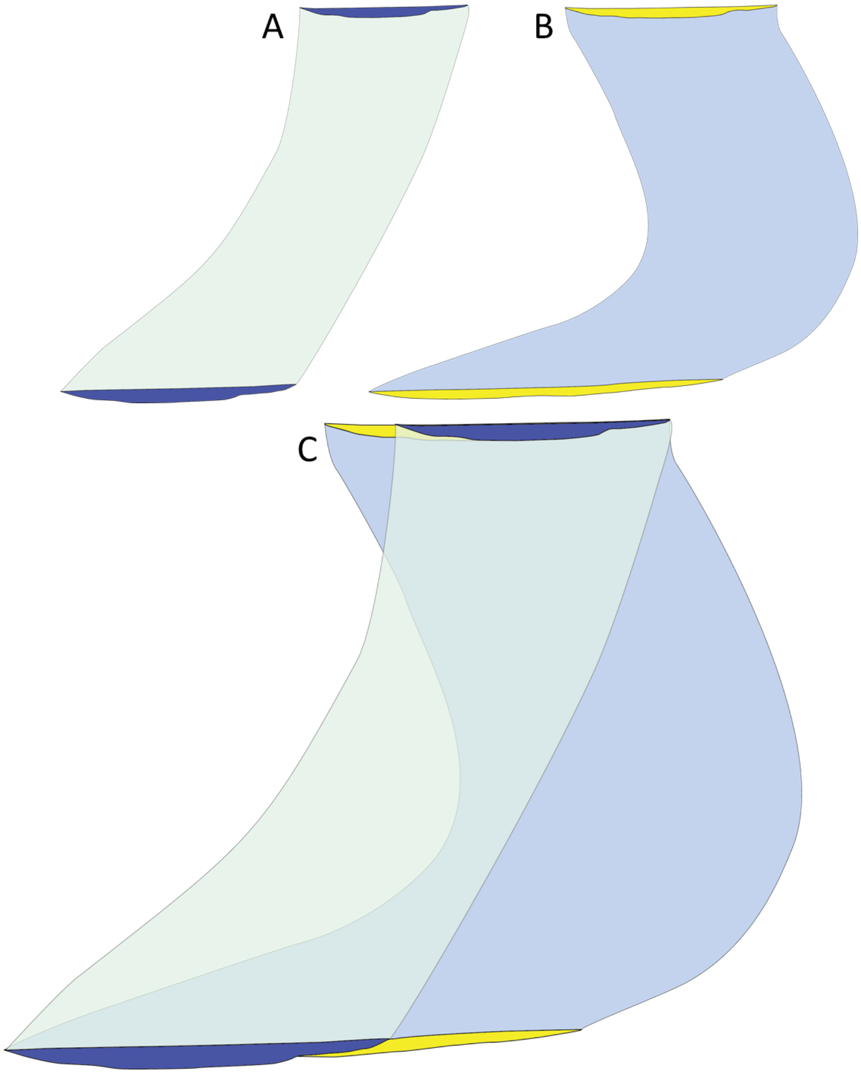


Figure 4.18: This figure illustrates the river paths of the two channels found in channel body 9. (A) Shows the river path of the upmost channel. (B) Illustrates river path of the lower most channel before the channel shown in A eroded into it. (C) Shows how the upper most channel eroded into the lower most channel. The different river paths illustrated here may explain why the layers are dipping to the SE on the eastern side, while on the western side the layers are dipping to the NW.

Channel body 9 is unfortunately not logged, but the log Blåfjellet E, which was logged by Hopen project participants in 2011(See Chapter 1), is situated not far from the channel body, hence it might be possible to say something about the environment that the channel body was deposited in (Figure 4.19).

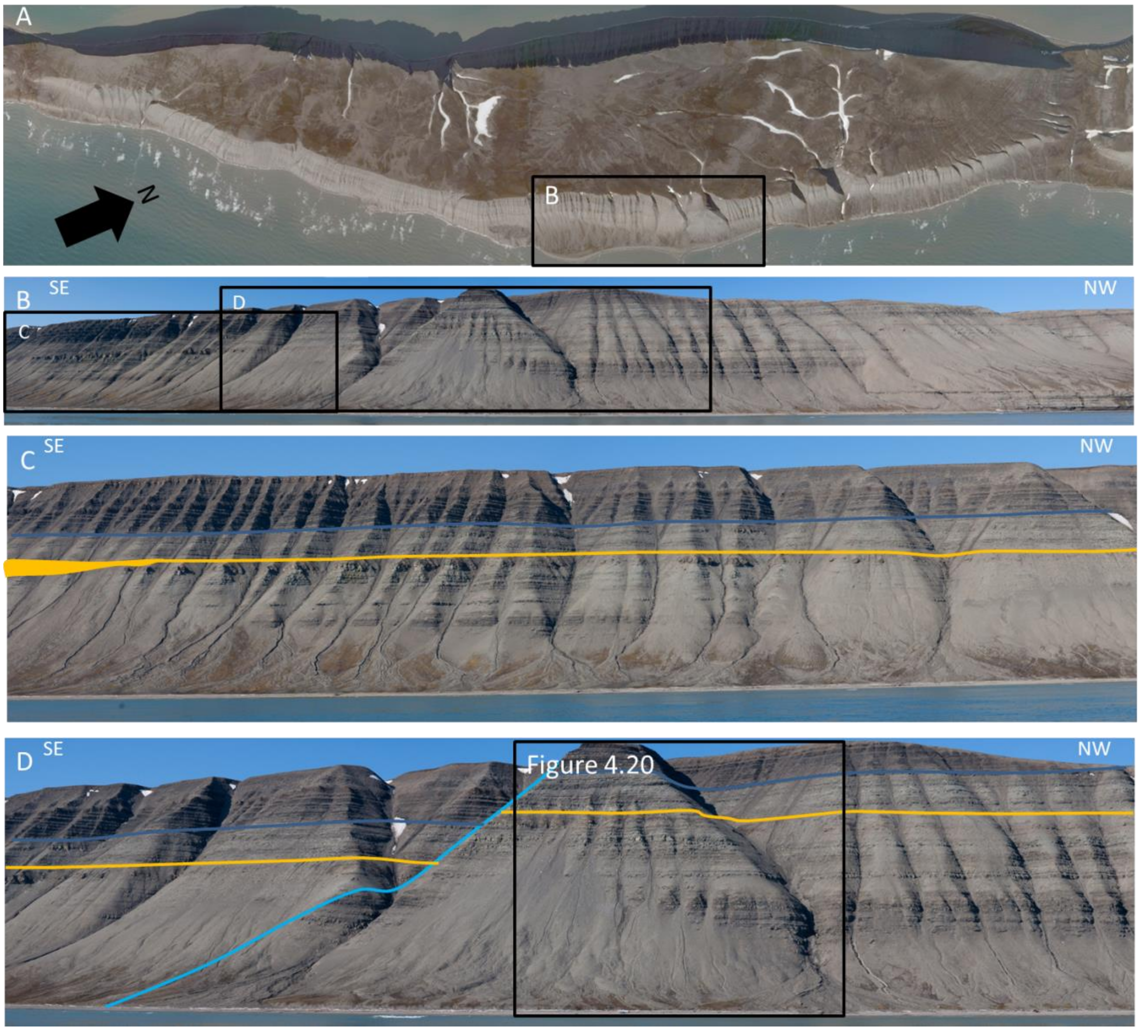


Figure 4.19: This figure illustrates the distance from Channel body 9 to the log called Blåfjellet E. (A) A plane-photo of Blåfjellet and surrounding areas (picture from Norwegian Polar Institute). (B) A panorama of the entire distance between Channel body 9 and the logged section. (C-D) Two photos showing where to expect finding the stratigraphic interval of Channel body 9 in the log. The horizontal blue line marks the Hopen member (See Chapter 3: Lateral distribution of possible marker horizons).

Unfortunately the stratigraphic interval that Channel body 9 is part of is covered by scree at the location of the log (Figure 4.20), but it is still possible to say something about the overlying and underlying intervals. Towards the top of this log one can recognise hummocky cross-stratification and wave ripples. Hummocky cross-stratification has been defined as a form of medium to large scale cross –stratification, deposited during storms in a shallow marine environment (Reading and Collinson, 2006), wave ripples also indicate shallow water environments (Reading and Collinson, 2006). This means that the Upper 46 meters of the log indicate a shallow marine environment (Figure 4.20) and is part of the Hopen member (See chapter 3). The sediments below the stratigraphic unit of Channel body 9 include several coal layers, plant remains and current ripples, indicating delta plain environment (Reading and Collinson, 2006). The layers surrounding the stratigraphical unit of Channel body 9 does not show any sedimentary structure, hence it is difficult to interpret the depositional environment.

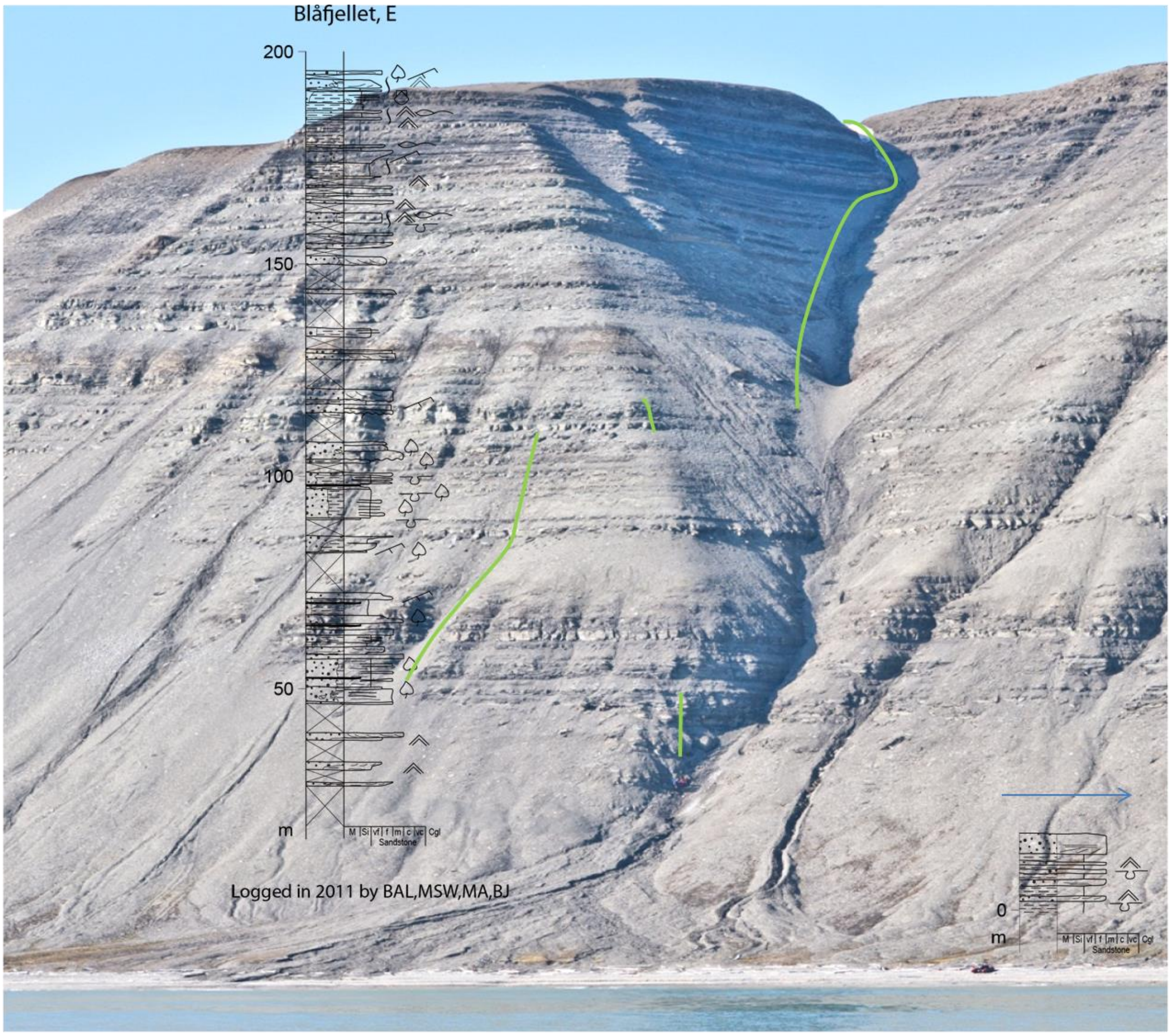


Figure 4.20: This figure displays a photo of the gully at Blåfjellet East and the associated log. The green line marks the hike done to collect the log. The small log seen in the bottom right corner is taken further NE.

4.2.5 *Channel body 10 (Western side of Kollerfjellet, NW of Hopen radio)*

Channel body 10 is most likely found on both sides of the island (Figure 4.21 and Figure 4.22). On the western side it is situated about 82 meters above sea level, where the top of the Channel body is located about 130 m below Hopen member (See Chapter 3). On the eastern side of the island the base of the channel body is situated approximately 90 meters above sea level, giving a slightly dip to the NW. The channel body is found to be about 25 meters thick on both sides of the island and has a width of approximately 815 meters on the western side. On the eastern side the width is difficult to estimate, because of lack of a clear pinch out to the SW. The channel body is displaced by a fault marked with black in Figure 4.22 on the western side of the island, while on the eastern side this fault is missing. On the eastern side of the island some of the layers seem to be dipping towards the south (Figure 4.23), but as the unit is strongly fractured and because the gullies are covered with scree, it is difficult to trace the layers.

On the western side of the island there is a lot of vegetation covering the channel body, making it difficult to investigate the internal geometry of the body (Figure 4.22).

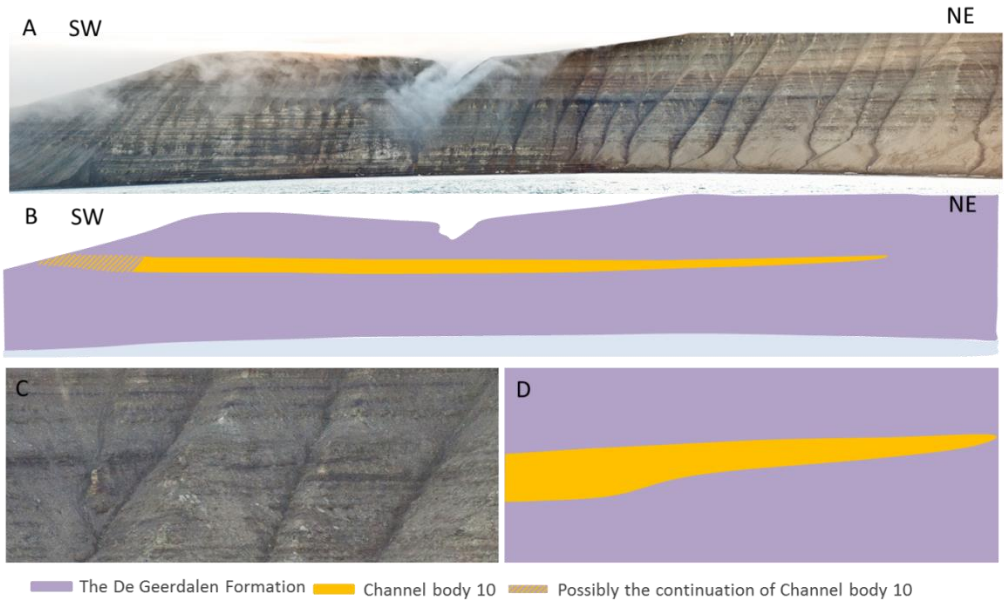


Figure 4.21: Illustration of Channel body 10 seen from the eastern side of the island. (A) An overview photo of the outcrop, NE of Hopen radio. (B) Interpretation of the photo shown in A. (C) A close up photo of the northern pinch out. (D) Interpretation of the photo shown in C.

