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A sedimentological study of the organic-rich Botneheia Formation (Middle Triassic) with emphasis on the ichnogenus Thalassinoides, Edgeøya, Svalbard

Master’s thesis in Geology
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Abstract

The Middle Triassic Botneheia Formation on Eastern Svalbard is the best source rock on the northwestern Barents Sea shelf with up to 12 % total organic carbon. Shale and silt were deposited in an open marine environment in a transgressive-regressive second order regime. Though the shales are often interpreted as anoxic, there are numerous occurrences of the trace fossil *Thalassinoides*, which is thought to depend on oxygenated bottom waters. Detailed studies linking *Thalassinoides* to the sedimentology are so far lacking on Edgeøya. This thesis aims to understand the formation and preservation of *Thalassinoides* burrows and investigates spatial and temporal variations.

During fieldwork in 2018, six field localities on Edgeøya were logged and sampled in detail. Logs were divided into sub-facies and correlated to total organic carbon data. A detailed, high-resolution study of the Muen plateau on Edgeøya describes the occurrences of *Thalassinoides*. Trace fossils were analysed using computed tomography scanning, thin-sections and morphological size measurements.

Results show that the occurrences of *Thalassinoides* are monospecific. The expected tiering structure with crosscutting relationships between ichnogenera is therefore absent, indicating that oxygenation periods were short. These findings differ from a qualitative study of the trace fossils from the Middle Triassic succession on Svalbard, where multiple ichnogenera are described. *Thalassinoides* are preserved both in silty shale and siltstones throughout the succession as networks of phosphate nodules, well visible on exposed bedding surfaces. Burrows preserved in siltstones are interpreted to be due to allocthonous transport during storm events. On the Muen plateau, *Thalassinoides* are found in 20 silty shale beds, alternating with laminated shale and coqina beds. These fluctuations indicate variation from oxic/dysoxic to anoxic bottom waters. A map of the trace fossil distribution on Edgeøya has been made, showing that *Thalassinoides* were most numerous in the upper Blanknuten Member.

Sammendrag

Den midt-triasiske Botneheiaformasjonen på den østlige delen av Svalbard er vurdert til å være den beste kildebergarten i den nordvestlige delen av Barentshavet med et totalt organisk karbon innhold på opptil 12 %. Skifer og silt ble avsatt i et åpent marint sokkel miljø i en andre ordens transgressiv-regressiv syklus. Skifer tolkes ofte til å være avsatt under anoksiske forhold, men i disse sedimentene er det funnet mange forekomster av sporfossilet *Thalassinoides*, som antas å være avhengig av et oksygenrikt bunnvann. Detaljerte studier som knytter *Thalassinoides* til sedimentologi har hittil manglet på Edgeøya. Målet i denne oppgaven har vært å forstå dannelsen og bevaringen av *Thalassinoides* samt å undersøke sted- og tidsmessige variasjoner i sedimentene.

På seks lokaliteter på Edgeøya ble det under feltarbeid i 2018 logget og tatt prøver. Loggene ble delt inn i under-facies og korrelert med totalt organisk karbon data. En detaljert, høyoppløselig studie fra Muen platået på Edgeøya beskriver forekomsten av *Thalassinoides*. Sporfossiler ble analysert ved hjelp av CT-skanning, tynnslip og morfologiske størrelsesmålinger.

Resultatene viser at forekomsten av *Thalassinoides* er monospesifikk. Den forventede lagdelingsstrukturen med ulike ichnogenera som krysser hverandre er ikke tilstede, noe som indikerer at oksygeneringsperiodene var korte. Disse funnene skiller seg fra en tidligere kvalitativ studie av sporfossilene fra midtre trias på Svalbard, hvor flere ichnogenera er beskrevet. *Thalassinoides* er godt bevart i både siltige skifre og i siltsteiner og er mest gjenkjennbare på eksponerte lagflater som nettverk av sammenhengende fosfatnoduler. Sporfossiler bevart i siltstein er tolket til å være tilstede på grunn av allokton transport under stormhendelser. På Muen platået ble *Thalassinoides* funnet i 20 ulike lag av siltige skifre vekslende med laminert skifer og skjell-lag. Disse fluktuasjonene indikerer variasjon fra oksisk/dysoksisk til anoksisk bunnvann. Et kart over sporfossil utbredelsen på Edgeøya har blitt laget og viser at det er mest *Thalassinoides* i den øvre delen av Blanknuten-leddet.

Acknowledgement

First of all, I would like to give a big thank to my supervisor Atle Mørk. I am grateful for the unique opportunity you gave me to spend three summers out in the field on Svalbard, which are experiences and memories I will never forget. Thank you for taking a lot of time to help, discuss and always believing in me during the work of this thesis.

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S.B.

Contents

1. Introduction

Worms have played a more important part in the history of the world
that most persons would at first suppose.
— Charles Darwin, 1881

Worms are one of many organisms producing traces in the substrate. Many of these traces are well preserved in the geological record and are called trace fossils (Bromley, 1990). The study of traces, ichnology, is an increasingly important field within sedimentary geology, palaeontology and biology. Ichnology contributes to the palaeoenvironmental understanding, facies interpretation, diagenesis, and sequence stratigraphy, all commonly used for petroleum exploration (Buatois and Mángano, 2011). As trace fossils are always regarded to be in-situ, they can provide valuable information of the bottom water conditions (Bromley, 1990; Buatois and Mángano, 2011). Additionally, the study of traces contribute to understand animal behaviour better and the history of the Earth.

On Svalbard, an Arctic archipelago, many of the worlds geological time periods are well-exposed due to lack of vegetation (Figure 1.1) (Elvevold et al., 2007). Svalbard is important to understand the geology in the region and in the Barents Sea.

The Middle Triassic is a period in the world history where it is only 5 million years since one of the worlds five mass extinctions, where 96 % of all marine species might have become extinct (Raup and Sepkoski, 1982). On Central Spitsbergen and Eastern Svalbard, the Middle Triassic Botneheia Formation was deposited, and is qualified to be one of the best source rocks in the region (Mørk and Bjorøy, 1984; Mørk and Elvebakk, 1999; Krajewski, 2008; Worsley, 2008; Lundschien et al., 2014). In this organic-rich succession, there are reported findings of the trace fossil assemblage *Thalassinoides* consisting of the ichnogenera *Taendium*, *Rhizocorallium*, *Polukladichnus* and *Thalassinoides* (Mørk and Bromley, 2008). Most findings have been of the *Thalassinoides* burrow, preserved as connected phosphate nodules

(Krajewski, 2008; Mørk and Bromley, 2008; Vigran et al., 2014; Hurum et al., 2014). This study investigates how trace fossils in the Middle Triassic succession on Edgeøya on Svalbard were formed, preserved and how the trace fossil distribution varies. Detailed studies of trace fossils on Edgeøya is currently lacking, and this thesis would contribute to give a more comprehensive picture of the trace fossil assemblage in this organic-rich source rock.

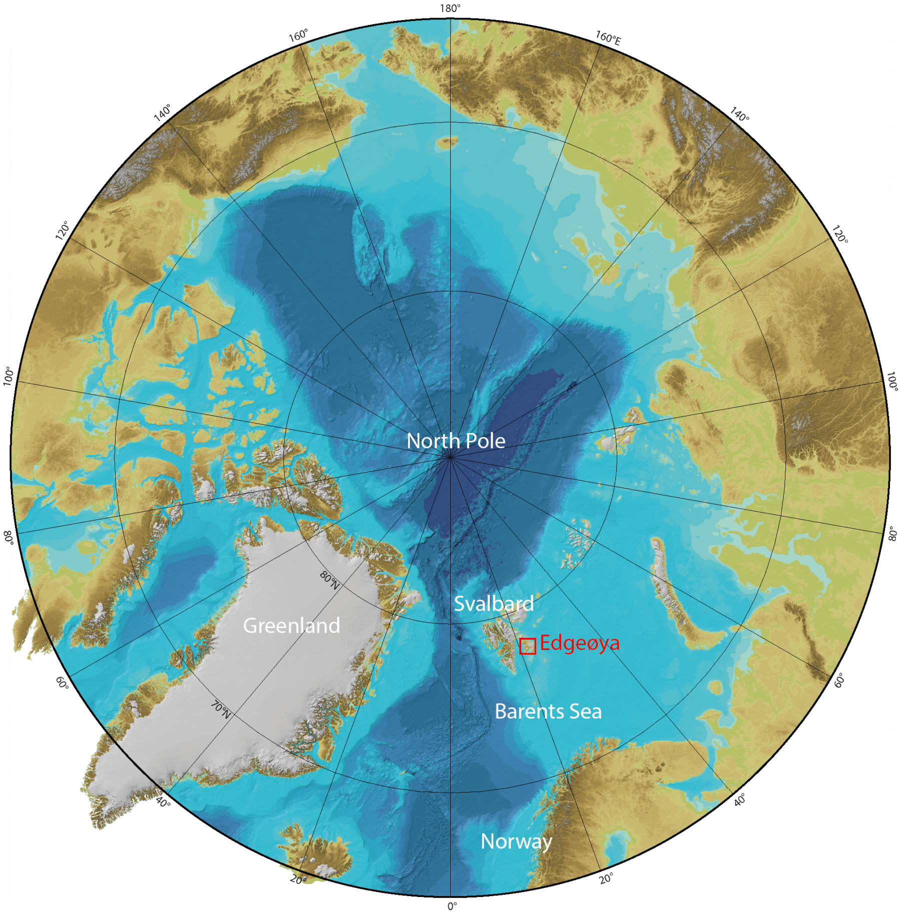

Figure 1.1: Regional map showing the current location of the Arctic archipelago Svalbard. The study area in this thesis, Edgeøya, is marked with a red square. Map from Jakobsson et al. (2012).

1.1 Previous studies

The Triassic succession on Svalbard has been studied for several years, the Norwegian Petroleum Directorate (NPD) and SINTEF Petroleum have worked over decades to gain a better understanding of the Barents Sea. This includes several scientific papers and 11 master thesis.

The "Botneheia Formation" was first discovered in 1865 by Lindström and later described as the "oil shale group" by Falcon (1928). Mørk and Bromley (2008) qualitatively described the trace fossils in the Middle Triassic succession on Svalbard, with the less focus on the eastern Botneheia Formation compared to the western Bravaisberget Formation. Krajewski (2008) conducted a detailed analysis of the Botneheia Formation, dividing it into several units, without a clear focus on ichnology and palaeontology. A more comprehensive description of the trace fossils of the Middle Triassic succession on Edgeøya on Svalbard is therefore needed.

1.1.1 Ichnofauna in the Middle Triassic of Svalbard

From the Middle Triassic of Svalbard, nine ichnogenera and three trace fossil assemblages have been identified, most are found in the Bravaisberget Formation, which is time-equivalent with the Botneheia Formation (Mørk et al., 1982; Mørk and Bromley, 2008). The trace fossil assemblages presented in Mørk and Bromley (2008) is based on qualitative rather than quantitative observations. The following trace fossil assemblages described are *Thalassinoides*, *Taenidium-Rhizocorallium* and *Polykladichnus* assemblage.

***Thalassinoides* assemblage:** Represents open shelf sedimentation and mainly an environment under normal wave base (Mørk and Bromley, 2008). The assemblages consist of the ichnocoenosis *Taenidium-Rhizocorallium*, *Polykladichnus*, and *Thalassinoides*.

***Taenidium-Rhizocorallium* assemblage:** Consisting of the ichnocoenosis *Taenidium* and *Rhizcorallium*. Present where there is an alternation of siltstone and mudstone in periods of higher energy, but in general the same open shelf environment as the Thalassinoides assemblages. Can also be present in delta top environments, where the ichnocoenosis *Rhizocorallium* dominates.

***Polykladichnus* assemblage:** Abundant in the upper part of the Bravaisberget Formation with higher energy environments mainly found in silt or muddy siltstone beds. Traces are produced in periods and seem to reflect a pattern of short periods of higher energy. The assemblage consist of *Polykladichnus*, *Taenidium* and *Rhizcorallium*.

The trace fossil assemblage from the Middle Triassic shows a reflection of the sedimentation source from the west (Figure 1.2) (Mørk and Bromley, 2008). The *Thalassinoides* assemblages dominate the Middle Triassic succession on Edgeøya, Barentsøya and eastern Spitsbergen. No sedimentary log from Edgeøya was presented in Mørk and Bromley (2008) study, but it was indicated that data from three localities on Edgeøya were used to produce the map in Figure 1.2. One sedimentary log from the Høgrinden, located on Barentsøya, an island further north of Edgeøya was included in their study. On Høgrinden the trace fossil *Thalassinoides* was present in the upper part of the Botneheia Formation, with the lack of other ichnotaxa (Mørk and Bromley, 2008).

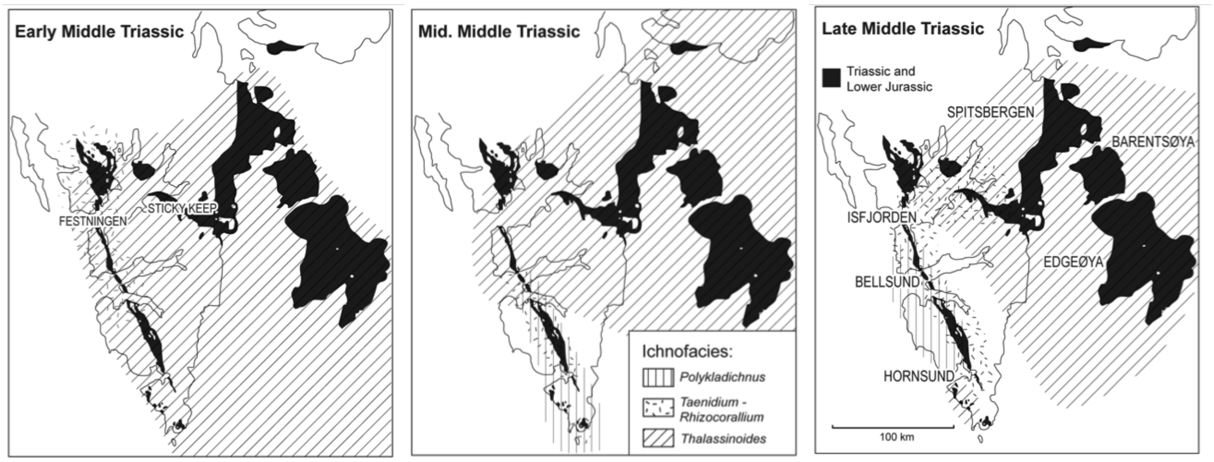

Figure 1.2: Distribution of trace fossil assemblages on Svalbard in the Middle Triassic. From Mørk and Bromley (2008).

In the Middle Triassic succession on Svalbard, cross-cutting relationships between different ichnotaxa is present forming tiering structures (Figure 1.3) (Mørk and Bromley, 2008). By selective cementation of *Thalassinoides* tunnels, phosphate nodules were formed (Mørk and Bromley, 2008). The phosphatization is according to Mørk and Bromley (2008) selective, and took place after the formation of the burrow by sediment infill and early diagenetic processes. Reworking under storm-events gave rise to the commonly found phosphorite conglomerate in the succession (Figure 1.3). Detailed studies of the phosphatization of the Middle Triassic succession on Svalbard do not link all the phosphate nodules in the succession to the burrow system of *Thalassinoides* and suggests that the correlation between phosphate nodules and *Thalassinoides* are over-interpreted (Krajewski, 2000, 2008).

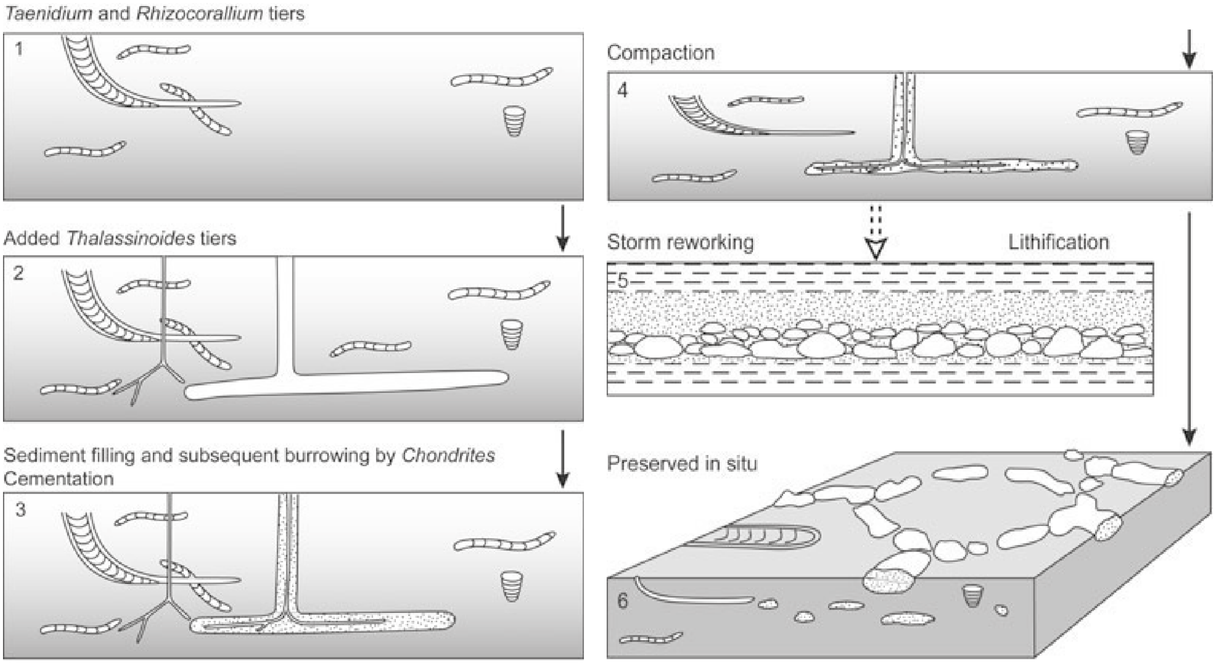

Figure 1.3: Tiering structure and the phosphatization and formation of phosphate nodules from *Thalassinoides* in the Middle Triassic succession. From Mørk and Bromley (2008).

1.2 Objective of the thesis

The main objective of the thesis is to further understand the formation, preservation and the spatial and temporal variations of the trace fossils in the Middle Triassic succession on Edgeøya, Svalbard.

1.3 Outline

The thesis constitutes a total of nine chapters including the introduction. The geological setting is presented to give an insight into the Triassic deposits which characterise the studied field area. Afterwards, a literature review of the basic principles of ichnology is presented. Furthermore, the methods applied to achieve the results in this thesis are described. Chapter 5, 6 and 7 presents the results of this thesis. The main results include sedimentary and ichnological analysis. Sedimentary logs are described and interpreted from different localities to find spatial and temporal variations of the trace fossils. Based on the findings from the different localities, ichnological analysis is presented to give a deeper insight into the systematic, preservation and size of the trace fossils. PMO numbers are currently lacking on the imaged samples, as the project will continue this will be given later. A discussion focusing on the major findings from this work in light of the established literature is presented in Chapter 8. At last, conclusions are given in Chapter 9.

2. Geological setting

The Svalbard archipelago is situated 74 – 81°N and covers an area of approximately 62 000 km^2 (Steel and Worsley, 1984; Worsley, 2008). The archipelago is located on the northwest corner of the Eurasian plate, where the North Atlantic mid-ocean ridge is separating Svalbard from Greenland (Elvevold et al., 2007). The archipelago has moved through a sequence of climatic zones, from equatorial in the Middle Devonian up to its present position in the Arctic region (Worsley, 2008). Today, Svalbard represents an onshore part of the northwestern margin of the Barents Sea Shelf, and gives a comprehensive overview of the geology in the region with most of the Earths history easily accessible for study (Elvevold et al., 2007; Worsley, 2008).

2.1 Triassic of Svalbard and the Barents Sea

During the Permian, the continents were merged in the supercontinent Pangea. The Uralian Mountains formed in the end of the Permian when Siberia moved towards Euramerica and closed the connection between the Boreal Sea and the Tethys Ocean (Figure 2.1) (Riis et al., 2008; Lundschien et al., 2014; Mørk, 2015). The orogeny resulted in a dramatic climatic shift in the northern latitudes. The climate changed from subtropical conditions with deposition of carbonates in the Permian to a temperate climate clastic sediment infill in the Triassic. The abrupt change in lithology and climate indicates a major hiatus in the end Permian, but the transition is poorly understood (Worsley, 2008; Vigran et al., 2014). The end Permian is marked by a mass extinction event where up to 96 % of all marine species might have become extinct, and as a consequence many ecological niches were open in the beginning of the Triassic (Raup and Sepkoski, 1982). Svalbard was during the Triassic Period situated at approximately 55 – 60°N on the northern margin of the Pangea supercontinent in a big embayment, facing the Panthalassa Ocean to the north (Figure 2.1) (Elvevold et al., 2007; Riis et al., 2008; Lundschien et al., 2014). Tectonically, the Triassic on Svalbard was a relatively quiet period, with some minor local faulting (Riis et al., 2008).

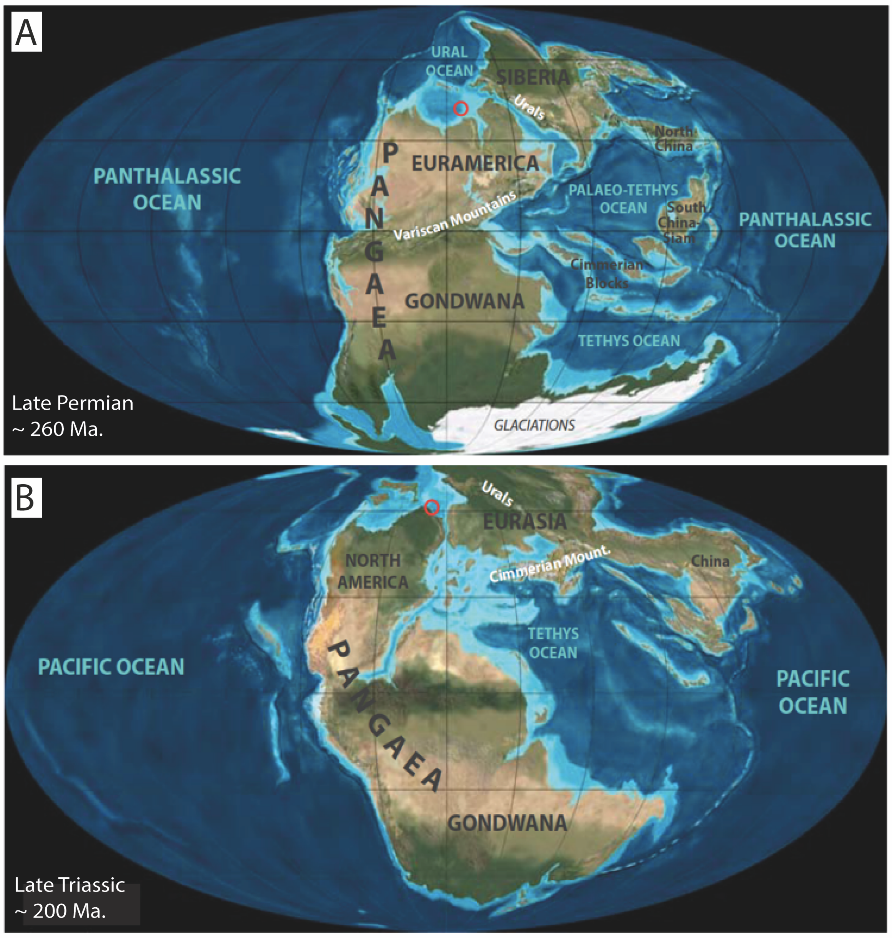

Figure 2.1: Global palaeogeography, the red circle marks the approximately location of Svalbard in **A)** Late Permian, **B)** Late Triassic. From Mørk (2015).

The palaeogeographic evolution of Svalbard and the Barents Sea during the Early, Middle and Late Triassic is shown in Figure 2.2. In the Early to Middle Triassic, sediment coming from Greenland in the west was an important sediment source. The Early Triassic sediments indicate a shallow to open marine environment (Figure 2.2A) (Riis et al., 2008). During the Middle Triassic there was progradation from west, with a more distal development on eastern part of Svalbard. In the early Anisian stage there was a major transgression resulting in deposition of fine grained organic rich shale (Figure 2.2B) (Mørk et al., 1982). Erosion from the newly formed Uralian Mountains, basement of Norway and the Kola Peninsula were the main clastic sediment sources to the Barents Sea during the Triassic. This clastic sediment reached the Svalbard embayment during the Late Triassic (Riis et al., 2008; Worsley, 2008; Lundschien et al., 2014).

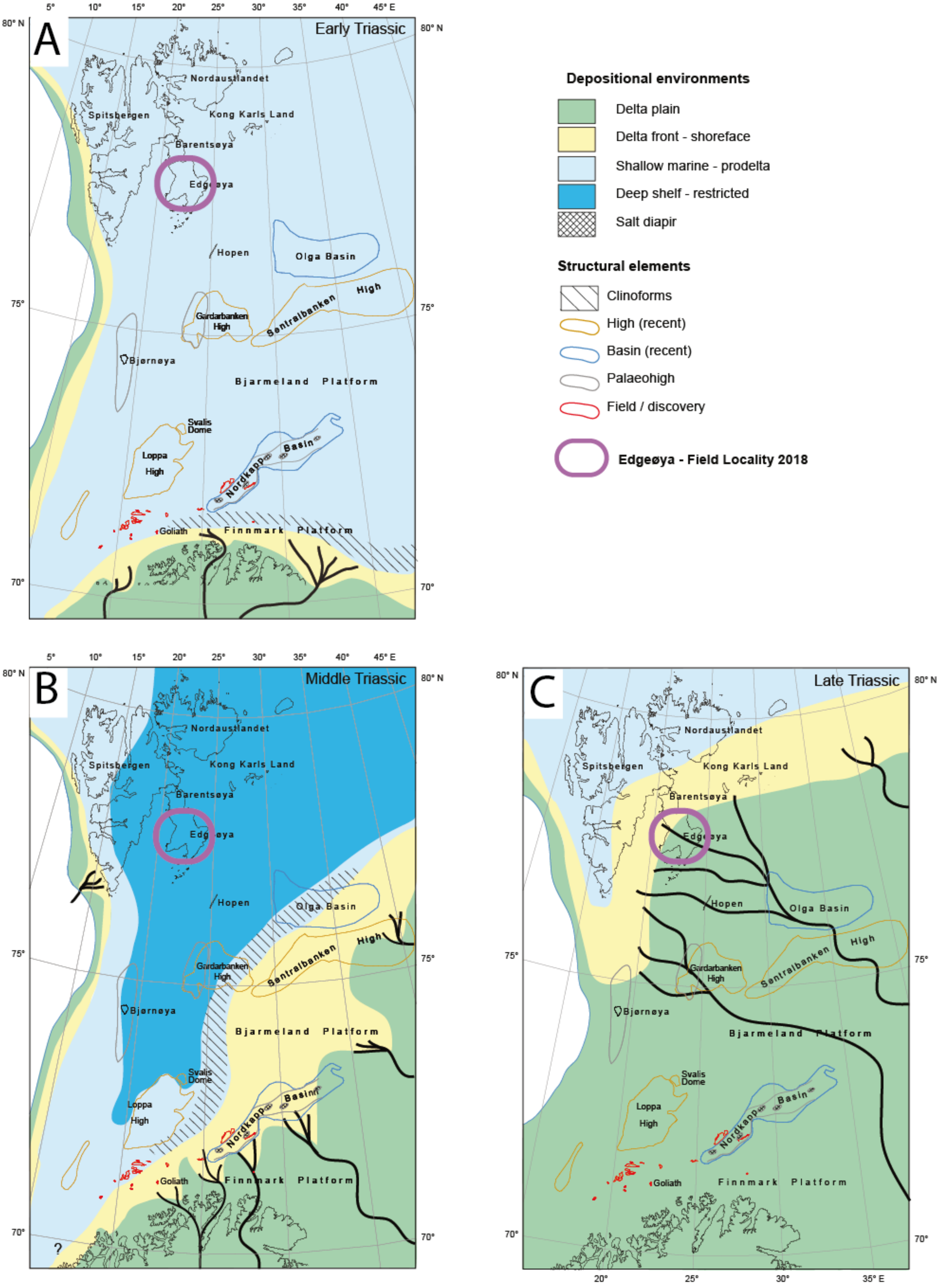

Figure 2.2: Palaeogeographic evolution of Svalbard and the Barents Sea during the Triassic, purple circle marks location of Edgeøya, the study area in this thesis **A)** Early Triassic **B)** Middle Triassic **C)** Late Triassic. From Lundschien et al. (2014).

Sediments from large river systems were filling in the Barents Sea from southeast forming prograding clinoforms. The depositional environments of the progressive infill ranges from deep basin to delta plain. The clinoforms are younger towards the northwest of the Barents Sea, and reached the Svalbard archipelago sometime in the Late Triassic (Figure 2.2C) (Høy and Lundschien, 2011; Lundschien et al., 2014; Riis et al., 2008). Consequently, the deposits from Svalbard are younger than the equivalent deposits in the Barents Sea (Riis et al., 2008). It has been stated that the bottom sets deposits produced from the clinoforms represent the organic-rich Steinkobbe Formation, facies equivalent with the Botneheia Formation (Høy and Lundschien, 2011).

2.1.1 Lithostratigraphy

The present lithostratigraphic overview of the Triassic at Svalbard and the Central Barents Sea is shown in Figure 2.3. The Triassic succession of Svalbard and the Barents Sea constitute of the lithostratigraphical groups Sassendalen and Kapp Toscana. Figure 2.4 shows a photo of the Triassic succession from eastern Svalbard marked with stratigraphic units. The total thickness of the Triassic strata ranges from 250 to 1200 metres (Lock et al., 1978; Mørk et al., 1982). There are a series of transgressive-regressive units in the Sassendalen Group which also can be traced across the Barents Sea Shelf (Mørk et al., 1989, 1999; Mørk and Smelror, 2001; Mørk and Bromley, 2008). The Sassendalen Group constitute the Early and Middle Triassic succession of Svalbard and the Barents Sea shelf, with a total thickness ranging from 700 to 1000 metres (Buchan et al., 1965; Mørk et al., 1999). The deposits are dominated by fine-grained clastic materials such as shales, siltstones and minor sandstones. The Kapp Toscana Group consist of the Late Triassic to Middle Jurassic deposits. This group mainly consist of sand- and mudstones with a sediment provenance from the Uralian orogeny (Mørk et al., 1999).

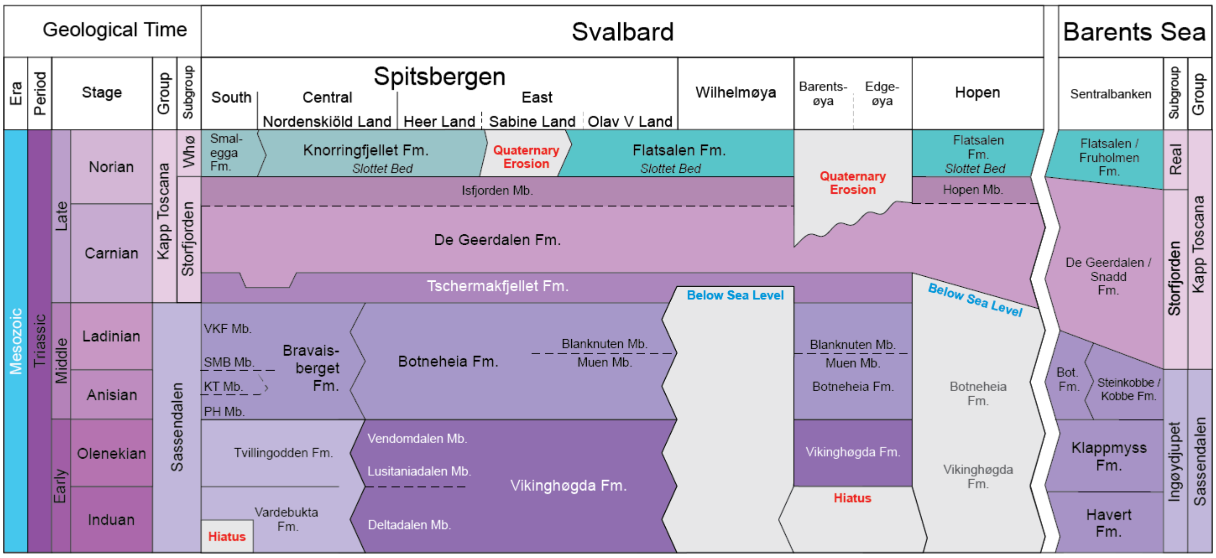

Figure 2.3: Lithostratigraphy of the Triassic succession of Svalbard and the Barents Sea. From Lord (2017).

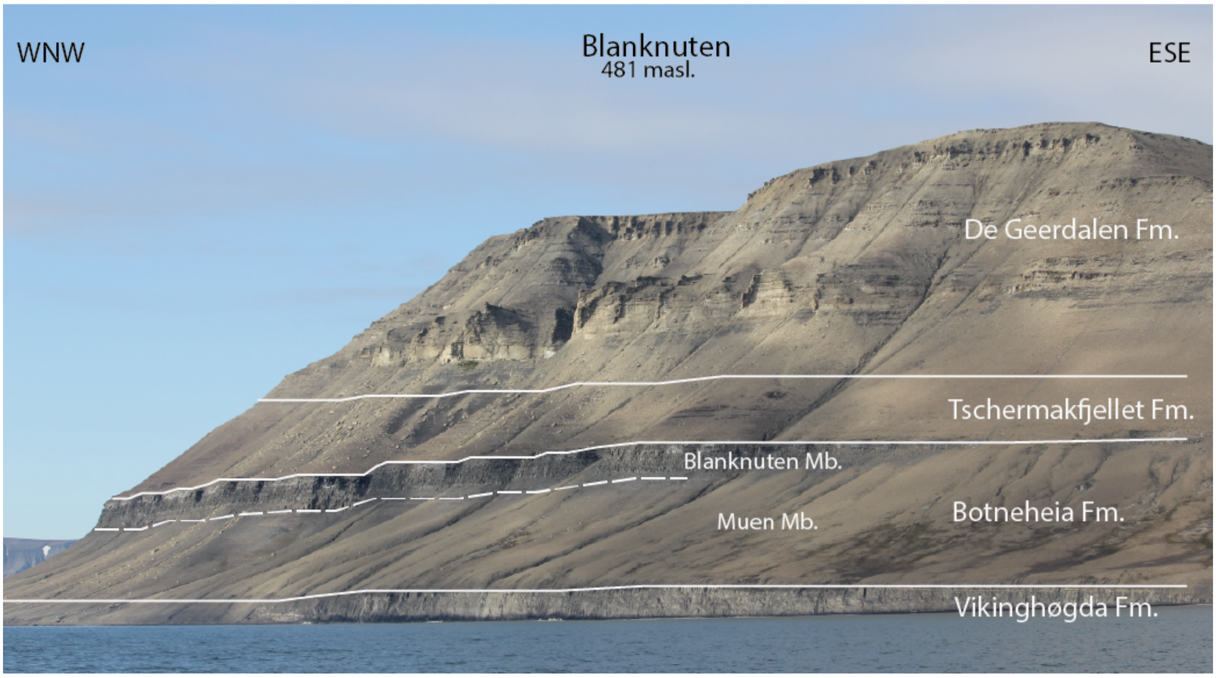

Figure 2.4: Photo of the Blanknuten Mountain on Edgeøya, showing the Triassic stratigraphic units of Eastern Svalbard. Photo: AM.