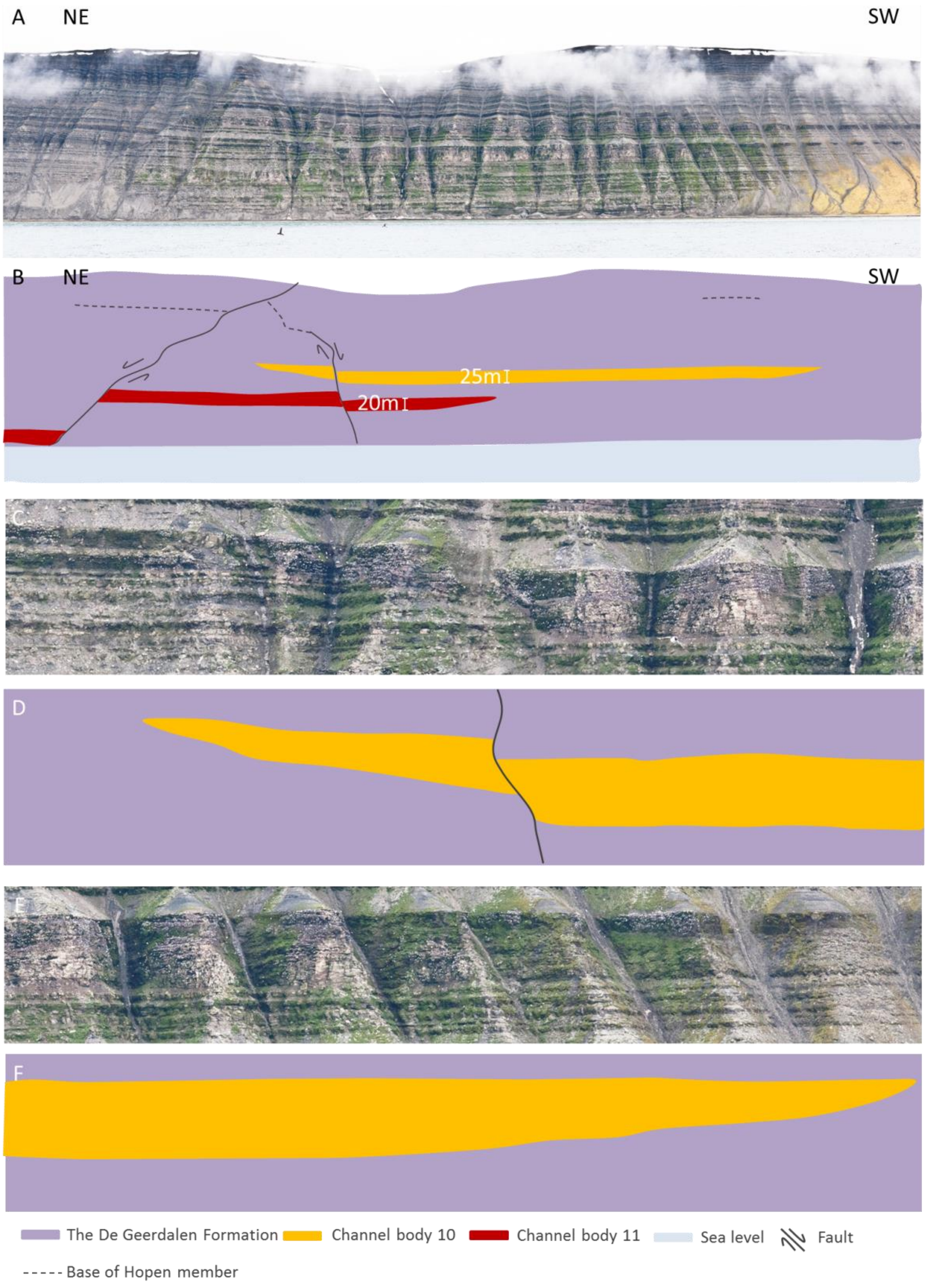


Figure 4.22: An illustration of the outcrop on the western side of the island. Where channel bodies 10 and 12 are displayed. (A) A overview photo of the outcrop on the eastern side of the island. (B) Interpretation of the two channel bodies. (C) A close up photo of the northern pinch out of Channel body 10. (D) Interpretation of the pinch out shown in C. (E) A close up photo of the southern pinch out of Channel body 10. (F) Interpretation of the pinch out shown in C.

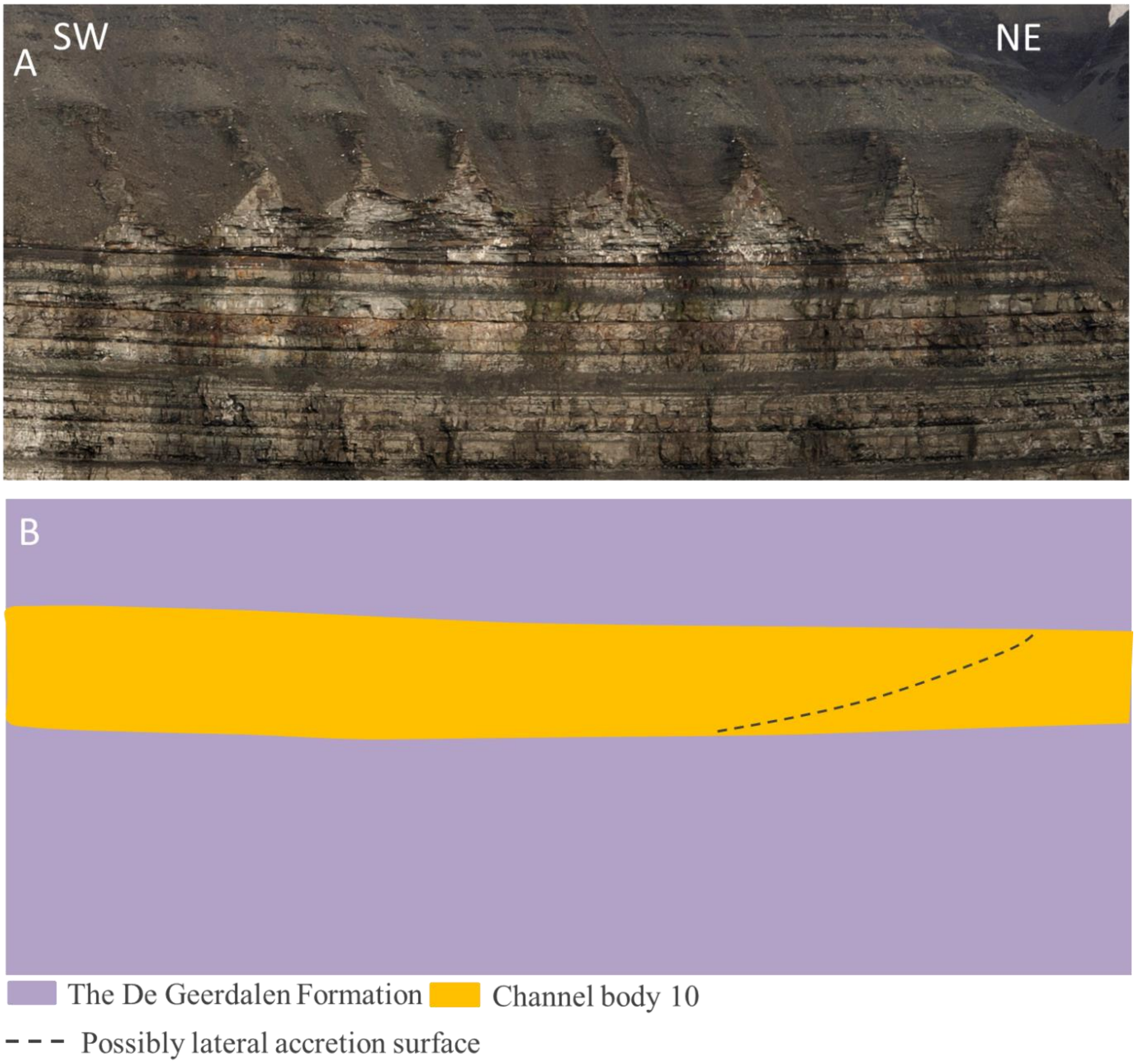


Figure 4.23: This figure displays the southern part of Channel body 10. (A) A photo of the southern part of Channel body 10. (B) An interpretation of the photo shown in A, with the interpretation of a possible lateral accretion surface.

(1) Discussion

Channel body 10 is most likely found towards the top of the log called Hopen Radio Nord (Appendix1). On the log Channel body 10 is found from 83.5 meters to the top of the log as the mountain side was very steep. The log shows an upward fining trend, from medium- fine grained, with through cross-section at the bottom grading into current ripples towards the top. These types of facies are often found in channels (Reading and Collinson, 2006) supporting the interpretation of this being a channel body, possibly point bar deposits (Miall, 2006). The underlying sediments consist of clay and silt. A bit further down in the stratigraphy one can see flaser and lenticular bedding, which may indicate tidal influence (Reading and Collinson, 2006). Flaser bedding is characterised by isolated drapes of mud amongst the cross-laminae of sand, while lenticular bedding is composed of isolated ripples of sand completely surrounded by mud (Reineck and Singh, 1980; Nichols et al., 2009). Since there is no indication of tidal influence in the logged channel body, one can suggest a relative sea level fall before the channel body was deposited. A bit further north another log called Gåsskaret has been collected (Appendix1). In this log one can see that there is evidence of hummocky cross-stratification, indicating shallow marine deposition (Reading and Collinson, 2006) above and below the stratigraphical interval of this channel body. This indicates several switches between marine and continental environment in this part of the De Geerdalen Formation.

The reason why the southern pinch out is difficult to find on the eastern side of the island, is most likely due to erosion. The flat area where we now find Hopen radio is one of five saddles found on the island. Each of these corresponds to the narrow necks in the islands plan. Harland (1997) suggested that these saddles are probably the remains of valleys in a much larger island. A possible interpretation is therefore that the southern pinch out was eroded away by the river or rivers creating the valley.

The dipping layers seen on Figure 4.23 can be indication of lateral accretion surfaces. If this interpretation is combined with the signs of this being a single-story channel and the lack of marine influence, one can argue that this might be a trunk channel (Olariu and Bhattacharya, 2006; Blum et al., 2013). Trunk channels are also suggested for Channel body 1 and 4, described in subsection 4.1.1 and 4.1.4 respectively. To strengthen this interpretation more detailed logging of the channel body is necessary.

4.2.6 *Channel body 11 (NE of Hopen radio)*

Channel body 11 is situated right NE of the meteorological station at Hopen. By using the PhotoModeler-model the thickness of the channel body was estimated to be about 15 meters and the width to be approximately 232 meters. The width was however difficult to estimate because there is no clear pinch out on the northern (right) side of the channel body (Figure 4.24B). On the western side of the mountain a channel body is located north, north- west of this channel body and can represent Channel body 11 on the other side of the island.

A down- cutting between what is marked with red in Figure 4.24B and D, and the rest of the channel body (orange in Figure 4.24B and D) can be seen. The sandstone unit found above the mentioned down cutting, is measured to be about 8 meters thick and 150 meters wide.

Channel body 11 is deposited in an area where Hopen member is most likely eroded away. The explanation for this interpretation is that the base of Hopen member is located about 240 meters above sea-level on the western side of this mountain, while the eastern side of the mountain displayed on Figure 4.24A is only about 200 meters high, hence the Hopen member is most likely eroded away on the eastern side of the mountain.

(1) Discussion

It is possible to follow the channel body all the way to the gully, where it stops. One can also see that the layers found on the right side of the gully resemble the layers found on the left side of the channel body (Figure 4.24A).This can mean that the missing pinch out on the right side of the channel body, is situated in the gully to the NE, covered by scree.

Another important feature found in Channel body 11 is the erosional surface shown in Figure 4.24. This can indicate that the channel body is multi-story, but most likely, as mentioned by Klausen and Mørk (submitted), this is just a mud-plug indicating where the channel ultimately has been abandoned.

The channel body seen on the western side of the island is however, interpreted as Channel body 12, which means that Channel body 11, is only found on the eastern side of Hopen. There are at least two findings that support this interpretation. First, the widths of the two cross-sections do not match. It is possible that the two cross-sections have a bit different orientation, but most likely, not large enough to make up for at least 300 meters width difference. Furthermore it seems like what is interpreted as Channel body 11, is situated below the stratigraphical level of Channel body 12. Some smaller errors in the PhotoModeler-model need to be considered, however, these are not near big enough to question the interpretation of these channel bodies. The outcrops of Channel body 11 on the western side of the island are most likely situated in an area covered by scree.

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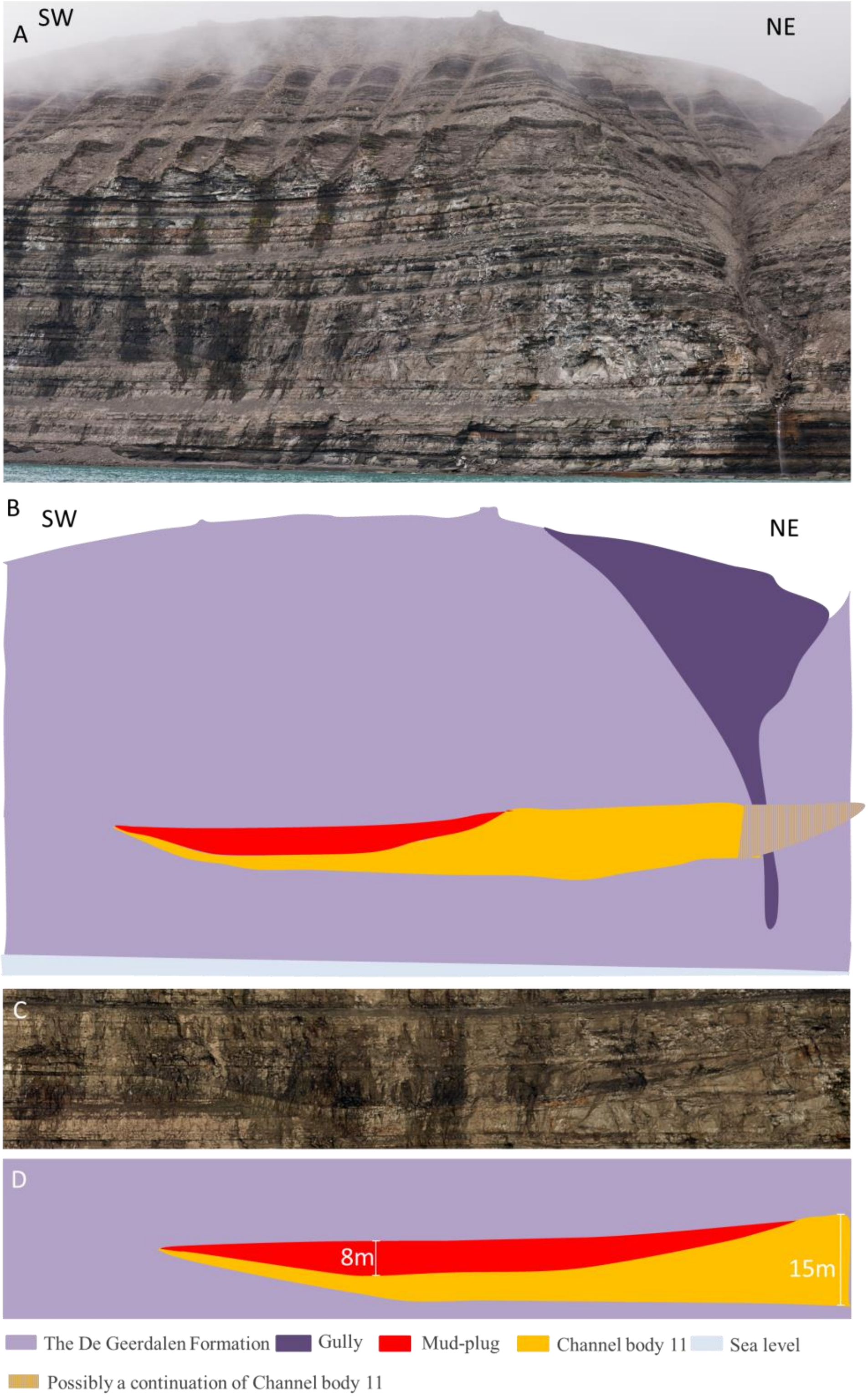


Figure 4.24: Photos and illustrations of Channel body 11. (A) An overview photo of Channel body 11. (B) An interpretation of the channel body found in A. (C) Zooming in on the actual channel body. (D) An interpretation of Photo C. Orange displays the part of the channel body that is not the mud-plug.

As mentioned in subsection 4.2.5, Channel body 10 is found on both sides of the island. On the western side of the island the top of channel body 10 was calculated to be 130 meters from the base of Hopen member. The distance from top of what is interpreted as Channel body 11 to the top of Channel body 10 on the eastern side, is about 70 meters. Assuming the same distances from top of Channel body 10 and base of Hopen member on the eastern side, Channel body 11 is situated approximately 200 meters below the Hopen member. That means that channel body 11 is the lowermost channel body described

4.2.7 *Channel body 12 (Western side of Kollerfjellet)*

The overview photo (Figure 4.22A and B) referred to in this subsection is displayed in subsection 4.2.5, Channel body 10, as both of these channel bodies are situated in the same area.

Channel body 12 is situated approximately 42 meters above sea level on the western side of Kollerfjellet. On the eastern side of the mountain the channel body is not found. The top of Channel body 12 is situated about 179 meters below Hopen member. The channel body is found to be about 20 meters thick, but the width is difficult to estimate as the pinch out to the NE is disturbed by a displacing fault (Figure 4.22). However, assuming that the grey sandstone unit sticking out at sea level (Figure 4.22) represents the same channel body, the width is estimated to be approximately 917 meters. Channel body 12 is displaced by two faults. The fault furthest to the south displaces the channel body with about 11 meters, while the other one (further to the north in Figure 4.22) has a displacement of about 40 meters. The displacement of the northern fault assumes that the grey sandstone unit sticking out at sea level is part of the channel body. On this channel body one can see a pinch out (Figure 4.25) towards the SW. The channel body is covered by a lot of vegetation, making it difficult to interpret the internal geometry of the channel body.

(1) Discussion

As described in subsection 4.2.6, Channel body 12 on the western side is most likely not the same as Channel body 11 on the eastern side of the island. Never the less this channel body should have been possible to see on one of the logged section on the eastern side of the mountain (Hopen radio nord and Gåsskaret in Appendix 1) if channel bodies 10 and 12 had more or less the same direction. Unfortunately it is not possible to see any channel body indications on the logs from the stratigraphical interval of Channel body 12. This can either be explained by missing logs from this interval, or that the channel is situated where we today find Hopen meteorological station and is eroded away by the same mechanisms as the southern pinch out of Channel body 10 (Subsection 4.2.5). The latter can be the case if Channel body 12 has a NNV-SSE direction, which is not unlikely. If the channel body is situated between the Hopen radio log and the log taken at Gåsskaret, it should have been possible to see it on the photos.

The distance from Hopen member indicates that the channel body is deposited as one of the oldest channel bodies on the island.

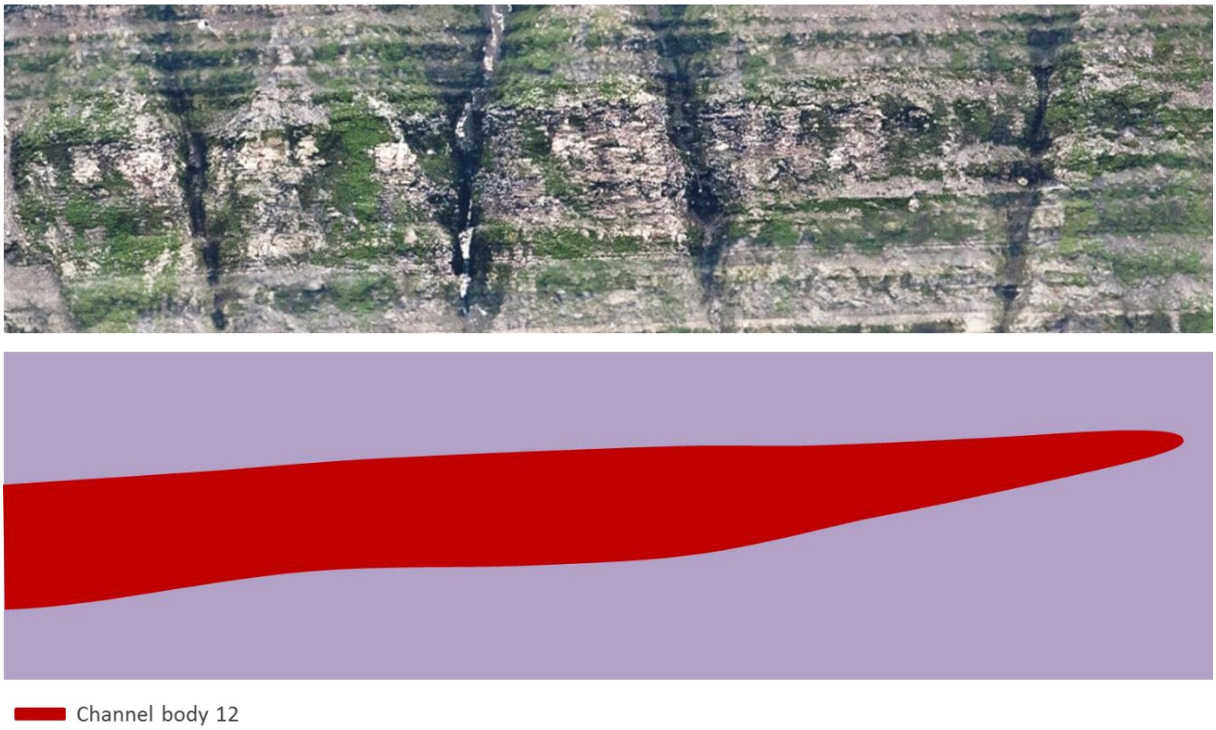


Figure 4.25: Illustration of the southern pinch out on Channel body 12. (A) A photo of the pinch out. (B) Interpretation of the photo shown in A.

4.2.8 *Channel body 13 (Western side of Werenskioldfjellet)*

Channel body 13 is situated on the western side of Werenskioldfjellet, south-west of Hopen radio, about 3 km SW of Channel body 12. It has a maximum height of around 22 meters and is approximately 210 meters wide. The channel is difficult to spot on the eastern side of the island, hence only the outcrop found on the western side of the island is interpreted in this thesis. The body is clearly cutting into the underlying sediments. The pinch out illustrated on Figure 4.26D clearly shows layers that have stopped towards, what is interpreted as the channel body. Because of scree located on the left side of the channel, it is difficult to find these layers on the other side (Figure 4.26 and Figure 4.27). It is also possible to see that the channel body pinches out on the right side of Figure 4.26C, into what looks like fine- grained sediments. It is difficult to see any big scale structures on this channel body because of heavy fracturing (Figure 4.26).

The bottom of the channel body is found approximately 50 meters above sea level and the top of the channel body is found about 190 meters below Hopen member.

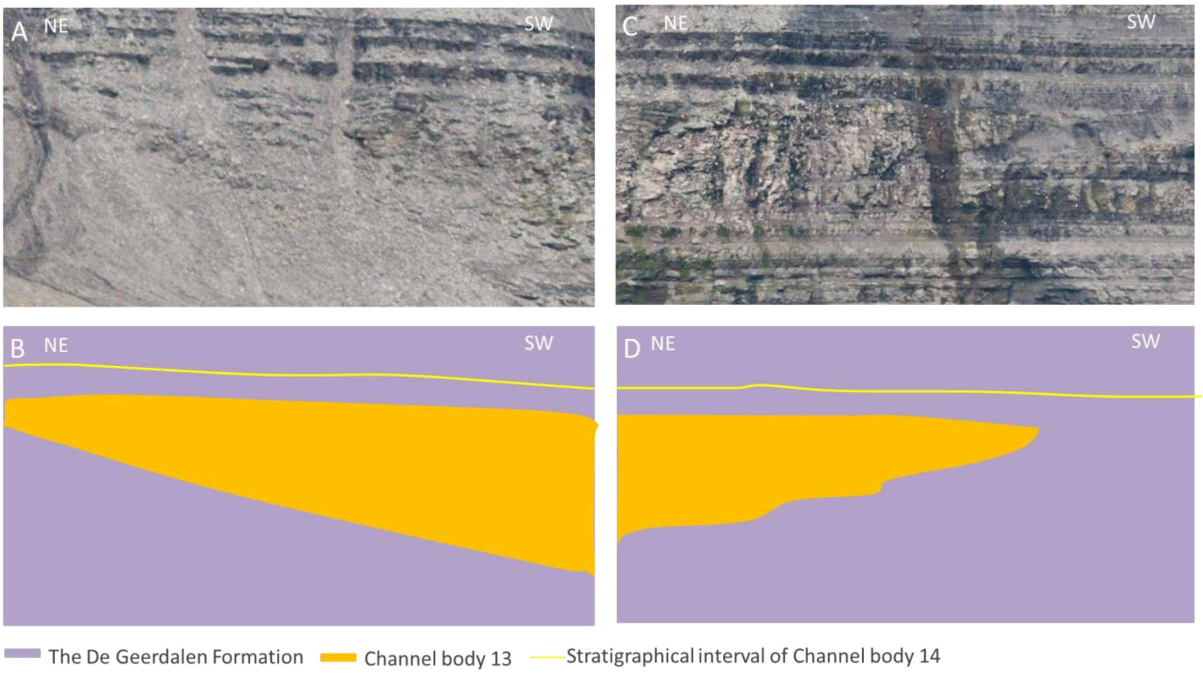


Figure 4.26: This figure illustrates the pinch out found on Channel body 13. (A) A close up photo of the northern pinch out. (B) Interpretation of the photo shown in A. (C) A close up photo of the southern pinch out. (D) Interpretation of the photo shown in C.

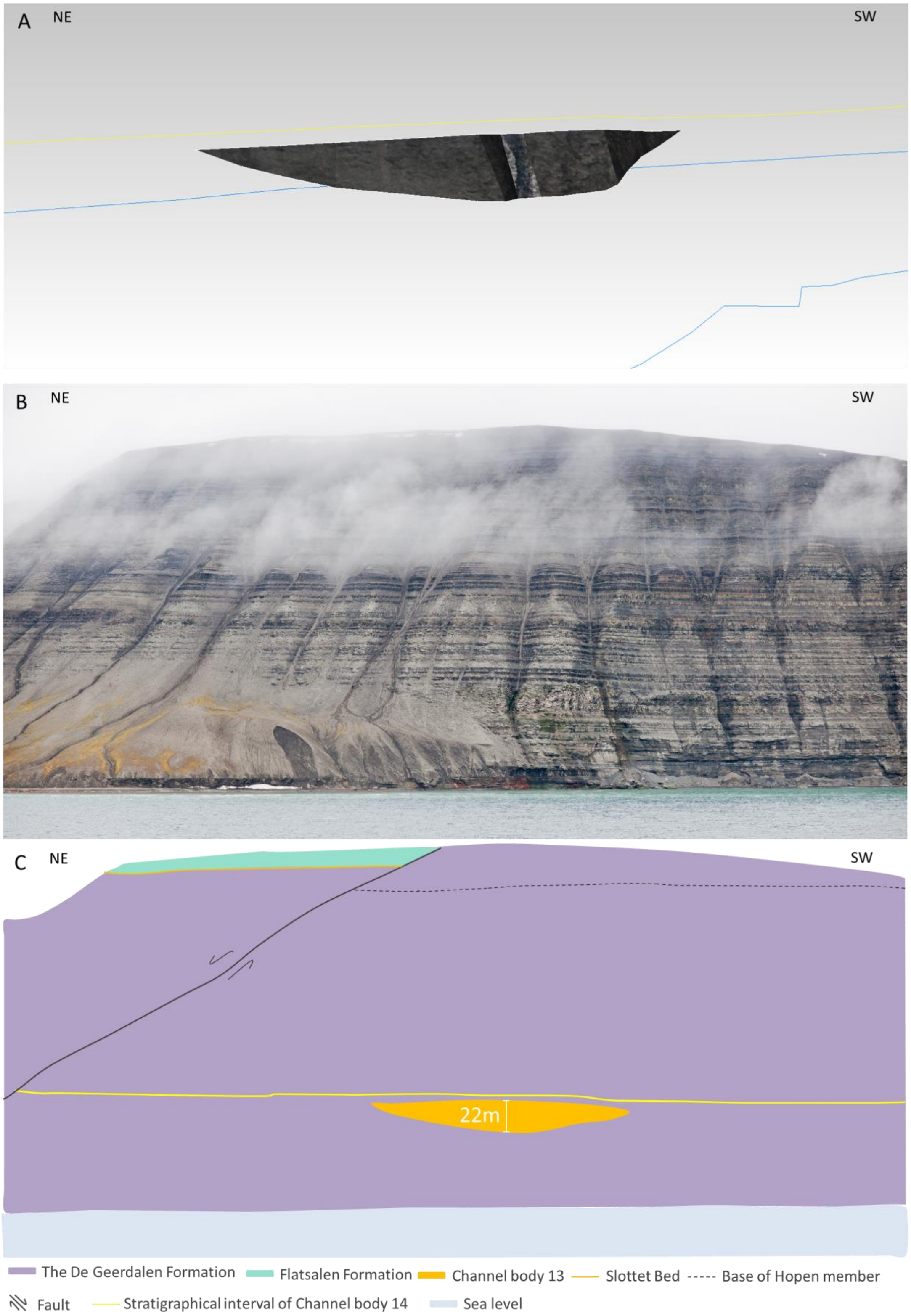


Figure 4.27: This figure illustrates Channel body 13 with the help of the PhotoModeler-model, photo and interpretations. (A) The PhotoModeler-model illustrating Channel body 13. Blue lines indicate sea level and yellow line indicate the stratigraphical level of Channel body 14. (B) A photo of Werenskioldfjellet, where Channel body 13 is situated. (C) Interpretation of the photo shown in B.

(1) Discussion

The top of the channel body is located approximately 190 meters below Hopen member, hence it is deposited earlier than Channel body 14 and is found about 6 meters lower in the stratigraphy. By knowing this, it is possible to follow the stratigraphic unit of Channel body 13 all the way to the Iversenfjellet log on the eastern side of the island. On this log (Figure 4.28C) it is possible to see that the stratigraphical unit of Channel body 13 consists of fine-grained sediments with wave ripples and current lamination, both structures that are not diagnostic for a certain depositional environment. This does not disprove the interpretation of Channel body 13 being deposited on the delta plain, but the limited sedimentological information available, makes it difficult to determine the exact depositional environment of this channel body.

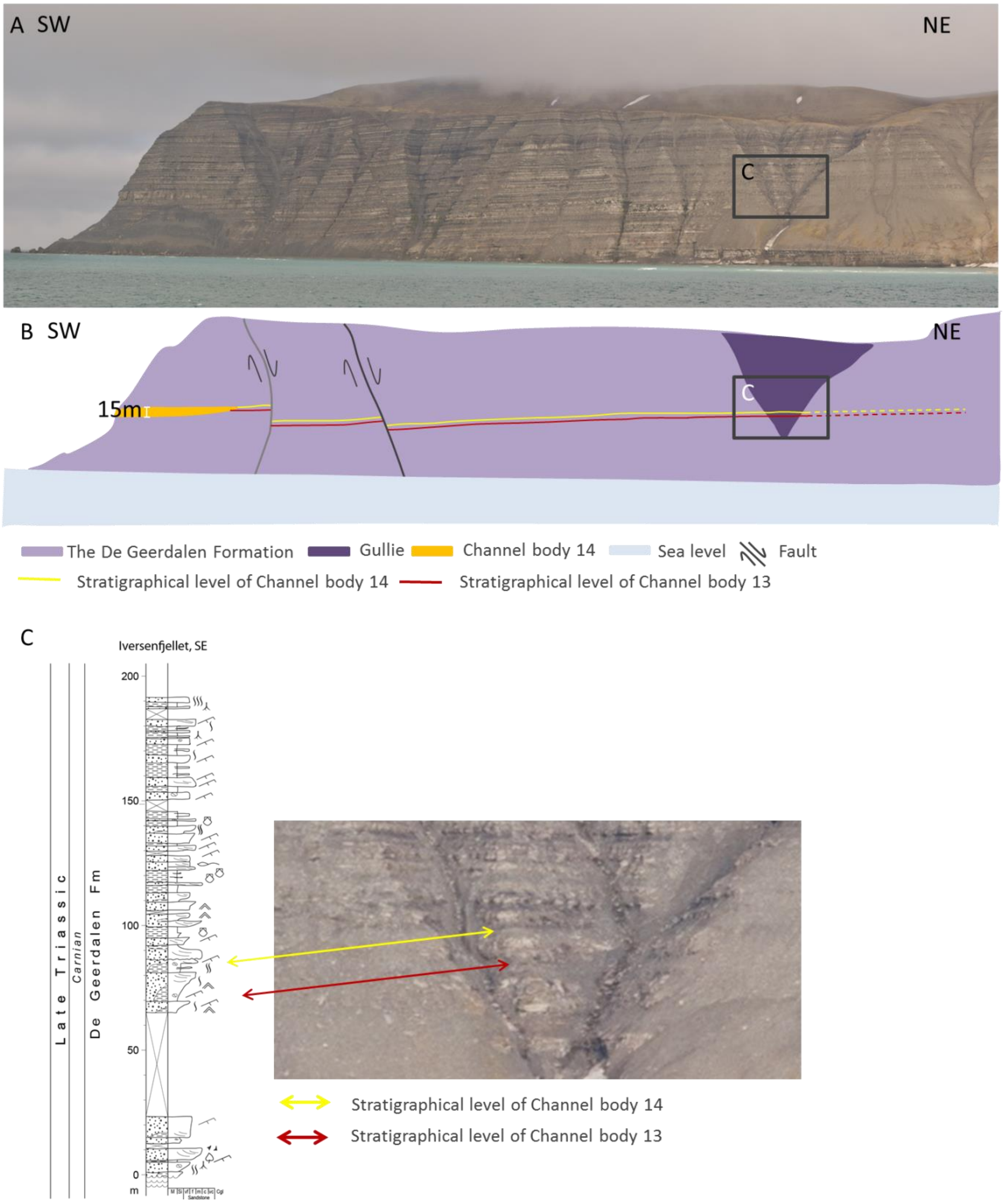


Figure 4.28: This Figure illustrates the log taken of Iversenfjellet in 2011 by Terje Solbakk, Hilde Krogh, Frode Karlsen and Marta S. Woldengen, as well as an overview photo of the area where the log is collected. (A) An overview photo of the area where the logged section was collected. (B) Interpretation of the photo shown in A. (C) Illustrates the log taken at Iversenfjellet, as well as a close up photo of the area where the stratigraphical interval of channel bodies 13 and 14 is logged. Channel body 14 will be described in the next subsection.

4.2.9 *Channel body 14 and associated fault (Iversenfjellet)*

Channel body 14 is situated on Iversenfjellet, the highest Mountain on Hopen. The channel body is positioned on the southern tip of the island. The thickness is about 15 meters, but the length of the body is not possible to estimate, as part of the channel body was most likely situated south of the island and has been eroded away. This also means that the thickness of the channel body possibly was larger further south. The channel body mainly consists of white to orange coloured sandstone. It is possible to see that the channel body disappears for about 170 meters where the sandstone unit pinch out towards the middle, as seen on Figure 4.29. Towards these two terminations there is a more fractured unit near the top of the channel body, possibly with a different grain size. These sediments seem to thicken towards both of the thinning units and it might be possible to follow this unit between the two pinch outs (Figure 4.29). By looking closely at the pinch out representing the termination of the channel body on the eastern side of the island, it is possible to see that the compact sandstone disappears and that the overlying, less compact, and possibly muddier unit thickens towards the channel pinch out (Figure 4.30).

The channel body is displaced by a fault for about 60 meters on the western side of the island (Figure 4.31), while on the eastern side of the island the same fault displaces the sediments with about 30 meters (Figure 4.30). On the western side of the island it is difficult to follow the fault-plane upwards in the stratigraphy, and one can clearly see that the Hopen member is not displaced by the fault (Figure 4.32). The fault seems to have a zigzag pattern where the lithology in the gullies is different from the lithology of the juxtaposed cliffs (Figure 4.32B), while towards the right of Figure 4.32C, one can see that both the gullies and the cliffs consist of the same lithology.

(1) Discussion

This is one of the most interesting channel bodies found on the island, mostly due to the disappearing of the channel body, displayed in Figure 4.29. A possible explanation for the disappearance of the channel body is that the respective channel has taken a turn towards the north or south. Hence, in the area where the channel body has disappeared, the channel has either turned to the north and the channel body is hidden inside the mountain, or it has turned southwards leading to erosion of the channel body as a consequence of the subsequent uplift. Either way, the channel body is clearly meandering, and the disappearing of the channel body is perhaps the best indication of a meandering river that can be found without detailed sedimentological logs and palaeocurrent measurements.