2.2 Middle Triassic of Svalbard

During the Anisian and Ladinian organic-rich sediment was deposited in basins covering a great extent of northern Alaska (Beaufort-Mackenzie), Arctic Canada (Sverdrup Basin) and the Barents Shelf including Svalbard. The organic matter may have developed during normal productivity, but the preservation of it was particularly good in the period. Additionally, restricted bottom-water conditions, low continental run-off together with sea bed topography contributed to low sediment supply (Leith et al., 1993).

On Svalbard, the Middle Triassic succession consist of the time equivalent Bravaisberget and Botneheia Formation. Major transgressive-regressive cycles characterise these deposits (Mørk et al., 1989). A major transgression in the early Anisian may have produced phosphate-rich shale found in lower Bravaisberget and in the Botneheia Formation (Mørk et al., 1982). The Steinkobbe Formation located in the Svalis Dome and central Barents Sea is facies equivalent with the Botneheia Formation on Svalbard (Mørk and Elvebakk, 1999). The Middle Triassic deposits seem to have good potential for being excellent source rock for oil and gas (Mørk and Bjorøy, 1984; Leith et al., 1993).

The Bravaisberget Formation crops out in western Spitsbergen and is characterised by a coarsening upward trend with mudstone at the base grading towards a higher influx of silt and sand (Mørk and Elvebakk, 1999; Mørk et al., 1982; Krajewski et al., 2007). The Bravaisberget formation is interpreted being a regressive deltaic unit with a prograding delta front (Mørk et al., 1989). The Botneheia Formation is present on Central Spitsbergen and Eastern Svalbard and is dominated by fine-grained clastic sediments, developed in an open shelf environment (Mørk et al., 1982; Worsley, 2008; Krajewski, 2008; Vigran et al., 2014).

2.2.1 Botneheia Formation

The sediments from the Botneheia Formation were already known by Lindström in 1865 and described by Falcon (1928) as the "oil shale group" in the first stratigraphic review of the Triassic succession on Svalbard. Buchan et al. (1965) defined the whole Middle Triassic of Svalbard as the Botneheia Formation. Mørk et al. (1982) described the succession as the Botneheia Member and restricted it to Eastern and Central Spitsbergen. Pčelina (1983) first used the Botneheia Formation name for the Eastern and Central part of Spitsbergen, and the Formation was included in the lithostratigraphy by Mørk et al. (1999).

The Middle Triassic Botneheia Formation is present in Central and Eastern Spitsbergen on Svalbard and extends into the northwestern Barents Sea Shelf (Mørk et al., 1982, 1999). The succession ranges in thickness from 168 metres in northern Nordenskiöld Land to 80 metres on eastern Svalbard (Mørk et al., 1999). The Botneheia Formation rest on the Early Triassic Vikinghøgda Formation and is overlain by the Late Triassic Tschermakfjellet Formation (Figure 2.3) (Mørk et al., 1999). The Botneheia Formation forms a coarsening upward succession with mudstones in the base that grades into calcareous siltstones (Mørk et al., 1982, 1989). The succession mainly consist of dark shale rich in phosphate nodules interrupted by yellow siltstone beds. The Botneheia Formation has a rich benthic fauna with the abundant bivalve genus *Daonella* and an infauna of the abundant trace fossil *Thalassinoides* (Mørk and Bromley, 2008; Vigran et al., 2014). The algae *Tasmanites*, ammonoids and ichthyopterygian remains are also common (Vigran et al., 2008; Hurum et al., 2014). The succession is rich in organic matter and constitutes the best source rock in the area with up to 12 wt.% TOC (Krajewski, 2008). The formation is interpreted to be deposited in a mainly anoxic open shelf environment, interrupted by oxic periods (Mørk and Bromley, 2008; Krajewski, 2013).

The Botneheia Formation is divided into the Muen Member and the overlying Blanknuten Member, both having their type section on Edgeøya, Eastern Svalbard (Mørk et al., 1982; Krajewski, 2008). Krajewski (2008, 2013) did a detailed description based on bed-by-bed study, petrographic methods and geochemistry and recognised two major sedimentary facies: black shale facies and phosphogenic black shale facies. The Formation was further divided into nine lithostratigraphic units, five in the Muen Member (Unit 1 - 5) and four in the Blanknuten Member (Unit 6 - 9) (Figure 2.5) (Krajewski, 2008, 2013).

Muen Member

The Muen Member is the lower succession of the Botneheia Formation, of Anisian age and is defined by Krajewski (2008). The Muen mountain on Edgeøya is the type locality to the member. The main lithology is shale and mudstone with phosphate nodules appearing towards the top. The total thickness ranges between 54 and 65 metres, but due to poor exposure it is often difficult to measure. The change in lithology from resistant grey mudstone and siltstone to soft, fissile black shale marks the lower boundary with to the Vikinghøgda Formation (Krajewski, 2008). The lower boundary marks the beginning of the transgressive cycles in the Triassic (Mørk et al., 1989). The lower and middle Muen Member is classified by Krajewski (2013) as the Black shale facies (Unit 1 - 4). The first appearance of phosphate in the formation is in the upper part of Muen Member (unit 5) and belongs to the phosphogenic black shale facies (Figure 2.5) (Krajewski, 2008, 2013).

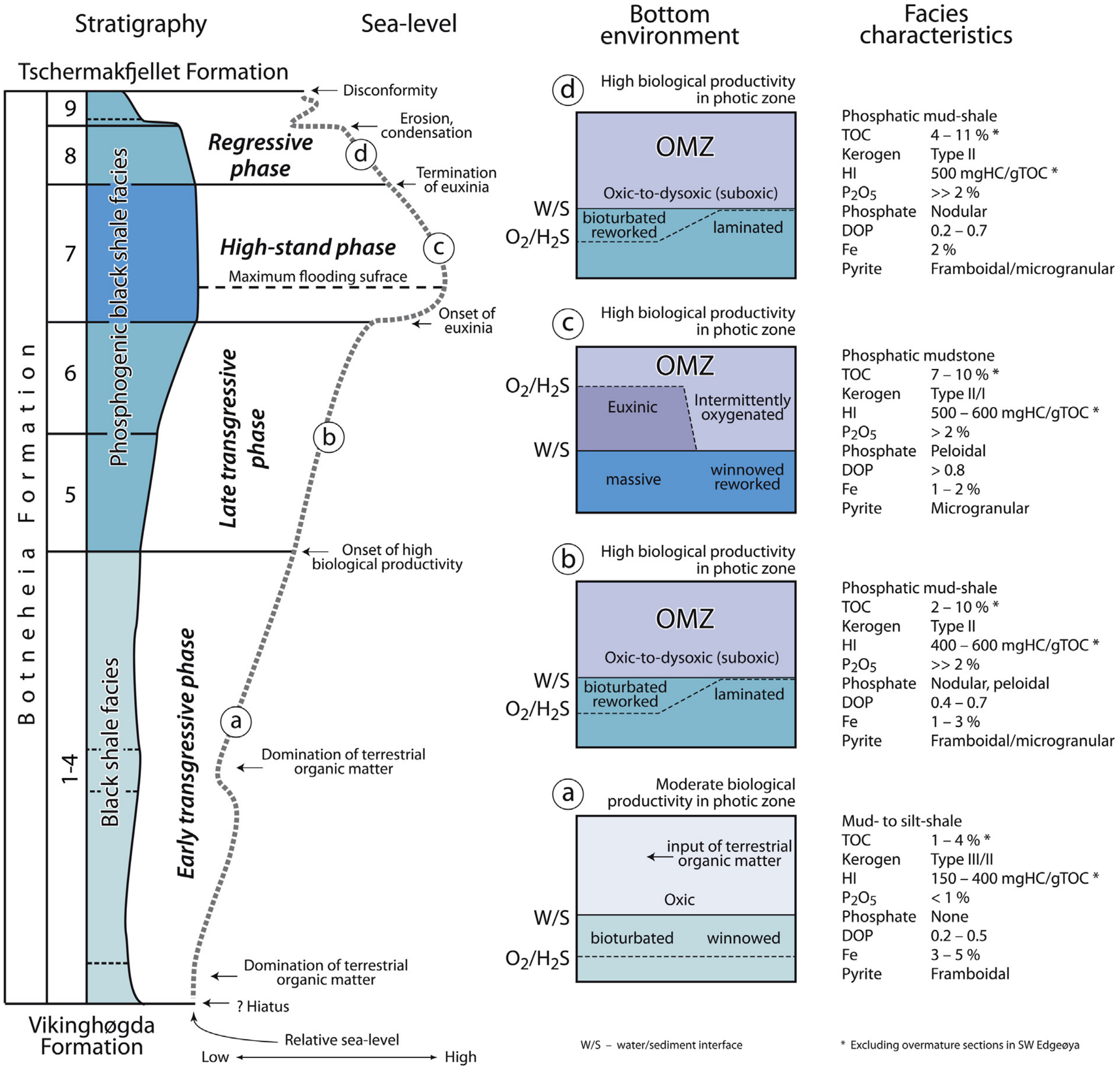

Figure 2.5: The Middle Triassic Botneheia Formation on Edgeøya and the position of the black shale facies and phosphogenic black shale facies together with the lithostratigraphic units (1 - 9). Early transgressive phase (unit 1- 4), Late transgressive phase (unit 5 - 6), High stand phase (unit 7) and Regressive phase (unit 8 - 9) with an interpreted sea level curve and bottom environment conditions. From Krajewski (2013)

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Blanknuten Member

The Blanknuten Member is the prominent cliff-forming unit of upper Botneheia Formation (Mørk et al., 1999). It is traceable throughout central Spitsbergen and Eastern Svalbard. First defined as the oil shale member (Falcon, 1928), later the Blanknuten Bed by Mørk et al. (1982)

and now as the Blanknuten Member (Mørk et al., 1999). The name has its origin from the mountain Blanknuten on western Edgeøya (Figure 2.4). The total thickness varies from 30 to 40 metres (Krajewski, 2008). The age ranges from late Anisian to the Ladinian, the upper Ladinian is probably missing (Lock et al., 1978; Krajewski, 2008). The Blanknuten Member mainly consists of black, organic-rich shales with silty calcareous beds deposited in a open marine shelf (Mørk et al., 1999). The boundary between Muen and Blanknuten Member is at the base of the cliff-forming mudstones and shale and at top of a carbonate cementstone with flattened ammonoids (Mørk et al., 1999; Krajewski, 2008). The upper boundary of the Blanknuten Member represents the upper boundary of Botneheia Formation and the Sassendalen Group and is where the overlying Tschermakfjellet Formation with purple-weathering sideritic concretions is present. Blanknuten Member represent the phosphogenic black shale facies (Unit 6-7), where the sediment is enriched with phosphate. Black shale is interbedded with bioturbated sections and coqina beds filled with the bivalve *Daonella* spp. (Mørk and Bromley, 2008; Krajewski, 2013).

2.2.2 Phosphate in the Botneheia Formation

The phosphogenic black shale facies in the Botneheia Formation includes phosphate deposits as nodules, burrows, peloids, coprolites and phosphatized skeletal remains (Krajewski, 2000, 2008, 2011). Nodules and peloids are the most common phosphate deposits present in the formation. Nodules and peloids have its origin ranging from fully oxic shallow shelf to suboxic to anoxic deep shelf with local euxinic depressions (Krajewski, 2008). Deposition of apatite seem to be linked to water-sediment interface where the formation of phosphate ion is highest (Krajewski, 2011). Phosphorous is of vital importance for modern and once living organisms. In the marine environment, especially phytoplanktons are known to be rich in phosphorus in addition to carbon and nitrogen. Phosphor can be present in the sea water both as inorganic and organic forms (Baturin, 1982). Phosphor allows for high growth of organisms in the upper water column. Organisms remains and organic debris that are not consumed, accumulates on the sea bottom where there is reducing conditions. At the seafloor phosphor is deposited and accumulated in the sediment. The pore water in the sediment get concentrated with phosphate. From the phosphate rich pore water, carbonate apatite gets precipitated by diagenesis processes(Boggs, 2013).

Phosphate nodules in modern environments mainly have it origin from oceanic upwelling zones of deeper water masses rich in phosphor (Figure 2.6). Diagenetic processes followed by mechanical reworking of phosphate grains during lower sea level seem to be forming phosphate nodules (Boggs, 2013). The phosphogenic facies development in the Middle Triassic of Svalbard is relatively similar to modern coastal upwellings. A rapid precipitation of carbonate fluorapatite in the upper organic rich sediment column seem to be the cause of the phosphate in the Botneheia Formation at Svalbard according to Krajewski (2011).

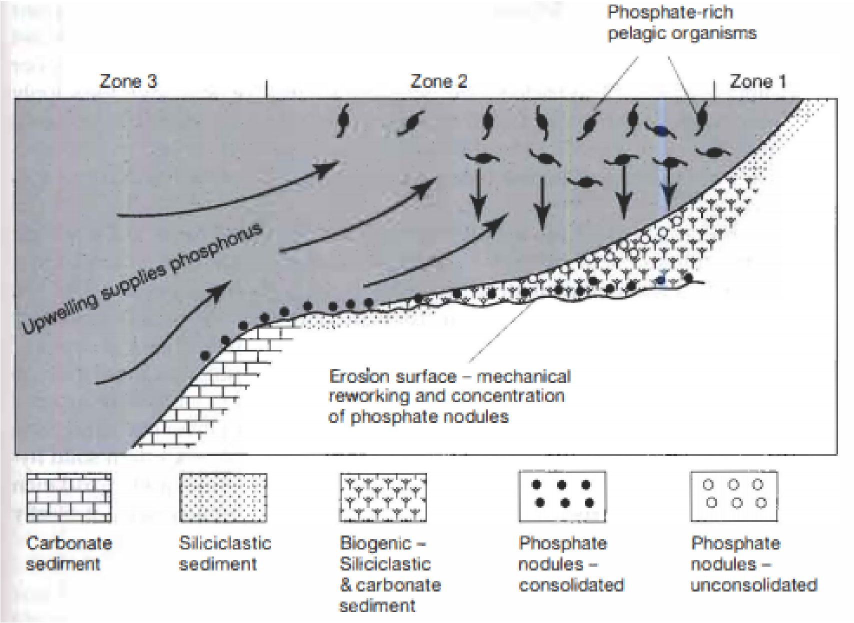


Figure 2.6: Schematic illustration of formation of phosphorites in upwelling zones on open ocean shelves From Boggs (2013) after Baturin (1982)

3. General principles of ichnology

Traces are structures in grains, rocks and sediments, produced by the life processes of animals, and can be grouped into burrows, bioerosion trace fossils, trails, trackways and plant-root traces (Bromley, 1990; Knaust, 2017). The most common trace category is burrows. A trace fossil is defined as: "A morphologically recurrent structure resulting from the life activity of an individual organism (or monospecific group of organisms) modifying the substrate" (Bertling et al., 2006). The study of recent traces and trace fossils is called ichnology, which is divided into neoichnology and palaeoichnology. Neoichnology is the study of traces of living animals, palaeoichnology is the study of traces made by extinct animals (Bromley, 1990).

3.1 Neoichnology

In marine or lacustrine environments the trace making animals predominantly have an endobenthic or epibenthic modes of living. Endobenthic animals lives in the sediment on the lake- or seafloor, epibenthic lives on the surface of sediment at the bottom of the lake- or seafloor (Bromley, 1990). Animals disturb and burrow in the sediment for multiple reasons. Some animals spend their entire life in a burrow, while other disturb the sediment more accidentally (Bromley, 1990). The basal reason why endobiont animals burrow is particularly to solve four essential problems:

- Respiration
- Reproduction
- Protection
- Feeding

By burrowing and living within the sediment, animals are protected from the overlying environment and are concealed from potential predators (Bromley, 1990; Buatois and Mángano, 2011).

One of the challenging aspects by studying traces, is to link traces to the animal that made them. The trace maker is rarely present in the studied trace. Different animals can produce the same type of traces, and the same animal can produce different traces. The study of traces gives a broad range of information regarding food supply, environment, ecosystems, animal-sediment relationship and animal behaviour (Buatois and Mángano, 2011).

3.1.1 Feeding strategies

Different feeding strategies have been adapted by trace making animals in order to consume essential food and nutrients. The feeding strategies are based on where the food resources are located, what the organism eat and the availability of the nutrients (Buatois and Mángano, 2011).There are three common feeding strategies:

Suspension feeding: Animals capture particles from the water column and do not have to move around in order to gather food. Many epibenthic organisms have adapted this type of feeding and are dependent on natural flows in the water for nutrition (Bromley, 1990; Buatois and Mángano, 2011)

Deposit feeding: Animals scavenge through the sediment for essential nutrients. Most of the endobiont organisms are deposit feeders. The animals are often specialised and extract only grains containing specific organic components (Bromley, 1990).

Detritus feeding: The animal feed on loose organic particles in the depositional interface. At the depositional interface there is a rich supply of continually renewed organic material. The animals protect themselves in the sediment and feeds around the burrow aperture (Bromley, 1990; Buatois and Mángano, 2011)

3.1.2 Modes of interaction

Substrate properties such as grain size, sorting, water content and shear strength, all have a major impact of how endobiont organisms can burrow into the substrate. An universal terminology of how animals moves in the sediment is currently missing. However, Bromley (1990) suggested a classification of the mode of which the infaunal animals interacts with the substrate (Buatois and Mángano, 2011), related to sedimentary characteristics (Figure 3.1).

Intrusion: The animal penetrates through the substrate, displacing sediment by their body, before the displaced sediment refills behind the animal.

Compression: The animal penetrates through the substrate and compacts the surrounding sediment, forming an open burrow. This is common for bivalves and worms.

Excavation: The animal loosens compacted sediment and displaces it.

Backfill: The animal loosens sediment in the front of the direction of movement and transports it either around sediment around or through the animal's body. The sediment is redeposit behind the animal.

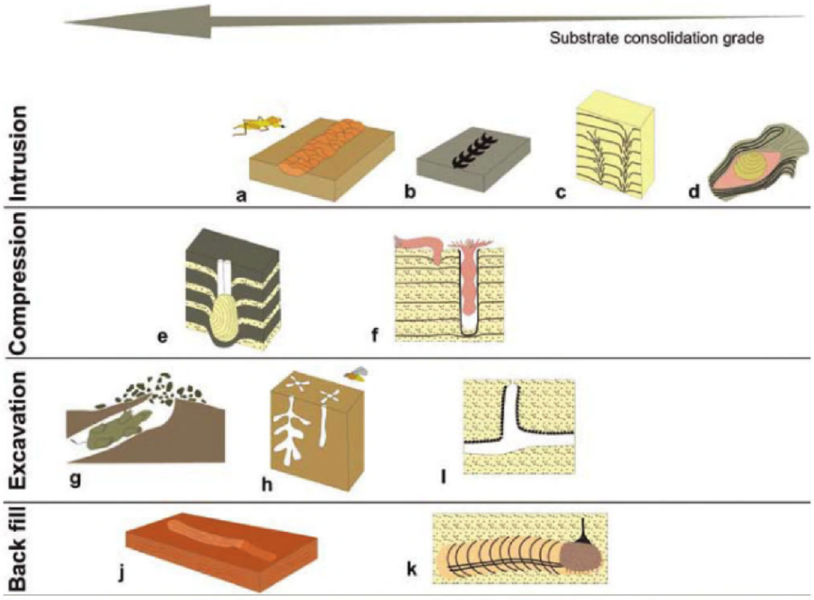


Figure 3.1: Different modes of interaction with increasing substrate consolidation grade. Modified by Buatois and Mángano (2011) from Bromley (1990).

The consistence of the substrate is divided into soupground, softground, firmground, hardground and concealed firmground (Bromley, 1990).

3.2 Palaeoichnology

There are several terminologies for describing the distribution and the occurrence of trace fossils. The most common terminologies are tiering, ichnofacies, ichnotaxa assemblages and ichnofacies (Bromley, 1990). Palaeoichnological studies, the study of trace fossils, provides information on the palaeoenvironment, sedimentation and oxygenation. As many trace making animals are sensitive to changing environments, the presence of trace fossils provides information about conditions before, during and after deposition of a bed (Mcilroy, 2004). Trace fossils are highly related to the animal behaviour and actions (Bromley, 1990). In most cases the organism behind the traces is not preserved. Under certain circumstances, the trace maker has been found well preserved (Knaust, 2017).

3.2.1 Trace maker: Crustacean

Crustacea is a group of arthopods, which can be traced back to the Cambrian period until today. Crustaceans are thought to be the originating organisms of multiple trace fossils found in the geological record, e.g *Thalassinoides* and *Ophiomorpha*, and several other deposit feeding trace fossils (Bromley, 1990). Crustaceans are mainly marine, but some lacustrine species exist today. Crustacea is a subphylum within Euarthropoda, 75 % of all crustaceans belongs to the class Malacostraca (Altin et al., 2014). Figure 3.2 shows two different crustacean inside a burrow (lumen). Due to the low preservation potential, body fossils of crustaceans in the fossil record are rare (Whicher et al., 2016). It can also be challenging to compare body fossils to ichnofossils (Carmona et al., 2004). There are five occurrences of a Jurassic crustacean fossilised in the trace fossil *Thalassinoides* (Sellwood, 1971; Bromley and Asgaard, 1972; Fürsich, 1974; Monaco and Garassino, 2001; Whicher et al., 2016). The last report of remains of the crustacean *Glyphea regleyana*, are from the Middle Jurassic Inferior Oolite Formation of Oborne, Southern England (Whicher et al., 2016). The burrow system of *Thalassinoides* were probably formed by different genera of the deposit feeder crustaceans. Modern burrows systems of *Callinassa*, a genus of crustacean, shows the similar burrow morphology as *Thalassinoides* burrows, but burrows of the lobster *Nephrops norvegicus* and *Alpheus* and the crab *Goneplax rhomboides* also shows many similarities (Shinn, 1968; Farrow, 1971; Rice and Chapman, 1971; Fürsich, 1973). During increased chemical stress in the water column, the *Callianassa* have adapted a behaviour to modulate the burrow environment by irrigation (Thompson, 1967; Gingras et al., 2011). These behavioural adaptions are mainly observed in tidal water environments, as the irrigation water have to be regularly changed to maintain the environmental stress (Gingras et al., 2011).

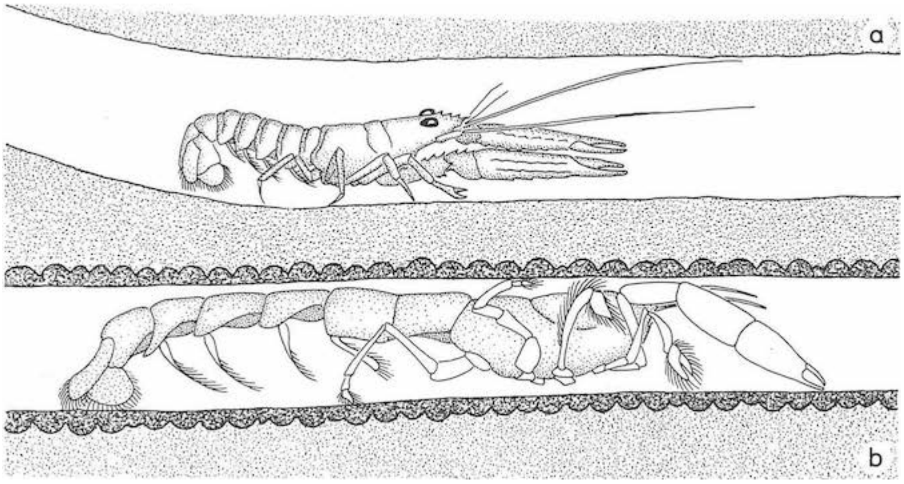


Figure 3.2: Drawings of crustaceans in burrows A) *Nephros norvegicus* B) *Callinassa major*. From Bromley (1990).

3.2.2 Trace fossil nomenclature - Ichnotaxon

An ichnotaxon is the taxonomic unit of an identified trace fossil (Bromley, 1990). International Code of Zoological Nomenclature (ICZN) consist of established rules of how to use nomenclature to classify animals and fossil materials. In the 4th edition of the ICZN (1999), Art. 16.4, species of trace fossils were required to have holotypes in similar way as biological species do. It is stated *"A name proposed for ichnotaxa is a family group name, genus group name or species group name according to in which it is first established"* (ICZN (1999), Art. 10.3).

3.2.3 Ichnofacies

The ichnofacies concept was established by Seilacher (1964) and defined as *"A characteristics association of trace fossils recurrent in time and space and directly reflects the environmental conditions as bathymetry, salinity and substrate character"*. The ichnofacies model combines ichnology and sedimentology and can be used to characterise the depositional environments and to gain specific information on e.g. oxygen, salinity and sedimentation rates (MacEachern et al., 2012). Six ichnofacies were established and the names were based on the ichnotaxon characteristic for the facies (Seilacher, 1967). Later several ichnofacies have been established, and currently it is in total 15 formally defined ichnofacies (Figure 3.3) (MacEachern et al., 2012; Buatois and Mángano, 2011). Most trace fossils are restricted to one ichnofacies, and the preserved actions of the organisms is often a direct response to the environmental conditions Seilacher (1964).

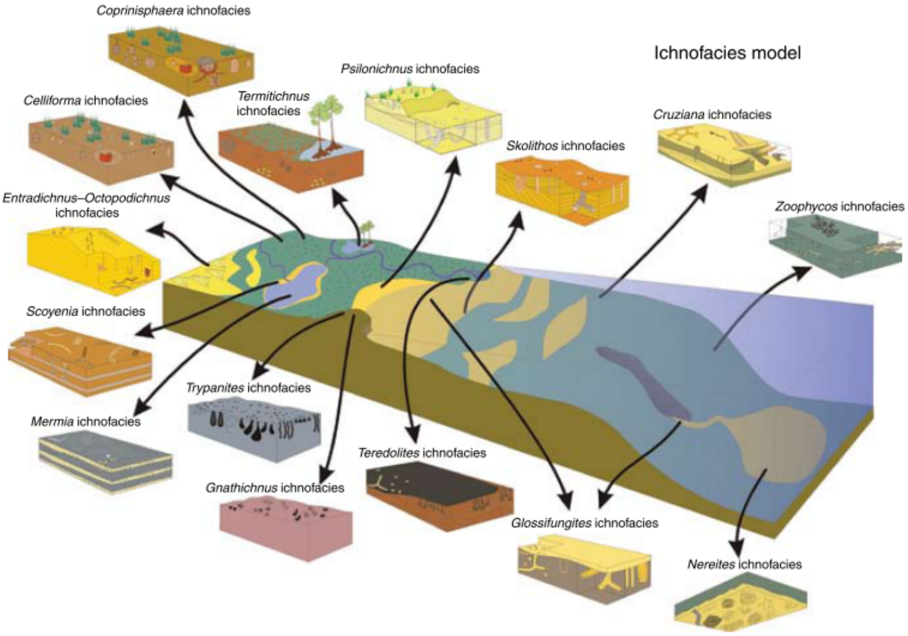


Figure 3.3: Established ichnofacies indicating specific environmental conditions. From Buatois and Mángano (2011).

Thalassinoides is crossing different ichnofacies and relates to the three distinct ichnofacies: *Cruziana*, *Terdeoloites* and *Glossifungites*. The *Cruziana* ichnofacies is restricted to marine softground and is dominated by horizontal burrows in moderate to low energy conditions. The *Cruziana* ichnofacies occur from lower shoreface to lower offshore in wave-dominated seas, though from above fair-weather base to storm wave base (MacEachern and Pemberton, 1992; MacEachern et al., 1999; Buatois and Mángano, 2011). The *Glossifungites* ichnofacies is substrate-controlled ichnofacies (Buatois and Mángano, 2011). Vertical burrows dominate the *Glossifungites* ichnofacies, characterised by a low ichnodiversity and a high abundance of traces. *Glossifungites* ichnofacies appear in firmgrounds often in shallow water with high-energy (MacEachern et al., 1992, 2007; Buatois and Mángano, 2011). *Teredolites* is likewise as *Glossifungites* a substrate-controlled ichnofacies. *Teredolites* ichnofacies are usually present in woodground borings as drifted peat deposits in shallow marine and mariginal marine environments (Pemberton and Wightman, 1992; Buatois and Mángano, 2011).

3.2.4 Ichnofabric

The ichnofabric concept was first introduced by Ekdale and Bromley (1983) in a study of the Upper Cretaceous in Western Denmark. Later the term ichnofabric was defined by Ekdale et al. (1984) as *"the internal texture and structure of the substrate and is a result of bioturbation and bioerosion"*. The term is useful for describing the effect of the behaviour of the organism in the substrate (Ekdale et al., 2012). Ichnofabrics are divided into simple and composite ichnofabrics (Figure 3.4) (Bromley and Ekdale, 1986). A monospecific ichnotaxon means that only one type of trace fossils is present. With a monospecific ichnotaxon, the ichnofabric is of the simple ichnofabric type (Figure 3.4A). In some cases of simple ichnofabric the primary stratification of the sediment is visible, in other cases the entire bed is totally bioturbated by the one ichnotaxon and no primary structures are visible (Ekdale et al., 2012). Composite ichnofabrics is when a successive community is replaced or when a community are tiered and go through upward migration. Successive communities can be replaced by environmental changes, as for example increased consolidation of the sediment (Figure 3.4B). Upward migration of a tiered community is mainly in response to slow sedimentation and reflects gradual accretion on the sea floor (See section 3.2.4) (Figure 3.4C) (Bromley and Ekdale, 1986; Buatois and Mángano, 2011). Composite ichnofabrics are more abundant in the stratigraphic record than simple ichnofabrics (Buatois and Mángano, 2011).

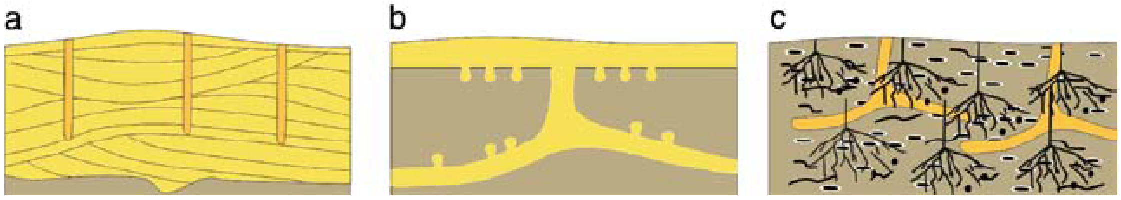


Figure 3.4: Different types of ichnofabrics from Buatois and Mángano (2011). **A)** Simple ichnofabric **B)** Composite ichnofabric: successive communities replaced by other communities **C)** Composite ichnofabric: tiered community with upward migration. From Buatois and Mángano (2011).

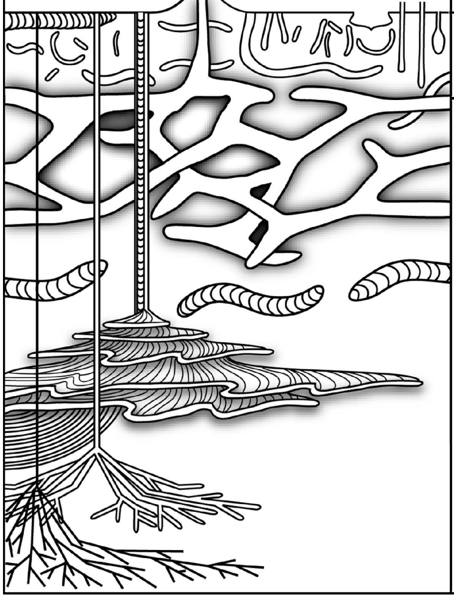
The ichnofabric concept has different practical applications. The validity of the ichnofabric concept has been discussed, as the concept is frequently misunderstood (Ekdale et al., 2012; Buatois and Mángano, 2011). There is currently no agreement on the naming of different ichnofabrics, and it might be over one hundred distinct ichnofabrics described (Bromley, 1990).

The concept *"Ichnofabric approach"* is to apply the ichnofabric concept and linking it to sedimentary data in order to do palaeoenvironmental reconstructions (Bottjer and Droser, 1991; Buatois and Mángano, 2011). Another application of the ichnofabric concept considers both biogenic and physical effects within the sediment (Taylor and Goldring, 1993). Taylor and Goldring (1993) came up with a descriptive scheme to analyse and describe bioturbation and ichnofabrics to be used for outcrop and core analysis. Ichnofabric analysis describes the ichnotaxa present, the type and size of the ichnotaxa, the percentage of bioturbation and the order of emplacement of each ichnotaxon (Taylor and Goldring, 1993; Buatois and Mángano, 2011). Trace fossils could be highlighted by a contrasting colour or minerals which differentiate from the host rock. These colour and mineral differences are often caused by diagenetic processes (Ekdale et al., 2012; Knaust et al., 2012).