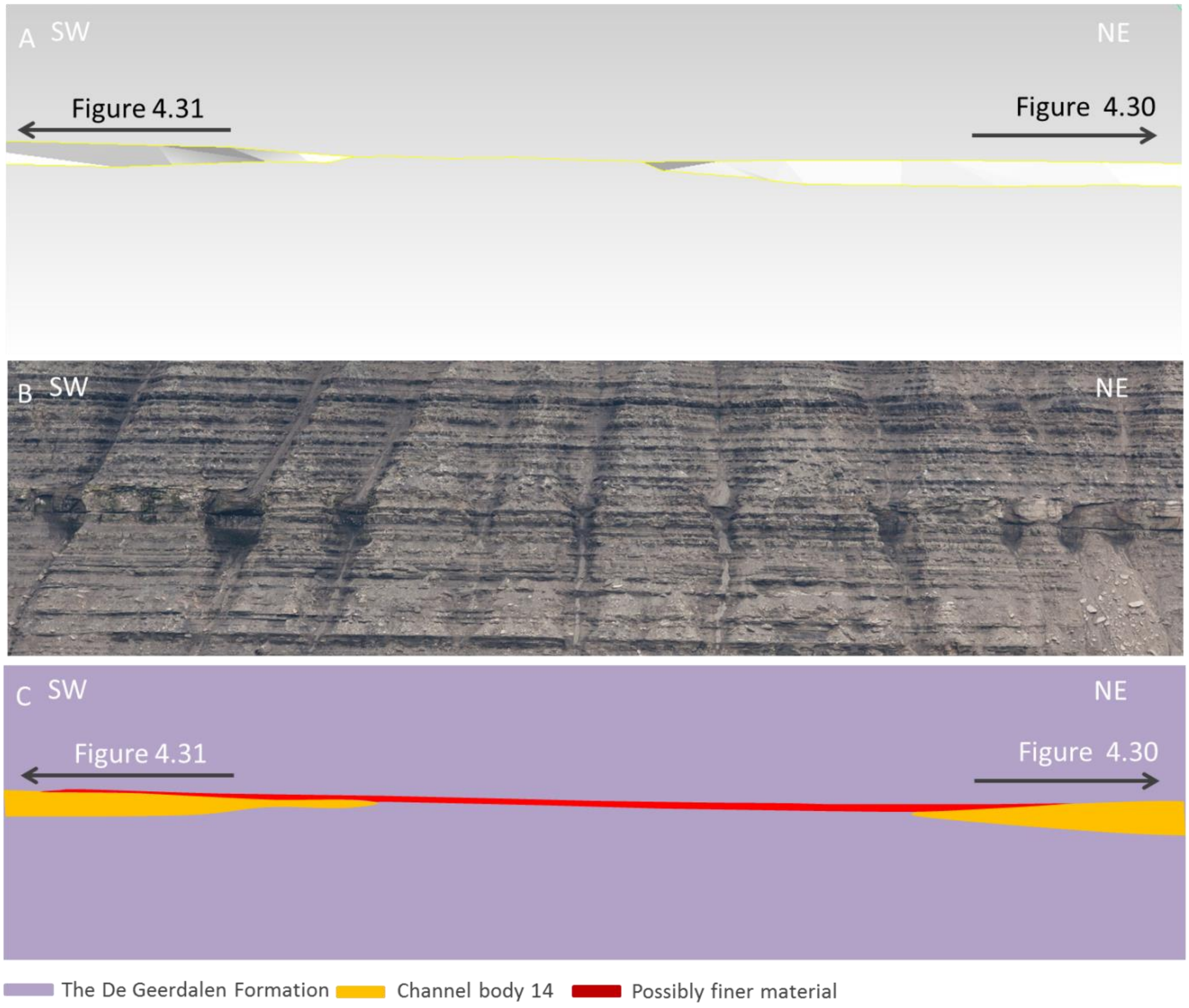


Figure 4.29: This figure illustrates the middle part of Channel body14.
(A) PhotoModeler-model illustration of the middle part Channel body 14. (B) A photo illustrating the disappearance of Channel body 14. (C) Interpretation of the photo shown in B.

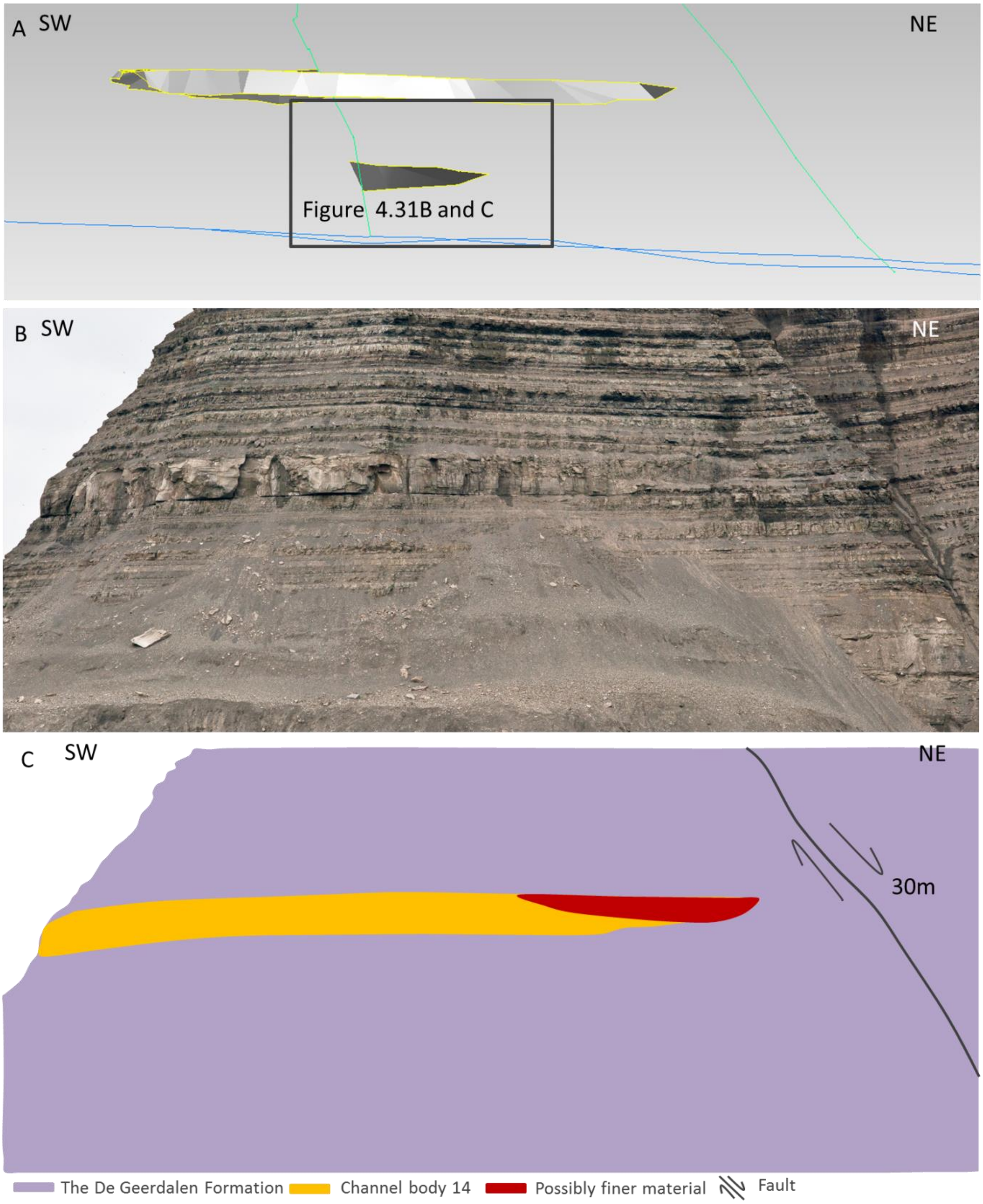
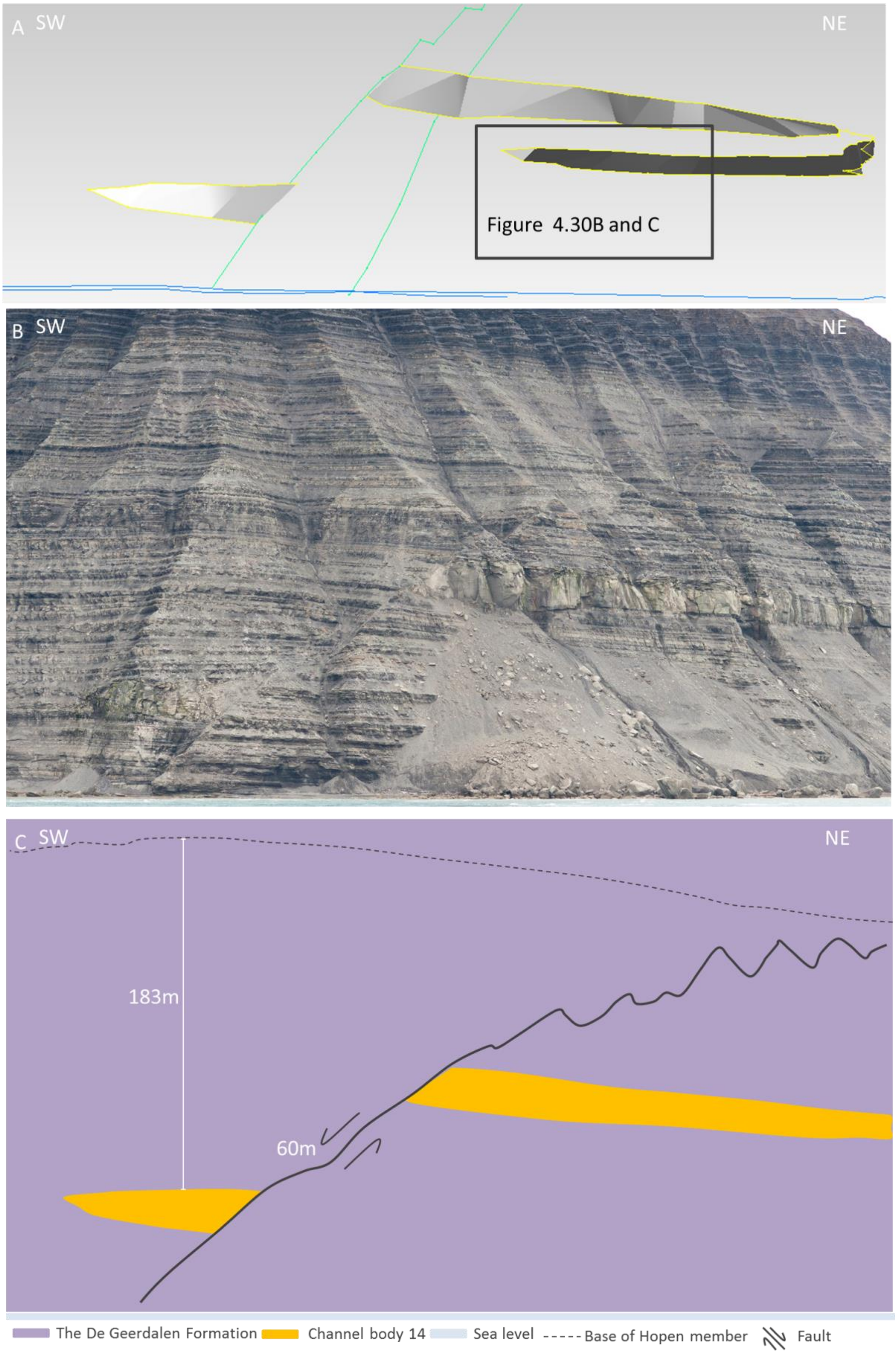


Figure 4.30: Illustrating the eastern part of channel body 14. (A) The PhotoModeler-model of Channel body 14. The picture is taken from the eastern side of the island. The light coloured part of the channel body is illustrating the cross-section on the eastern side of the island. (B) A photo of the eastern side of Channel body 14. (C) Interpretation of the photo shown in B.



4.31: This figure illustrates the western part of Channel body 14. (A) The PhotoModeler-model of Channel body 14. The picture is taken from the western side of the island. The light coloured part of the channel body is illustrating the cross-section on the western side of the island. (B) A photo of the western side of Channel body 14. (C) Interpretation of the photo shown in B.

There are no sedimentological logs covering Channel body 14, due to restricted accessibility of the channel body. Channel body 14 is located in an area with steep cliffs and abundant rock falls. To say something about the depositional environment of the respective stratigraphical interval, one therefore needs to follow the stratigraphy to the nearest log. The closest log is situated SE of Iversenfjellet and is displayed in Figure 4.28C. On this log one can see that the stratigraphical interval of Channel body 14 consists of fine- grained material with wave ripples and ripple lamination, similar to the sediments found in the stratigraphical interval of Channel body 13. Fine- grained sediments with these kinds of structures can be found in the interdistributary areas of the delta plain (Reading and Collinson, 2006), meaning that a possible interpretation of Channel body 14 is a distributary channel. However, there are no, observed, diagnostic sedimentary structures to strengthen this theory. The lack of tidal influence in the deposits of this stratigraphical interval, as well as in the units above and below, can indicate that Channel body 14 is a fluvial dominated, distributary channel.

The more fractured sediments found in and possibly between the pinch outs seen in Figure 4.29, can be interpreted as levee deposits. Levees are ridges built on either side of a channel (Reading and Collinson, 2006). Regarding this as a meandering channel where the channel body disappears as the channel turns, the sediments displayed with red in Figure 4.29 are suggested to be levee deposits.

A possible explanation for the disappearing of the fault, as described above, is erosion. As seen on the photos and in the pictures of the PhotoModeler-model, the fault is found at the edge of the island. The difference in lithology between the gullies and the cliffs (Figure 4.32B) can clearly indicate that the areas, which have undergone more erosion (gullies), are part of the rock record that has been faulted down, hence they are on the northern side of the fault plane. The cliffs represent the sediments south of the fault-plane, which are not displaced by the fault. That means that where it is possible to see the fault, the sediments south of the fault are not eroded away (Figure 4.32).

If we assume that the theory about the southernmost fault disappearing towards the top of the island, is true, the distance from Hopen member to Channel body 14 must be measured from the displaced part of the channel body (on the left side of the fault in Figure 4.31C). The distance is then 183 meters.

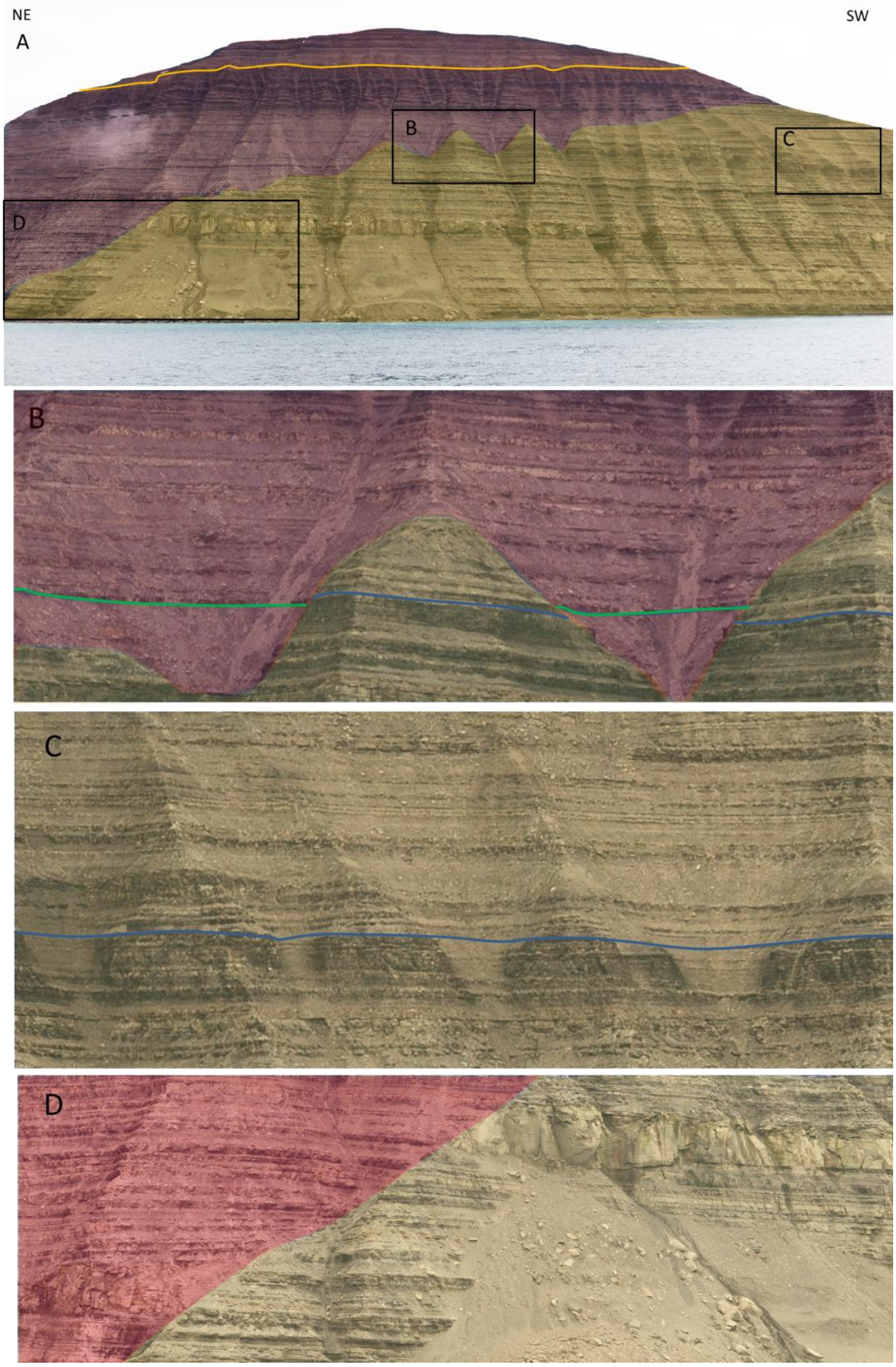


Figure 4.32: Interpretation of fault plain of the fault displacing Channel body14. (A) Photo and interpretation of the fault plain. (B) A close up photo of the gullies and cliffs with different sediments. (C) A close-up photo illustrating that the gullies and cliffs consist of the same sediments in this area. (D) A photo of the western most part of the fault, which show a clear displacement.

4.3 Channel Body Group 3

The channel bodies described in this subsection are the smallest channel bodies interpreted. Only one of the channel bodies is interpreted by comparing the geometrical parameters with nearby logs. The interpretation of the remaining channel bodies are only based on what is visible on the photos, and in some cases also by comparing the channel bodies with similar looking channel bodies previously described.

Table 4.3: Overview of channel bodies described in Chapter 4.3: Channel body group 3.

Channel body	**Size (thickness, width)**	**Logged**	**Probability for channel body**
15	7 m thick and 100 m wide	No	Low -> Medium
16	The PhotoModeler-model is not oriented correctly in this area	No	Medium
17	5 m thick and 150 m wide	Compared with a log nearby	Medium
18	22 m thick and 210 m wide	No	Medium

4.3.1 *Channel body 15 (NW of Braastadskaret)*

Channel body 15 is only found on the western side of the island and is situated just before the northern most neck. By using the PhotoModeler-model the thickness of the channel body is estimated to be approximately 7 meters and the width to about 100 meters, hence this is one of the smallest channel bodies interpreted. The channel body has most likely an erosional surface as shown in Figure 4.33. The channel body consists of dipping layers, which are abundant in the majority of the channel body. Only the areas marked with red in Figure 4.33C and D, show no indication of dipping layers.

The channel body is deposited 25 meters below the base of Hopen member.

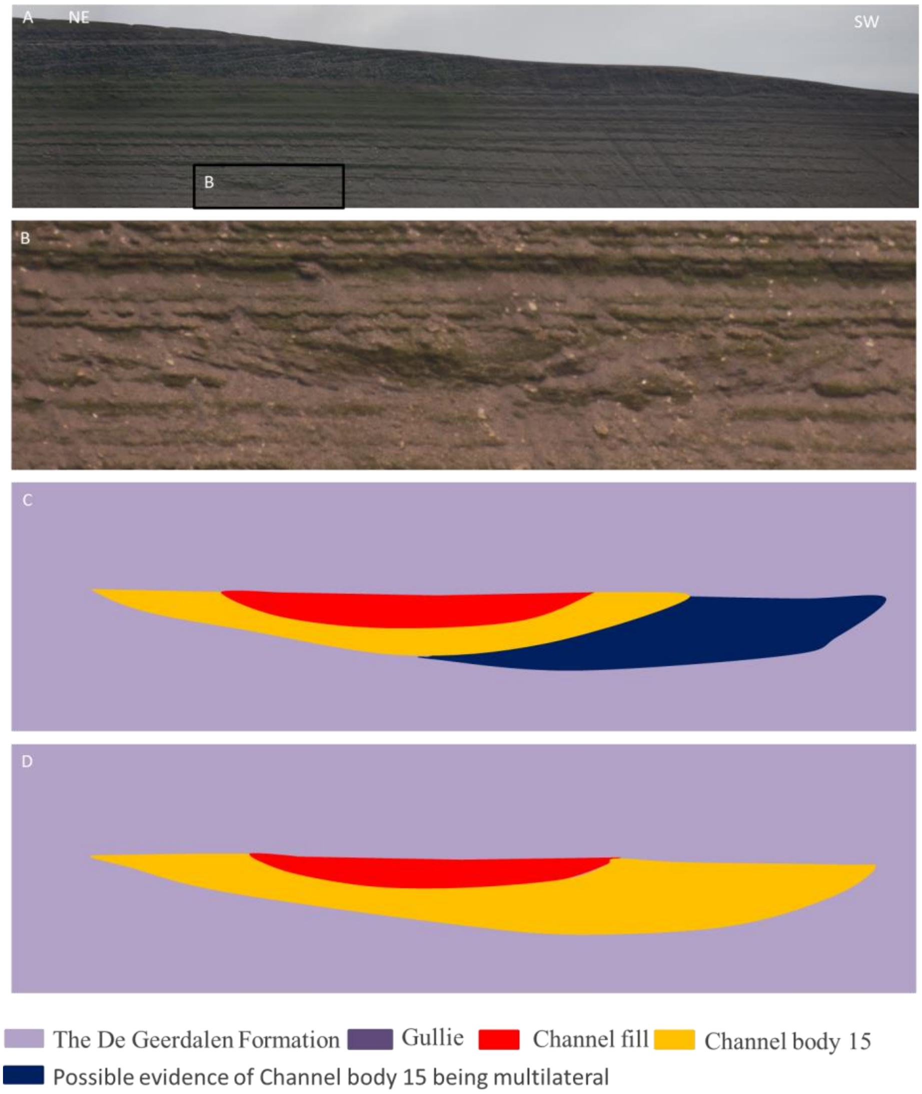


Figure 4.33: This figure illustrates the outcrop NW of Braastadskaret. (B) Zooming in on Channel body 15. (C) An interpretation of the channel body as multi-story. (D) An interpretation of the channel body as singe-story.

(1) Discussion

The infill of the channel (Marked with red in Figure 4.33C and D), might be a mud-plug. A mud-plug consists of clay, silt and peaty organic material (Shepherd, 2009), and can indicate an infill of the channel where the channel ultimately has been abandoned. The rest of the channel body most likely consists of point bar deposits. The part of the channel body interpreted as point bar deposits shows indications of evenly dipping layers, which can indicate that the channel migrated laterally. Such structures are suggested by Gibling (2006) to represent point bar deposits. Since there is no log taken of this channel body there are uncertainties regarding this interpretation and a log is necessary to get a more precise description of the channel body.

4.3.2 *Channel body 16 (Blåfjellet South)*

Channel body 16 is located, only a few hundred meters south of Channel body 3, but is situated higher up in the stratigraphy. The thickness and width of the channel body is difficult to estimate since the body is located on the western side of Blåfjellet, an area where the PhotoModeler-model is not working optimally. The channel body is mostly dark brown to black coloured with some lighter coloured sediment in between. A dark layer found at a lower stratigraphical level, is found on both sides of the channel body. Where the actual channel body is situated, this darker layer is missing, most likely eroded away by the respective channel. It is also possible to see that parts of the channel body do not have dipping layers (Marked with red in Figure 4.34D). On the photo, the pinch outs seem to consist of finer-grained material (Figure 4.34C).

The Hopen member is most likely situated towards the top of the mountain, as shown in Figure 4.34B. Due to problems with the orientation of the PhotoModeler-model in this area, the distance from the Hopen member to Channel body 16 is difficult to estimate.

(1) Discussion

The depositional environment is difficult to interpret for this channel body, partly because there is no log associated to it, but also because the channel body does not resemble any of the other channel bodies described. Even though it is not possible to measure the distance to the base of Hopen member, one can to a high degree of certainty say that the distance is no more than 100 meters, based on what is seen on photos (Figure 4.34B). As will be discussed further in Chapter 5, this area is dominated by fluvial deposition on the delta plain, which might imply that this is a channel body with fluvial characteristics.

One can also argue that the area marked with red in Figure 4.34D, is the infill of the channel body, perhaps represented by a mud-plug, as described in subsection 4.3.1.

Another feature found on this channel body is that the pinch outs seem to consist of finer-grained material. This might have nothing to do with the sediments deposited at this stratigraphical level, but instead just caused by covering scree.

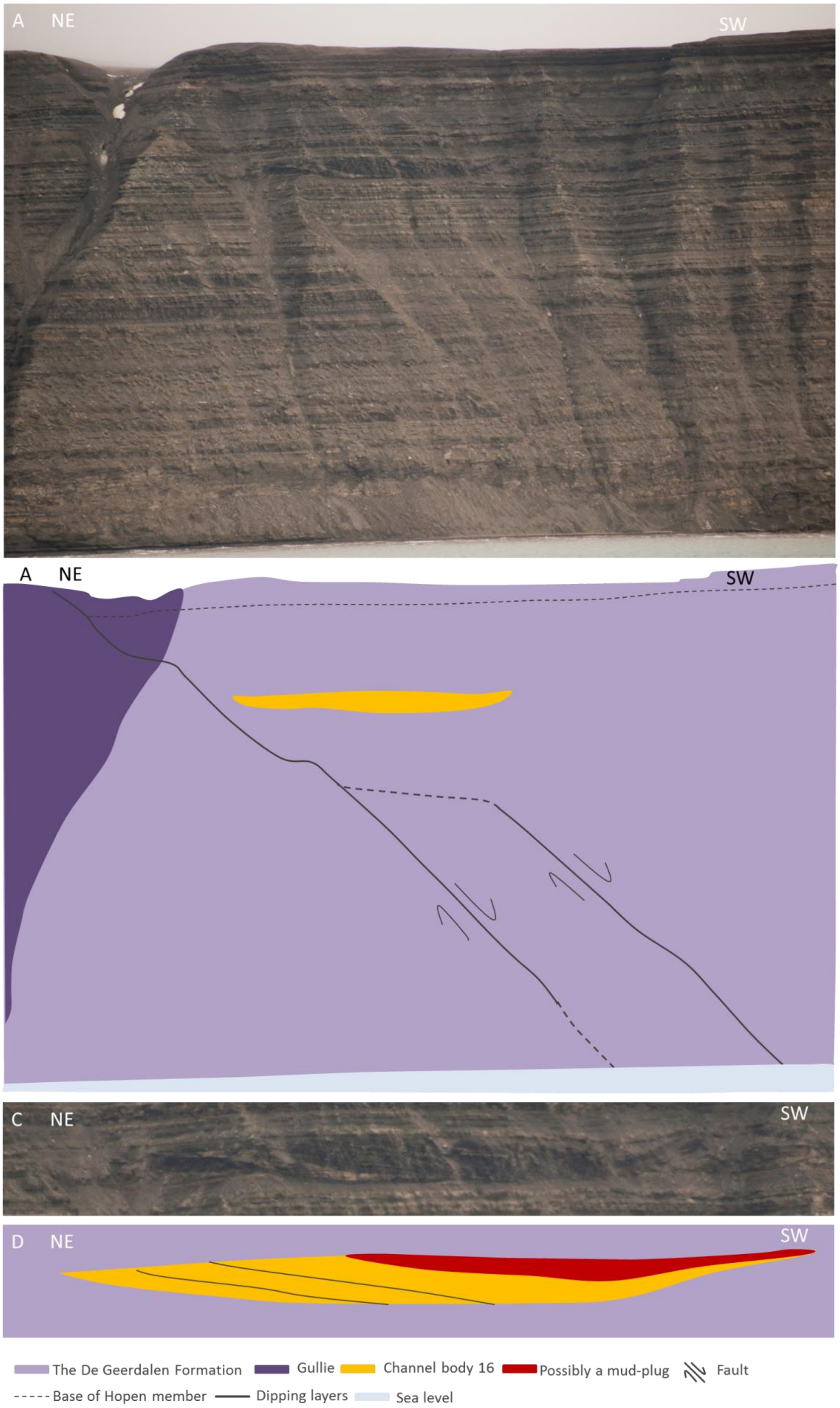


Figure 4.34: This figure illustrates the outcrop where Channel body 16 is situated. (A) A overview photo of the outcrop situated SW of Blåfjellet. (B) Interpretation of the photo shown in A. (C) A close up photo of Channel body 16. (D) Interpretation of the photo shown in C.

4.3.3 *Channel body 17 (Djupskaret)*

Channel body 17 is located only a few hundred meters south of channel body 4. It has a maximum thickness of around 5 meters and is approximately 150 meters wide. It is possible to see a clear transition between light coloured layers dipping towards the north (Figure 4.35) and darker sediments (marked with red in Figure 4.35E), which seem to erode into the lighter coloured sediments. On the southern side of the light coloured layers, one can still see dipping layers, but with a darker colour (Figure 4.35).

By extrapolating the Hopen member from Johan Hjortfjellet further south, one can estimate that Channel body 17 is situated about 135 meters below Hopen member.

(1) Discussion

A log was taken through Djupskaret on the 2011 expedition to Hopen (Figure 4.35A). This log is taken a bit north of Channel body 17, and hence they did not log the actual channel body. The channel body is situated towards the top of this gully, hence the upper most part of the log will be the stratigraphical interval of Channel body 17. In this part of the log (Figure 4.35) the sediments contain ripple lamination and root structures, as well as what might be paleosols. Paleosols are defined as a floodplain marker horizon by Miall (2006), which confirms that it is deposited on the delta plain. This leads to the assumption that this channel body is deposited on the delta plain and might be a fluvial dominated distributary channel.

When examining the photo of this channel body, one can see that the darker coloured sediments (red in Figure 4.35E) are most likely a mud-plug filling in the channel where the channel ultimately has been abandoned. The more light coloured part is than perhaps point bar deposits, as described in subsection 4.3.1.

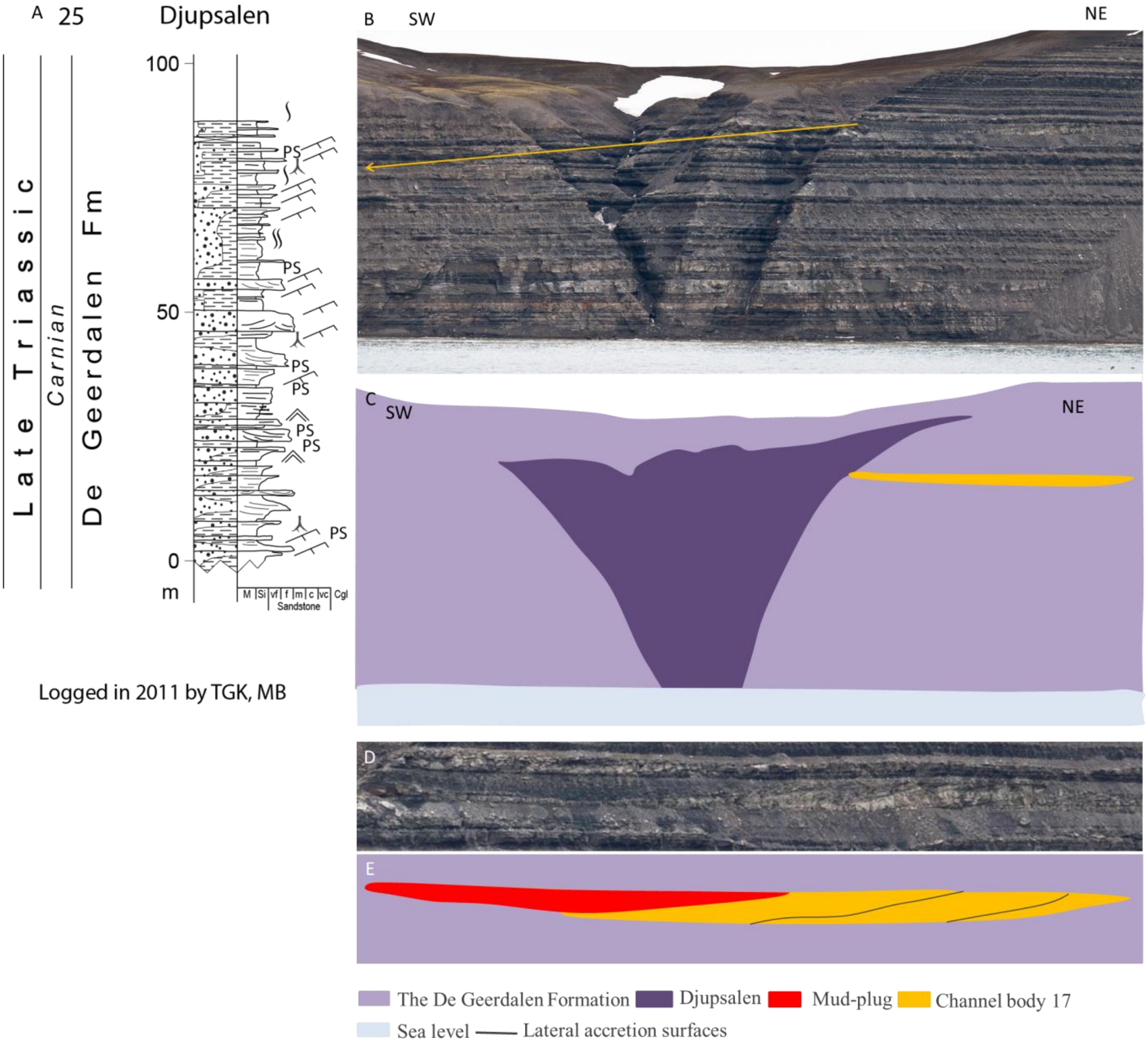


Figure 4.35: This figure illustrated Channel body 17 and the Djupsalen log collected by Tore G. Klausen and Morten Bergan. (A) Illustrates the log of Djupsalen. (B) A overview photo of Djupsalen and Channel body 17. (C) Interpretation of the photo shown in B. (D) A close up photo of Channel body 17. (E) Interpretation of the photo shown in D.