Tiering

Tiering is when the marine habitat of endobiont organisms is divided into different vertically depths, where different ichnotaxa are present at specific sediment depths (Figure 3.5) (Bromley and Ekdale, 1984, 1986). Tiering of the substrate is mainly in response to chemical, physical and biological factors (Bromley, 1990; Buatois and Mángano, 2011). The most important environmental conditions controlling tiering are consolidation of the substrate, availability of organic matter and oxygen. In soft, fine-grained marine sediments deposited in conditions with low oxygen, the pore-water oxygenation gradient are the dominant control of tiering (Savrda and Bottjer, 1989b). The tiering model can only be accurately applied to distinctly burrowed beds (Savrda and Bottjer, 1989a; Martin, 2004). The result of tiering is that the deepest and last burrow is the most visible, and in some cases the entire trace fossil community can be defined by the youngest or deepest trace present (Bromley and Ekdale, 1986; Bromley, 1990). In general, sediment is partitioned into three zones: mixed zone, transition zone and historical zone (Figure 3.5). The mixed zone includes the upper few centimetres of the substrate, and is often totally bioturbated, it is filled with water and the preservation potential is normally low. The transition zone is heterogeneous and have less biological activity, although the traces are generally well preserved. The historical zone is often beneath the zone of bioturbation

(Bromley, 1990). Crosscutting relationships between different animal activities is a result of tiering which could produce a variety of ichnofabrics (Ekdale and Bromley, 1983; Hasiotis, 2012). As Figure 3.5 shows, the mixed zone has 100 % bioturbation, with no characteristic trace fossil present. In the transition zone, there is less bioturbation and as a result the preservation potential increases. Deeper structures are better preserved in the substrate for several reasons (Bromley, 1990). Deeper structures are less affected of crosscutting of other trace making animals, the deeper tiers contain less water and often suffer less of compactional deformation, and structures produced by deposit feeders are often filled with a contrasting material from the host rock and are therefore more visible (Bromley, 1990).



Zone	Tier	Characteristic Trace Fossils	Amount of Bioturbation (%)	% Work of community	% Preserved bioturbation	% Work of tier preserved
Mixed	1	None	100	70	0	0
	2	None	100	10	0	0
	3	*Planolites*	100	10	15	5
Transition	4	*Thalassinoides*	90	5	80	60
	5	*Taenidium*	10	2	2	80
	6	*Zoophycus*	1	2	2	95
	7	*Chondrites* (large)	0.5	0.5	1	98
	8	*Chondrites* (small)	0.05	0.5	0.5	100

Figure 3.5: Tiering of trace fossils below the water-sediment interface showing the transition zone and the mixed zone. Obtained from Hasiotis (2012) modified from Bromley (1990).

3.2.5 Oxygenation

Oxygen is one of the main factors controlling the distribution of animals living in aquatic environments. Table 3.1 shows a common terminology used by geologists with an overview of the different oxygen regimes.

Table 3.1: Terminology for oxygen regimes for environment facies, biofacies and physiological regimes, from Tyson and Pearson (1991).

	Oxygenation regime:		
Oxygen (ml/l):	**Environments Facies:**	**Biofacies:**	**Physological regime:**
8.0 - 2.0	Oxic	Aerobic	Normoxic
2.0 - 0.2	Dysoxic	Dysaerobic	Hypoxic
0.2 - 0.0	Suboxic	Quasi-anaerobic	
0.0 (H_2S)	Anoxic	Anaerobic	Anoxic

The surface water in marine environments are usually saturated with oxygen, and the amount of oxygen depends on salinity and temperature of the water (Demaison and Moore, 1980; Oschmann, 1988). In deeper water masses, the oxygen saturation depends on mixing and convection by water currents (Oschmann, 1988).

Trace fossils provide information which contributes to interpretation of the palaeo-oxygen levels in pore waters and bottom waters (Grimm and Föllmi, 1994). The presence of trace fossils indicates that the bottom water was enriched with oxygen when the organisms burrowed in the sediment. With decreasing oxygen content, the trace fossil diversity, burrow diameter, burrow depth, and bioturbation density tend to decrease (Wetzel, 1998; Buatois and Mángano, 2011). Sediments deposited in low oxygen settings often contain a high amount of organic matter. The high organic matter could serve as potential food source for the infaunal organisms. Living in anoxic sediment is not feasible to most organisms including crustaceans. Lack of trace fossils in the sediment and presence of laminated mudstone could indicate anoxic conditions (Tyson and Pearson, 1991) (Figure 3.6). Bromley and Ekdale (1984) described how the trace fossil *Chondrites* can tolerate low oxygen contents in the sediments and therefore tends to be the latest burrow in a tiering sequence. In sediments with a low trace fossil diversity, it can be difficult to discriminate between what is controlled by oxygen and what is controlled by the substrate. A low trace fossil diversity or lack of trace fossils can reflect either a soupy substrate or dysoxic/dysaerobic conditions (Wignall, 1993). In dysaerobic settings deposit feeders and detritus feeders tend to be dominating. In dysaerobic settings the tiering structure is often poorly developed (Buatois and Mángano, 2011).

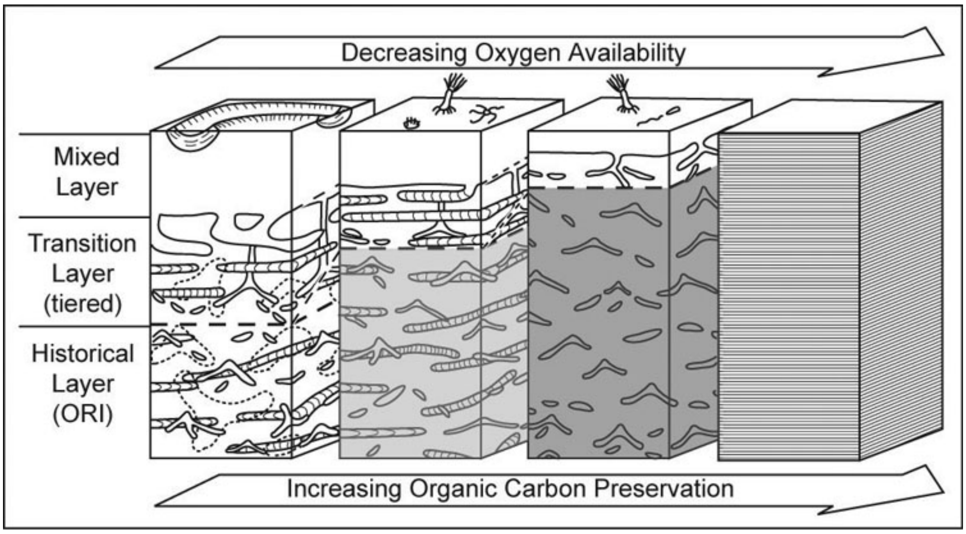


Figure 3.6: The expected change in bioturbation density and burrow with a decreasing benthic oxygen availability. From Morrow and Hasiotis (2007) modified from Savrda and Bottjer (1991).

When detailed vertical sedimentary analysis are available, a relative palaeo-oxygenation curve can be constructed (Savrda and Bottjer, 1989b). The palaeo-oxygenation are recognised by using trace fossil diversity, size and depth correlations, where an increase in one of these factors gives an increasing level of oxygen. The palaeo-oxygen curve gives a qualitative and interpretative indication of the bottom water conditions. It is often impossible to determine the oxygenation of the bottom water on the basis of the trace fossils alone (Savrda and Bottjer, 1989b).

In laminated, organic-rich mudrocks two types of redox-events can be recognised: short-term oxygenation events and extended oxygenation events (Savrda and Bottjer, 1989a). The short-term oxygenation events have a duration of several days to hundred years and have a thin primary strata, little or no cross-cutting between the biogenic structures and a simple vertical segregation (Savrda and Bottjer, 1989a). In contrast, extended oxygenation events have a longer duration and have a thicker primary strata with extensive cross-cutting of ichnogenera (Savrda and Bottjer, 1989a).

3.2.6 Trace fossil size

Few studies worldwide focus on trace fossil size analysis, though the analysis has proven to be a useful tool for palaeoenvironmental conditions (Ekdale et al., 1984; Preuss and Bottjer, 2004). It is well established in literature that the relative burrow diameter is a proxy for the size of the burrowing organism (Grimm and Föllmi, 1994). As construction of a burrow network requires work, larger organisms construct larger burrows compared to smaller organisms. The burrow diameter of a common crustacean, *Calinassa*, can be 1 to 5 times the diameter of the original diameter of the organism (Phillips 1971). A low burrow diameter is attributed to increased chemical stress in the sedimentary environment, which is associated with a reduced salinity and lowered dissolved concentrations of oxygen Gingras et al. (2011).

3.2.7 Preservation of trace fossils

The potential for trace fossils to be preserved is highly variable and depends on several factors. With increasing bioturbation, older traces will be disrupted, homogenising the sediment. In cases where the mixed layer is fully bioturbated with gradual accretion on the seafloor, a burrow must reach into the transition zone to be preserved (Bromley, 1990). Trace fossils are in-situ indicators though they can not withstand reworking. The preservation of organisms is often a direct response to the environmental conditions (Seilacher, 1964).

Toponomic classification

One way of classifying trace fossils is by toponomy, or the study of forms (Seilacher, 1953). Traces are either made within a substrate, at the surface of a substrate or at the contact between two lithologies. In the toponomic classification, trace fossils are classified based on how they are preserved in the sedimentary bed. (Rindsberg, 2012) Figure 3.7 shows the classification with both Seilacher (1953) version and the modified version of Martinsson (1965). A trace fossil preserved at the base of a surface is called hypichnia, preserved at the top is called epichnia and preserved trace fossil within the bed is called endichnia. Semirelief is the combination of epichnia and hypichnia. In cases where the trace is defined in the enclosing sediment it is classified as full relief (Seilacher, 1953; Rindsberg, 2012)

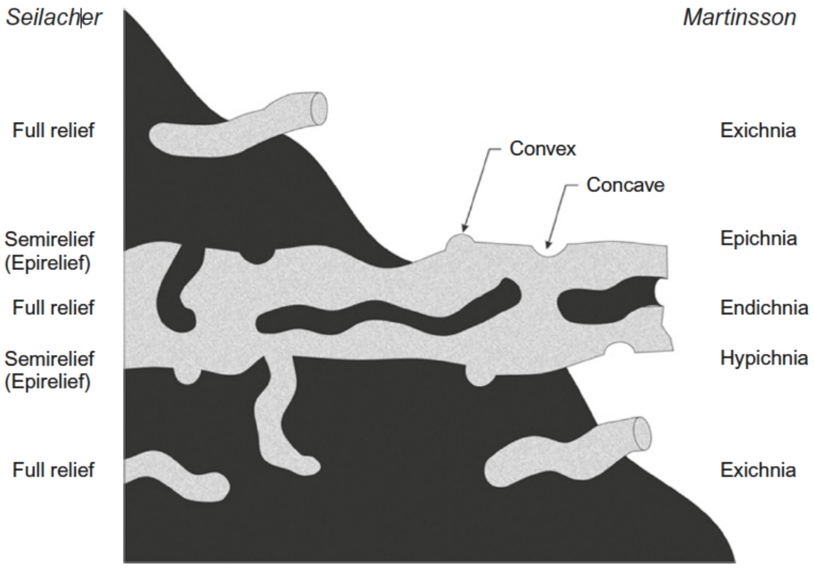


Figure 3.7: Comparison of Seilacher (1953) and Martinsson (1965) showing the tophonomic classification. Obtained from Rindsberg (2012) modified from Bromley (1990)

4. Methods

4.1 Fieldwork

During the summer of 2017 and 2018 fieldwork was conducted. This master thesis focus on collected outcrop data from a one-month long field trip to Edgeøya on Svalbard summer 2018. The field team consisted of two master students, two PhD students, a supervisor, field assistant and two representatives from the Norwegian Petroleum Directorate. The field team was transported with a helicopter to a sailboat in Agardhbukta. A 50 feet sailboat owned by the Dale Oen Experience was the accommodation during the stay. Transport to and from the field localities was with a zodiac. There were two field campaigns, one studying the De Geerdalen Formation (Røstad in prep.), and the other field campaign studying the Botneheia Formation. Data collected from the Middle Triassic Botneheia Formation were used in this thesis. The Botneheia Formation was studied in detail at six localities during the field period. At each field locality, several field days were spent in order to do detailed studies.

Fieldwork summer of 2017 took place on Oscar II Land on western Svalbard with a duration of nine days. The authors aim of the 2017 field season was to get an introduction to fieldwork and the Triassic sedimentary rocks of Svalbard. Sedimentary logging and sampling were performed from the Bravaisberget Formation. Data collected from Oscar II Land is not the main focus in this master thesis because the Middle Triassic succession on western Svalbard belongs to the Bravaisberget Formation.

4.1.1 Logging procedure

Six localities were logged and sampled. A GPS point was taken by the beginning and the end of the logging. A folding rule was used to obtain vertical height profile, and the log was drawn in scale 1:5, 1:20 or 1:50. In the sedimentary log, grain size, lithology, height, sedimentary structures, fossils, trace fossils, bioturbation, phosphate nodules and colour were noted. HCl (5 %) were used to differentiate between dolomite and calcite. Samples for geochemistry were taken every 2. meter. In total, 611 samples were collected, 67 of these were samples from phosphate nodules and *Thalassinoides*. Sample and photo number were noted at the correct height in the sedimentary log.

4.1.2 Trace fossil analysis

In the outcrops, ichnological observations were performed bed-by-bed. The observations of the trace fossils follows Rodríguez-Tovar et al. (2017) methodology on outcrops. All trace fossils were recorded and analysed in the field. The individual trace fossils shape, length, diameter and taphonomy were observed. In addition, drawings of the traces were performed. In order to record the trace fossil position in the sediment, it was noted in the sedimentary log where the traces were found. A limited amount of traces were possible to collect and bring back to the laboratory and to record their position and shape, photos were taken of the observed trace fossils.

4.1.3 Digitisation of field data

The sedimentary logs were later redrawn from field notes to millimetre paper and scanned to PDFs. Adobe Illustrator CC 19 was used for digitising the logs. Photos of trace fossils were redrawn in Adobe Illustrator CC 19 to outline their shape and expression.

4.1.4 Sources of error

Main errors related to the fieldwork and sedimentary logging is observations, interpretations and height measurements. Observations and interpretations can be exaggerated or overlooked, and this varies from individual to individual. Steep terrain is typical in the studied succession and might have affected the quality of the data. The digitisation of the data might have caused observations being lost or some of the data being over-interpreted.

4.2 Laboratory work

4.2.1 Thin sections

Twelve selected samples were cut and prepared before delivered to the Thin Section Laboratory at NTNU. The samples were selected based on localities, quality of the sample and the location in the sedimentary logs. The laboratory prepared polished thin sections. All samples were oriented perpendicular to the bedding plane. The thin sections were later analysed using the microscope Nikon Eclipse E600W. Camera Spot Insight was used taking pictures of the thin sections with the use of the software Spot insight. Also, photos of the thin sections were taken with the use of the Progres software.

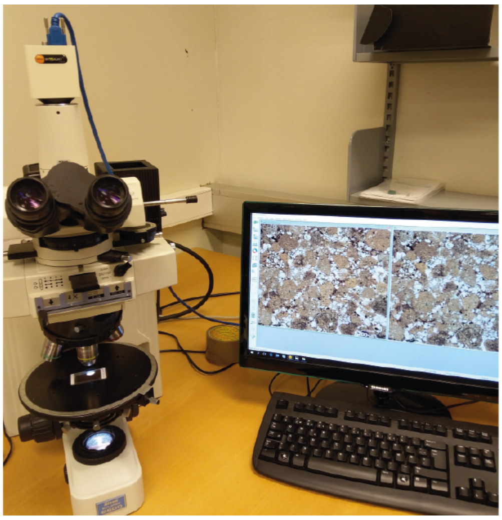


Figure 4.1: The Microscope Nikon ECLIPSE E600W used to analyse the thin sections, installed with the SPOT insight camera and the software Camera Spot Insight which was used to take photographs of the different thin sections.

Carbonate staining in thin section

The use of Alizarin red S dissolved in hydrochloric acid (HCl) solution is a widely used method to differentiate between common carbonates (Dickson, 1965). In this work, it was necessary to distinguish between calcite and dolomite. Procedures by Dickson (1965) were followed. 0.1 gram of Alizarin red S mixed with 0.2 % HCl. The thin sections were left in the solution for a maximum of 15 seconds, washed gently in distilled water and dried. The thin section was further investigated in a microscope. If pink staining colour the mineral was calcite if colourless the mineral was dolomite.

4.2.2 Trace fossil size

Trace fossil size analysis has proven to be a useful tool when analysing trace fossils and correlation to palaeoenvironmental conditions (Preuss and Bottjer, 2004). The burrow diameter and width of the trace fossils were measured to determine the diameter-width consistency throughout the succession, and to compare with other studies of Middle Triassic *Thalassinoides* burrows.

Samples of the trace infill of *Thalassinoides* were collected in the field from well-exposed bedding surfaces from different heights in the succession. Each sample included fragments of the trace infill, and by using a sliding caliper each representative fragment was measured. A box-plot of the measurements was made.

4.2.3 Computed tomography scanning (CT-scan)

Computed tomography (CT) scanning is a three-dimensional non-destructive visualisation. Images are created based on the X-ray attenuation variation in the objects, which relates highly to the density (Ketcham and Carlson, 2001). X-ray Computed tomography was first developed for medical use, later used in palaeontology and the last years it has become frequently more used for geological applications (Conroy and Vannier, 1984; Ketcham and Carlson, 2001). CT can characterise sediment-filled fossil borings otherwise being inaccessible (Knaust, 2012). The sample is positioned on a rotational table between an X-ray source and an X-ray detector and when cathode rays interact with materials, X-rays are produced (see Figure 4.2) (Cnudde et al., 2006). The X-rays are further converted to digital radiographs and for one CT scan, hundreds of radiographs are needed from different rotation angles. To further calculate the cross-sections through the object a computer alogarithm are used called FDK (Cnudde et al., 2006).

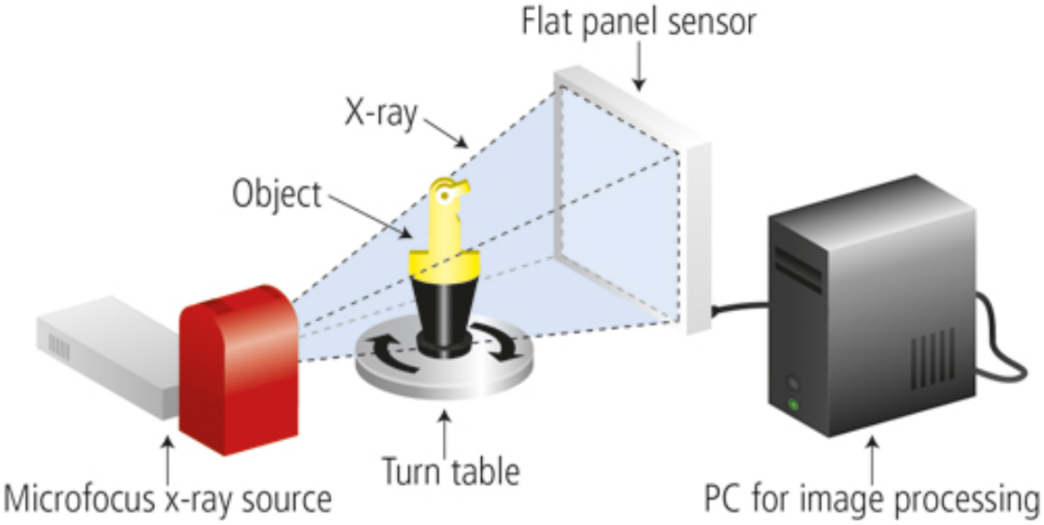


Figure 4.2: The basic principle of a industrial microfocus-CT with a X-ray source, rotating table and a X-ray detector (Flat panel sensor). From Hamamatsu (2019).

On the Natural History Museum (NHM) in Oslo, CT-scans of selected samples collected from the field were performed. With close cooperation with Associate professor Øyvind Hammer, CT-scans were performed on a Microfocus X-ray Tomography, type Nikon Metrology XT 225 ST (Figure 4.3A). Samples with a size larger than 15x15x10 cm were preferred, when larger samples is time-consuming and would not give a high-resolution quality on the CT-scans. Each sample was placed inside the CT-scanner as shown in Figure 4.3B. The scan parameters had a voltage of 215 kv, current of 400 μA and a 2.5 mm copper filter were used. The exposure time were 1 second and in total 3016 pojections were used with 4 frames each projection. The voxel size were 60 μm. To further process the CT-scans, the software Avizo 8.1 was used.

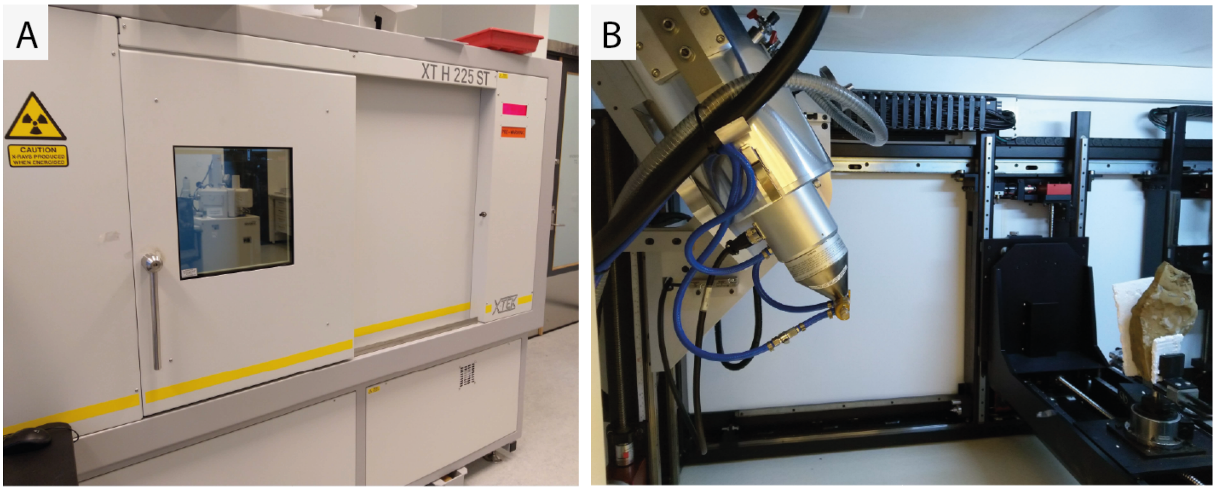


Figure 4.3: **A)** Microfocus-CT, NIKON Metrology XT 225 ST **B)** Inside of the CT-scanner showing the Microfocus X-ray source to the left, and the rock sample to the right.

4.2.4 LECO method of estimating TOC

When determining the rocks ability to generate hydrocarbons, the amount of organic carbon present in the rock is a crucial factor (Law, 1999). In this study, the total organic carbon (TOC) data were used to investigate how changes in the TOC responded to the occurrences of trace fossils and bioturbation throughout the studied successions. Rock-Eval pyrolysis and LECO method are conventional techniques used to analyse a rock for TOC. Here, the LECO method was used, which is the most common method to obtain TOC at present time (Law, 1999). In addition total carbon (TC) and total sulfur (TS) were obtained.

During the field season of 2018 on Edgeøya, samples to be used for organic geochemistry were collected on all localities and correlated with the sedimentary logs. The LECO method was later performed on data from one locality by Fredrik Wesenlund, a PhD candidate at the University of Tromsø (UiT).

The following procedure was performed to obtain the TOC, TS and TC by the LECO method. Each sample had a vertical resolution of approximately 10 cm. In the laboratory, the samples were cleaned in water and placed in a drying cabinet on 30°C over the night. Possible contaminants as calcite and moss were removed. Approximately 0.7-0.9 decilitres of the representative part of the total sample was crushed to gravel in an agate mortar. Visible phosphate nodules were removed. To homogenise and pulverise the material, the sample was crushed with a Retsch PM 100 on 450 rpm in 10 minutes with an agate container and ball. From the material, 2.0 grams of the shale dust were warmed up to 104 °C in a drying cabinet to be ready for LECO analysis. For the total organic carbon analysis, 0.4 - 0.5 grams of the heated shale flour was treated with 10 % HCl in several times until the acid did not react with the shale flour. Afterwards, the acid-treated flour was rinsed with water to remove the acid from the flour and heated on 104°C over the night to remove the remaining water left in the flour. For TC and TS analysis, 0.23-0.25 g of the heated shale flour was placed in a crucible. The LECO CS744 was used for the TOC, TC and TS analysis. To start the combustion of the LECO instrument, a constant amount of the combustion accelerator were combusted together with the shale flour. The instrument was calibrated according to LECO calibration standard (part. no. 501-505). The instrument was within the values of the calibration (Carbon: 0.541 +/- 0.009 g, sulfur: 0.0160 +/- 0.0009 g). To make sure that all the samples were completely burned each crucible was controlled. The TOC, TC and TS were presented in an excel sheet.

Graphs were made from the data from the Blanknuten NW Valley and Muen and later correlated to the sedimentary logs. The TOC and TS data obtained from the Blanknuten NW Valley were from samples collected during the field season of 2018. The TOC and TS data from the Muen locality were collected during fieldwork in August 2017 performed by Fredrik Wesenlund and Sten-Andreas Grundvåg from the UiT. The TOC and TS data were correlated to this year sedimentary log, which might cause some margin of error related to the exact height in the log.

5. Sub-facies in the Botneheia Formation

A sub-facies analysis including lithofacies, biofacies and ichnofacies were performed in the successions in the Blanknuten Member on Edgeøya, Svalbard. On all sedimentary logs presented in Chapter 6 the different sub-facies are marked.

5.1 Definition of facies

Facies is of high importance in geology and has widely been used in sedimentology. The term was already introduced in 1669 by Nicolas Steno (Teichert, 1958). In modern time it was used by Amanz Gressly in 1838 in Upper Jurassic strata (Boggs, 2013). A sedimentary facies is the total sum of characteristics of a sedimentary unit (Middleton, 1973). A facies analysis is useful for doing field analysis to correlate vertically and laterally rock units, and to investigate spatial and temporal variations. Depending on the focus of observation, facies could be divided into lithofacies, biofacies and ichnofacies. Lithofacies is identified based on lithology and describes the chemical and physical properties of the rock. Observations and descriptions which mainly focus on the fossil content are referred to as biofacies. Ichnofacies focus on the trace fossils present the rock. The sum of lithofacies, biofacies, ichnofacies and other observations would constitute a sedimentary facies (Nichols, 2009).

5.2 Sub-facies analysis

Two sedimentary facies were recognised by Krajewski (2008) from the Botneheia Formation: non-phosphogenic and phosphogenic facies. In this work, the phosphogenic facies was further divided into sub-facies. A sub-facies is a further division of a facies (Nichols, 2009). The sub-facies in the succession includes lithofacies, biofacies and ichnofacies with subsequent units.

The sub-facies analysis is based on sedimentary logs and observations from Edgeøya on Svalbard. The sedimentary logs are presented in Chapter 6. In total six sub-facies were recognised including three lithofacies, two biofacies and one ichnofacies. A summary of these sub-facies is given in Table 5.1. A detailed description and interpretation of the sub-facies recognised on Edgeøya are presented in the following sections.

Table 5.1: Sub-facies of the phosphogenic facies in the Botneheia Formation on eastern Svalbard including lithofacies, biofacies and ichnofacies.

Sub-Facies:		Thickness:	Description:
Lithofacies:			
LF-1	Dark silty shale	10 - 200 cm	Massive to laminated dark/grey silty shale. TOC: 6 - 10 %, pyrite is common
LF-2	Shale with phosphate nodules	2 - 100 cm	Shale rich in phosphate nodules occurring as lags, phosphorite conglomerate or occasionally incoherent nodules
LF-3	Yellow weathered siltstone	10 - 50 cm	Compact siltstone, recurrently occurring.
Biofacies:			
BF-1	Coqina beds	1-5 cm	Different species of *Daonella* spp. Beds completely filled with bivalves
BF-2	Microcoqina beds:	0.2 - 1 mm	Small juvenile bivalves forming microcoqina beds, crowded accumulations visible in thin section.
Ichnofacies:			
IF-1	*Thalassinoides*	2 - 20 cm	Beds rich of the trace fossil *Thalassinoides* occurring as horizontal burrows. The burrows are filled with phosphate and occur in silty shale and siltstone beds.

5.2.1 Lithofacies (LF)

The lithofacies recognised in the succession is divided into dark silty shale (LF-1), shale with phosphate nodules (LF-2) and yellow-weathered siltstone beds (LF-3).

LF-1: Dark silty shale

Description: The LF-1 is a dark or grey silty shale. The LF-1 sub-facies could be massive as shown in Figure 5.1B, or laminated as shown in Figure 5.1A and C. The grain size was clay with a minor contribution of silt. The silt content in LF-1 was to some extent varying. Most beds had planar lamination. The space between each lamina was variable and ranged from a few mm to 2 cm (Figure 5.1C). In some beds, the shale was weathering out as paper shale, with an extremely thin lamina. The total organic carbon (TOC) content ranged from 6 to 10 wt.%. Pyrite was common in the succession and was visible as orange/brown staining (see Figure 5.1D). In general, the LF-1 had a strong oil odour. Calcite and septarian concretions were common in the succession. The concretions are usually rich in well-preserved fossils. The LF-1 lithofacies could appear simultaneously with the BF-1 and IF-1.

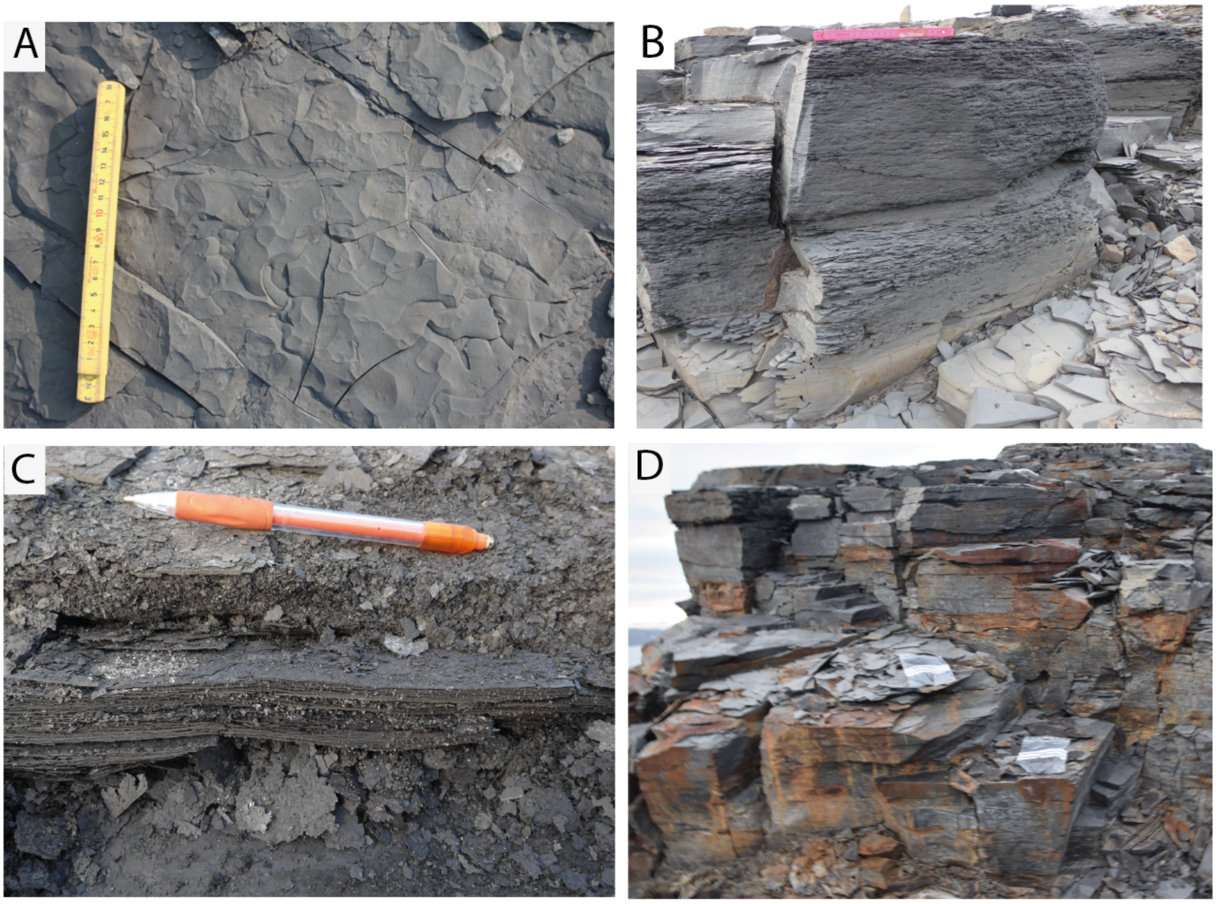


Figure 5.1: Sub-lithofacies LF-1: Dark silty shale **A)** Horizontal bedding plane, grey dark shale with no macrofossils or trace fossils present, from Muen Plateau, Edgeøya. 20 cm folding rule for scale. **B)** Calcite cemented, massive shale from Skrukkefjellet, Edgeøya, 20 cm folding rule for scale. **C)** Paper shale in upper Blanknuten Member from Muen Plateau, Edgeøya. 15 cm pen for scale **D)** Shale with pyrite, from Skrukkefjellet, Edgeøya.

Interpretation: Silty shale is relatively common in the geological rock record. For clay and silt size particles to settle in suspension, low energy in the water column is required. Shale is relatively common in marine environments under the storm wave base. Also, shale is likely to be deposited in rivers, deltic, lagoonal and tidal-flat environments (Boggs, 2013).

The high TOC present in the dark, silty shale reflects a depositional environment with preferable conditions for the preservation of organic matter. Quiet water is crucial for clay-sized particles and organic matter to accumulate on the bottom of the sea. Most of the worlds organic carbon are preserved in mudstones, which have been given them much attention in the petroleum exploration industry (Potter et al., 2005). Low energy and anoxic conditions have for a long time been considered to be the main prerequisite for the preservation of such organic-rich sediments (Demaison and Moore, 1980). Recent studies reveal that organic matter appears across a range of depositional settings and dynamic regimes (DeReuil and Birgenheier, 2018). Organic matter is a result of varying rates and interactions of organic production, destruction and dilution (Bohacs et al., 2005). Figure 5.2 shows two contrasting models to explain the deposition of organic-rich matter in marine depositional environments. The two models include a static model favouring anoxic conditions (Figure 5.2A) and a model with high primary productivity in a dynamic system (Figure 5.2B)(Rullkötter, 2006).

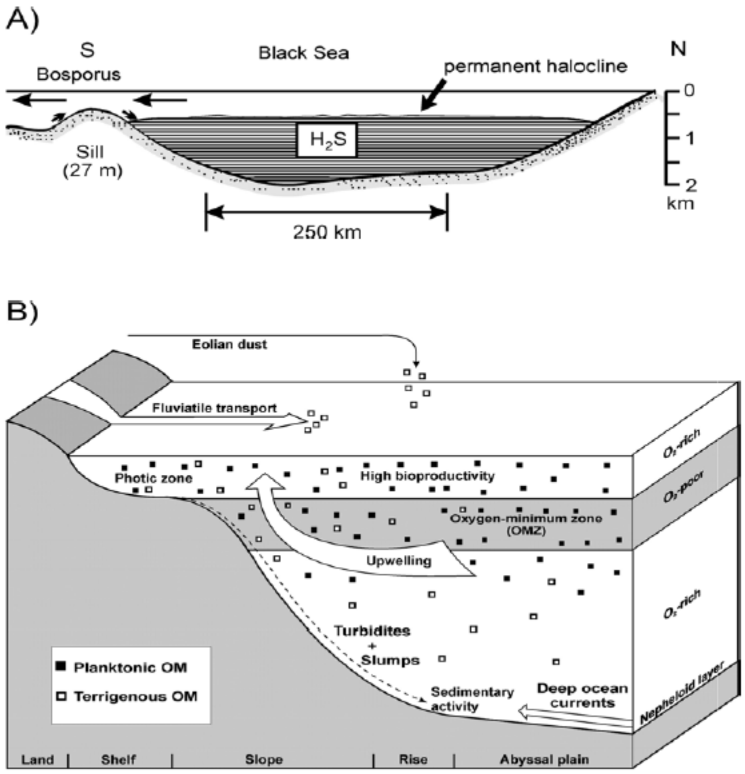


Figure 5.2: Organic matter accumulation in sediment **A)** Static model favoring anoxic conditions in a stagnant basin **B)** Dynamic system with a high primary productivity. Figure from Rullkötter (2006).

Planar lamination is common in mud and silt-rich sediment and develops where sediment settles in suspension on a planar sediment surface, and the currents are too weak to further transport the sediment (Southard, 2006). Bioturbation and/or bottom currents can disrupt the planar lamination. Detailed studies of lamination world-wide have broadened the understanding that multiple styles of lamination exist and several causes and processes have led to the formation (Yawar and Schieber, 2017). Laminated black shale do not necessarily have to be produced predominantly during anoxic conditions, dysoxic conditions might also produce laminated shale (Wignall, 1993). Lamination is visible in the field as a result of good preservation potential in a low energy setting with few burrowing animals disturbing the laminae (Southard, 2006; Boggs, 2013).

Pyrite is a common mineral in grey and black shales and is characteristic under reduced oxygen conditions. Pyrite forms during early diagenesis by the reaction of H_2S formed from sulfate reduction of bacteria (Berner et al., 1979; Boggs, 2013). The amount of iron minerals reactive with H_2S, the dissolved sulfate availability, salinity and the amount of organic matter influence the extent of formation of pyrite in marine sediments (Berner et al., 1979). Presence of pyrite indicates oxygen-poor conditions during deposition of the sediment or early diagenesis and burial (Boggs, 2013).

The presence of carbonate cement in organic-rich mudstones or shale is mainly a result of increased bicarbonate alkalinity. Increased bicarbonate alkalinity is linked to anaerobic or dysaerobic oxidation of organic matter associated with microbial respiration that includes Fe-reduction, sulfate-reduction or methanogenesis (Taylor and Macquaker, 2014). An increase in alkalinity favours precipitation of carbonate (Boggs, 2013). Concretions are secondary sedimentary structures which form after deposition and during sediment burial. Gradually rounded concretions build up around a nucleus (e.g. shell fragment) after precipitation of minerals (Boggs, 2013). The calcite concretions found in the Botneheia Formation started to grow during early diagenesis with good preservation of fossils inside the concretions (Krajewski, 2008).

Overall, the LF-1 silty shale is interpreted to be deposited in a marine environment above the storm wave base, with preferable conditions for the preservation of organic matter.

LF-2: Shale with phosphate nodules

Description: The sub-lithofacies LF-2 was found in the succession as shale rich in phosphate nodules. The phosphate nodules had a variable size and shape, with a diameter ranging from 0.5 - 2 cm and a width ranging from 0.2 - 1 cm. The LF-2 sub-lithofacies could be present in outcrop as lags of nodules (Figure 5.3A), phosphorite conglomerate (Figure 5.3B) or occasionally incoherent nodules in the shale (Figure 5.3C and D). Usually, no bivalves or other macrofossils were associated with the sub-lithofacies. In thin section, phosphate peloids and Radiolaria was common. Horizontal bedding planes might have coherently phosphate nodules, which could be the trace fossil *Thalassinoides* (IF-1).

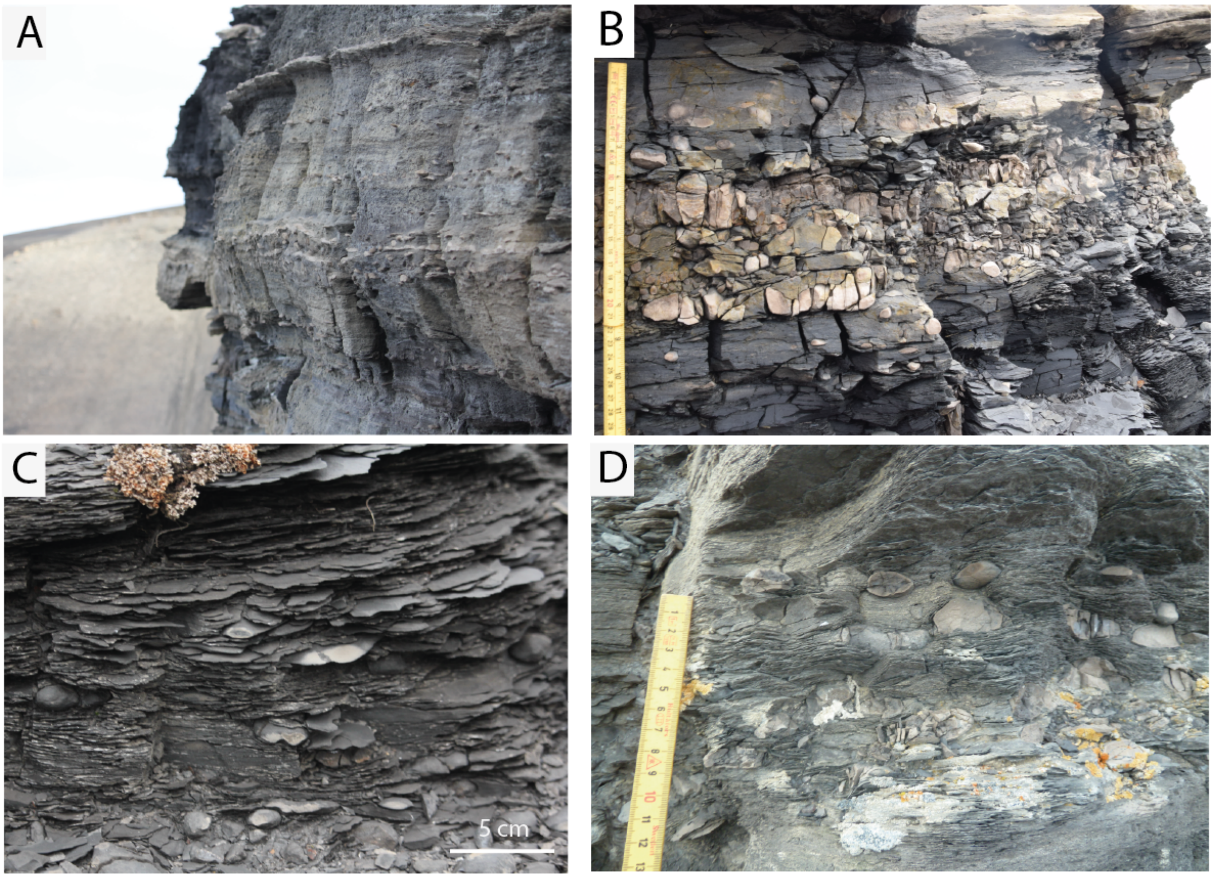


Figure 5.3: Sub-lithofacies LF-2: Shale with phosphate nodules **A)** Lags of phosphate nodules in dark shale with yellow weathering colour, from Skrukkefjellet East, Edgeøya **B)** Phosphorite conglomerate from Skrukkefjellet East, Edgeøya. **C)** Dark silty shale with occasionally incoherent rounded phosphate nodules, from the Muen locality, Edgeøya. **D)** Rounded phosphate nodules, from Krykkjeglupen, Edgeøya.

Interpretation: The presence of the sub-lithofacies LF-2 is interpreted as a marine environment characterised by upwelling, as previously concluded from the Botneheia Formation (Krajewski, 2011). Phosphate forms as a response to high biological activity, diagenetic processes and mechanical reworking (see Section 2.2.2 and Figure 2.6). Phosphate nodules grow slowly and record changing water chemistry during their formation (Roe et al., 1982). The succession on Edgeøya showed many similarities with modern upwelling zones in coastal areas (e.g. Peru) (Demaison and Moore, 1980). In modern upwelling zones, nodules tend to occur at the sediment-water interface close to the oxygen minimum zone at depths ranging from 250 - 550 metres (Roe et al., 1982). Phosphate nodules have its origin in the Botneheia

Formation from shallow oxic to deep anoxic shelf with local euxinic depressions (Krajewski, 2011). Phosphate deposits are mainly formed during oxic/dysoxic conditions, examples from anoxic/euxinic conditions are few (Krajewski, 2013). Phosphate conglomerate and lags of nodules could have been produced during heavy storms and later modified by compaction, which results in phosphate nodules with varying size and shape appearing together (Mørk and Bromley, 2008). Some flattened phosphate nodules could be trace infill of the trace fossil *Thalassinoides* as discussed by Mørk and Bromley (2008). Radiolarians, observed in the thin sections are known to be well preserved within phosphate nodules in the Middle Triassic succession on Svalbard and elsewhere (Kidder, 1985; Kagan Tekin et al., 2006).

LF-3: Yellow weathered siltstone beds

Description: The sub-lithofacies LF-3 represent solid and compacted yellow-weathered siltstones with thicknesses between 10 to 50 cm (Figure 5.4). The beds were recurrent throughout the upper part of the Blanknuten Member. The siltstone beds were calcite or dolomite cemented. The results obtained from carbonate staining in thin sections indicated dolomite in several siltstone beds (Table B.2). Ammonoids, phosphate nodules and *Thalassinoides* were common within these siltstone beds. In some beds, ripples were observed. *Interpretation:* The LF-3 yellow weathered siltstone beds recurrently found in the succession was classified as a silstone as it contained more than 2/3 silt-sized particles. Silt can be transported with suspension and saltation (Potter et al., 2005). The silt-sized particles are interpreted to have been transported into the basin after heavy storms, and deposited in an environment near or above the storm wave base. Detailed studies of the silstone beds have been done with a focus on diagenesis, referring to the siltstone beds as carbonate-cementstone (Krajewski, 2008). It was suggested that the carbonate-cementstones developed during diagenesis, though before compaction of the sediment took place (Krajewski, 2008). Thin sections from this work confirm the presence of dolomite in the siltstone beds. Diagenesis is processes modifying the sediment taking place at temperatures and pressures higher than the weathering environment and below 250°C (Boggs, 2013).

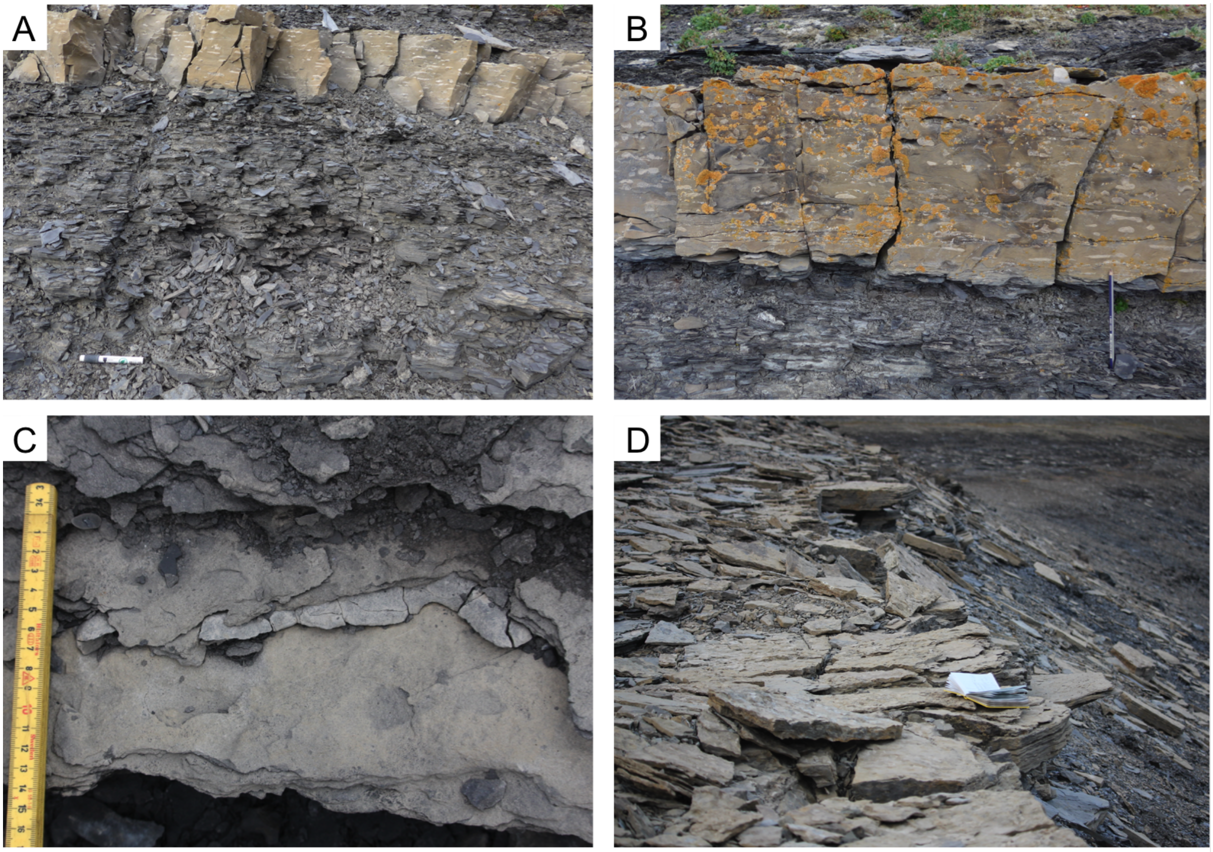


Figure 5.4: Sub-lithofacies LF-3: Yellow-weathered siltstone beds **A)** Abrupt boundary between silty shale (LF-1) and the overlying yellow weathered siltstone bed (LF-3) filled with phosphate nodules, from the Blanknuten Valley, Edgeøya. **B)** A 40 cm thick siltstone-bed (LF-3) filled with white weathered phosphate nodules from the Krykkjeglupen, Edgeøya. **C)** Small siltstone beds from the Muen locality, Edgeøya. **D)** 50 cm thick siltstone bed with visible horizontal *Thalassinoides* from Skrukkefjellet, Edgeøya.

5.2.2 Biofacies (BF)

BF-1 - Coqina beds

Description: The biofacies BF-1 consisted of beds rich in the bivalve *Daonella* forming coqina beds (Figure 5.5). Some beds were fully composed of the flat bivalve *Daonella* as shown in Figure 5.5. Other beds had a more sporadic appearance of the bivalves and are not included in the biofacies BF-1. The coqina beds were observable in outcrop without a hand lens. Different species of *Daonella* were present in different beds in the Botneheia Formation. Unfortunately, wet weather in several localities made the bivalves less visible. The beds rich in bivalves were chaotic and did not seem to show any organised pattern. Usually not observed in combination with *Thalassinoides* (IF-1).

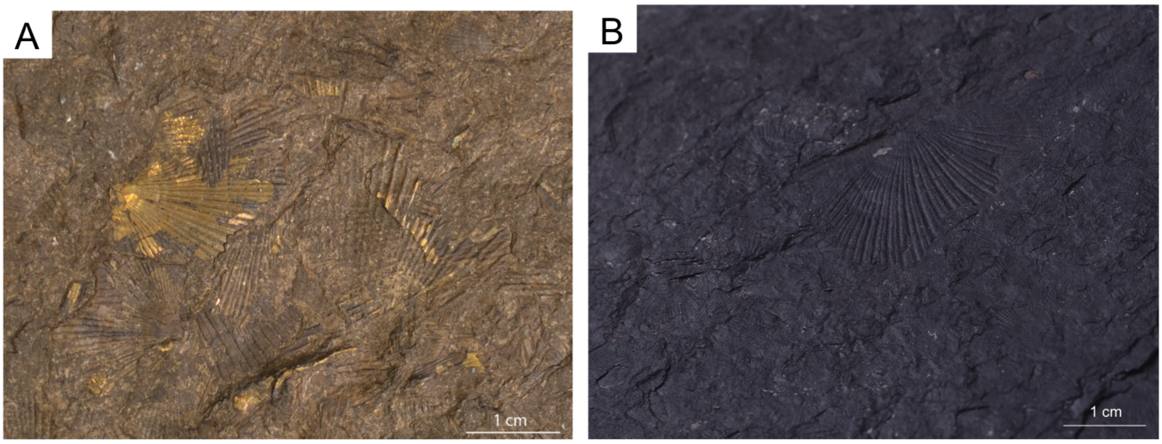


Figure 5.5: Sub-biofacies BF-1: Coqina beds **A)** Coqina bed full of fragmented *Daonella* sp. from the Muen Plateau. **B)** Well preserved *Daonella* sp. with minor juvenile bivalves, from the Muen, Edgeøya.

Interpretation: The thin-shelled bivalve *Daonella* is usually found in organic-rich shale (Wignall, 1993). A previous master thesis connected different species of *Daonella* to the stratigraphy in the Botneheia Formation (Bakke, 2017). *Daonella* bivalves are facies dependant and subjected to live in a dysoxic-oxic environment (Schatz, 2005). The main reason for the widespread distribution of *Daonella* is dispersion during the planktonic larval phase. The *Daonella* bivalve is prevalent in the Triassic succession worldwide. Several modes of living have been suggested for the *Daonella*. Schatz (2005) concluded that *Daonella* had an epibenthic mode of living suited to live in a soupy, soft substrate (Figure 5.6). An epibenthic mode of living means that the animal lives on the sediment surface of the bottom of the sea. The occurrence of *Daonella* in the organic-rich shale indicates that they were able to tolerate low oxygen content (Wignall, 1993). Studies of modern benthic bivalves suggest that they can tolerate dysoxic conditions (Pearson, 1975). *Daonella* is usually monospecific, and with low diversity in the sediment, this is also the case in the Botneheia Formation. Survival of bivalves is in general dependent on oxygen, substrate, salinity, temperature and pH (Schatz, 2005). A periodic settlement as observed in the Botneheia Formation is likewise found from other field areas worldwide. The recognisable vertical cliffs in the Blanknuten Member are mainly formed by calcite cementation from the bivalve *Daonella* (Vigran et al., 2014). The different species of the *Daonella* are not distinguished in this study.

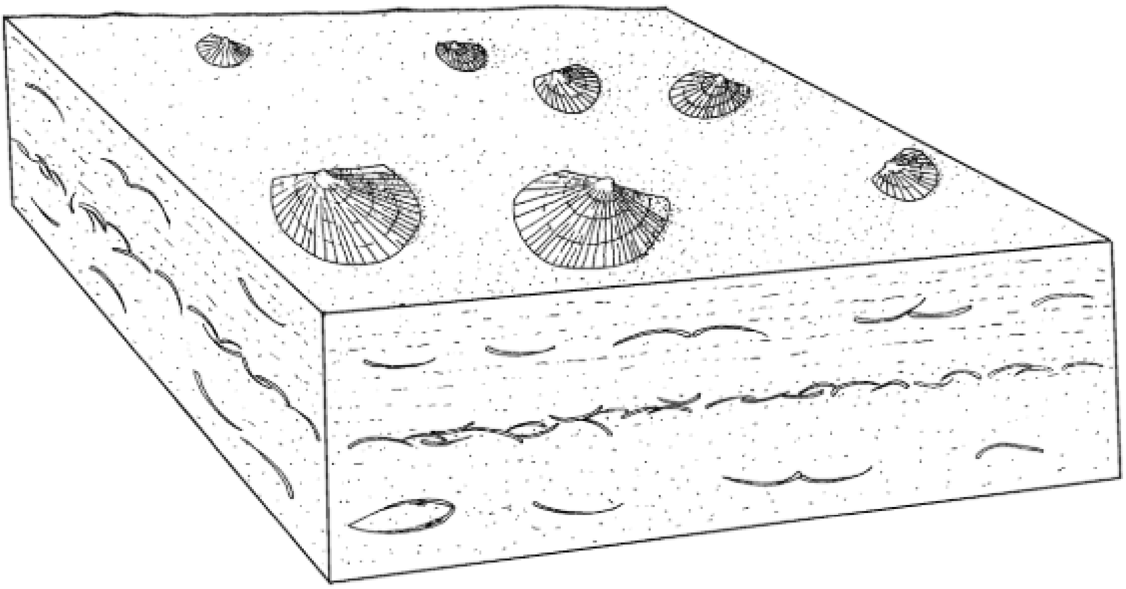


Figure 5.6: The epibenthic *Daonella* bivalves living on a soupy and soft substrate. From Schatz (2005).

Where BF-1 was present in the succession, it was usually an absence of *Thalassinoides* and bioturbation. One explanation to the absence of burrowers could be the lower oxygen rates in the sediment. However, the soft sediment *Daonella* lives within is not a suitable habitat for burrowing animals (Schatz, 2005).

BF-2 - Microcoqina beds

Description: In thin section chaotic accumulation of juvenile bivalves ranging from 0.2 - 1 millimetre in size was present (see Figure 5.7). Carbonate staining was performed on the thin sections, which confirmed that the microcoqina consisted of calcite. It is not possible to recognise microcoqina in hand specimen, though the microcoqina had a significantly reduced sized compared to BF-1. It was a high accumulation of microcoqina in siltstone beds (LF-3) generally in association with peloids and *Tasmanites*. Often the microcoqina was present in the same bed as the trace fossil *Thalassinoides* (see Figure 7.4D).

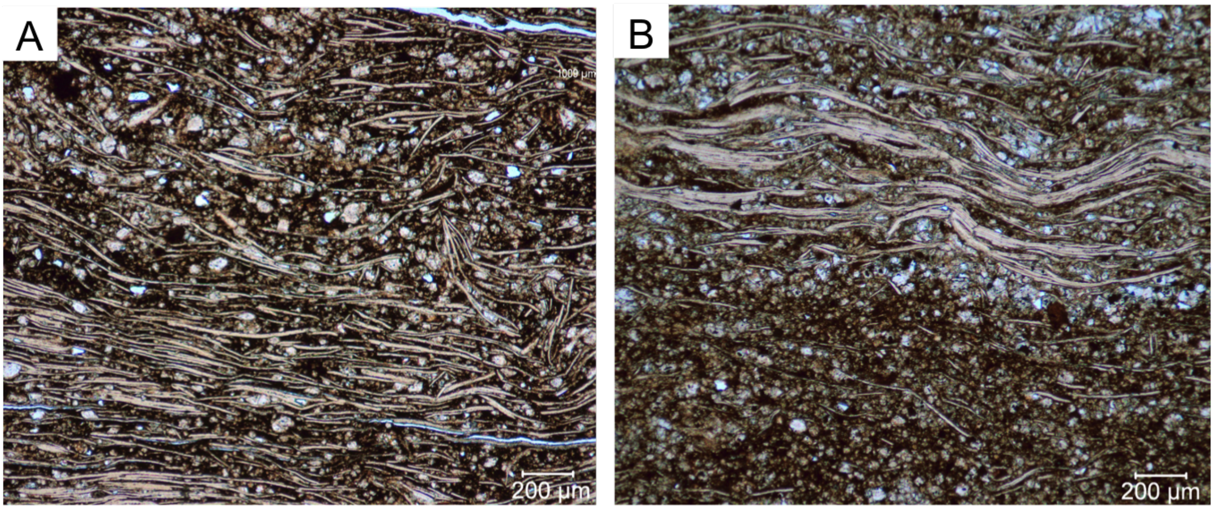


Figure 5.7: Thin section of the sub-biofacies BF-2: Microcoqina beds **A)** Reworked microcoqina in a silty dolomite rich bed from Muen. **B)** Thin section from Skrukkefjellet showing layered microcoqina in a silty bed.

Interpretation: Microcoqina beds are here referred to as juvenile bivalves. During the bivalves larval stage, the organisms continue to develop while drifting in the water column. Modern larvae stages have a duration of 2-3 weeks. The pelagic life mode is the most sensitive stage of the bivalve life cycles, though it is especially sensitive to physical and chemical stresses. During the pedal stage, the larvae sink down to the substrate. The juvenile bivalve would find a proper substrate by sensors in the foot where metamorphosis takes place and initiate the benthic existence of the bivalve (Annuziato and Cooper, 2018). Extreme conditions as oxygen depletion and other physiological stresses as temperature, salinity and pH could increase mortality events of larval and juvenile bivalves (Schatz, 2005). If the juvenile bivalves settle in anoxic sea bottom conditions, a mass mortality is likely to occur (Vigran et al., 2008). In the Middle Triassic succession on Edgeøya, the beds rich in microcoqina often occur together with *Tasmanites*, previously interpreted to reflect a low oxygen content during deposition which results in mass mortality (Mørk and Bromley, 2008; Vigran et al., 2008).

In the successions on Edgeøya microcoqina is common in the siltstone fraction. The co-appearance of the microcoqina in siltstone is a result of recycled material settled out in suspension (Vigran et al., 2008). Deposition of mud above the recycled material prevents oxygenation and enhance the preservation of the microcoqina beds (Vigran et al., 2008). Similar occasionally appearances of microcoqina present in the Botneheia Formation is found in other black shales worldwide (Schatz, 2005). In the black shale of the Kimmeridge Clay from the Late Jurassic, microcoqina were interpreted to be mass mortality events caused by seasonal fluctuation in oxygen (Oschmann, 1988). According to Mørk and Bromley (2008) the accumulation of microcoqina is highest in the organic rich part of the Botneheia Formation. As the focus of this study was on trace fossils, and only 12 thin sections were available, not all the microcoqina beds BF-2 were covered in this work.

5.2.3 Ichnofacies (IF)

IF-1 - *Thalassinoides*

Description: The trace fossil *Thalassinoides* was preserved either in the silty shale (LF-1) or in siltstone beds (LF-3) in the Middle Triassic succession on Edgeøya. The traces were dominantly horizontal, and visible on several bedding planes throughout the succession. The traces were filled with phosphate. Monospecific occurrences of *Thalassinoides* dominates, as few other ichnotaxa was found. Body fossils or scratches after the trace maker were not recognisable in association with *Thalassinoides*. See Chapter 7 for a comprehensive description and analysis of *Thalassinoides*.

Interpretation: Thalassinoides was observed in silty shale(LF-1) and siltstone beds(LF-2). *Thalassinoides* have previously been documented and observed in siltstone beds in the Middle Triassic succession on Eastern Svalbard (Mørk and Bromley, 2008), though not well documented from the silty shale in the succession. *Thalassinoides* is a marine indicator and is present in a wide range of depositional environments, from shallow to deep marine. However, *Thalassinoides* is not a suitable depth indicator (Ekdale, 1992; Myrow, 1995). For the trace making animal to live within the sediment, it is essential that the sediment is oxygenated. Trace making animals are never observed in fully anoxic environments (Wetzel, 1998). The presence of the IF-1 in the succession indicates that the bottom water was well oxygenated when the trace making animal lived in the sediment.

In this work *Thalassinoides* has been recognised on a local scale on Edgeøya, with few other ichnotaxa present. Lack of other ichnotaxa makes it difficult to confidently classify the trace fossil into one of the already established ichnofacies. Because of lack of other ichnotaxa, it was decided to name the occurrences of the trace fossil *Thalassinoides* in the succession for the local ichnofacies IF-1 - *Thalassinoides*, and not within any of the established ichnofacies defined by Seilacher (1964). See Chapter 8 for a comprehensive discussion of the trace fossil

Thalassinoides found in the Botneheia Formation on Edgeøya.

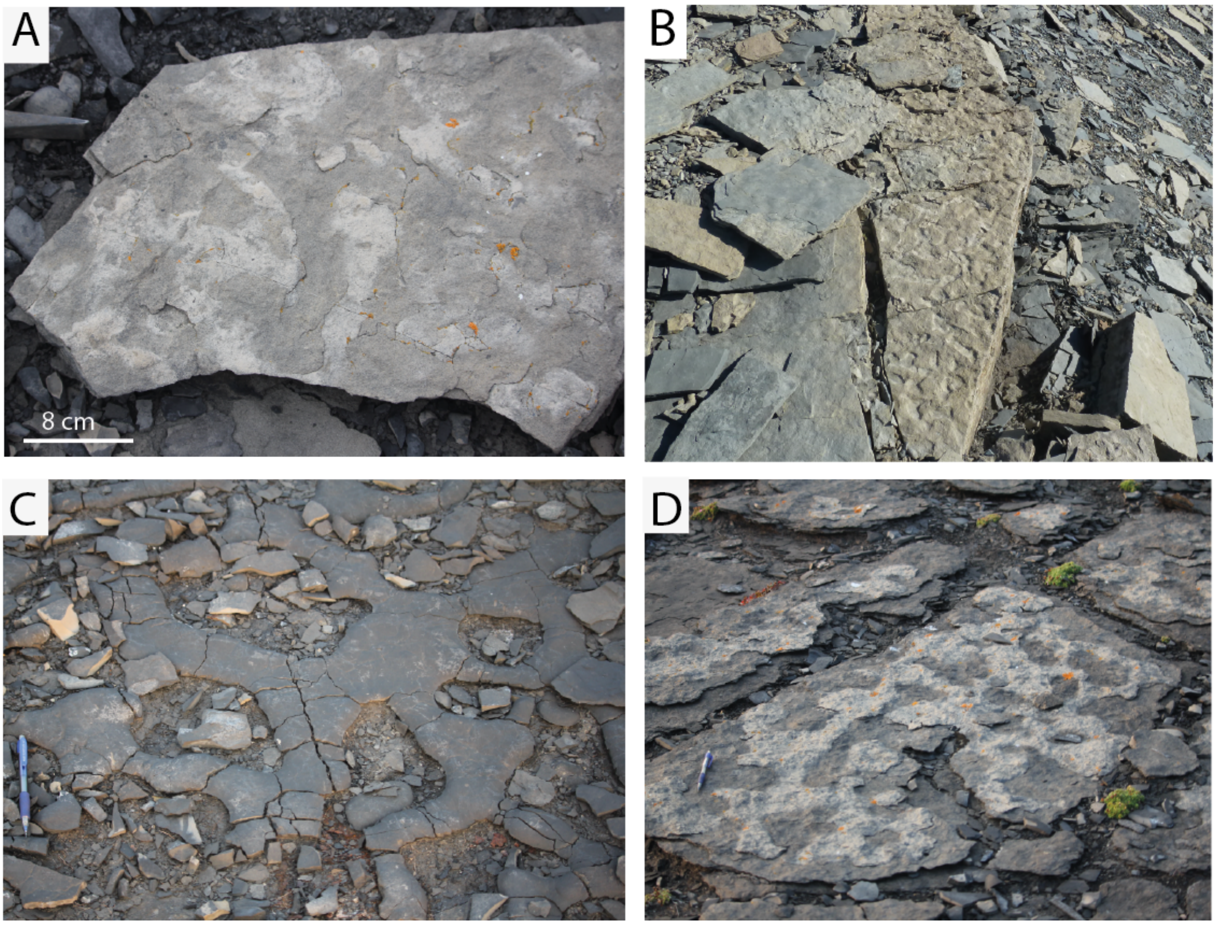


Figure 5.8: Sub-ichnofacies IF-1: *Thalassinoides* **A)** Silty bedding plane with white coloured trace infill of *Thalassinoides* from Muen, Edgeøya (12 metre height in log). **B)** Yellow silty bed with the trace fossil from Skrukkefjellet, Edgeøya. **C)** Network of *Thalassinoides* from the Muen Plateau. **D)** White weathered *Thalassinoides* burrows on silty shale (LF-1) from the Muen Plateau. 14 cm pen for scale.

6. Logged sections: Edgeøya, Svalbard

The following chapter includes field observations, descriptions and sedimentary logs from localities visited on Edgeøya the field season of 2018. These data are presented to investigate the occurrences of *Thalassinoides*. Each locality is described based on observations from the field, photographs and information gained from samples and thin sections. After each description, a short interpretation follows the logged sections. Figure 6.1 shows an overview map of the localities and their GPS coordinates are given in Table B.1 in Appendix.

In all sedimentary logs presented, three columns mark the different sub-facies throughout the succession. One column marks the absence of bioturbation, which could give valuable information. Overview photos of the logged sections and photos of special phenomena are associated with the sedimentary log. Where TOC and TS data is available, it is included in this chapter together with the sedimentary log. A legend is given in Appendix B.2.

The Muen locality (see Section 6.1) is more comprehensively described compared to the other localities. The comprehensive description of the Muen was obtained because of the well exposed horizontal bedding planes, where spatial and temporal variations of *Thalassinoides* can be studied.