4.3.4 *Channel body 18 (Kvasstoppen)*

Channel body 18 is situated on Kvasstoppen around 2.5 km from the highest peak of Iversenfjellet. The channel body is only found on the western side of the island as the mountain is not high enough on the other side of the island. The thickness of the visible part of this channel body is about 30 meters. Due to the fault marked on Figure4.36B and D, only parts of the channel body are visible and the width of the channel body is impossible to estimate. The fault has a displacement of about 56 meters, which has led to erosion of the channel body on the northern side of the fault. It is most likely possible to see the bottom of the channel body on top of the mountain on this side of the fault. This can be said because the layers underlying the channel body on the southern side of the fault, are also recognized towards the top of the mountain on the northern side (Figure 4.36). What looks like sandstone rocks on the top of the mountain (Marked with orange on Figure 4.36 B and F) are than most likely part of Channel body 18. It might be possible to see a pinch out towards the south of the channel body, but most likely this pinch out was situated further south and has been eroded away (Figure 4.36).

It is difficult to estimate the distance from Channel body 18 to the Hopen member, as the Hopen member is not visible in this area. However, by extrapolating the Hopen member from Iversenfjellet, the location of the top of Channel body 18 is found to be approximately 50 meters from Hopen member.

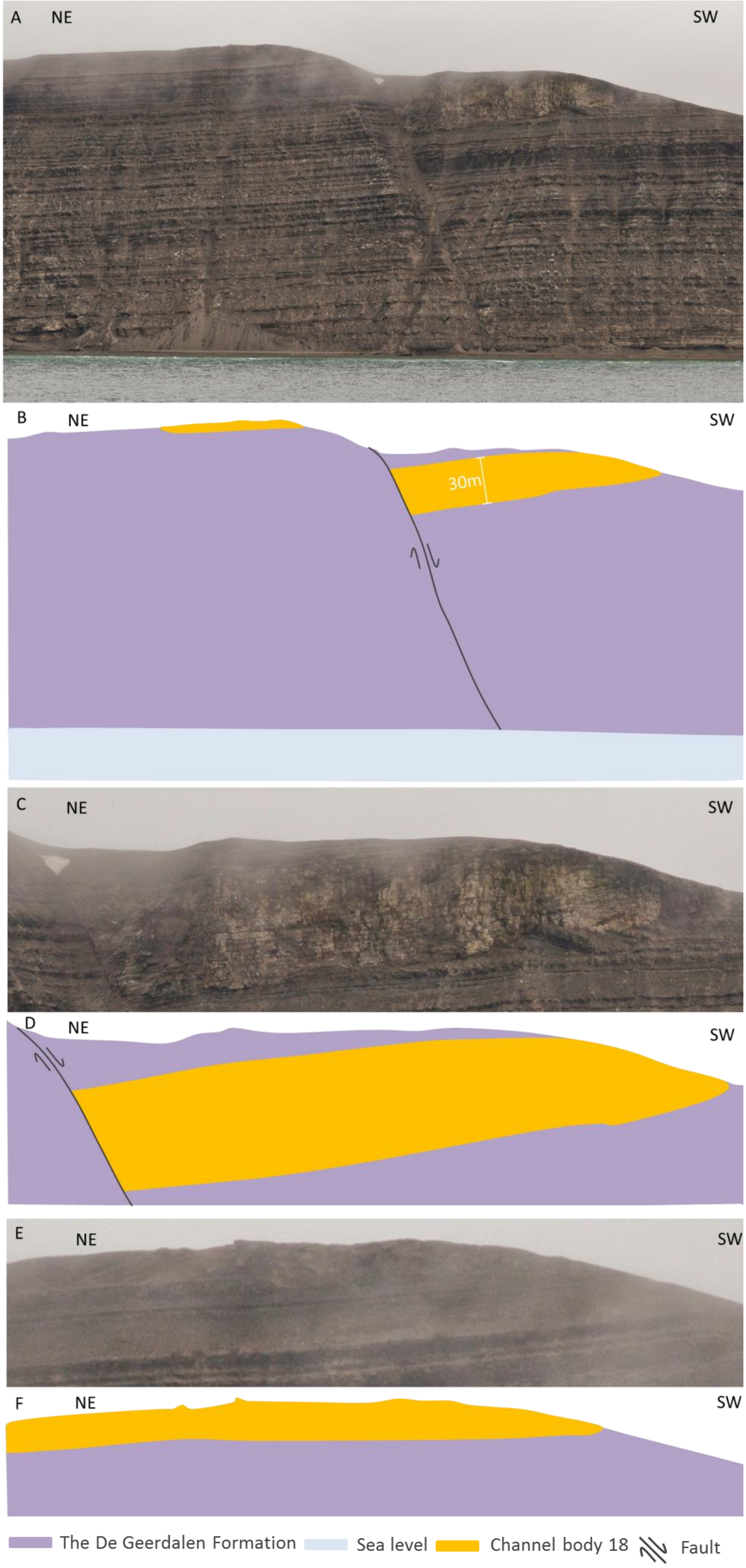


Figure 4.36: This figure illustrates Channel body 18. (A) An overview photo of area where Channel body 18 is situated. (B) Interpretation of the photo shown in A. (C) A close up photo of Channel body 18 on the southern side of the fault. (D) Interpretation of photo C. (E) A close up photo of the Channel body 18 on the northern side of the fault. (F) Interpretation of the photo shown in E.

(1) Discussion

As shown in Table 4.3, it is only medium probability for this being an actual channel body. This is because there is no associated log which can establish what kind of environment the stratigraphical interval of this channel body was deposited in and one cannot see any clear pinch outs either, confirming that it is a channel body. The reasons for why this can be a channel body is that one can see that some layers stopping towards the channel body and one can possibly see that the layer stopping against the channel body on the southern side of the fault, being visible again towards the end of the channel body on the northern side of the fault (Figure 4.36 A, C and E). Another reason for interpreting this as a channel body is its place in the stratigraphical record. 50 meters below the Hopen member are interpreted as a delta plain environment on the logs collected at the island (See Chapter 5: Discussion). The most likely situation for finding sandstone unit of this size on a delta plain is if it is a distributary channel. Because the interdistributary areas are less sandy, and commonly contain a series of relatively thin, stacked coarsening- and fining- upwards facies successions, which are usually less than ten meters thick (Bhattacharya, 2006) and not sandstone units up to 30 meters thick.

5. Discussion

5.1 Map relevant features

By combining the PhotoModeler-model with additional photo material, several features considered relevant for mapping have been found. Each of these features have been discussed in their own subsection, but a more overall discussion of some of the most important findings will be presented in the present chapter.

One of the map relevant features is, what in this thesis, is referred to as Hopen member. This member can possibly reflect deposition above a transgressive system tract. A transgressive system tract is formed when the sea-level is rising rapidly (Reading and Levell, 2006). This might be the situation on Hopen, where the depositional environment has changed from fluvial dominated, tidally influenced delta plain setting to shallow marine. If this is the case there are two questions that need to be addressed. First, is this change to more marine sediments due to a local change in sea level, or is this a possible evidence for a regional transgression. For the last assumption to be valid one should be able to confirm this theory by finding a similar trend at other locations at Svalbard, or in the upper part of the Snadd Formation in the Barents Sea.

The Isfjorden Member, first described as Isfjorden "Formation" (Pčelina, 1983) is deposited in Early Norian and is situated in the upper part of the De Geerdalen Formation. The type section of this Member is found at Storfjellet (Knarud, 1980) (Figure 1.1), which is situated about 55 km from Longyearbyen, west of Storfjorden and around 250 km NW from Hopen. On this mountain the Isfjorden Member is approximately 87 meters thick. At Edgeøya the upper part of the De Geerdalen Formation is not preserved, but on Wilhelmøya a marine upper part of the De Geerdalen Formation is present (SINTEF project data). The sediments found in Isfjorden Member resemble the Hopen member. The Isfjorden Member consists of alternating shales and evenly bedded, thin to thick-bedded silt and sandstone, with wave and ripple lamination, abundant plant fragments, carbonate beds, phosphate nodules, multi-coloured shale and reddened sandstone. The type section at Storfjellet (Mørk et al., 1999; Knarud, 1980), as well as the log from Dalsnuten (Mørk et al., 1982, 1999) show abundant hummocky cross-stratification. Sediments with this kind of structure are normally deposited in a shallow marine environment, between fair weather wave base and storm wave base (Reading and Collinson, 2006). Hummocky cross-stratification is also abundant in the logs taken of Hopen member (Figure 3.1 and Figure 3.3 from Chapter 3). Mørk et al. (1999) interpreted the Isfjorden Member to be deposited in a restricted shallow marine environment, and as mentioned, a shallow marine origin is also interpreted for the Hopen member. This can indicate that assumption number two is correct and that the transgression to shallow marine sediments seen at the base of Hopen member actually is of a regional character.

There is also found, what might be a 3rd order sequence boundary of mid Carnian age in the Sverdrup Basin and in the Barents Sea (Embry, 1997; Egorov and Mørk, 2000). Embry (1997) suggests that this high order sequence boundary was generated by episodic global stress regime changes, which were driven by plate tectonic reorganizations. This sequence boundary is possible to correlate with a sequence boundary found in the northern Himalayas, as well as in the southwestern USA. If this actually is a global sequence boundary, the sequence boundary should also be possible to find on Svalbard, which means that Hopen member can represent this correlation.

Another map relevant feature found on Hopen is the lateral extension of the well-known Slottet Bed described in Subsection 3.2. The descriptions in this subsection show that by combining the PhotoModeler-model and the associated photos, Slottet Bed is found in at least two new areas, not previously highlighted on the geological map (Dallmann, 2009). This means that the Slottet Bed is most likely more lateral extensive on the island than earlier described.

5.2 Thickness variations of the De Geerdalen Formation and the equivalent Snadd Formation

There is a clear thickness variation of the De Geerdalen Formation at Svalbard, from Hopen in the southeast to central Spitsbergen in the west. The island of Hopen only displays the upper 300 meters of the De Geerdalen Formation, but fortunately the French company Fina drilled two exploration wells in 1971 and 1972, which give more information about the thicknesses of the formations. One of these wells is displayed in the publication by Riis et al. (2008). On this log one can see that there are almost 700 meters between the underlying Botneheia Formation and the Slottet Bed, which marks the top of the De Geerdalen Formation. On the other hand, by studying the log of Storfjellet (Mørk et al., 1999) one can see that the thickness of the De Geerdalen Formation is less than 250 meters, and even further west, the log at Bravaisberget (Krajewski et al., 2007) displays a thickness of the De

Geerdalen Formation of no more than 210 meters. Riis et al. (2008) also report that the De Geerdalen Formation at Edgeøya is markedly thinner than what is seen on Hopen.

To take this correlation even further one can also compare these thicknesses with the thicknesses of the equivalent Snadd Formation in the Barents Sea. Riis et al. (2008) shows a core log from Sentralbanken high and east of Kong Karls Land, where the thickness of the Snadd Formation is more than 700 meters.

An explanation for this thinning of the De Geerdalen Formation towards the west might be that the De Geerdalen Formation at Hopen and the Snadd Formation further east are deposited in a basin. Riis et al. (2008) argues that thickness variations of the Tschermakfjellet Formation at Edgøya and East of Kong Karls Land are 100 and 400 meters respectively. The thickness increase implies a larger accommodation space east of Svalbard, which could be related to a deeper shelf prior to the deltaic infilling (Riis et al. 2008). The interpretation is also consistent with the interpretation of a deeper water environment of the uppermost Botneheia Formation in the core east of Kong Karls Land, than in the eastern Svalbard (Edgøya) (Riis et al., 2008).

Unfortunately there is no available description of Tschermakfjellet or Botneheia formations at Hopen, which could have helped determine if the Triassic sediments in the Hopen area were deposited in a basin or not. However, by comparing the thickness of the De Geerdalen at Hopen (700 m) with the thickness of the Snadd Formation east of Kong Karls Land (approximately 750 m) one can see that they have more or less the same thickness (Riis et al., 2008). This can indicate that the De Geerdalen at Hopen is deposited in a basin as the Snadd Formation east of Kong Karls Land and at Sentralbanken high. This also indicates that the De Geerdalen at Hopen has more in common with the Snadd Formation in the Barents Sea than the De Geerdalen Formation at the rest of Svalbard.

5.3 Placing the channel bodies in the stratigraphical record

18 different channel bodies, situated in the upper part of the De Geerdalen Formation, have been studied with the aim of investigating the geometry, heterogeneity and distribution of the channel bodies across the island of Hopen. Here the rock record will be discussed from youngest to oldest. This means that I will start with the stratigraphical interval closest to the Slottet Bed, which is the regional marker on Hopen, and work down in the stratigraphy.

Due to the easily recognizable Hopen member, this has been used to find the stratigraphic position of the channel bodies described in Table 5.1.

Table 5.1: The table displays the distance below the base of Hopen member to each of the described channel bodies.

Channel body	Distance below the base of Hopen member
8	4 meters
4	18 meters
2	24 meters
15	25 meters
9	28 meters
6	29 meters
5	42 meters
7	50 meters
18	50 meters
1	60 meters
16	>100 meters
10	130 meters
17	135 meters
3	140 meters
11	179 meters
14	183 meters
13	190 meters
12	200 meters

Hopen member represents 70 meters of shallow marine sediments, situated at the uppermost part of the De Geerdalen Formation. In this interval there is no indication of channel bodies. The uppermost channel body is Channel body 8 which is situated only 4 meters below the base of Hopen member. Going further down in the stratigraphy, between the base of Hopen member and Channel body 3 (estuary channel complex) the sediments show a clear heterolithic composition, where tidal deposits are interfingering with fluvial and interdistributary bay facies. This heterolithic interval can be seen on several logs (Appendix1). This is also mentioned by Klausen and Mørk (submitted).

Towards the lower part of this interval, between 100-130 meters below the base of Hopen member, the log at Johan Hjortfjellet shows indications of shallow marine deposition. These marine deposits are also possible to trace in the logs taken at Hugosøkket and Gåsskaret (Appendix1), but are not as prominent further south. Never the less, it is important to recognize that there are not found any channel bodies in this part of the stratigraphy of Hopen, which support the interpretation of this interval being less influenced by fluvial deposition.

Even further down in the stratigraphy Channel body 3 is deposited. This is the only channel body where we have clear documentation for tidal influence. The interval of this channel body is not found in the northern part of the island, but further south the stratigraphical interval of Channel body 3 seems to stay tidally influenced.

None of the channel bodies deposited more than 140 meters below the base of Hopen member are logged, but by looking at their geometry and relation to juxtaposed sediments they seems to be fluvial dominated. This is supported by several logs taken at the southern part of the island, where the lower parts of the logs, show more fluvial dominated, delta plain deposition.

One can also recognize that there are three channel bodies described as trunk channels (channel bodies 1, 4 and 10). As mentioned in Subsection 4.1.1 a trunk channel is the upstream equivalent of a fluvial distributary channel (Olariu and Bhattacharya, 2006; Blum et al., 2013) and might represent the principle routing for major parts of the sediments in the area. It is interesting that these three channel bodies are situated at different parts of the island, Nørstefjellet, Johan Hjortfjellet and North of Hopen Radio respectively. Another interesting feature is that these channel bodies are situated at totally different places in the stratigraphical record. The uppermost channel body, Channel body 4 is situated 18 meters below the Hopen member, Channel body 1 is situated 60 meters below Hopen member, while Channel body 10 is situated 130 meters below Hopen member. This can indicate that these three channel bodies, are in fact made up by the same channel and that they are situated at different places at the island due to delta switching.

To summarize one can say that the overall depositional environment at Hopen, below the base of Hopen member, is interpreted as a fluvial dominated, tidal influenced delta plain, which is transitional to estuarine and marine influenced paralic environment. This is supported both by the logs taken at the island, as well as the geometry and the relation to juxtaposed sediment of the different channel bodies described. This interpretation is also supported by Klausen and Mørk (submitted).

As shown in Table 5.1 the channel bodies on the island are spread over almost the entire stratigraphy of the island, hence it is difficult to divide the island into stratigraphical intervals where channel bodies are more frequently deposited. Some intervals however, might be possible to recognize on the basis of what is discussed in this subsection and these are summarized in Table 5.2.

Table 5.2: This table illustrates important stratigraphical intervals found at Hopen, based on where the different channel bodies are situated.

Stratigraphical important intervals	**Channel bodies**
Hopen member (70 meters)	No channel bodies detected
Upper fluvial (0-100 meters below the base of Hopen member)	11 channel bodies
Shallow marine interval (100-130 meters below the base of Hopen member)	No channel bodies detected
Middle fluvial (130 -140 meters below the base of Hopen member)	2 channel bodies
Lower tidal (140 to approximately 160 meters below the base of Hopen member)	Channel body 3 (estuary channel complex)
Lowermost fluvial (160-200 meters below the base of Hopen member)	5 channel bodies

6. Conclusions

- 18 channel bodies are recognised in the De Geerdalen Formation on Hopen.
- Most of the channel bodies found on the island show a NW-SE flow direction, indicating a NW prograding delta, supporting the understanding of sediment input from the Ural Mountains to the SE.
- The PhotoModeler- model has made it possible to estimate the thickness of the black interval found at the uppermost part of the De Geerdalen Formation, referred to as the Hopen member. The thickness is measured to approximately 70 meters, both in the PhotoModeler-model and at the logged sections.
- Sedimentological logs have confirmed that the Hopen member consists of shallow marine sediments and that the base of Hopen member represents a transgressive system track. The only one mapped in the De Geerdalen Formation at Hopen.
- The Hopen member might be part of a more regional transgression, flooding the delta plain. This is indicated by deposition of shallow marine sediments both in the uppermost part of the Snadd Formation and in the De Geerdalen Formation on Central Spitsbergen (Isfjorden Member).
- The PhotoModeler-model has made it possible to find out where the Slottet Bed may occur. Investigations predict Slottet Bed in several areas where it has not been firmly recognised yet.
- The PhotoModeler-model, combined with photo interpretations and sedimentological logs, has made it possible to place the different channel bodies at the right stratigraphical interval relative to each other, based on their distance from the base of the Hopen member.
- The sediments of the De Geerdalen Formation at Hopen are divided into several different stratigraphical intervals. The segregation is based on the amount of channel bodies found in each interval, sediment structures found in the logged channel bodies, the geometry of the channel bodies, the channel bodies relation to juxtaposed sediments and environmental indicators found in associated sedimentological logs without coverage of channel bodies. This leads to an interpretation of the depositional environment, below the base of Hopen member, as being a fluvial dominated, tidally influenced delta plain, in a transitional to estuarine and marine influenced paralic environment (the different stratigraphical intervals are summarized in Table 5.2).