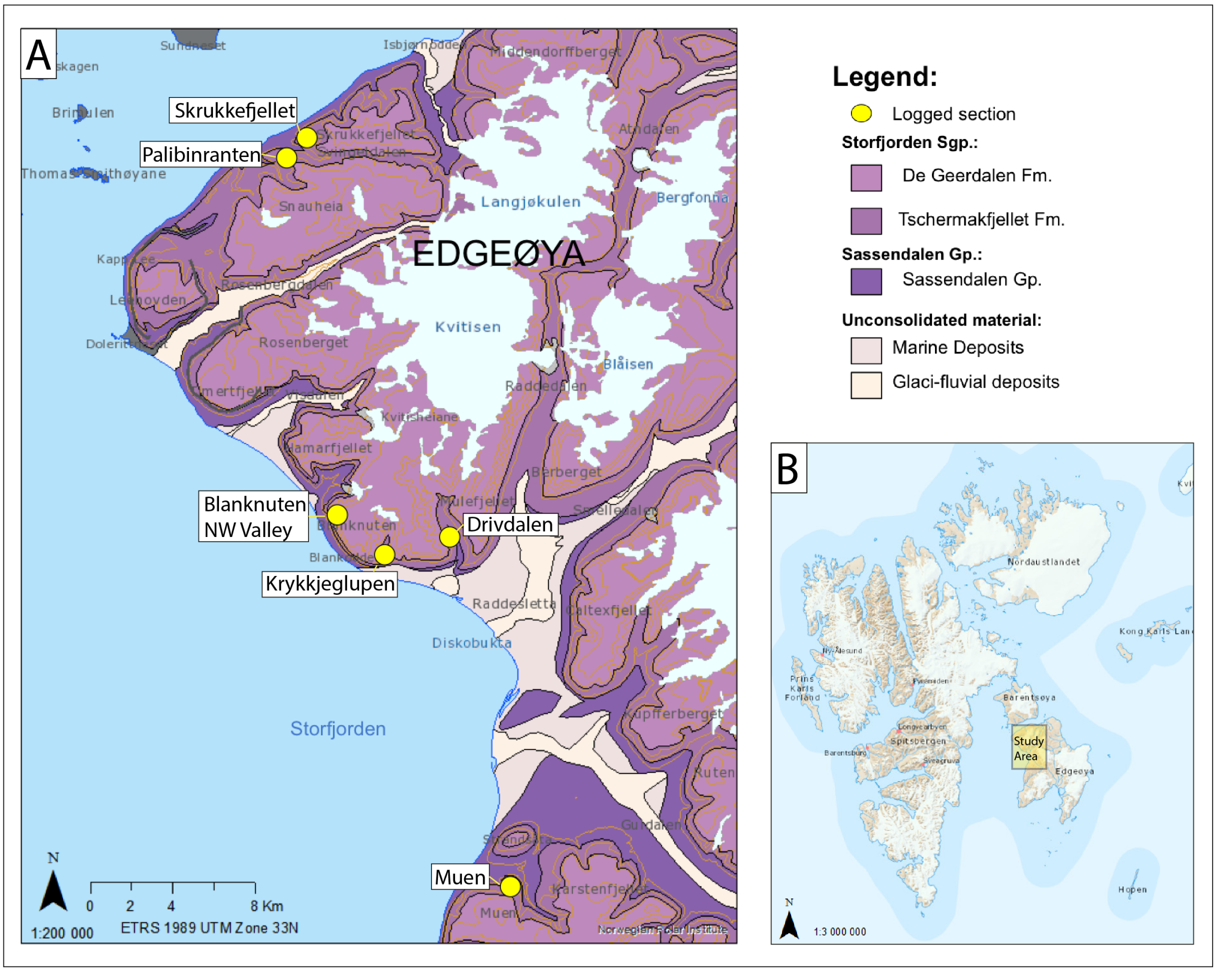


Figure 6.1: **A)** Map of logged sections on Edgeøya. **B)** Map of Svalbard showing the study area marked in yellow. Base map and geological map retrieved from the Norwegian Polar Institute.

6.1 Muen

Date: 08.08.18, 10.08 - 14.08.18

Muen is located on western Edgeøya and is the type section for the Muen Member in the Botneheia Formation (Krajewski, 2008) (Figure 6.1). Steep slopes and cliffs rim the mountain, and towards the upper base of the Botneheia Formation, the mountain forms a plateau (Figure 6.2A). On this same plateau, a well-preserved ichthyosaur was recovered (Hurum et al., 2014). Brekke et al. (2014) did detailed analysis of the Muen locality with focus on organic geochemistry. Also, Muen was one of the main localities where the Botneheia Formation were divided into different members and units by Krajewski (2008).

The locality had bedding planes easily accessible for study and vertical and lateral changes could easily be tracked. The logged section had a vertical height of 32.5 metres and was originally drawn in 1:20 scale (Figure 6.2B, 6.3). A total span of 233 samples was collected from the locality to be used for ichnology, palaeontology and geochemical analysis. The description and interpretation described of the logged section are divided into the following three intervals:

- Interval 1: 0 - 14.6 metres
- Interval 2 (Muen Plateau): 14.6 - 15.8 metres
- Interval 3 15.8 - 32.5 metres

Interval 2, the Muen plateau, had excellent bedding planes with extensive vertical variations (Figure 6.2C, 6.6). The plateau made it easy to observe the bedding planes laterally, to cover both the vertical and lateral variations present. This is the first time such a bed-to-bed analysis have been performed on the Muen Plateau with the main focus on ichnology.

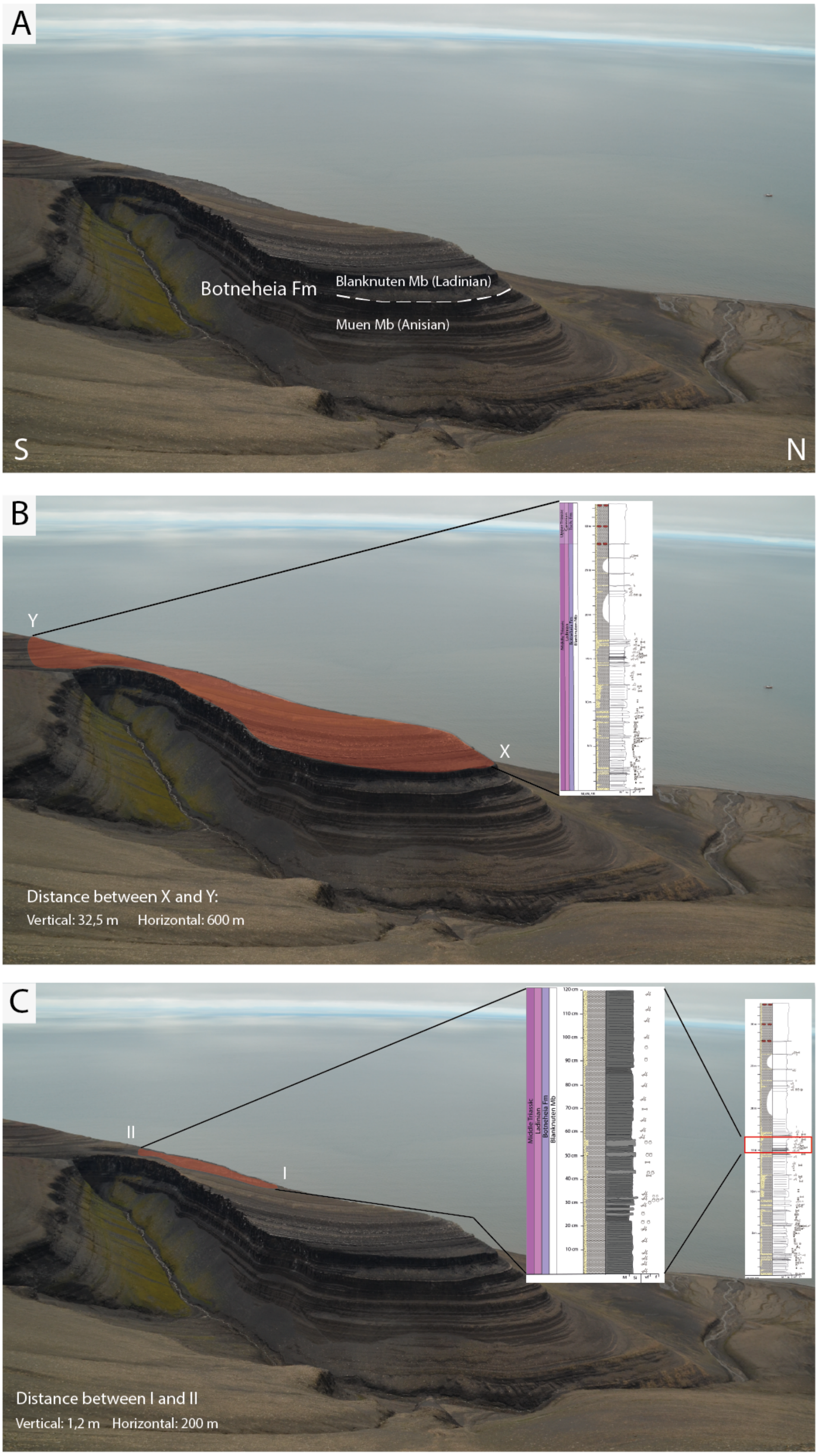


Figure 6.2: **A)** Overview photo of the Muen locality with the location of the Botneheia Formation and the boundary between the Muen Member and the overlying Blanknuten Member **B)** The total logged section of the Muen locality. The red area marks the entire extent of the logged area. The vertical height from log start (X) and log end (Y) was 32.5 meter, and the horizontal distance between log start (X) and log end (Y) was 600 meters. **C)** Interval 2 - the Muen Plateau. The red area marks the entire extent of the Muen Plateau. The vertical height from log start (I) and log end (II) was 1.2 meter, and the horizontal distance between log start (I) and log end (II) was 200 meters. Photo: FT.

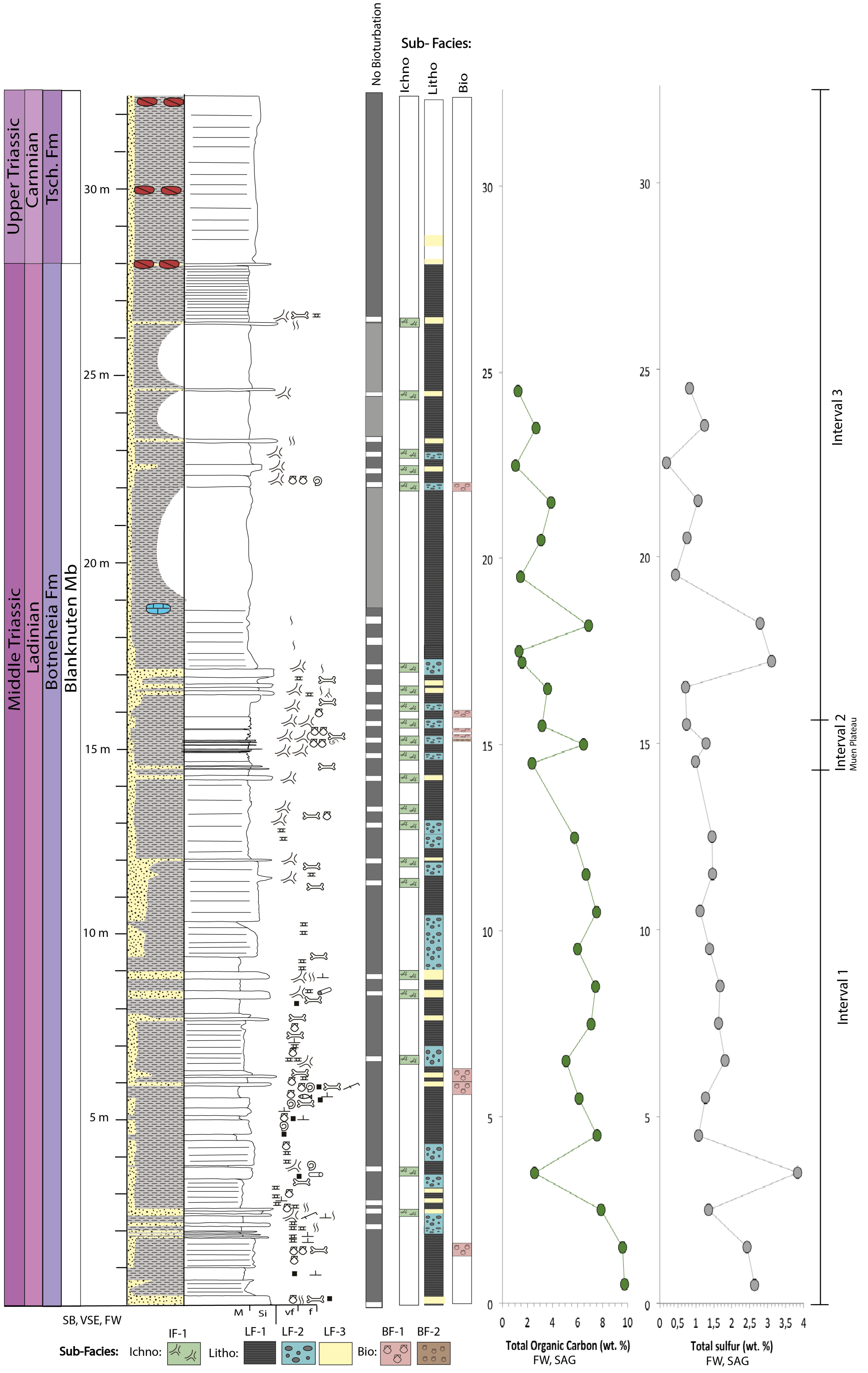


Figure 6.3: Sedimentary log of the Muen (MUE1-18), 32.5 meter with sub-facies, no bioturbation and geochemistry data, TOC and TS data from Wesenlund (in prep.)

Interval 1: 0 - 14.6 metre

Interval 1 starts from the base of the sedimentary log up to the base of Interval 2 (Muen Plateau). Here follows a relatively comprehensive description of the logged section on Muen, all description refers to the log in Figure 6.3.

Description: The sedimentary log started with a prominent blue to white weathered calcite-cemented siltstone (LF-3) rich in bone fragments, bivalves and bioturbation. The blue weathered siltstone bed was laterally traceable, and above this bed, good bedding planes were present (Figure 6.4C). Above and up to 2.5 metres, LF-1 silty shale and paper shale was inter-bedded with LF-3 siltstone (Figure 6.4A). The TOC content in the inter-bedded part was relatively high, 7.8 - 9.7 wt.%. The TS value ranges from 1.3 - 2.6 wt.%. The siltstone beds were filled with flattened and rounded phosphate nodules. Above a 15 cm thick yellow calcite-cemented siltstone LF-3, with ripples and bigger phosphate nodules compared to earlier observations was present. In the field, these phosphate fillings were interpreted to be the first occurrences of trace fossil *Thalassinoides* (IF-1) in the succession. The horizontal burrow of *Planolites* were observed at 3.4 metre height in the log (Figure 6.4E). Approximately 10 cm above, *Thalassinoides* and ammonoids were present in LF-1/LF-2, here the TOC value was 2.5 wt.% which was remarkably lower (see Figure 6.4B). Further up in the succession fine laminated shale with strong oil odour was present. Also, it was a clear change from a few to more abundant occurrences of flat phosphate nodules. The nodules had a light-weathered colour, and after removal of the weathering surface, the colour was black. Further up in the succession, the colour of the shale changed from dark to grey with fragments of phosphate nodules together with ammonoids and Ichthyopterygian remains. The oil odour was still strong in the grey silty shale. From 4 to 6 metres height in the log, LF-1 was inter-bedded with silty shale and paper shale and with a less frequency of phosphate nodules. In the paper shale, the bivalve *Daonella* sp. and pyrite, together with ammonoids, fish- and Ichthyopterygian remains were common. Above, a yellow siltstone bed LF-3 was again present and showed bioturbation, ripples and some fragments of bivalves, no *Thalassinoides* were present in this bed.

Figure 6.4D shows a typical silty shale in the succession rich in phosphate nodules at 7 metres height in the log. In a siltstone bed (8.4 metre), *Thalassinoides* and remains of a fossilised tree were present (Figure 6.4H).

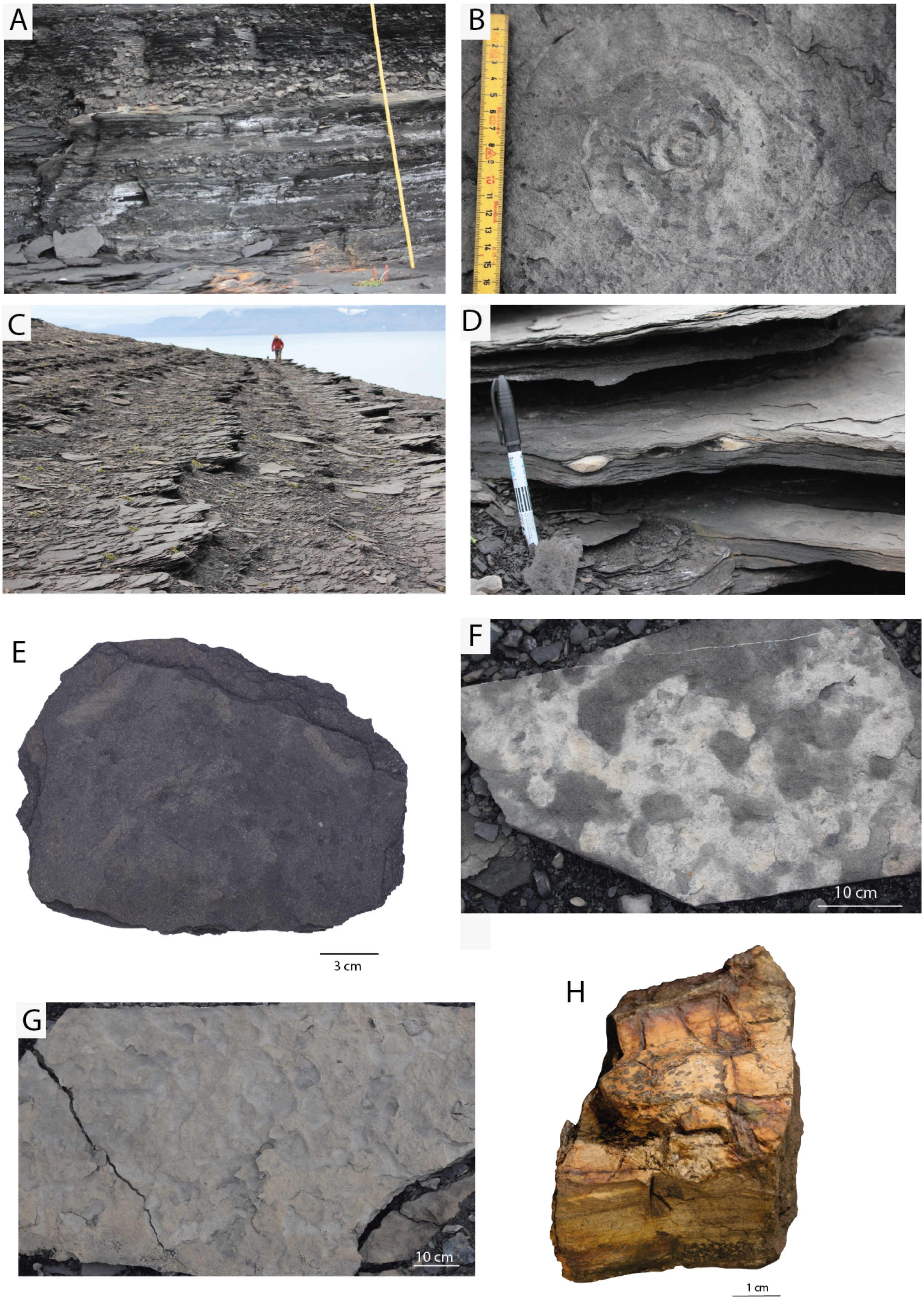


Figure 6.4: Field photos from the Muen locality, Interval 1 (0 - 16.2 metre) **A)** Inter-bedding of silty shale (LF-1), shale with phosphate nodules (LF-2) and siltstone (LF-3) from 1.80 - 2.5 metres height in log. **B)** Ammonoid in a siltstone bed from 3.8 metres. **C)** Staircase structure showing prominent siltstone bed, typical of the Muen locality. **D)** Typical silty shale rich in phosphate nodules at 7 metres. **E)** The trace fossil *Planolites* in the silty shale, 3.4 metres. **F)** Bedding plane of *Thalassinoides* at 13 metres. **G)** Bedding plane of *Thalassinoides* at 8.8 metres. **H)** Fossilised tree found at 8.4 metres height in the log.

At 8.8 metres in the log, a 5 cm thick silt bed filled with *Thalassinoides* traces were visible on bedding surfaces. These bedding surfaces were investigated in detail (see Section 7.2 and Figure 6.4 G). Non-connected phosphate nodules were common in the succession, and flattened nodules were especially common in the paper shale. In several siltstone beds the trace fossil *Thalassinoides* were observed (Figure 6.4F). Finally, last siltstone bed before the Muen Plateau (Interval 2), had a yellow weathered colour with some occasional occurrences of bivalves and again phosphate nodules interpreted as *Thalassinoides*.
To summarise, a total of 10 observable beds of *Thalassinoides* were present in Interval 1. The lower part of Interval 1 had few appearances of *Thalassinoides* and was present mainly in the siltstone beds (LF-3). Further up in the succession, against the base of the Interval 2, *Thalassinoides* was more abundant in both the silty shale (LF-1) and in the silstone beds (LF-3). Generally, the succession contained a dark, silty shale alternating with siltstone beds and some beds rich in phosphate nodules. In total 11 beds of siltstone were found to be present in Interval 1. The TOC content was relatively high with an average value of 6.8 wt.%. The *Tasmanites* algae was not visible in any thin sections or in outcrop.

Interpretation: Alternating beds of silty shale (LF-1), shale with phosphate nodules (LF-2) and silstone beds (LF-3) found in the succession indicate deposition in a dynamic system with high primary productivity. The presence of *Thalassinoides*, *Daonella* sp. and Ichthyopterygian remains indicate a marine environment. In the Interval 1, ten isolated beds of *Thalassinoides* were present. The isolated beds had absence of tiering and other ichnotaxa. It is a chance that some trace fossils could have been ignored in the field when studying the succession. Usually, the lack of trace fossils is described by oxygen deficiency. In the lower part of the interval, *Thalassinoides* were mainly found in the siltstone beds (LF-3). The siltstone beds were interpreted to indicate storm events, and these storm events represent a period with a higher erosion rate (Mørk and Bromley, 2008). The storm event beds could have brought more oxygen into the basin which made the sediment feasible for trace making animals to live. The presence of *Thalassinoides* in the siltstone beds could be interpreted to be a result of storm deposits bringing trace making animals into the basin (FöIlmi and Grimm, 1990). It is likely to believe that the presence of *Thalassinoides* in the siltstone beds in Interval 1 could originally be formed by allochthonous trace makers establishing in a dysoxic environment. Several similarities of the sediment found in the Botneheia Formation is also present in the Mancos Shale from the Cretaceous succession of Utah, USA (DeReuil and Birgenheier, 2018). In the

Mancos shale, rapid deposition of siltstone beds was punctuated with low sedimentation periods indicating varying sedimentation rate (DeReuil and Birgenheier, 2018). According to DeReuil and Birgenheier (2018), the siltstone beds indicate event beds coming into the basin as storm events and might have contributed to a higher influx of organic matter. This may also be the case for the siltstone beds present in the Interval 1 present at Muen.

The relatively high TOC on the Muen locality indicate preferable good preservation for organic matter. The TOC content was relatively stable in Interval 1, though some variations occur. The TOC content seemed to be lower in the beds where *Thalassinoides* were observed, especially on the *Thalassinoides* bed at 2.5 and 3.8 metres and against the top of the Interval 1. The influx of silt material contributed to a higher dilution of organic matter. Oxygen present in the bottom water while trace making animals disturbed the sediment reduced the availability of preservation of organic matter due to the lack of entirely anoxic conditions in the bottom water (DeReuil and Birgenheier, 2018). The reported abundant algae from the Botneheia Formation *Tasmanites* were not found on the Muen locality. Brekke et al. (2014) observed the similar absence of the *Tasmanites* on Muen and Reddikreidet and discussed if the *Tasmanites* were replaced either by quartz or dolomite crystals, or a combination of them. A more detailed investigation is needed to be able to understand the replacements of the *Tasmanites* algae.

Interval 2 - Muen Plateau: 14.6 - 15.8 metre

The easily accessible bedding planes present at the Muen Plateau makes this locality unique for studying trace fossils in high-resolution (Figure 6.5). The vertical height of the plateau was only 120 cm high. The horizontal width of the plateau varied between 40 – 70 metres, and the horizontal length was approximately 200 metres (Figure 6.2C). Each individual bed had a great areal extent, where lateral changes were traceable. Detailed sampling, logging and photographing were performed during two long field days to get as high-resolution data as possible. The sedimentary log shown in Figure 6.6 were logged in scale 1:5. The sedimentary log has three sub-facies columns with lithofacies, biofacies and ichnofacies.

Figure 6.5: Overview photo from the Muen locality, white line indicating the Interval 2 - Muen Plateau.

Description: In total 20 beds of *Thalassinoides* were found on the Muen Plateau. The trace fossil was found to be monospecific, with no other ichnotaxa present. *Thalassinoides* found on the Muen Plateau were preserved in the silty shale. When considering both the trace infill, sediment and ichnofauna, *Thalassinoides* on the Muen Plateau belongs to both the sub-facies LF-2 and IF-1. The first occurrences of the trace fossil *Thalassinoides* showed a great lateral extent, though the trace infills were partly fractured. Above a 3 cm thick silty shale bed was present, overlain by a new bed of *Thalassinoides* (Figure 6.6A). Within a 20 cm height, 6 beds of the trace fossil were present inter-bedded with the LF-1 silty shale (Figure 6.6B). In general, 50 to 80 % of the bedding plane was covered by *Thalassinoides*. No other macro-fossils or ichnotaxa were found in these beds. The burrow diameter of the trace fossils in these beds showed some variation and ranged from 20 to 50 mm. The burrow diameter and width is shown in Figure 7.6 and represents the samples MUE1-18-52A and up to 55D. The preservation of the traces was variable. At 22 cm in the logged succession, the first appearance of coqina beds, BF-1 were found. The succession was in general characterised by alternating beds of BF-1, *Thalassinoides*-beds IF-1, and LF-1. In some beds, juvenile bivalves were completely dominating. From 35 to 55 cm, it was lack of *Thalassinoides* in the succession. Here, 3 beds were fully composed of unidirectional, flat-lying *Daonella* alternated with silty shale (LF-1) (Figure 6.7, 5.5A and 6.6E and F). Figure 6.7B shows the boundary between a dark shale and the D1, the first of the three *Daonella*-beds. Above the uppermost *Daonella*-bed (D3), it was again a bed where approximately 80 % of the bed was filled with *Thalassinodes*. In general, the plateau continued to alternate between the silty shale with *Thalassinoides* (LF-2 and IF-1), dark shale (LF-1) and silty shale rich in bivalves and/or bone fragments (LF-1 and BI-1).

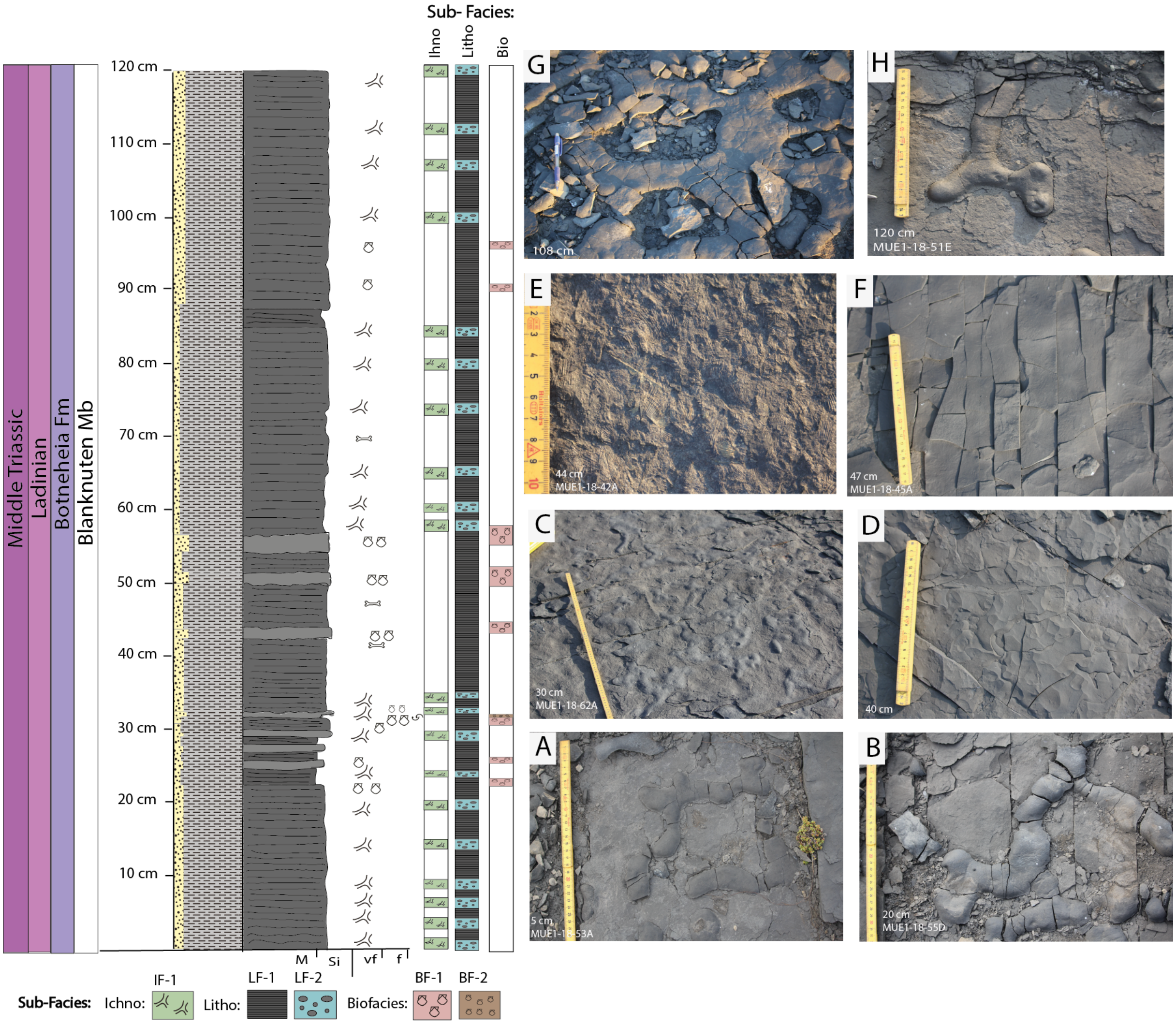


Figure 6.6: Sedimentary log of the Muen Plateau (120 cm), with subfacies and field photos. **A)** Trace fossil *Thalassinoides* at 5 cm height in the log. **B)** Trace fossil *Thalassinoides* at 20 cm. **C)** Trace fossil *Thalassinoides* at 30 cm. **D)** Dark shale with no ichno- og bio- subfacies at 40 cm. **E)** Bed fulfilled with *Daonella* sp. BI-1 at 44 cm height in the log. **F)** Dark shale (LI-1) at 47 cm in the log. **G)** Trace fossil *Thalassinoides* at 108 cm. **H)** Trace fossil *Thalassinoides* at 120 cm.

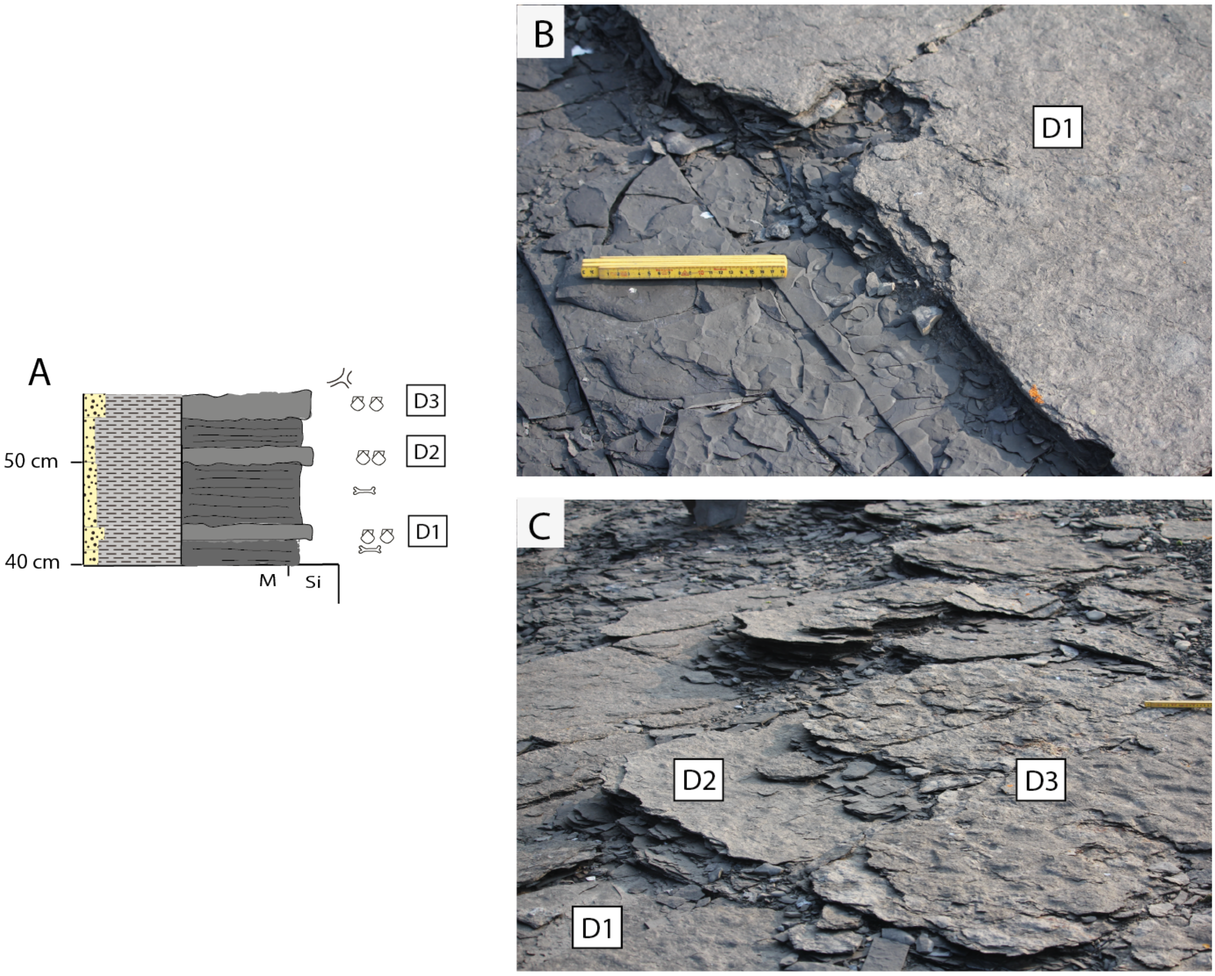


Figure 6.7: A) Sedimentary log of the Muen Plateau from 40 - 58 cm indicating the three beds fully composed of the flat-lying *Daonella* sp., BF-1, marked as D1, D2 and D3 alternating with silty shale LF-1. **B)** Silty shale and the overlying *Daonella*-beds indicated as D1. **C)** Showing the distribution of the three *Daonella*-beds and how it is alternating with the silty shale LF-1.

Interpretation: This is the first time a high-resolution bed-to-bed analysis with the focus on infauna and benthic fauna have been performed on the Muen Plateau. The observed *Thalassinoides* was found in the silty shale, which differs from the observations in Interval-1, where most of the trace fossil was found in siltstone beds.

The lower part of the Interval 2 - the Muen Plateau, contained beds filled with *Thalassinoides* (IF-1) in a silty shale which alternated with silty shale (LF-1) having an absence of trace fossils and macrofossils. The alternation indicates a variation of oxic, dysoxic and anoxic conditions in the bottom water. Where *Thalassinoides* were present, dysoxic or oxic conditions were likely, though oxygen is of vital importance for the trace making animals like crustaceans. Dark and laminated sediment with the absence of trace fossils indicates anoxic settings. The observation of *Thalassinoides* occasionally occurring on the Muen Plateau have been mentioned in multiple articles, though not described in full detail and correlated to the stratigraphy (Krajewski, 2008; Pawellek, 2011; Hurum et al., 2014; Vigran et al., 2014). It was suggested by Pawellek (2011) that the beds full of *Thalassinoides* in the upper part of the Blanknuten Member represent a recurrent short-term improvement in the bottom water, and that storm events brought oxygen to the bottom water. However, storm-events is not a likely explanation of the appearances of trace fossils on the Muen Plateau, but rather short-term oxygenation of the bottom water. Storm-events are more likely for the siltstone beds observed in Interval 1.

Many assemblages of the bivalve *Daonella* observed worldwide are allochthonous. Because they are allochthonous, it is not appropriate to draw links between the bivalves mode of life (Schatz, 2005). It is an increased amount of disarticulated single bivalves further up in the stratigraphy of the Botneheia Formation, interpreted to be caused by an increase in energy also responsible for the reworking (Bakke, 2017). When the bivalves are disarticulated, the two hinges are no longer connected. The three distinct tightly packed bed filled with *Daonella* (D1, D2 and D3) observed represents disarticulated broken shells. The preliminary interpretation of these *Daonella* beds is that they are allochthonous and transported by bottom currents with postmortem transport. After the bivalves death, the soft parts are removed and the bivalve shell could be transported by currents, this drift is what is referred to as postmortem transport (Yacobucci, 2018). Ichtyopterygian remains and bones have probably been transported together with *Daonella*. The lack of the trace fossil *Thalassinoides* associated with *Daonella* indicates that the sediment was deposited quite rapid and crustaceans did not have time to settle in the substrate.

Alternating beds of infauna, benthic fauna and laminated shale throughout the succession indicate changes in the bottom environment. Observations obtained from the Muen Plateau seem to indicate a dynamic depositional environment where the bottom water changes from being oxygenated with the presence of trace fossils, to non-oxygenated where laminated shale is dominating. Siltstone beds (LF-2) was not observed in interval 2 (Muen Plateau), indicating the absence of storm events coming in. However, oxygen has probably been present in the bottom water in some beds on the Muen Plateau indicated by the presence of *Thalassinoides* and *Daonella*-beds interpreted to be transported by bottom-currents. Though not transported as storm events as indicated by Pawellek (2011).

Interval 3: 15.8 - 32.5 metre

Interval 3 represents the upper sediment of the Botneheia Formation and up to the base of the Tschermakfjellet Formation.

Description: Interval 3 were highly scree-covered, and mainly the more resistant silstone beds were available for study. The scree-covered areas were interpreted to represent the silty shale LF-1 sub-facies. In the lower part of the succession, against the base of the Interval 2, grey silty shale was inter-bedded with siltstone beds. Some of these siltstone beds was rich of *Thalassinoides* (Figure 6.8B). The TOC content ranged from 2 - 3 wt.%. Above 28 metres in the sedimentary log, grey shale with purple weathered siderite nodules was present (Figure 6.8A).

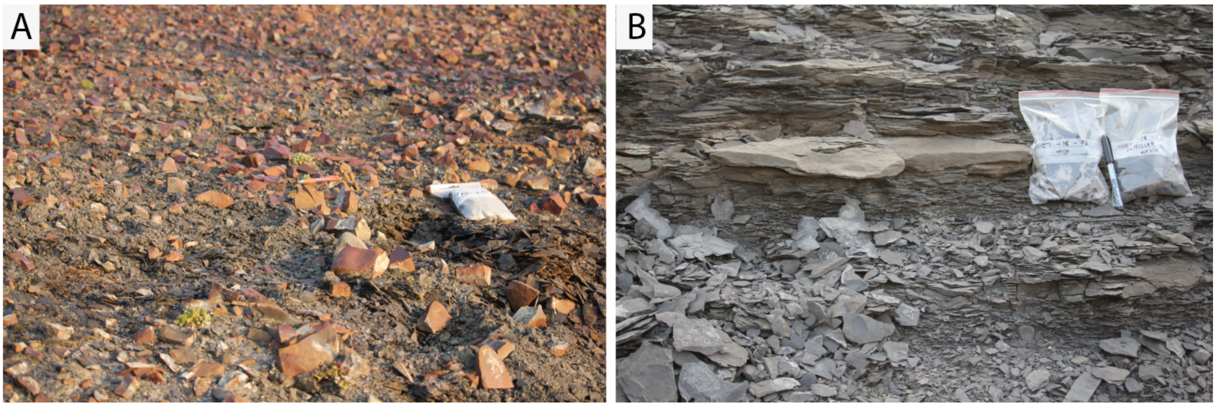


Figure 6.8: **A)** Purple weathered siderittic nodules representing the Tschermakfjellet Formation. **B)** Typical siltstone bed inter-bedded with silty shale from Interval-3, 16 - 16.8 metre.

Interpretation: The low TOC content in Interval 3 was also observed by Krajewski (2013). The Interval 3 correlates with Krajewski (2013) units 8 and 9 which were interpreted to be the regressive phase of the Middle Triassic cycle. The boundary between the dark silty shale and the more grey shale rich in purple siderite nodules represents the boundary between the Botneheia Formation and the Tschermakfjellet Formation. The Tschermakfjellet is regarded to reflect more oxic conditions compared to the underlying Botneheia Formation and interpreted to indicate a pro-delta environment (Mørk et al., 1999).

6.2 Krykkjeglupen

Date: 31.07.18, 07.08.18

Krykkjeglupen is located on the northern side of Diskobukta on Edgeøya and is a nesting place for birds, on the eastern side of the mountain Blanknuten (Figure 6.1). The succession is the type locality of the Blanknuten Member (Mørk et al., 1982; Mørk and Elvebakk, 1999). The bottom part of the Botneheia Formation was mainly scree-covered, and the logging started where the first accessible in-situ shale representing the base of the Blanknuten Member (Figure 6.9). In total 59 metres were logged (Figure 6.10).

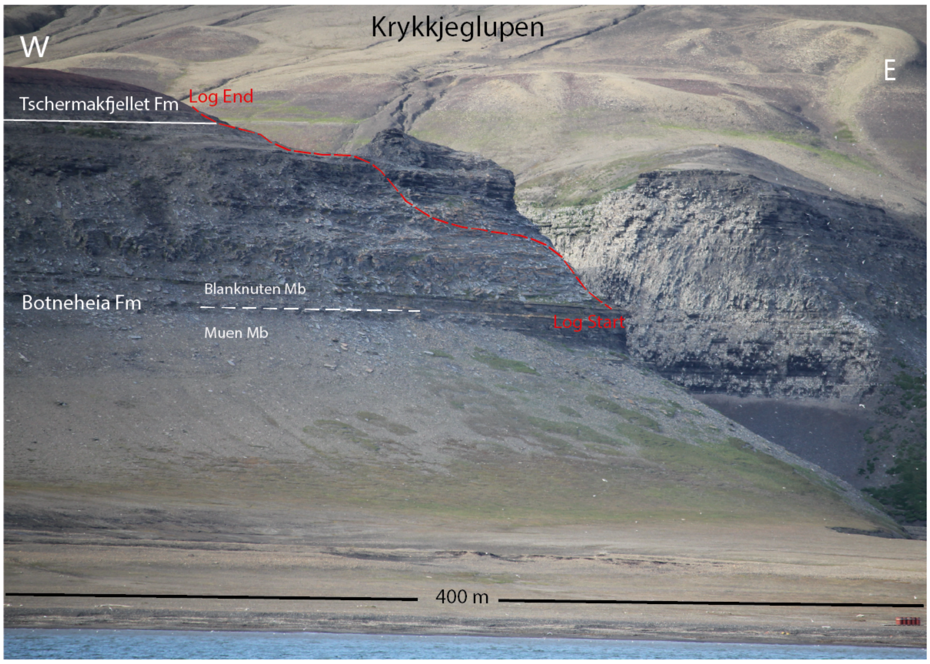


Figure 6.9: Overview of the logged sections on Krykkjeglupen with indication of formation names and the stratigraphic boundaries. The red dashed line indicates the logged succession.

Description: The first 2.3 metres of the logged section on Krykkjeglupen is shown in Figure 6.11A. Here the first 1.9 metres contained a dark, grey silty shale with abundant occurrences of phosphate nodules (LF-2). The nodules had an average diameter of 2 cm and a thickness of 0.5 cm. Above a 40 cm homogeneous siltstone bed was present, with flattened white weathered phosphate nodules (LF-3) (Figure 6.11A). Throughout the succession grey to black coloured shale was common (LF-1) with some beds rich in phosphate nodules representing the sub-facies LF-2. LF-1 and LF-2 were usually interrupted by siltstone beds (LF-3).

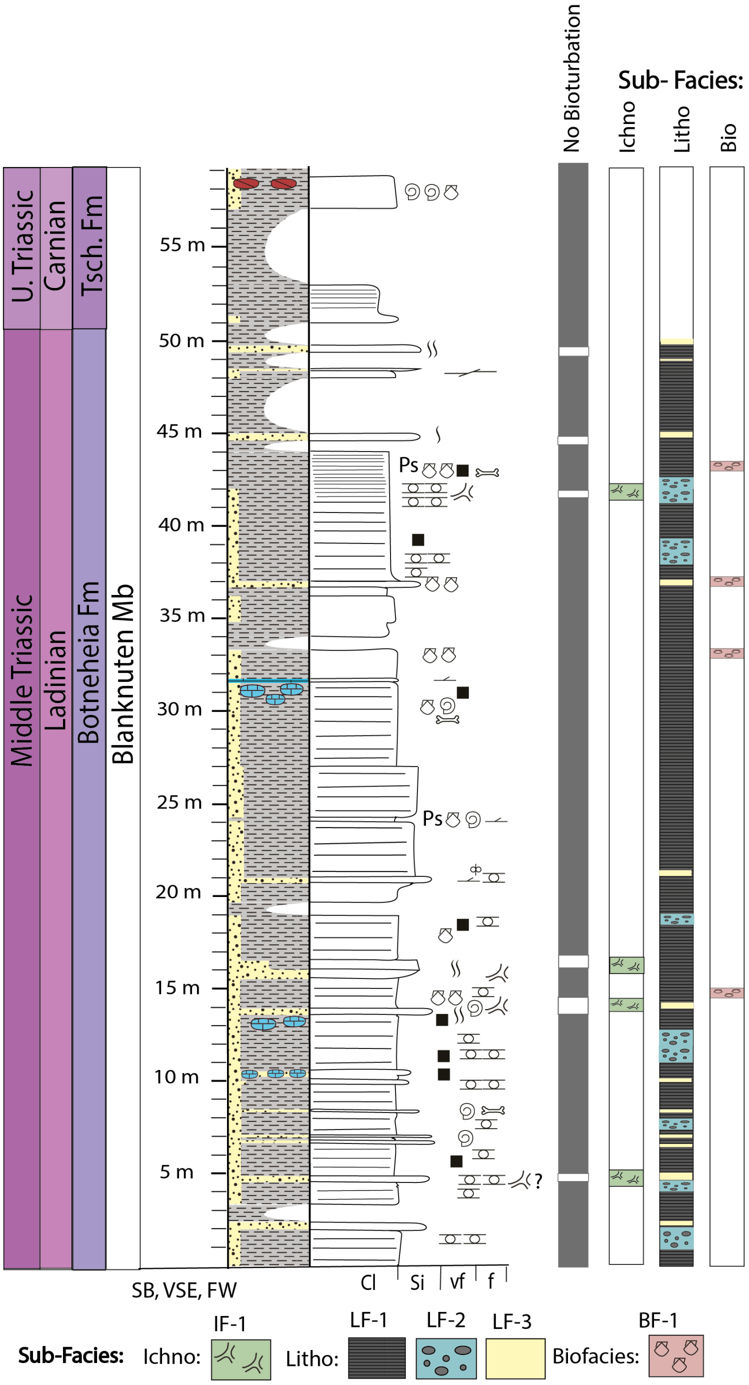
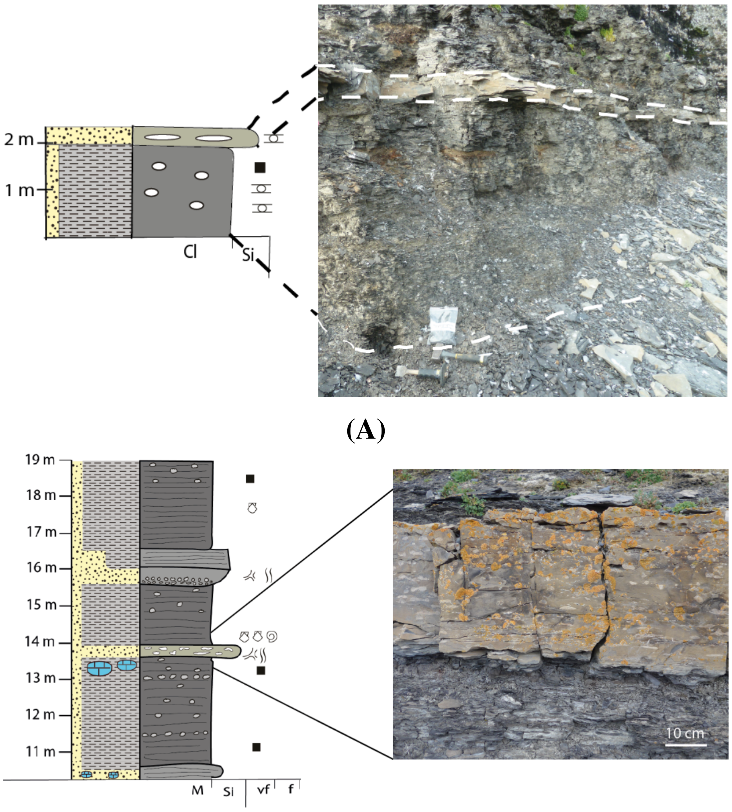


Figure 6.10: Sedimentary log of the Krykkjeglupen succession (59 metres). The column "No bioturbation" marks in grey where in the succession it is lack of bioturbation.

At 4.5 metre in the log, a 30 cm thick yellow weathered siltstone bed was present, the colour was grey after removal of the weathering surface. The siltstone was filled with elongate white weathered phosphate lenses, with a lateral diameter up to 20 cm. In the field it was discussed to be flattened fillings of the trace fossil *Thalassinoides*, this was rejected due to lack of recognisable connected tunnels. Other siltstone beds had an absence of phosphate nodules and were rich in ammonoids and ichthyopterygian remain.

Figure 6.11B shows a high-resolution log from 10 - 19 metres, phosphate nodules have been drawn in the log to better visualise their appearance. A 45 cm yellow siltstone bed (LF-2), rich in white weathered phosphate nodules are present and the bed is bioturbated. These phosphate nodules was interpreted in the field to be fillings from the trace fossil *Thalassinoides* (IF-1) (Figure 6.12B). It was difficult to distinguish between phosphate nodules and connected phosphate nodules representing *Thalassinoides*. A CT-scan was performed from a sample from this bed and is described in Section 7.5 and shown in Figure 7.8A and B.



(A)

(B)

Figure 6.11: A) The first 2 metres of the logged section with a correlated field photo showing shale with phosphate nodules overlain by a siltstone bed. **B)** The logged succession from 10 - 19 metres with a correlated photo. The photo shows a 45 cm thick siltstone bed filled with white weathered phosphate nodules, which is after a CT-scan confirmed to be *Thalassinoides*.

The first visible *Daonella* sp. was found 14 metres in the sedimentary log. Further up in the succession, the shale was homogeneous, calcite-cemented, and no phosphate nodules were visible (Figure 6.12B). A thin section of the bed were obtained and shows radiolaria, phosphate and peloids (see Figure 6.12C). Bivalves and ammonoids were frequently found in the succession. Paper shale was present in some intervals, which is a highly weathered shale with a thin lamina. As indicated on the log, varying sizes of calcite concretions appear infrequently in the silty shale. Against the top of the succession, horizontal bedding planes were easily accessible and here *Thalassinoides* was observed as shown in Figure 6.12A. The upper part of the Botneheia Formation was affected by local deformation against the East. Above, purple weathered siderite nodules and grey shale were abundant. Few appearances of *Thalassinoides* were found in the succession. It must be taken into account that if a better outcrop with a greater amount of bedding surfaces were available, more *Thalassinoides* would probably have been discovered.

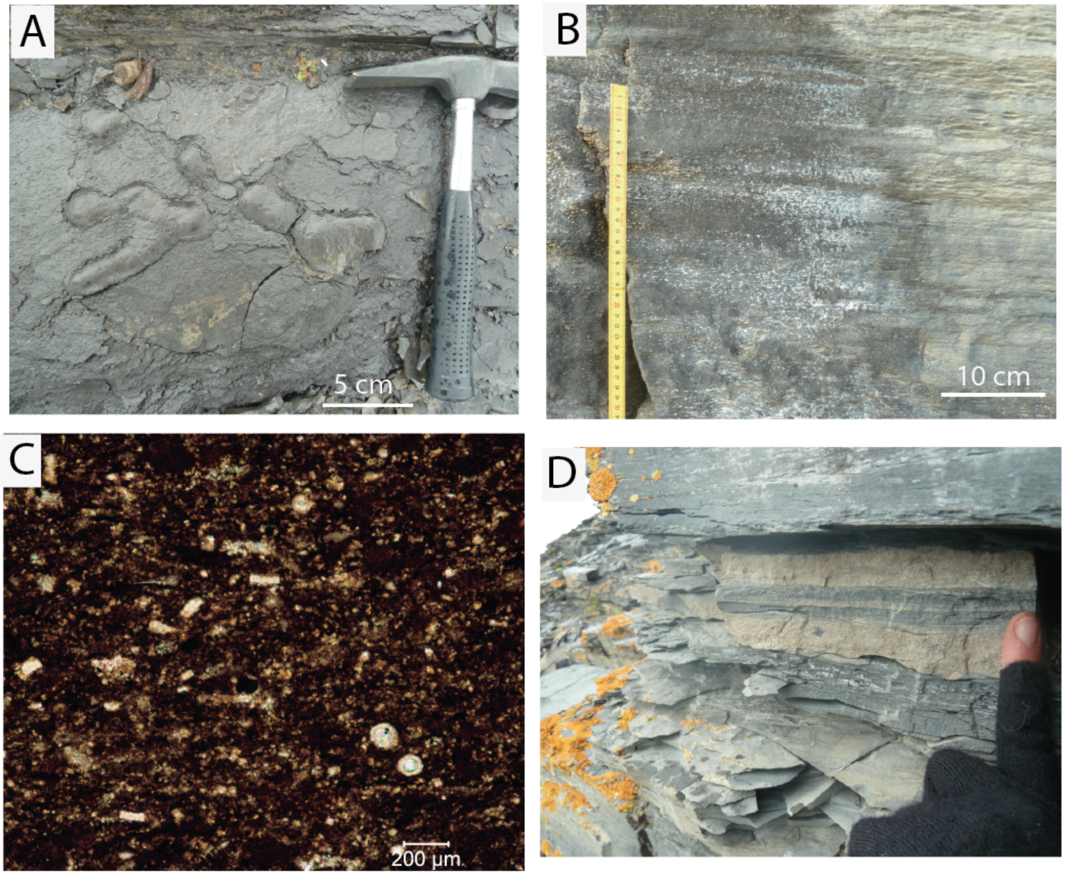


Figure 6.12: Field photos from Krykkjeglupen **A)** *Thalassinoides* recognised at horizontal bedding plane, Subfacies: IF-2 and LI-1 (42 metres in log). **B)** Typical calcite cemented shale in the Botneheia Formation, subfacies: LI-1 (22 metres height in log). **C)** Thin section of peloids (21 metres, sample: BLA1-18-30A). **D)** White beds indicating peloids, same bed as **C**).

Interpretation: The CT-scan presented in Figure 7.8 proves the existence of *Thalassinoides* in a siltstone bed on Krykkjeglupen. The presence of *Thalassinoides* in siltstone beds was found on several localities in the Botneheia Formation and have previously been documented in the literature by several authors (Mørk and Bromley, 2008; Krajewski, 2013; Vigran et al., 2014; Bakke, 2017). The presence of *Thalassinoides*, IF-1, on horizontal bedding planes found in the silty shale in the upper part of the Blanknuten Member correlates well with observations from the Muen Plateau (see Section 6.1). It could be more ichnofauna and *Thalassinoides* present in the silty shale in the succession on Krykkjeglupen than recorded. Due to few horizontal bedding planes, lack of colour difference, oxidation of the sediment and probably compaction the trace fossils were not easily recognised, which is relatively common problems when studying biogenic structures in mudstones (Wetzel, 1998). The main control on the presence of organisms constructing trace fossils is the oxygen availability in the bottom water (Potter et al., 2005). Due to the presence of the trace fossil *Thalassinoides* in the upper part of the logged section on Krykkjeglupen, oxygen was likely to be present in the bottom water. The presence of *Thalassinoides* in the siltstone beds is interpreted to be a result of storm deposits bringing trace making animals into the basin. Faceal pellets are likely to be produced in bioturbated sediments and is common from other field areas in such deposits (Potter et al., 2005). Microscopic peloids are according to Krajewski (2013) formed by the rapid precipitation of phosphate in the organic-rich succession. The alternation of the different sub-facies indicates variations in the oxygen regime in the succession logged on Krykkjeglupen, which seem to represent a dynamic system.

6.3 Blanknuten NW Valley

Date: 03.08.18 - 05.08.18

The Blanknuten NW Valley is located on the northwestern side of the mountain Blanknuten (Figure 6.13). It is the same mountain forming the type section of the Blanknuten Member (Mørk et al., 1982; Mørk and Elvebakk, 1999) and the hypostratotype for the Blanknuten Member (Krajewski, 2008). The Blanknuten NW Valley shows good exposure of the Botneheia Formation on both sides of the valley. Due to steepness and exposure quality, the first 38 metres of the succession were logged on the southwestern part of the valley (Figure 6.13A) and later correlated with a silty bed on the opposite side of the valley (Figure 6.13B). The sedimentary log in Figure 6.14 presents the logged succession of the upper Muen Member and the Blanknuten Member in the Botneheia Formation from 73 - 120.5 metres. In addition, a column with "no bioturbation", sub-facies, total organic carbon and total sulfur is presented beside the sedimentary log in Figure 6.14. The logged section from 0 - 73 metres, which represents the upper 6 metres of the Vikinghøgda Formation and 67 metres of the Muen Member is attached in the Appendix B.3.

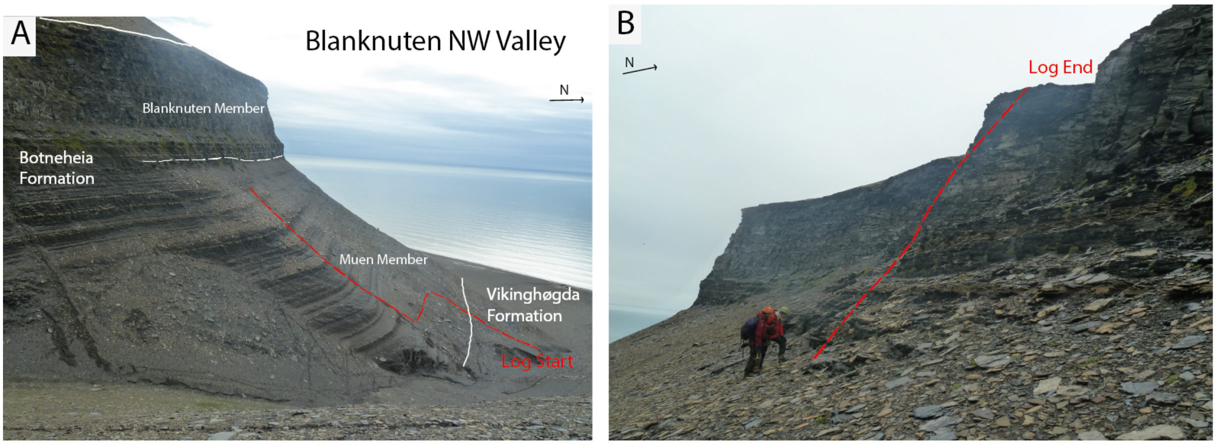


Figure 6.13: Overview photo of the Blanknuten Valley. Location of the logged section on the Blanknuten Valley (red dashed line) **A)** The lower part of the sedimentary log (0 - 73 metres) representing the Upper Vikinghøgda Formation and the Muen Member in the Botneheia Formation. Photo: FW **B)** The logged section from 73 - 120.5 metres representing the upper Muen Member and the Blanknuten Member, presented in a sedimentary log in Figure 6.14.

Description: The logged succession started with a dark silty shale rich in phosphate nodules (LF-2) which alternated with siltstone beds (LF-3). Few *Daonella* sp. were found in the succession, and those found were present in the upper part of the Blanknuten Member sediments. Most silstone beds observed in the succession were rich in phosphate nodules.

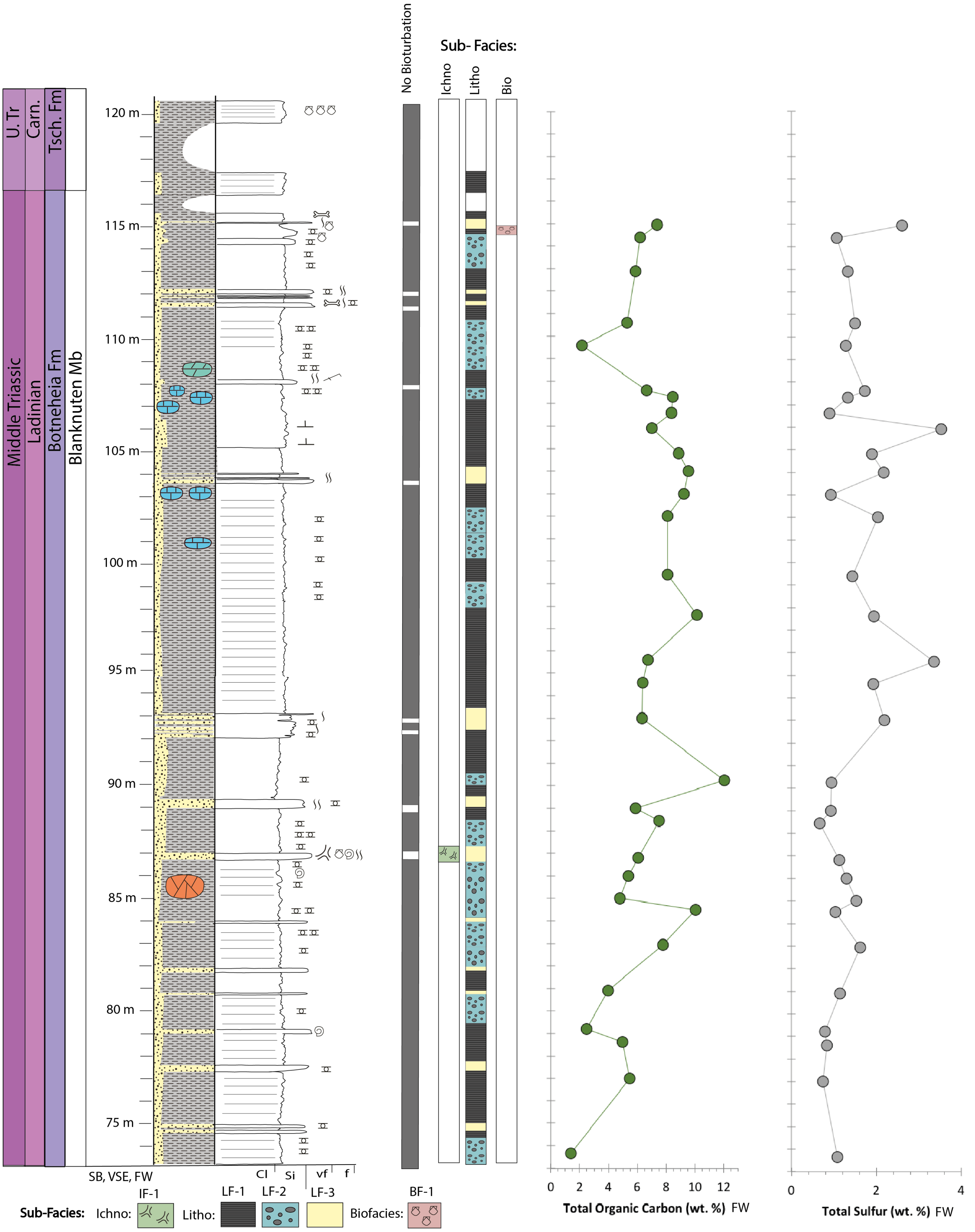


Figure 6.14: Sedimentary log of the Blanknuten Valley (BLA2-18) together with "no bioturbation" column, subfacies and geochmistry data. The geochemistry data; Total Organic Carbon (TOC) and Total Sulfur (TS) is data from collected from the logged section from Wesenlund (in prep.)

By application of HCl (5%) on a fresh fracture, the siltstone beds were interpreted to be calcite-cemented. By application of the Alizarin red S dissolved in 0.2 % HCl in thin section, dolomite was proven for a sample taken 86 metre in the log (see Appendix B.4). From 84 metres and above phosphate nodules were common in the silty shale and were present either as phosphorite conglomerate or frequently appearing nodules in the dark silty shale or in the siltstone (Figure 6.15A).

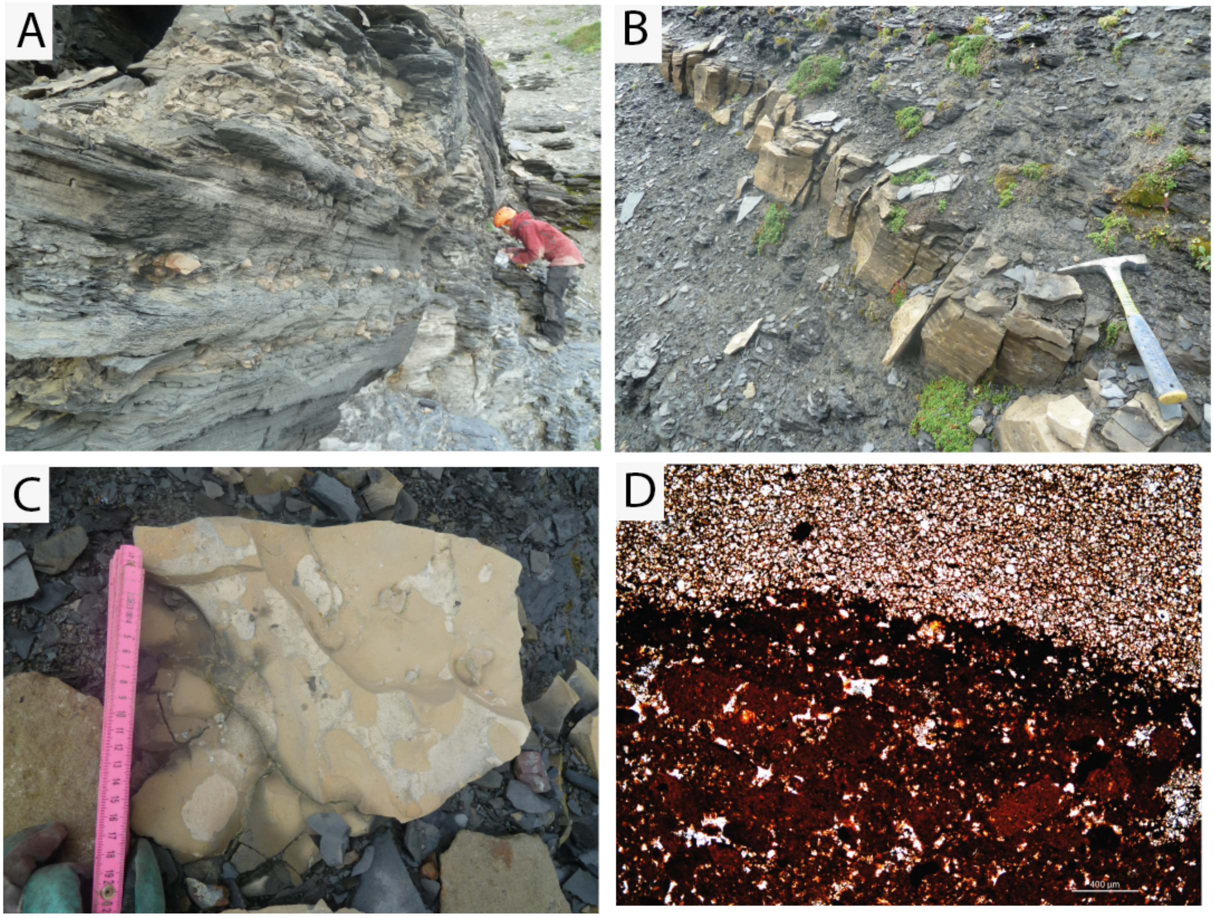


Figure 6.15: Field photos from the Blanknuten Valley **A)** Alternating beds of silty shale and phosphorite conglomerate (107 - 108 metres in log). **B)** A 20 cm thick siltstone bed with white oblong nodules interpreted to be the trace infill of *Thalassinoides* visible in horizontal view and CT-scan, subfacies: IF-1 and LF-3 (87 metre in log). **C)** *Thalassinoides* from the similar bed as **B)**. **D)** Thin section of the trace infill rich in phosphate and the burrow medium rich in dolomite (from 87 metre in the log).