- Three possible trunk channels are found on the island (channel bodies 1, 4 and 10). These channel bodies are found at different stratigraphical intervals, as well as at different locations at the island. Delta switching due to avulsion of the river can indicate that the sediments were delivered to the Hopen area by a river situated where Channel body 10 is located. Than the delta switched its course to the north and Channel body 1 was deposited. Towards the top of the De Geerdalen Formation the delta once again switched its course, and channel body 4 was deposited. Hence, these three channel bodies can have been created by the same river and are situated at different places at the island due to delta switching. The middle marine interval (Table 5.2) might also suggest delta switching, where the progradation of the delta happens south or north of the Hopen area.

6.1 Further work

There is a lot of potential for developing the PhotoModeler-model further. Due to complications, which occurred during the process of completing the model and limited time, the western side of Blåfjellet and Småhumpane is not properly oriented in the model and further work could therefore be done in order to complete the model for the entire island. To complete the model one need to take supplementary photos in areas where the photos are taken in bad weather, preferentially with an 85mm lens.

In addition the model could be integrated into the software Petrel. By using Petrel one could be able to make facies models based on the sedimentological logs and the distribution of channel bodies and estimate the heterogeneity of the sediments between the measured sedimentological logs. A Petrel-model would also make it possible to estimate net/gross values.

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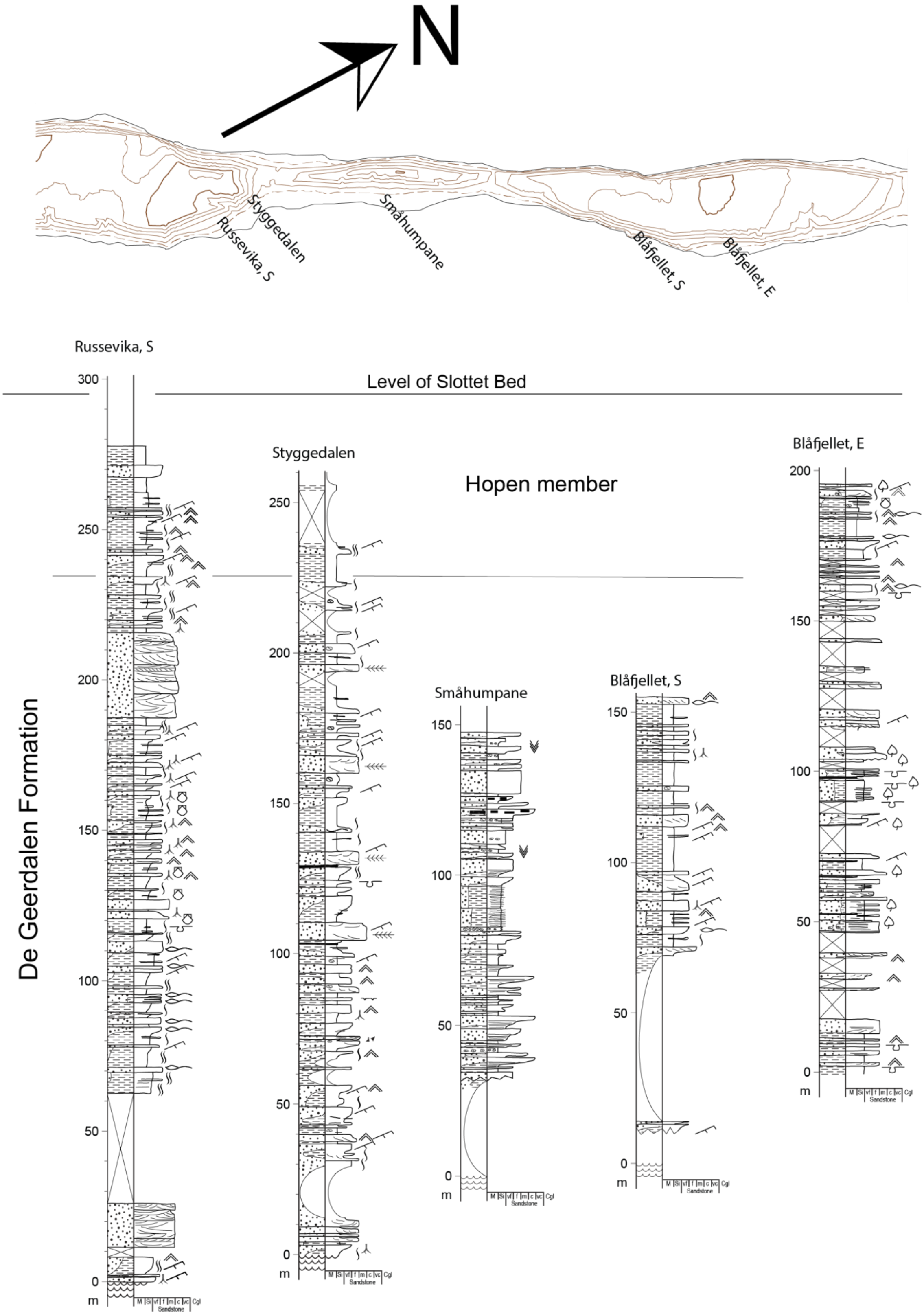
Appendix

Appendix 1: The measured sections collected at Hopen.



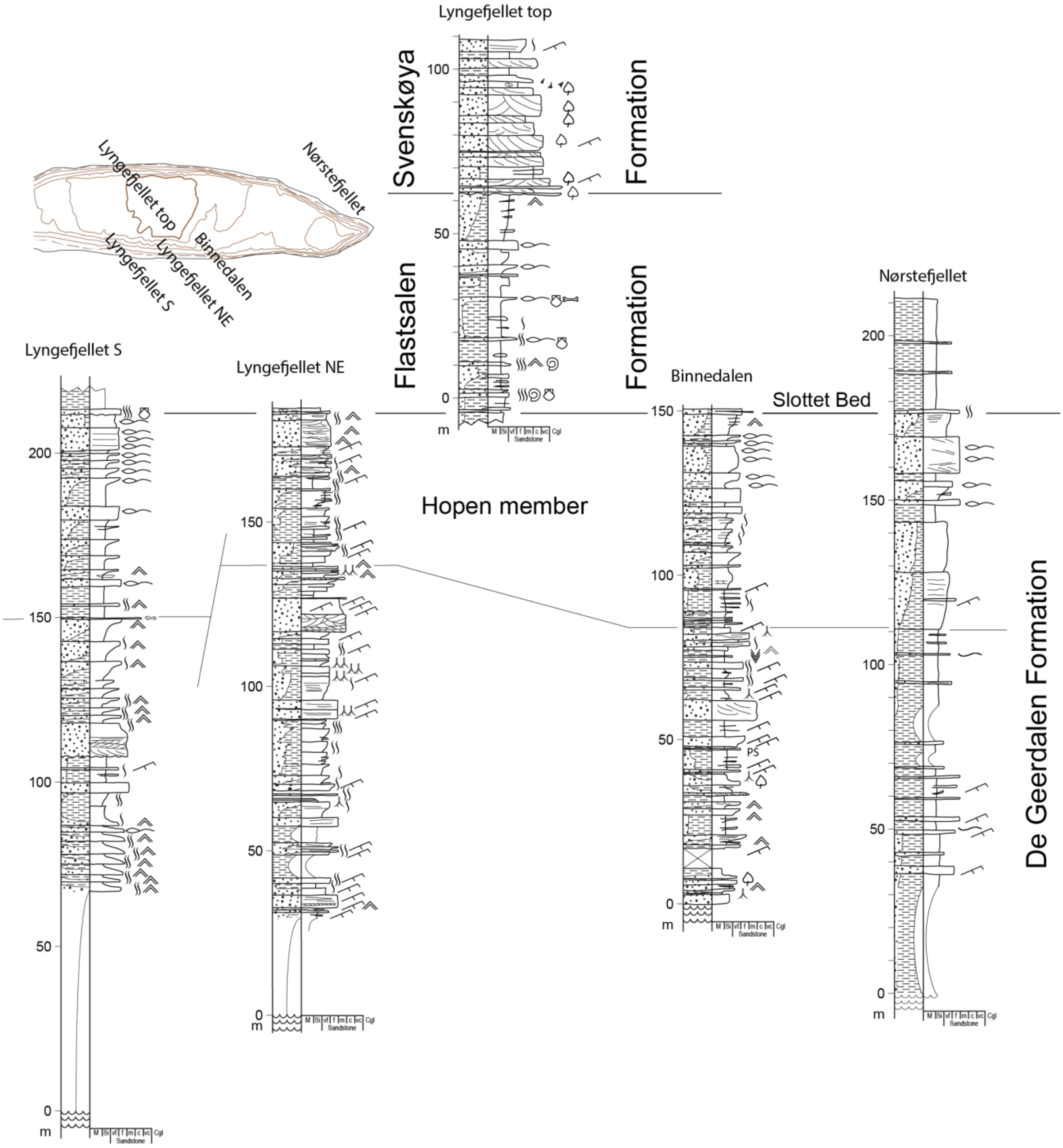
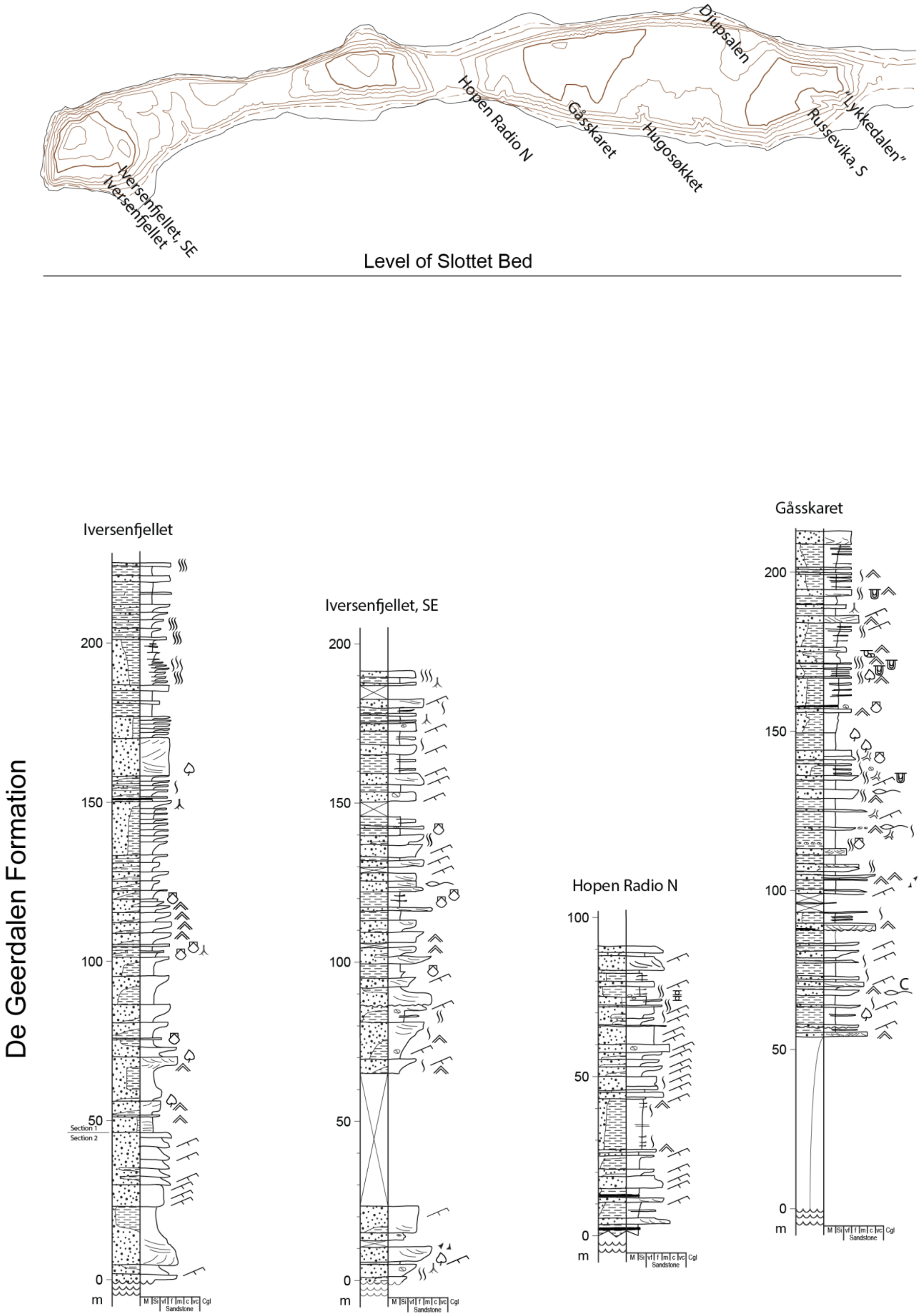


Figure 1: Illustrates the sedimentological logs collected at the northern part of Hopen, with correlation of the Slottet Bed and Hopen member. Drawn by Atle Mørk from field logs collected by the Hopen project group (Subsection 1.1).


Djupsalen
Hopen Radio N
Gåsskaret
Hugosøkket
Russevika, S
"Lykkedalen"
Iversenfjellet, SE
Iversenfjellet
Level of Slottet Bed
De Geerdalen Formation
Iversenfjellet
Iversenfjellet, SE
Hopen Radio N
Gåsskaret
Section 1
Section 2
0
50
100
150
200
m
M
Si
vf
f
m
c
vc
Cgl
Sandstone

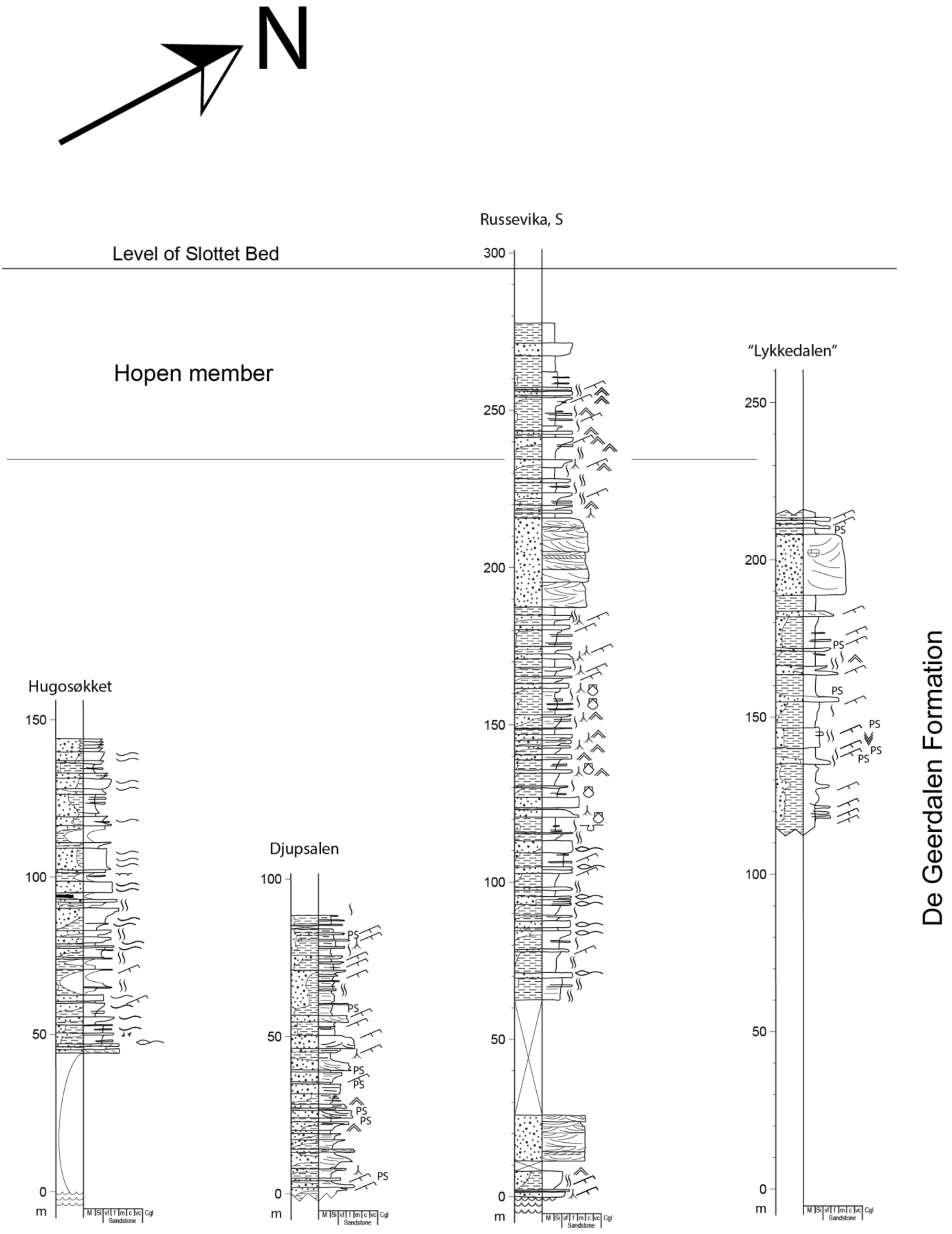


Figure 2: Illustrates the sedimentological logs collected at the southern part of Hopen, with correlation of the Slottet Bed and Hopen member. Drawn by Atle Mørk from field logs collected by the Hopen project group (Subsection 1.1).