Figure 6.16 presents the sedimentary log from 85 to 90 metres with associated field photos, TOC and TS data. The silty shale from 85 - 90 metres was rich in phosphate nodules and oblong lenses. A 20 cm thick yellow siltstone bed with elongate phosphate nodules, ammonoids and bivalves was present at 87 metres in the log. The elongated phosphate nodules were interpreted to be trace infill of the trace fossil *Thalassinoides*, which was the only bed where *Thalassinoides* IF-1 was recognised in this succession (Figure 6.15B and C). The thin section in Figure 6.15D shows the boundary between the yellow siltstone bed and the trace infill. The yellow siltstone, which represents the burrow medium of the trace fossil *Thalassinoides* was visible in thin section as beige fine-grained dolomite. The trace infill shown in the lower part on Figure 6.15D shows brown phosphate peloids and orange spots representing pyrite. The TOC data from the succession shown in Figure 6.16 ranges from 4.8 to 12 wt.%, the highest value was against the top of the interval. Total sulfur is ranging from 0.7 to 1.5 wt.%. The siltstone bed, which contained *Thalassinoides* had a TOC at 6 wt.% and a TS at 1.1 wt.%.

The lithofacies in the logged succession was alternating between dark shale (LF-1), shale with phosphate nodules (LF-2) and yellow weathered siltstone (LF-3) (Figure 6.14). The biofacies *Daonella* (BI-1) and ichnofacies *Thalassinoides* (IF-1) was found infrequently in the succession. The TOC throughout the succession (Figure 6.14) ranged from 1.4 to 12 wt.%. Total Sulfur was ranging from 0.7 to 3.5 wt.%.

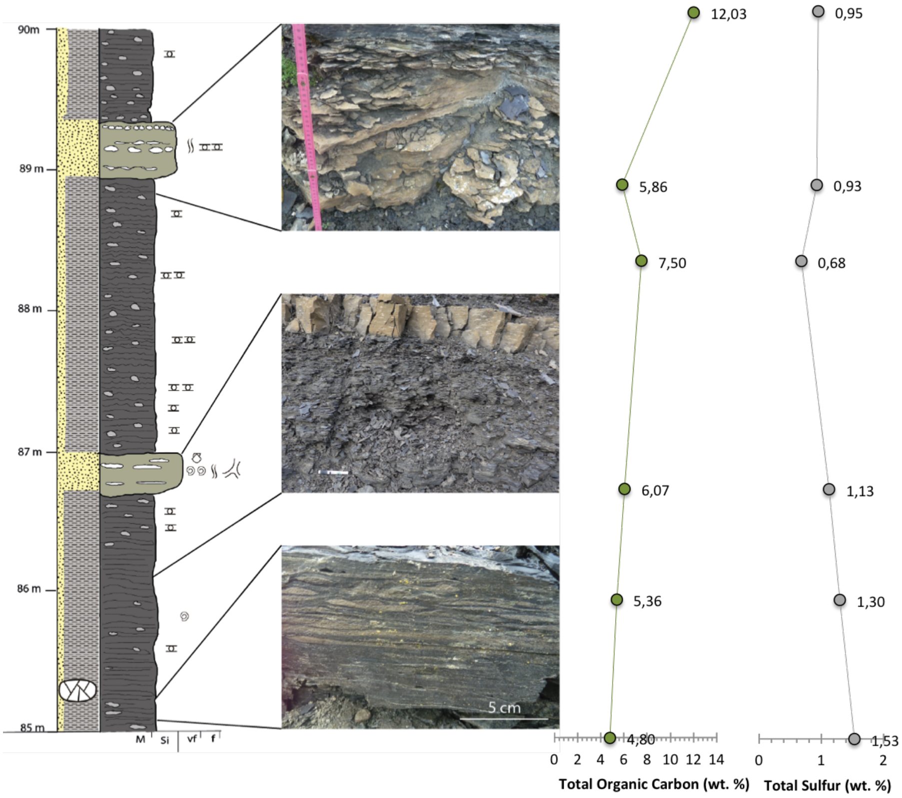


Figure 6.16: Sedimentary log from the Blanknuten Valley (85 - 90 metre) with correlated field photos, Total Organic Carbon and Total Sulfur (TOC and TS data from: Wesenlund (in prep.).

Interpretation: In the logged section of the Blanknuten Valley, one bed of *Thalassinoides* was recognised in a siltstone bed. The relatively low ichnological record in the succession could be explained by the lack of well exposed three-dimensional bedding planes. What has been recognised exclusively as phosphate nodules in the succession, could actually be the presence of the trace fossil *Thalassinoides*, though not possible to observe in vertical view. The one siltstone bed which shows clear evidence of *Thalassinoides* were likely to have been deposited during an event-bed bringing silt and the trace making animals into the basin. The siltstone beds with the lack of *Thalassinoides* is also likely to be transported into the basin as event-beds, though no or few trace-making animals were transported together with the silt material. Bad and wet weather during observation of the succession could have caused many of the *Daonellids* being impossible to detect. The organic matter content in the succession ranged from 1.4 to 12 wt.%, indicating variable preservation of the organic matter. The variations in the organic matter are linked to the preservation, production and the clastic dilution (Arthur and Sageman, 2005). Where it is a relatively low organic matter, it has been more input of clastic material into the basin which dilutes the organic matter and a lower organic matter production and preservation (DeReuil and Birgenheier, 2018). The alternation of LF-1, LF-2 and LF-3 present in the succession is much like the other observed successions on Edgeøya.

6.4 Drivdalen

Date: 01.08.18

Drivdalen is a valley on the northwestern part of the Diskobukta in between the mountains Drivdalsryggen in west and Mulefjellet in the east (Figure 6.1). The Botneheia Formation was poorly or almost not exposed on the northeast side of the Drivdalen valley against the Mulefjellet, though better exposed on the southwestern part against the Drivdalsryggen. The sedimentary logging was performed in the second ravine in the valley on the Drivdalsryggen side. A large river and steep cliffs made the best-exposed succession of the Botneheia Formation inaccessible. The logged succession in Drivdalen was therefore performed in a relatively poorly exposed area with a lot of scree-covering and a total of 34.5 metres were logged (Figure 6.17).

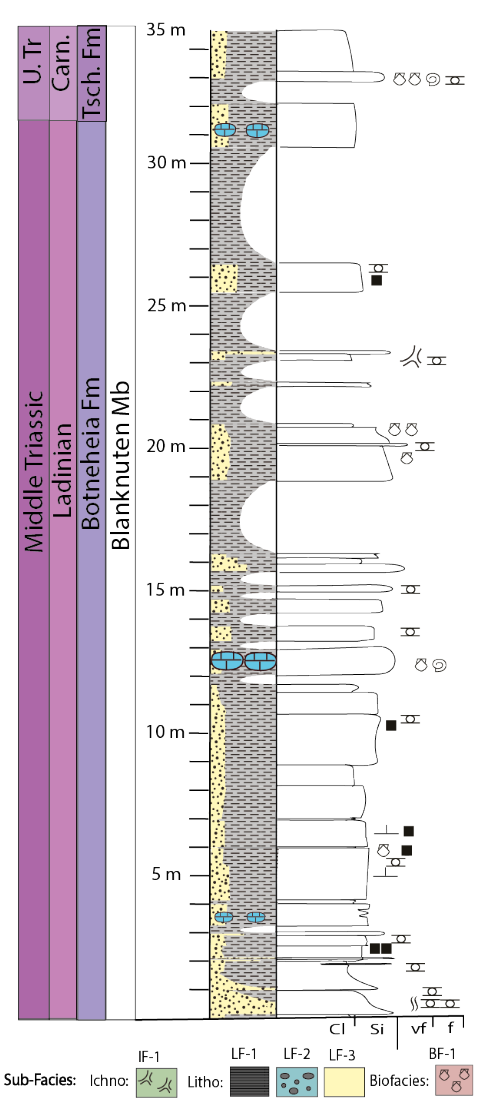


Figure 6.17: Sedimentary log of the Drivdalen succession, in total 35 metres. The column "No bioturbation" marks in grey where it is absence of bioturbation. Three columns marks the location of the ichno-, litho-, and the biofacies present in the succession.

Description: Two fining upward sequences ranging from silt to clay was present in the first two metres of the succession. Rounded phosphate nodules were abundant in the silt, and an undulating 0.5 cm thick laminae was present in the shale against the top of the fining upward sequence. Further up in the succession, silty shale rich in phosphate nodules was common (LF-1). The first appearance of the bivalve *Daonella* sp. was at 6 metres together with pyrite. The shale from 6 to 10 metre was massive and calcite-cemented and few phosphate nodules were present (Figure 6.18B). At 12 metres in the log, a bed with several calcite concretions was present having a width from 40 to 80 cm and a diameter of approximately 1 metre. Inside the concretions ammonoids and bivalves were present. Above this point, the succession was highly scree-covered which made the logging challenging (Figure 6.18C). In the succession, one exclusively bed of *Thalassinoides* is present in a siltstone bed, 23 metres in the sedimentary log.

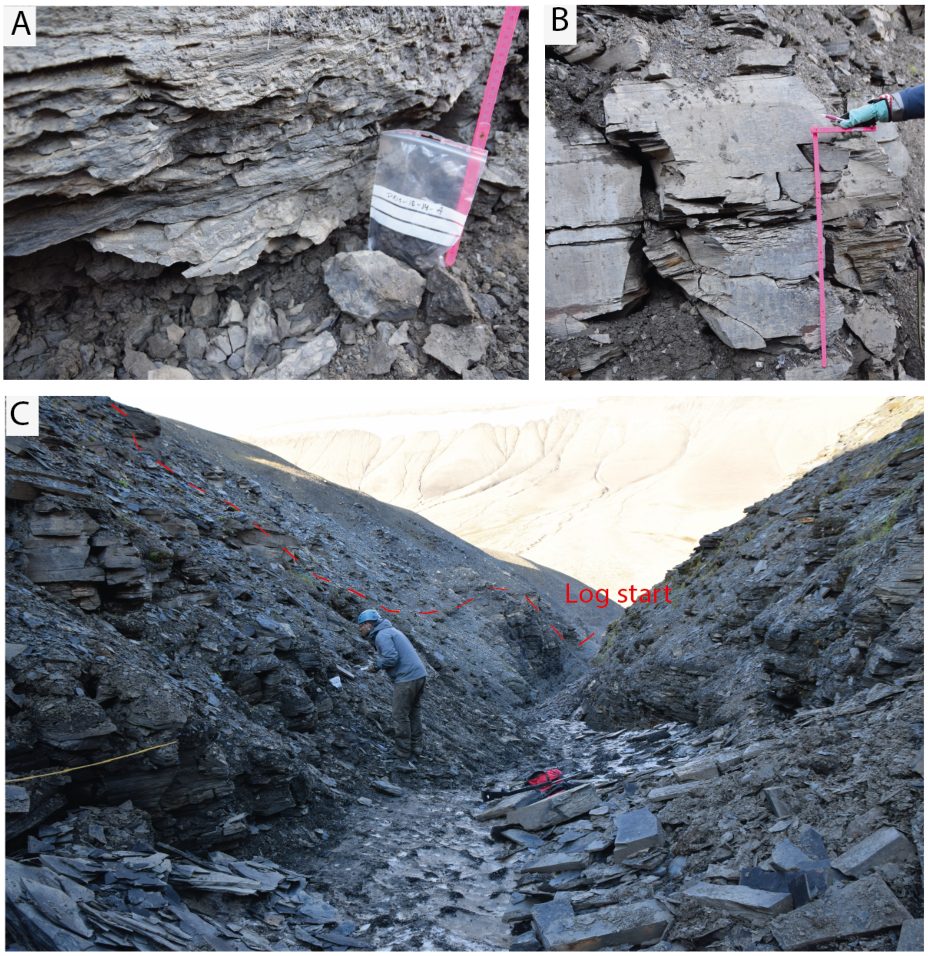


Figure 6.18: A) Typical silty shale rich in phosphate nodules, from 20 metres in the log. **B)** Massive calcite cemented silty shale. **C)** Parts of the Drivdalen area that was logged, highly scree covered.

Interpretation: The fining-upward sequences found in the succession might represent sediment coming in from storm pulses followed by quieter periods. *Thalassinoides* was not well documented in the logged succession, though the area was highly scree-covered. Many similar alternations of the lithofacies LF-1, LF-2 and LF-3 found on Drivdalen was found on the other localities observed on Edgeøya. Where phosphate nodules were present in the silty shale, some of these nodules could be the trace fossil *Thalassinoides*, though the absence of three-dimensional bedding surfaces made it difficult to actually observe the horizontal pattern of the trace fossil properly.

6.5 Skrukkefjellet

Date: 15.08.12

The Skrukkefjellet mountain is located on the Edgeøya side of the Freemannsundet (Figure 6.1). The southernmost ridge of the mountain was logged, and the sediments represent the upper part of the Blanknuten Member in the Botneheia Formation (Figure 6.19).

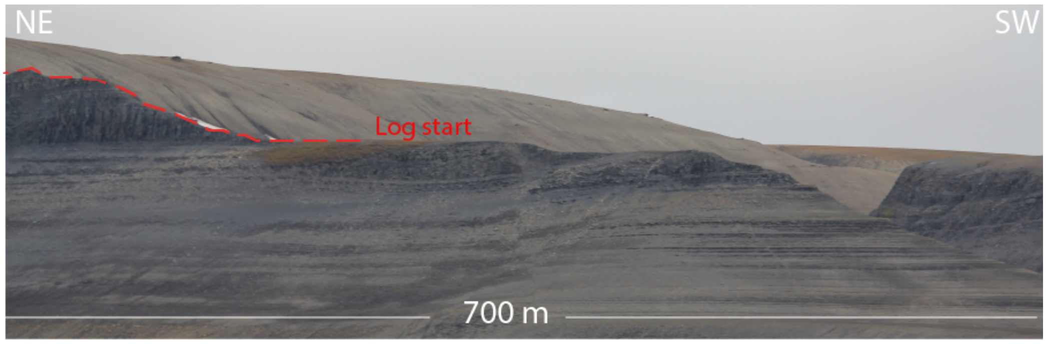


Figure 6.19: Overview photo of the Skrukkefjellet showing the logged succession in a red dashed line.

Description: The log started with a homogeneous silty shale rich in pyrite (LF-1) and with lack of macrofossils, phosphate nodules and bioturbation (Figure 6.21A). In general, the shale in the whole succession weathered light grey and after removal of the weathering surface it showed a dark brown/black colour. *Daonella* sp. and ammonoids were more frequently observed in the silty shale above 2 metres. Further up in the succession, the silty shale was rich in pyrite, *Tasmanites* algae, ammonoids and clusters of *Daonella* sp. was common and interrupted by two siltstone beds (LF-3). The first siltstone bed have a thickness of 6 cm and showed a yellow weathering colour. The base of the siltstone bed was bioturbated with ripples against the top of the bed. From a thin section acquired from this same siltstone bed phosphate, minor dolomite grains and *Tasmanites* algaes were observed (Figure 6.21G). A new siltstone bed was present 15.4 metres in the log and had a grey colour with bioturbation and ichthyopterygian remains (Figure 6.21B). The silty shale persisted further up in the succession, with few phosphate nodules present (LF-1). At 21.5 to 22 metres calcite-cemented septarian concretions were present within a soft, black paper shale. The septarian concretions had a horizontal distance of 10 metres between each concretion. The size of the concretions varied from a width of 40 - 60 cm and a diameter between 80 - 170 cm.

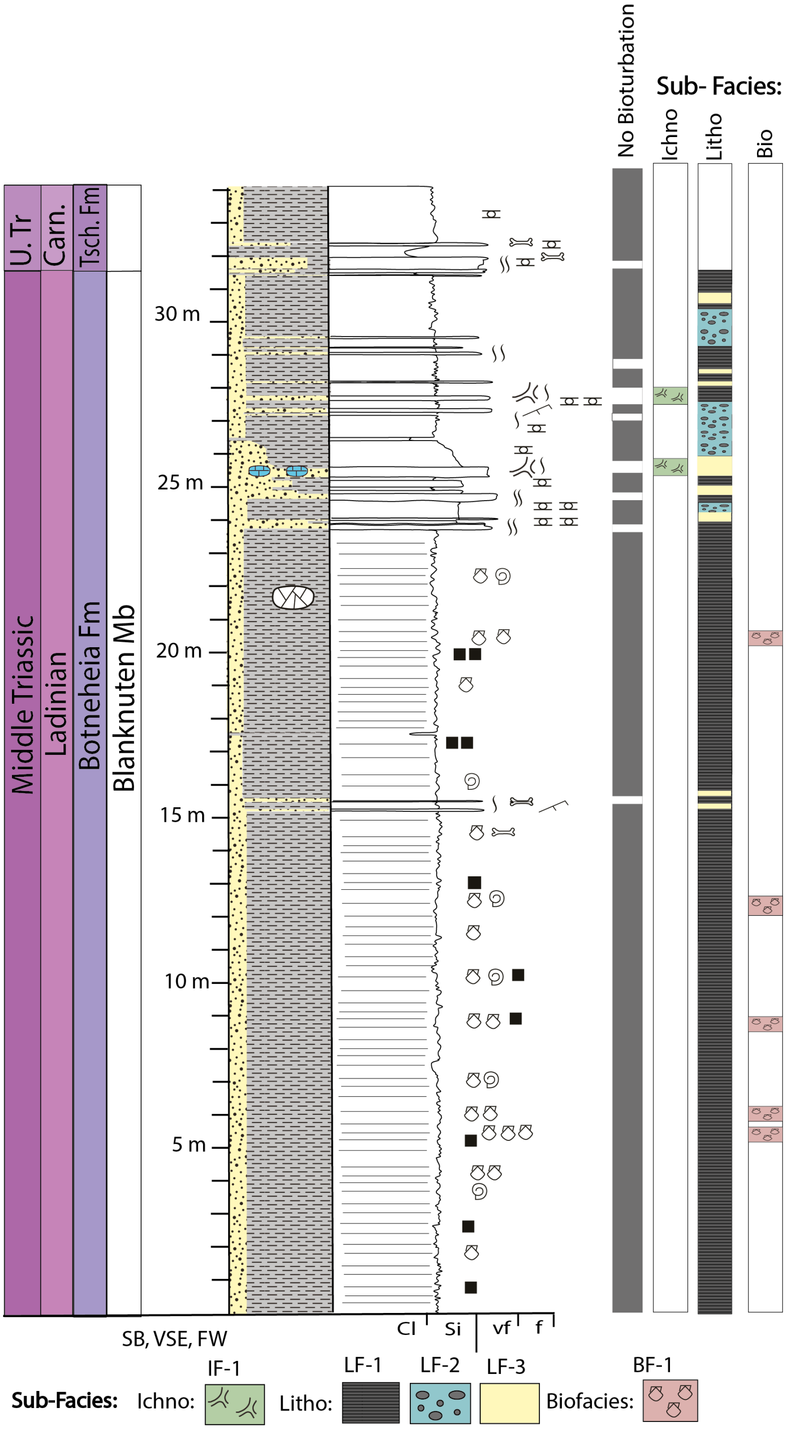


Figure 6.20: Sedimentary log of the Skrukkefjellet succession, in total 34 metres. The column "No bioturbation" marks in grey where it is absence of bioturbation. Three columns marks the location of the ichno-, litho-, and the biofacies present in the succession.

Above 24 metres in the log, phosphate nodules are more common in the succession. Some beds shows phosphorite conglomerate alternating with silty shale filled with phosphate nodules (LF-2) (Figure 6.21C).

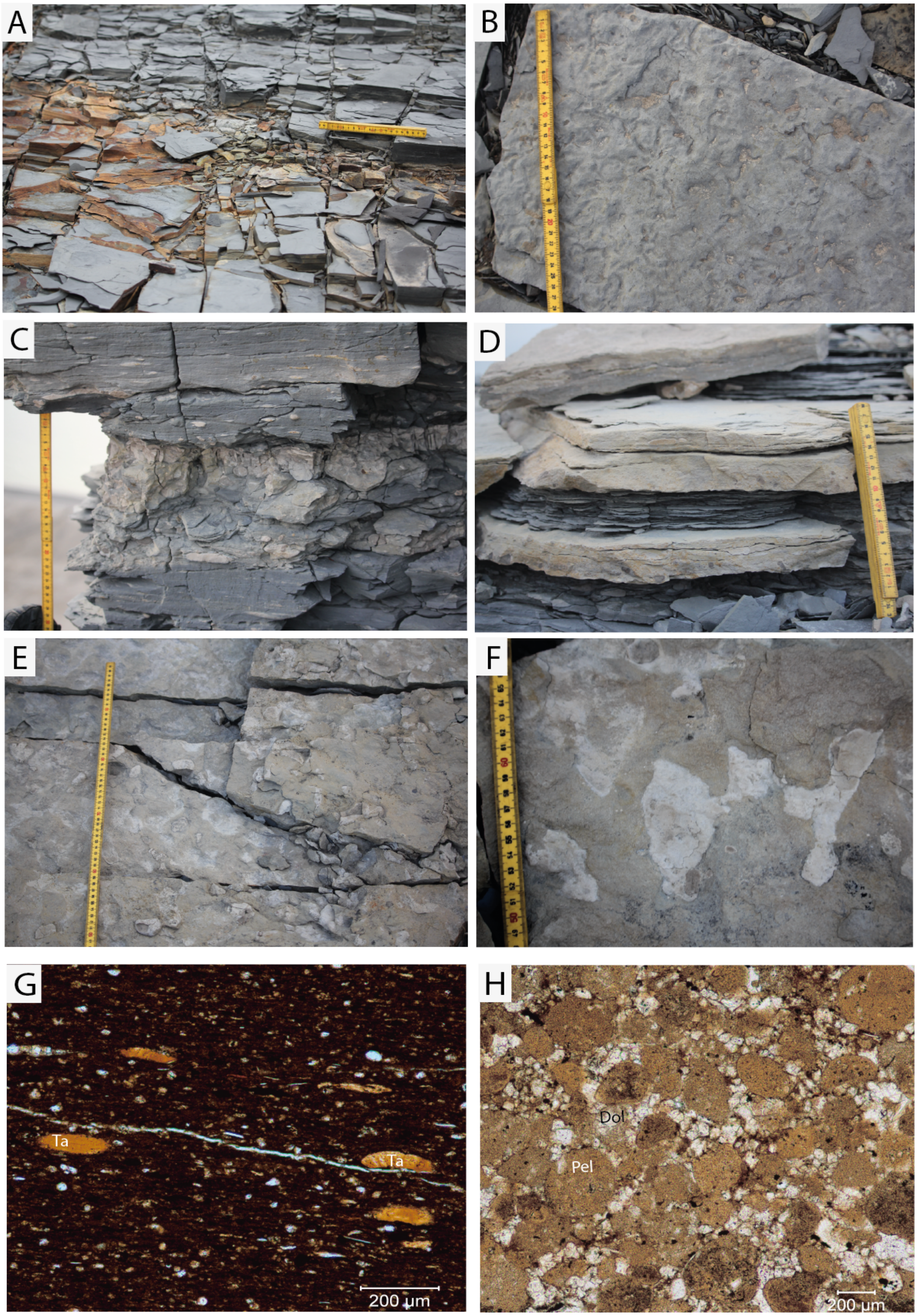


Figure 6.21: Field photos from Skrukkefjellet, Edgeøya **A)** Abundant grey shale, rich in pyrite (0 - 0.5 metre in the log). **B)** Grey, bioturbated siltstone (15.4 metre in the log). **C)** Phosphatic conglomerate with overlying silty shale with some phosphate nodules. **D)** Alternation between yellow siltstone and silty shale **E)** and **F)** show yellow siltstone bed with white phosphate nodules interpreted as *Thalassinoides* (25.8 metre in log). **G)** Thin section from 15.2 metres in the log showing phosphate and *Tasmanites* (orange oblong, marked as Ta). **H)** Thin section from a siltstone bed rich in dolomite (Dol) and peloids (Pel) from 27.3 metres in the log.

The first occurrences of the characteristic horizontal trace fossil *Thalassinoides* was found in the upper part of the succession in a yellow-weathered siltstone bed having a thickness of 10 cm (Figure 6.21 E and F). Figure 6.21D shows the typical appearance of yellow siltstone bed (LF-3) alternating with silty shale. In thin section, the siltstone beds showed dolomite grains and some beds was rich in phosphate peloids as shown in Figure 6.21H. The log ended where purple weathered siderite nodules were common within a grey shale interpreted as the Tschermakfjellet Formation.

Interpretation: The increasing amount of siltstone beds, phosphorite conglomerate and *Thalassinoides* against the top of the Blanknuten Member suggests a dynamic system. An increased silt supply indicates higher energy which was probably caused by storm events. These storm events brought trace makers in addition to silt from higher-energy environments to the distal part of the basin, which also contributed to supply the bottom water with oxygen. *Tasmanites* algaes were observed on Skrukkefjellet and not found on the other localities visited on Edgeøya. This was likewise reported by Brekke et al. (2014), which suggested a replacement by quartz and dolomite on the other localities further south (e.g Muen). The substitute of *Tasmanites* with quartz or dolomite have been linked to a thermally decomposing caused by the dolerite intrusion present south of the Diskobukta in the Vikinghøgda Formation, making the Skrukkefjellet less affected by the intrusion (Brekke et al., 2014). The dolerite intrusion could have caused the advanced maturity of the Botneheia Formation south of the Diskobukta (Mørk and Bjorøy, 1984; Brekke et al., 2014; Krajewski, 2013). The substitute of *Tasmanites* is debated and it requires more investigation to further understand this.

6.6 Skrukkefjellet East

Date: 20.08.18

The Skrukkefjellet East is located on the eastern part of the mountain Skrukkefjellet. No sedimentary log was made from this locality, due to the lack of well-exposed bedding planes. Some observations and samples were still collected from this locality. Several beds of phosphorite conglomerate (Figure 6.22B) and phosphate nodules occasionally occurring alternating with paper shale (Figure 6.22A). Against the boundary of the Tschermakfjellet Formation *Thalassinoides* was observed within a siltstone bed, which correlates well with observations from other localities on Edgeøya.

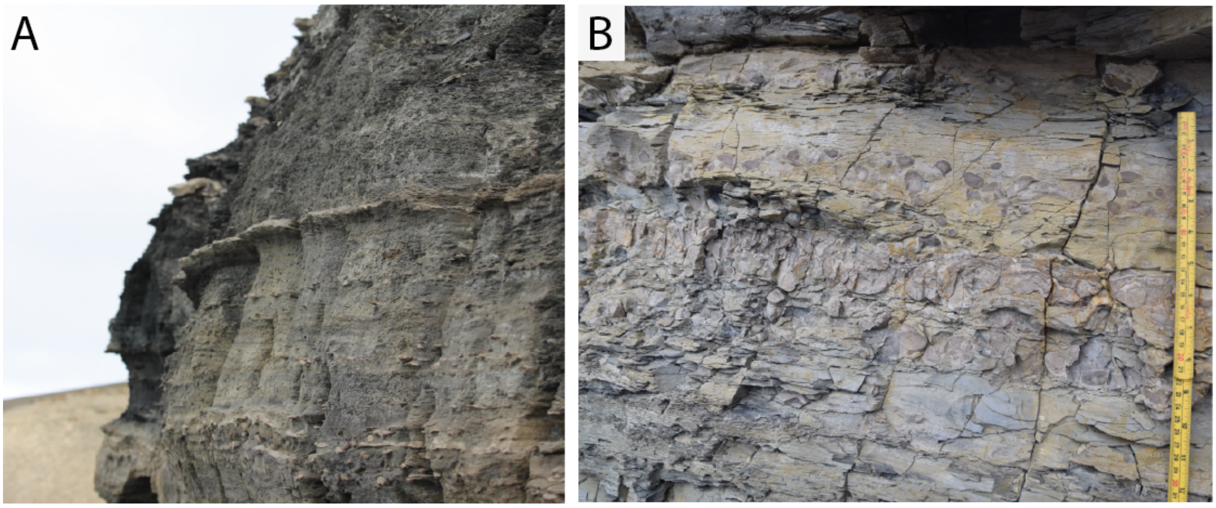


Figure 6.22: Field photos from the Skrukkefjellet East. **A)** Occasionally occurences of phosphate nodules in paper shale. **B)** Phosphorite conglomerate.

6.7 Palibinranten

Date: 19.08.18

Palibinranten is a mountain located on the southwestern part of the Freemansundet on Edgeøya (Figure 6.1). The northeastern ridge of the mountain was logged and had a total thickness of 10 metres (see Figure 6.23). The logged succession is presented in Figure 6.24 and represents the Blanknuten Member and the lower base of the Tschermakfjellet Formation. The area of interest was where the slope of the mountain was gentle enough to form horizontal bedding surfaces, which increased the chance to potentially study the occurrences of *Thalassinoides* trace fossil on Palibinranten.

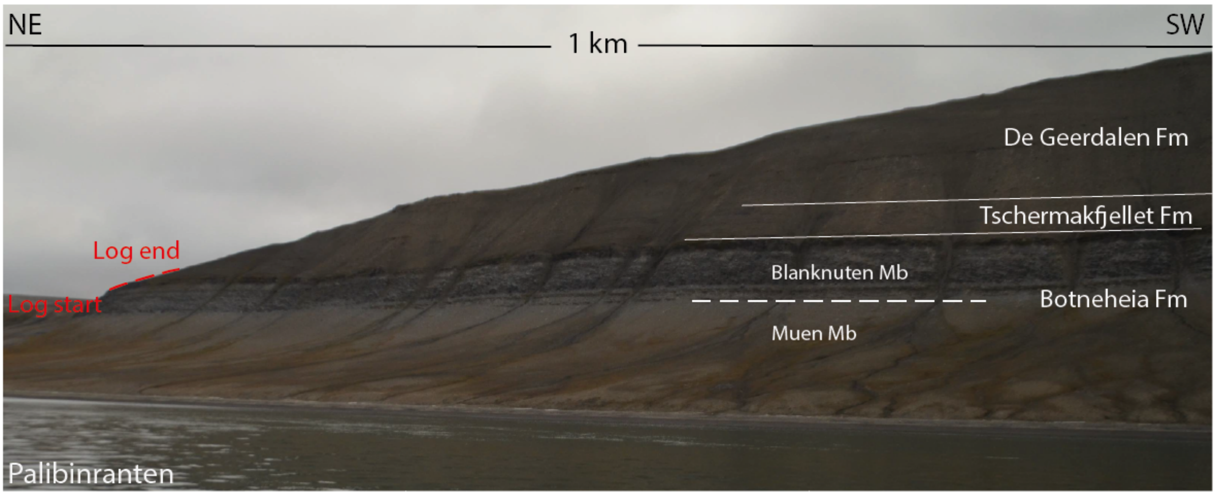


Figure 6.23: Overview photo of the Palibinranten with indication of formation names and the stratigraphic boundaries. The location of the logged succession is marked with a red dashed line.

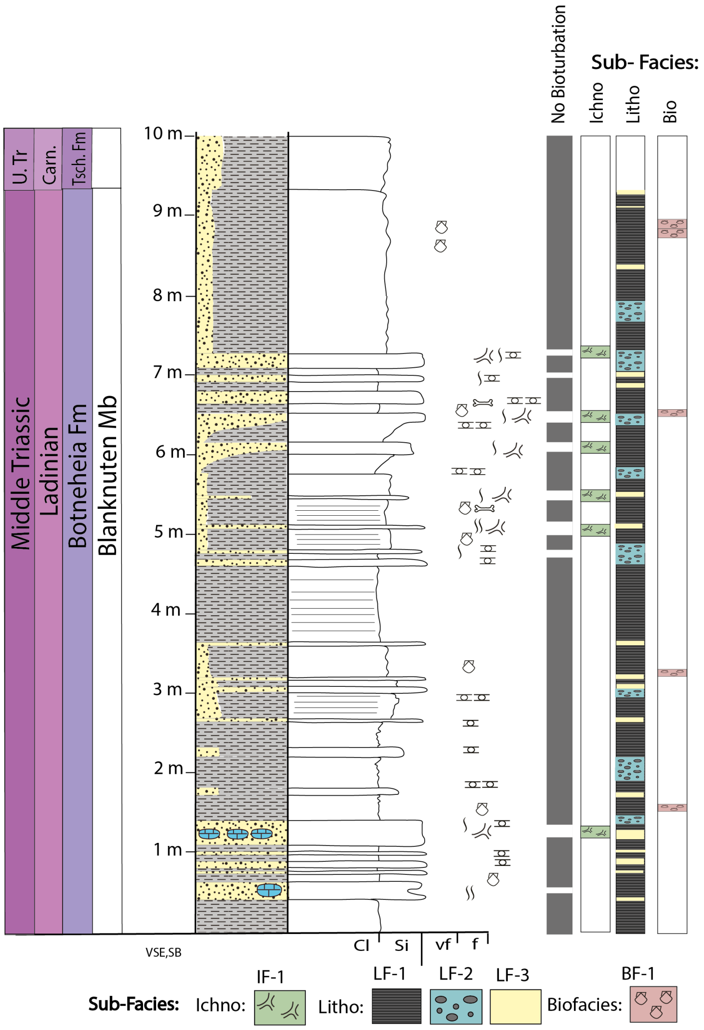


Figure 6.24: Sedimentary log of the Palibinranten succession, in total 10 metres. The column "No bioturbation" marks in grey where it is absence of bioturbation. Three columns marks the location of the ichno-, litho-, and the biofacies present in the succession.

Description: The succession started with a 40 cm thick dark shale unit (LF-1). Above siltstone with bioturbation (LF-3) alternated with shale(LF-1). The siltstone beds were rich in phosphate nodules and some beds appeared as phosphorite conglomerate (see Figure 6.26A). The first appearance of the trace fossil *Thalassinoides* were found 1.4 metres in the succession. Unfortunately, no good photos were taken of the trace fossil, though Figure 6.25 shows an indication of how it looked like. The siltstone beds filled with phosphate nodules and/or *Thalassinoides* alternating with dark shale persisted further up in the succession (see Figure 6.26B). In the silty shale the *Donella* sp. bivalves were abundant (BI-1). Connected phosphate nodules were recognised in several siltstone beds and interpreted to be the trace fossil *Thalassinoides* (IF-1) (Figure 6.26B). Due to only a few well exposed horizontal bedding planes, it was often difficult to recognise *Thalassinoides* on Palibinranten.