Appendix 2: Legend of the measured sections.

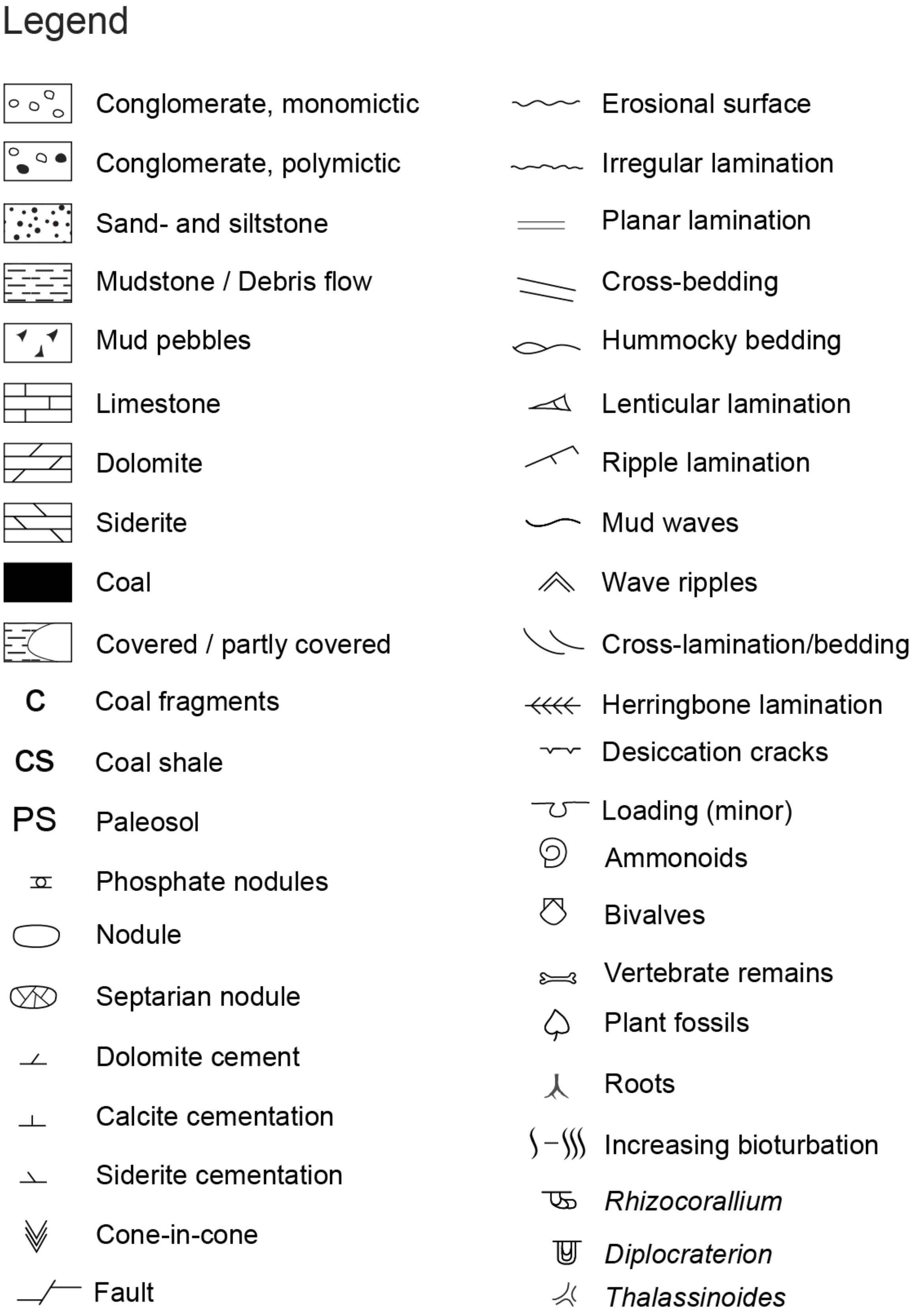


Figure 3: The symbols used on the logs displayed in this thesis.

Hopen member

Type section: The member is defined at Lyngefjellet South (Figure 3.1) at Hopen. The member is 68 m thick at the type locality.

Equivalents: The Hopen member is equivalent to the Isfjorden Member (Mørk et al., 1999), first described as Isfjorden Formation by Pčelina (1983).

Definition: The Hopen member constitutes the upper part of the De Geerdalen Formation. It consists of alternating shales and evenly bedded thin- to thick-bedded siltstone and sandstone beds. The lower boundary is defined by the transition from fluvial dominated, grey deposits to dark shallow marine sediments (Figure 3.1).

Appendix 4: Illustrations of the PhotoModeler-model

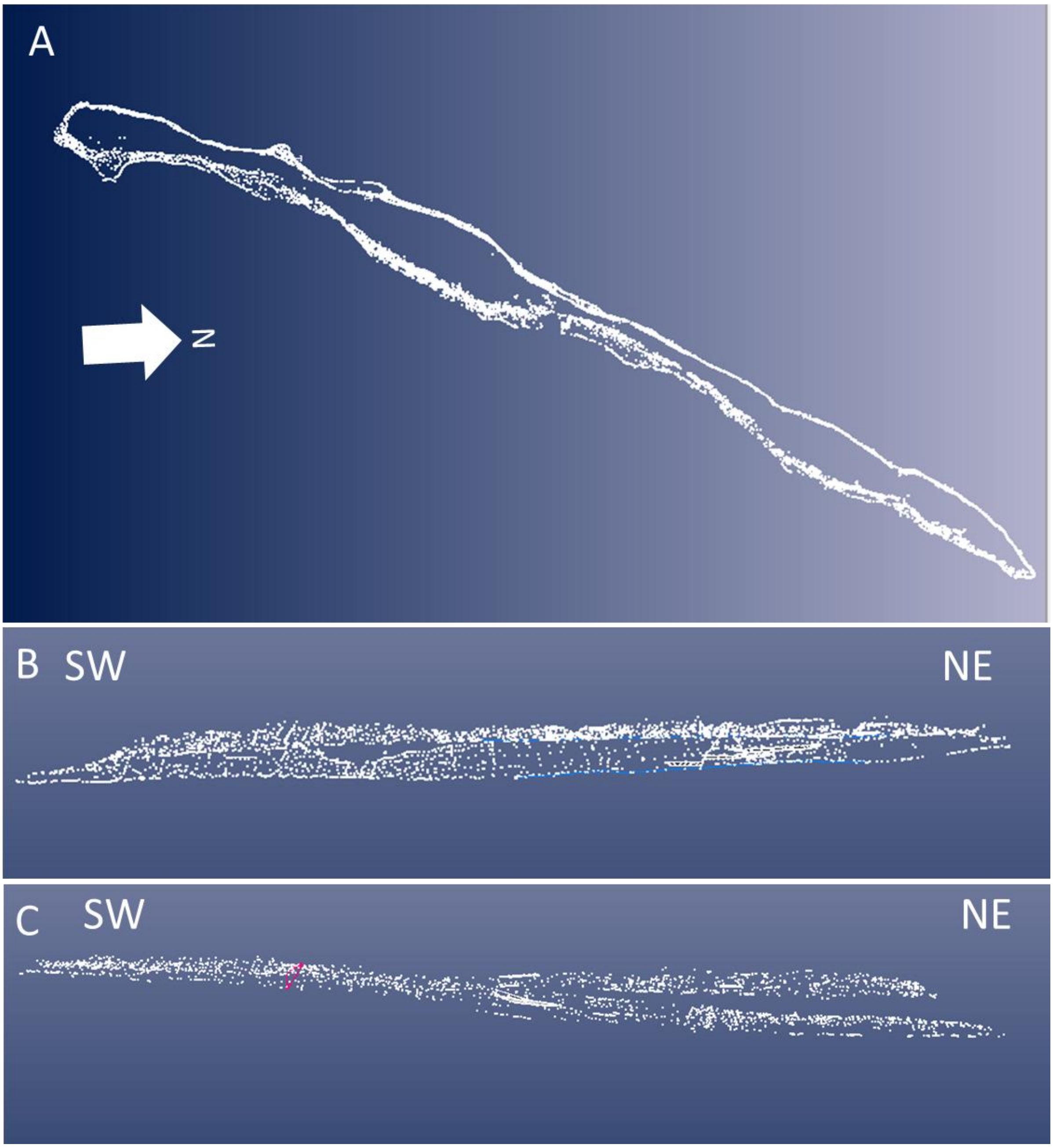


Figure 4: The figure illustrates the PhotoModeler-model. (A) An illustration of the PhotoModeler-model of the entire island. (B) Illustrates the PhotoModeler-model of the area from Johan Hjortfjellet and down to Hopen radio. (C) Illustrates the PhotoModeler-model of Blåfjellet. The model is twisted on the right side of photo C, hence the orientation is not optimal in this area.

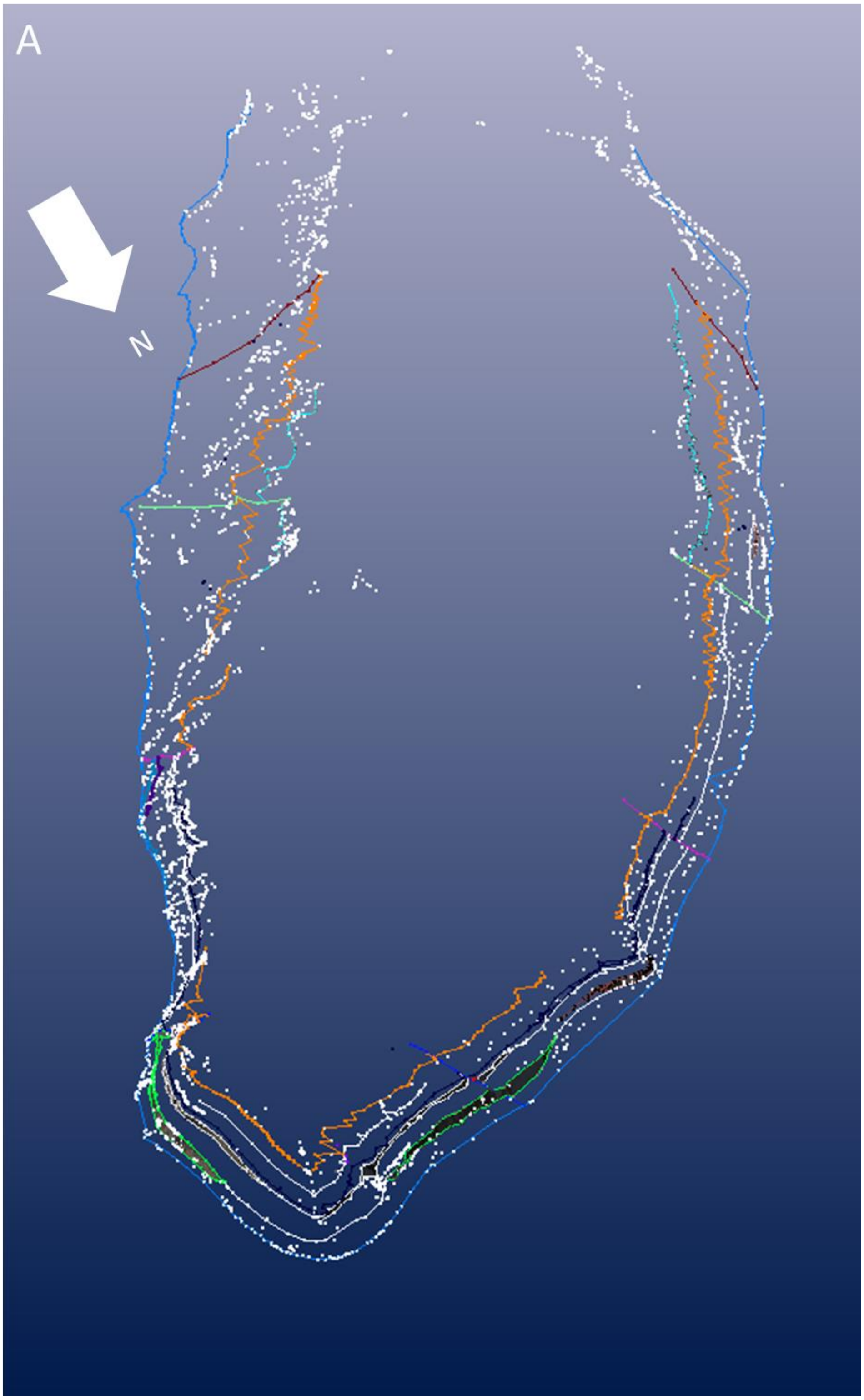


Figure 5: Illustration of the PhotoModeler-model of Lyngefjellet and Nørstefjellet (Northern part of the island). Orange: Slottet Bed. Light blue: Base of Svenskøya Formation. Dark blue: Sea-level. Green: Channel body 1.

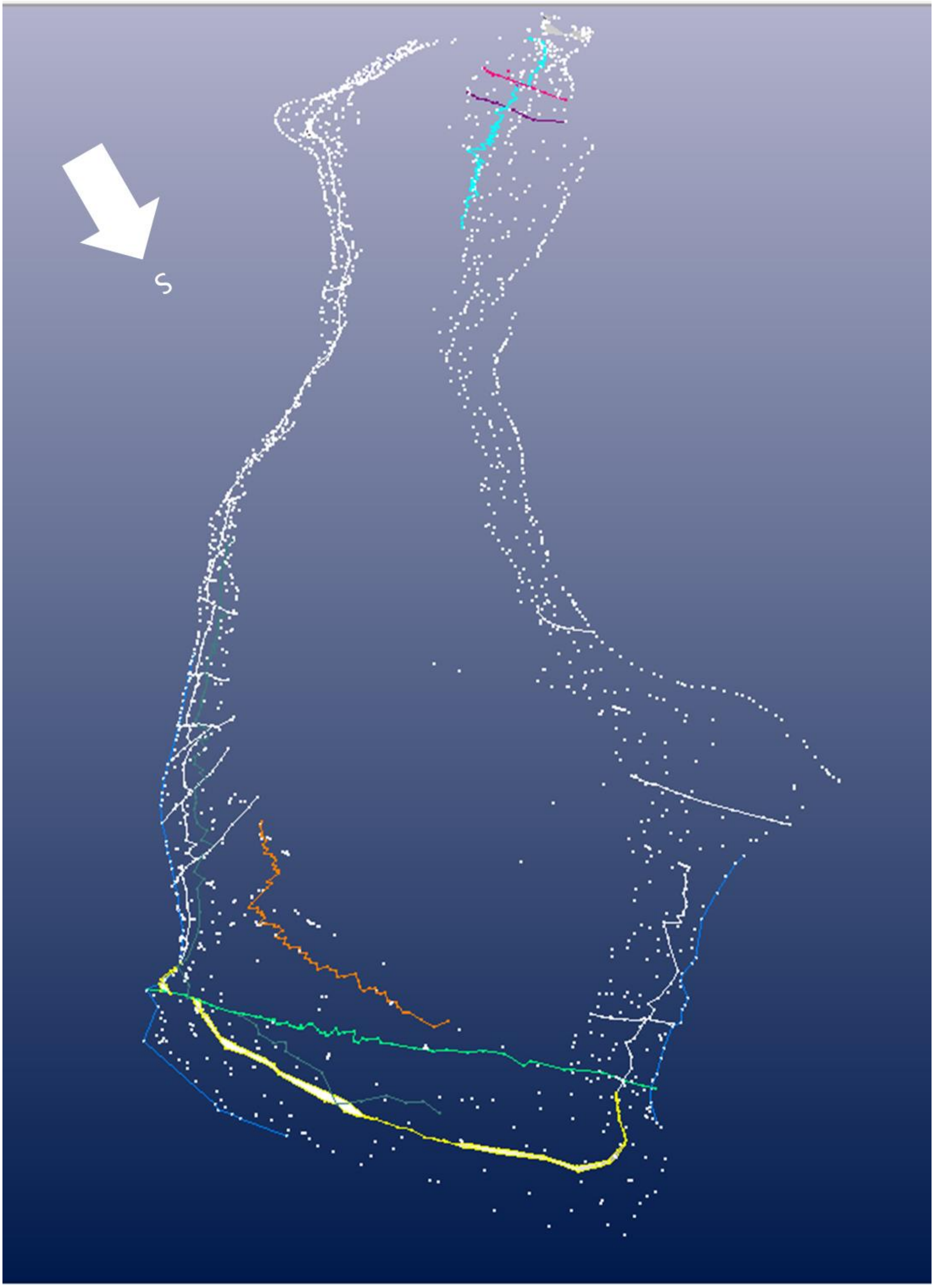


Figure 6: Illustration of the PhotoModeler-model of Werenskioldfjellet and Iversenfjellet (Southern part of the island). Orange: Slottet Bed. Green: Southernmost fault. Yellow: Channel body 14.