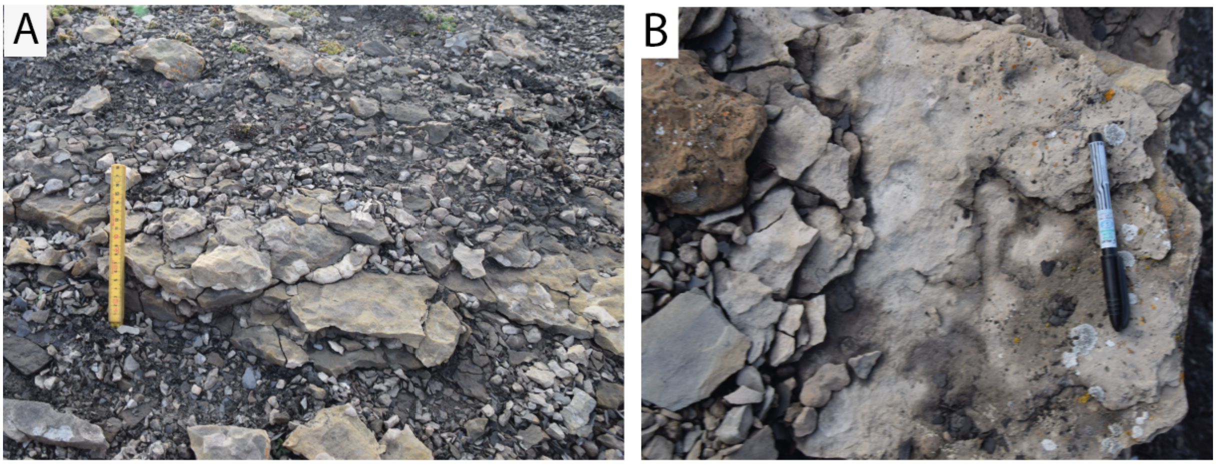


Figure 6.25: **A)***Thalassinoides* found at 7.2 metre in the succession. **B)** The first appearance of the *Thalassinoides* in the succession, from 1.3 metres.

Interpretation: In the logged succession on PalibinrantenIn 6 beds of *Thalassinoides* were observed in siltstone beds. The trace fossils were present in the Blanknuten Member as observed on other field localities visited on Edgeøya. 17 siltstone beds were present in the succession, which suggest episodic event-beds, interpreted to be filled in the basin during storm events. Phosphorite conglomerate was common to find in the succession, and was suggested by Krajewski (2008) to be a result of multiple episodes of reworking and winnowing, though the nodules showed evidence of mechanical rounding.

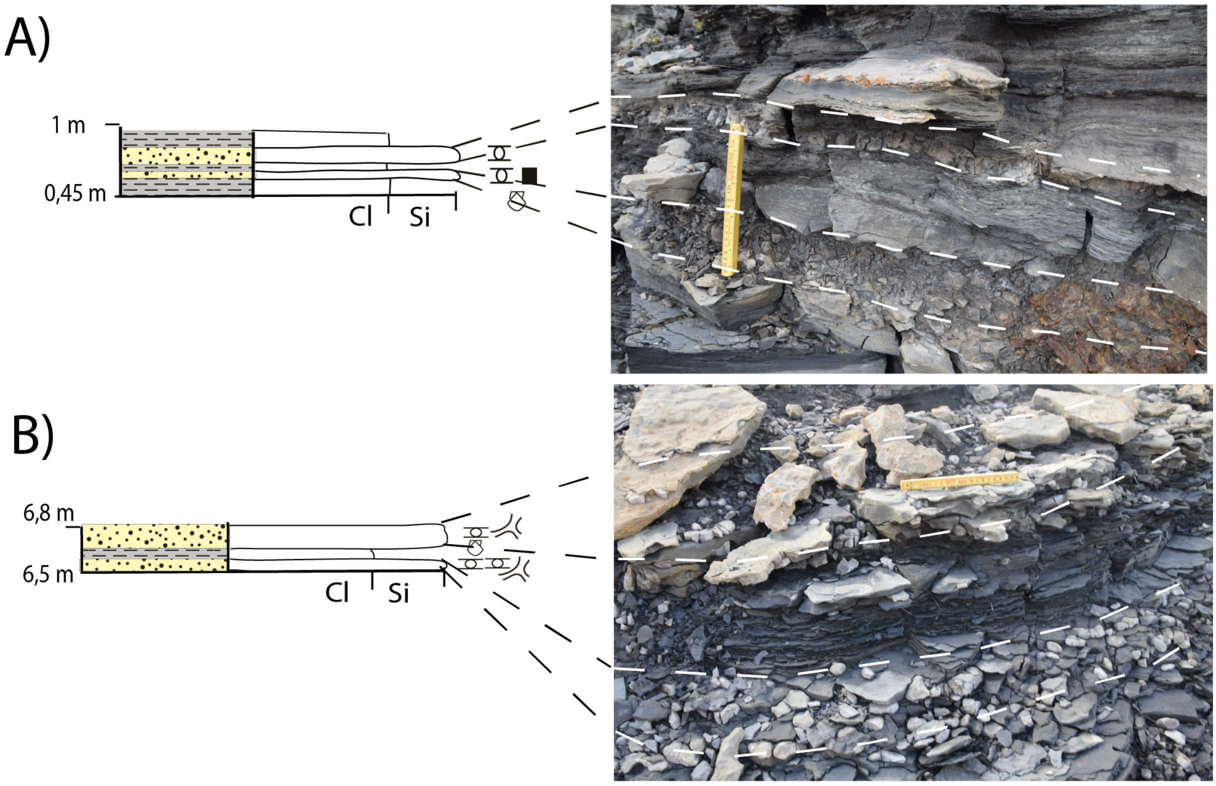


Figure 6.26: Excerpted sections from the sedimentary log correlated with field photos from the Palibinranten, 20 cm folding rule for scale **A)** 0.45 - 1 metre: siltstone beds classified as phosphorite conglomerate alternating with silty shale. **B)** Two siltstone beds alternating with silty shale. The siltstone beds are filled with connected white weathered phosphate nodules interpreted to be the *Thalassinoides*.

7. Ichnological analysis

The Middle Triassic succession on Edgeøya, Svalbard contains an abundant ichnological record. Although the succession is characterised by a low diversity ichnofauna with mainly monospecific occurrences of the *Thalassinoides*, rare findings of *Chondrites* and *Planolites* occur. The trace fossil *Thalassinoides* is present throughout the succession in the Blanknuten Member. In the following chapter results from the ichnological analysis, including the systematic ichnology, preservation, mineralogy analysis, trace fossils size distribution and CT-scan are presented.

7.1 Systematic ichnology

ICHNOGENUS: THALASSINOIDES Ehrenberg, 1944

Type ichnospecies: *Thalassinoides callianassae* from the Burdigalian Stage of the Vienna Basin (Ehrenberg, 1944).
Geological distribution: Cambrian - recent (Myrow, 1995)

***Thalassinoides* isp.**

Material: Samples (Figure 7.1) and material studied in the field (Figure 7.2).

Ichnogeneric diagnosis: Smooth-walled, cylindrical to elliptical burrow systems. Y- or T-shaped branches, the diameter is increasing at bifurcation points (Frey and Howard, 1985). Vertical shafts are connected to the surface and a horizontal branching polygonal network is present (Ekdale and Bromley, 2003). (For extended descriptions see Ehrenberg (1944); Kennedy (1967); Bromley and Frey (1974); Ekdale (1992)).

Description: Visible on horizontal bedding planes. In some beds, up to 80 % of the horizontal surface is filled with *Thalassinoides* (Figure 7.2A-C). The trace infill is connected phosphate nodules. No scratches or body fossils of the originating organism are found associated with the ichnogenus.

Ichnospecies composition: There are uncertainties related to the identification of the *Thalassinoides* ichnospecies (Yanin and Baraboshkin, 2013). The currently valid and accepted *Thalassinoides* ichnospecies are *T. horizontalis* (Myrow, 1995), *T. suevicus* (Rieth, 1935), *T. paradoxicus* (Woordward), *T. saxonicus* (Geinitz), *T. bacae* (Ekdale and Bromley 2003). *T. suevicus* (Rieth, 1935) and *T. paradoxicus* (Woordward) are the most common species mentioned in the literature according to Yanin and Baraboshkin (2013).

Remarks: *T. suvicus* is mainly a horizontal burrow, branched regularly with a dominantly Y-shape and is doubling its diameter at bifurcating points (Howard and Frey, 1984; Rodríguez-Tovar et al., 2008). The collected samples and the structures studied in the field in this work showed several similarities with the ichnospecies *T. suevicus*. The observed traces had an increasing diameter at the bifurcation point and a dominant, horizontal distribution. Due to the influence of diagenesis, the lack of excellent samples and the difficulty of separating Y- and T-shape, it is decided to keep the observations of the *Thalassinoides* in the Botneheia Formation to an ichnogeneric level.

Figure 7.1: Collected samples of the trace fossil *Thalassinoides* from the Middle Triassic succession on Edgeøya, Svalbard. White helping lines highlight the burrows **A)** White tunnels indicating the trace infill of the *Thalassinoides* in a siltstone burrow medium. The burrow diameter is increasing on the bifurcation points, from Muen, Edgeøya. **B)** Depressions representing under-track of the *Thalassinoides* in a siltstone, from Muen, Edgeøya. **C)** White elliptical burrows, Skrukkefjellet, Edgeøya **D)** Part of a *Thalassinoides* burrow system within a siltstone burrow medium, from Palibinranten, Edgeøya **E)** White cylindrical infill of the *Thalassinoides* within yellow weathered siltstone, Skrukkefjellet, Edgeøya **F)** Phosphate infill of the *Thalassinoides* found in a silty dark shale on the Muen Plateau, Edgeøya.

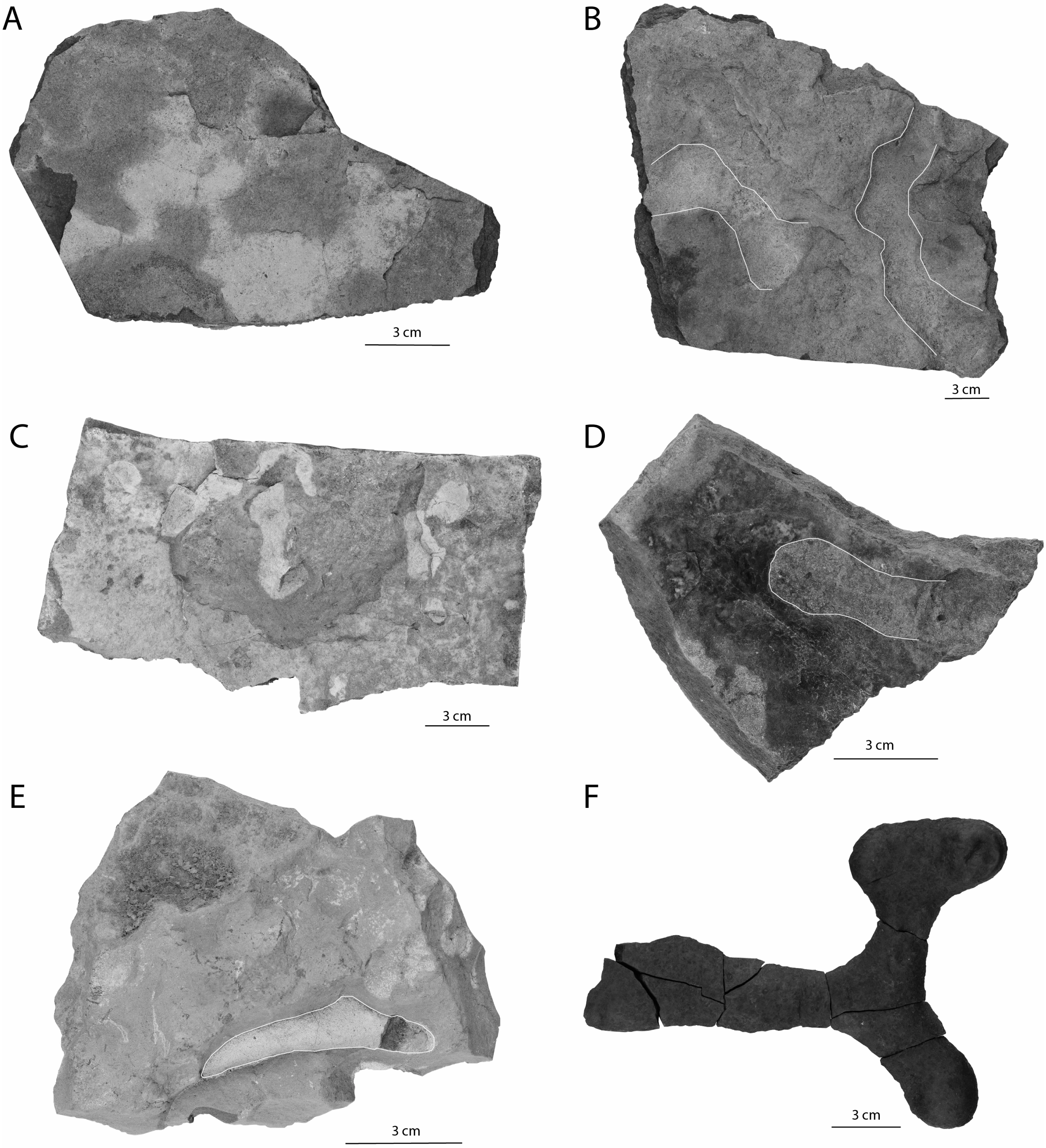


Figure 7.1

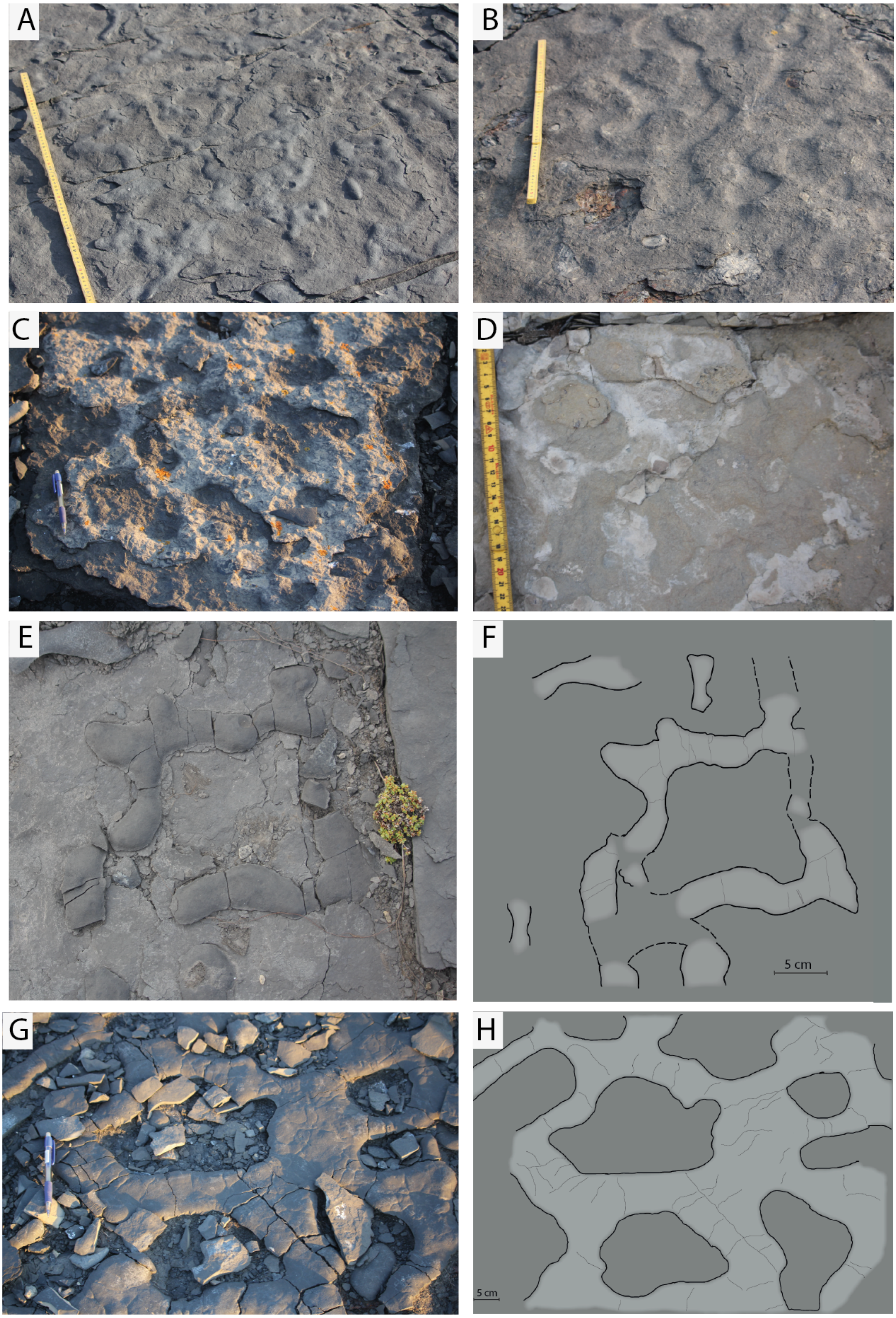


Figure 7.2

Figure 7.2: Field images of *Thalassinoides* taken on horizontal bedding planes found in the Middle Triassic succession on Edgeøya, Svalbard. **A)** Extensive burrow network of *Thalassinoides* representing approximately 50% of the bedding plane, Muen Plateau, Edgeøya. **B)** Under-tracks of *Thalassinoides* in a silty shale, Muen Plateau, Edgeøya **C)** Network of *Thalassinoides* in a silty shale. Diagenetic processes enhancing the visibility of the trace fossil, Muen Plateau, Edgeøya. fossil **D)** White coloured trace infill of *Thalassinoides* present in a yellow-weathered siltstone burrow medium, Skrukkefjellet, Edgeøya. **E)** Connected phosphate nodules representing trace infill of *Thalassinoides*, some of the trace infill is weathered away. Photo was taken from the Muen Plateau, Edgeøya **F)** Redrawn sketch of **E**),light grey colour indicating the burrow, dark grey is the burrow medium. The dotted line is an interpretation of how the trace maker originally was moving in the substrate. **G)** Extensive network of *Thalassinoides* from the Muen Plateau, Edgeøya **H)** Redrawn sketch of **G**), light grey colour indicating the burrow, dark grey is the burrow medium.

ICHNOGENUS: PLANOLITES Nicholson, 1873

Type ichnospecies: *Planolites vulgaris* (Nicholson and Hinde, 1874)
Geological distribution: Precambrian - recent

Planolites isp.

Material: Sample (MUE1-18-10C) and material studied in the field (Figure 6.4E).

Ichnogeneric diagnosis: Simple, rarely branched, unlined, straight to tortuous burrow with structure-less infills which is differing from the lithology of the host rock (Pemberton and Frey, 1982)

Description: The slightly curved burrows are visible on horizontal bedding planes as slightly curved burrows, within dark silty shale as being the host rock.

Remarks: A few ichnogenera were found, but the ones found did not show any clear evidence of *Planolites*. However, *Planolites* isp. is common in such depositional environment and is often associated with *Thalassinoides*. In addition, *Planolites* isp was found by Mørk and Bromley (2008) in the same succession. Thus, the trace fossil might be present, but in this study the validity of the ichnogenus is weak.

ICHNOGENUS: CHONDRITES Stenberg, 1823

Type ichnospecies: *Fucoides antiquus*, (Brongniart, 1828)

Geological distribution: Precambrian - recent

***Chondrites* isp.**

Material: Material studied in the field.

Ichnogeneric diagnosis: Branching regular tunnel systems, mastershafts which branches at depth and forms a dendritic burrow network (Osgood, 1970; Fürsich, 1974)

Description: Not easily recognised in the outcrop. Observation of *Chondrites* was seen as small traces (0.5 - 1 cm) overprinting the ichnogenus *Thalassinoides*.

Remarks: In the outcrop, the ichnogenus are not easily recognised and it appears to be some uncertainty regarding the recognition. However, the *Chondrites* isp. is expected to find cross-cutting or in the trace fossil infilling of the previously formed ichnogenus *Thalassinoides* as observed by Mørk and Bromley (2008) in the Middle Triassic succession of Eastern Svalbard.

7.2 Preservation

The preservation and the degree of exposure of trace fossils vary in the successions on Edgeøya. *Thalassinoides* are preserved in two ways: within the dark silty shale and in siltstone-beds (see Section 5.2.1). The preservation is full-relief or semi-relief.

The burrow system of *Thalassinoides* form horizontal networks and in outcrop, no vertical shafts were recognised. The traces are most visible on horizontal bedding planes, where they form extensive and regular networks. Unfortunately, the Muen Member is significantly scree-covered, and the Blanknuten Member forms a characteristic cliff, only a limited amount of horizontal bedding planes were exposed and could be studied. At the Muen locality in southwestern Edgeøya, bedding planes are easily accessible for study (Figure 6.1). *Thalassinoides* traces were here studied in detail throughout the upper part of the Blanknuten Member (see Figure 7.2 and Section 6.1). Figure 7.2 shows the diversity of the trace fossil and how they appear in the field on Muen. Figure 7.2 D-H is a compilation of field photos and sketches. The sketches contain some interpretation of how the trace maker could have been moving in the substrate. Un-connected phosphate nodules are found on top of certain bedding planes (Figure 7.3A). These could be *Thalassinoides*-rich bedding planes that have been affected by erosion, physical weathering (e.g freeze-thawing) and chemical weathering (e.g oxidation). Consequently, as the un-connected phosphate nodules shown on Figure 7.3A are present on the Muen locality, in the proximity of other findings of *Thalassinoides* it is believed that the un-connected phosphate nodules originally is the trace fossil *Thalassinoides*. There is often an uncertainty associated with the identification of trace fossils, regarding whether the observed structure is a result of biogenic or sedimentary and/or diagenetic processes. Figure 7.3B shows elongated phosphate nodules in a silty shale. The observations in vertical view made it challenging to differentiate between *Thalassinoides* and phosphate nodules. Vertical shafts would be expected for the trace fossil *Thalassinoides*, but were not found in the successions observed on Edgeøya.

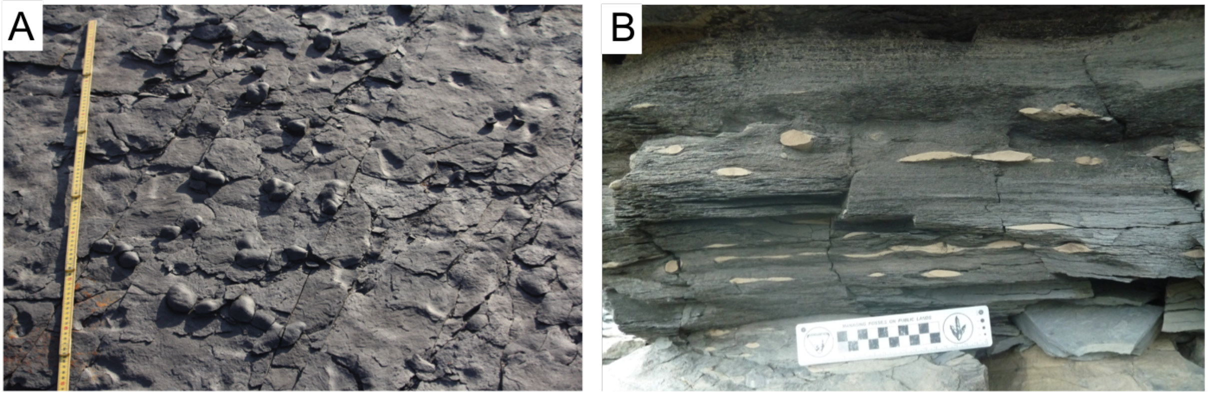


Figure 7.3: **A)** Horizontal bedding plane with non-connecting phosphate nodules from Muen. **B)** Elongated phosphate nodules in a silty shale obseved in vertical view on Krykkjeglupen.

On the Muen locality (see Section 6.1) there were multiple well exposed bedding planes some up to 80 % covered by *Thalassinoides* burrows. One bedding plane found at height 8.8 meter in the sedimentary log was investigated in detail and had a size of 93 x 60 x 5 cm (Figure 7.4). Approximately 50 % of the bedding plane were covered by *Thalassinoides* in yellow-weathering siltstone. The traces were preserved as semi-relief showing a white to grey colour. Figure 7.4 shows a photo and a sketch of the investigated bedding plane. The size of the trace fossils varies on the bedding plane. Thick burrows are interpreted to be bifurcation points. The investigated bedding plane on Muen has a smaller bed below where phosphate nodules are present (see Figure 7.4B_1). Samples for thin sections were collected from the yellow-weathered bedding plane and from the trace infill of *Thalassinoides*, respectively (Figure 7.4). The mineralogy in the thin section on Figure 7.4A_3) is mainly dolomite and the texture shows microcoqina. The trace infill consists of phosphate, Radiolaria and some fragmented bivalves (Figure 7.4B_2).

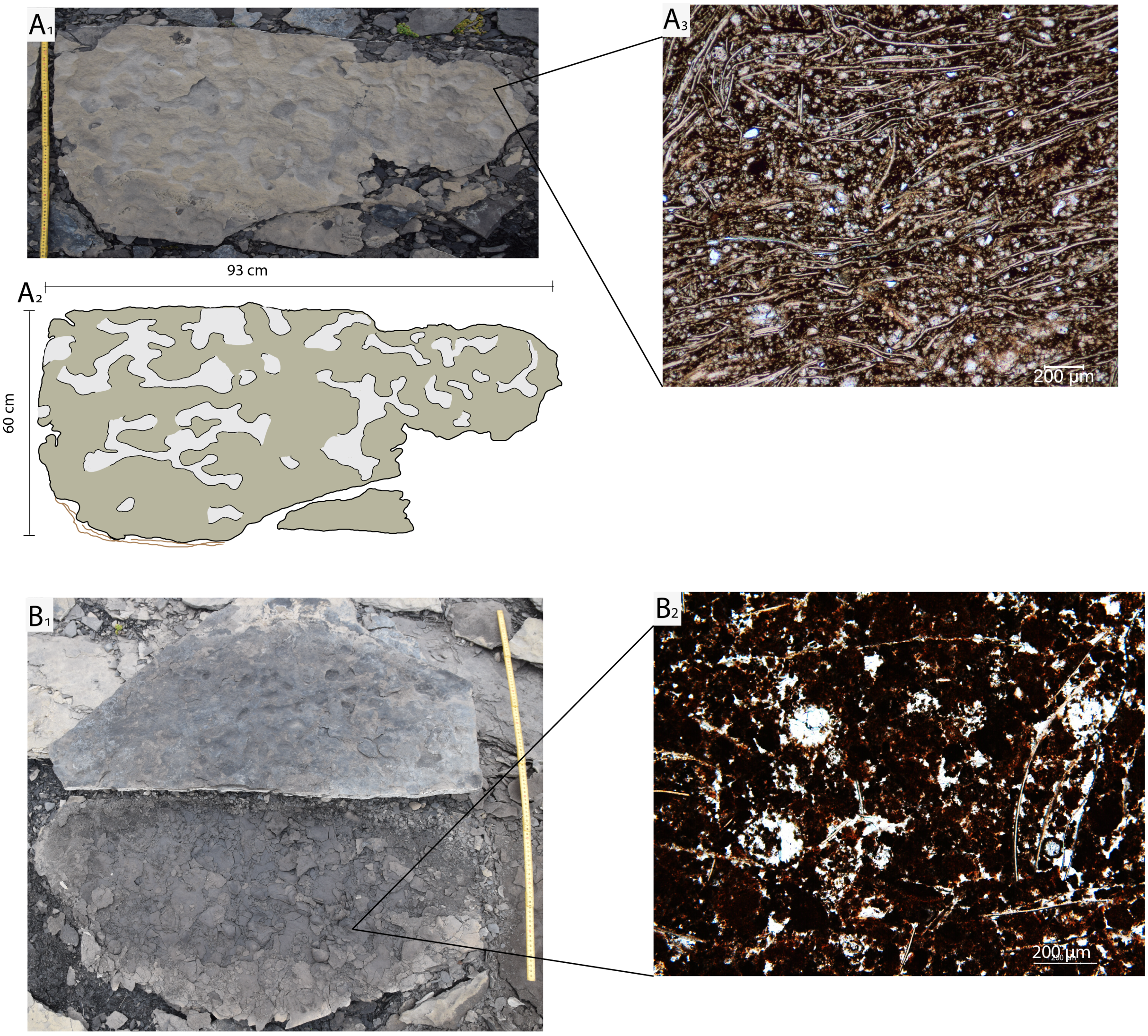


Figure 7.4: Examples of *Thalassinoides* from Muen, Edgeøya **A**$_1$) Block of *Thalassinoides*. **A**$_2$) Redrawn sketch of the bedding plane in **A**$_1$), with some interpretations of how the trace maker were moving in the burrow medium. **B**$_1$) Phosphate infill from an underlying bedding plane, interpreted as *Thalassinoides*. **A**$_3$) Thin section of the yellow burrow medium showing reworked microcoqina, phosphate and dolomite grains. **B**$_2$) Thin section of the trace infill showing Radiolaria, phosphate and minor microcoqina.

7.3 Trace infill

The trace infills of *Thalassinoides* were interpreted to be connected phosphate nodules. The trace infills were investigated by preparing thin section samples from different beds. The thin section shown in Figure 7.5A was taken from the boundary of the trace infill and the burrow medium. The burrow medium (upper part of the thin section) consisted of dolomite crystals, while the burrow infill (lower part of the thin section) brown phosphate peloids and pyrite were abundant. Figure 7.5 B-D shows thin sections of trace infill found in three different beds. Moulds of Radiolaria and phosphate peloids were present in all the investigated thin sections.

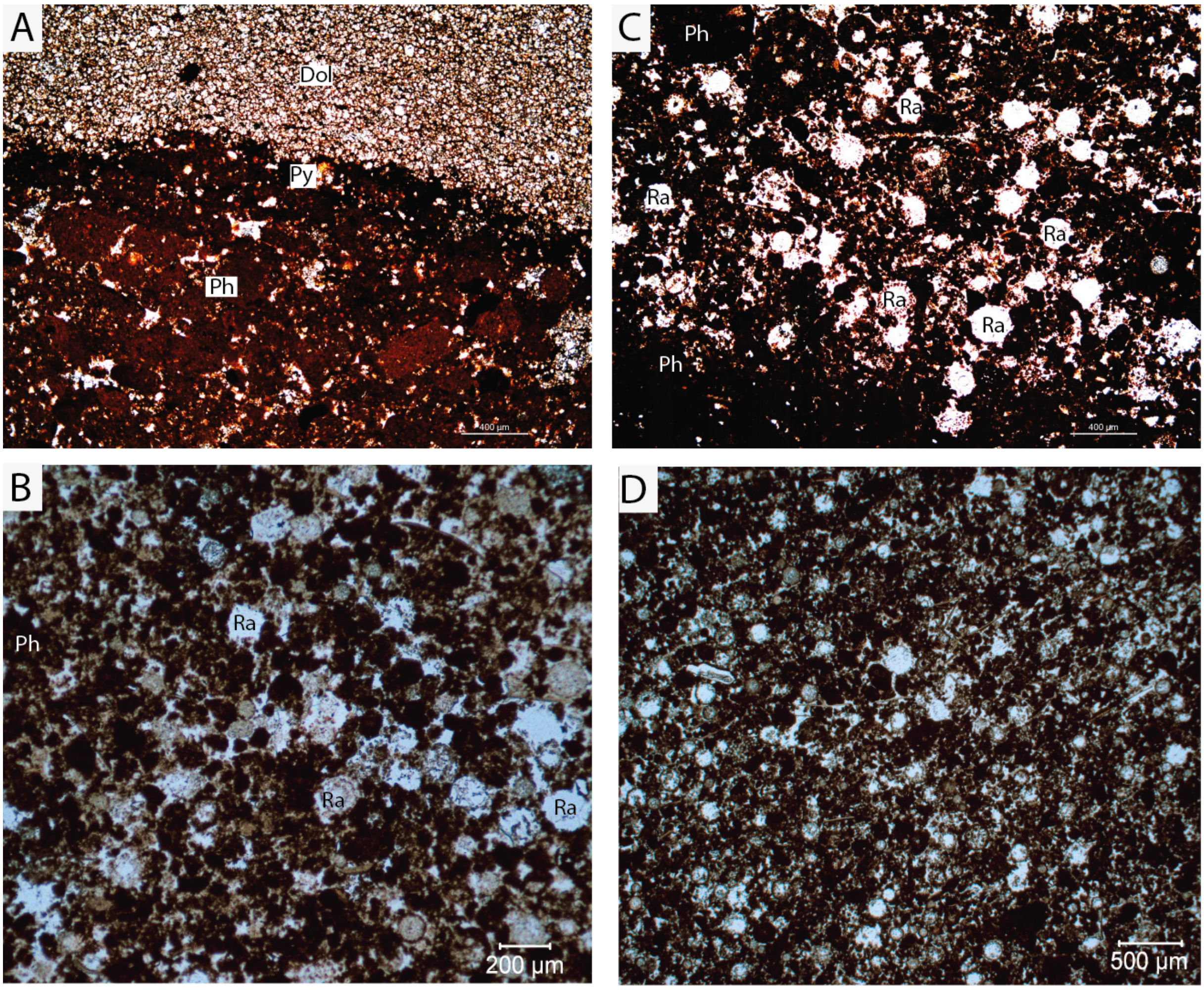


Figure 7.5: Thin sections of *Thalassinoides* trace infill, Dol = Dolomite, Py = pyrite, Ra = Radoiolaia, Ph = Phosphate **A)** Trace infill in the lower part of the thin section including phosphate and pyrite, burrow medium in the upper part, a dolomite rich siltstone. From Blanknuten NW Valley, Edgeøya. **B)** Trace infill rich of Radiolaria and phosphate peloids, Muen, Edgeøya. **C)** Trace infill rich in Radiolaria and phosphate peloids, Muen, Edgeøya. **D)** Relatively similar as **B)** and **C)** with Radiolaria and phosphate from Muen, Edgeøya.

7.4 Trace fossil size

Here follows the results from the trace fossil size analysis of *Thalassinoides* including burrow diameter and burrow width from samples from Muen.

7.4.1 Burrow diameter

The burrow diameter of *Thalassinoides* was measured throughout the succession, and compared to other studies of *Thalassinoides* from the Middle Triassic world-wide. The box-plot presented in Figure 7.6 shows the burrow diameter of *Thalassinoides* traces found on mainly from the Muen Plateau (see Section 6.1). The samples in Figure 7.6 are presented in stratigraphic order, with younger traces towards the right.

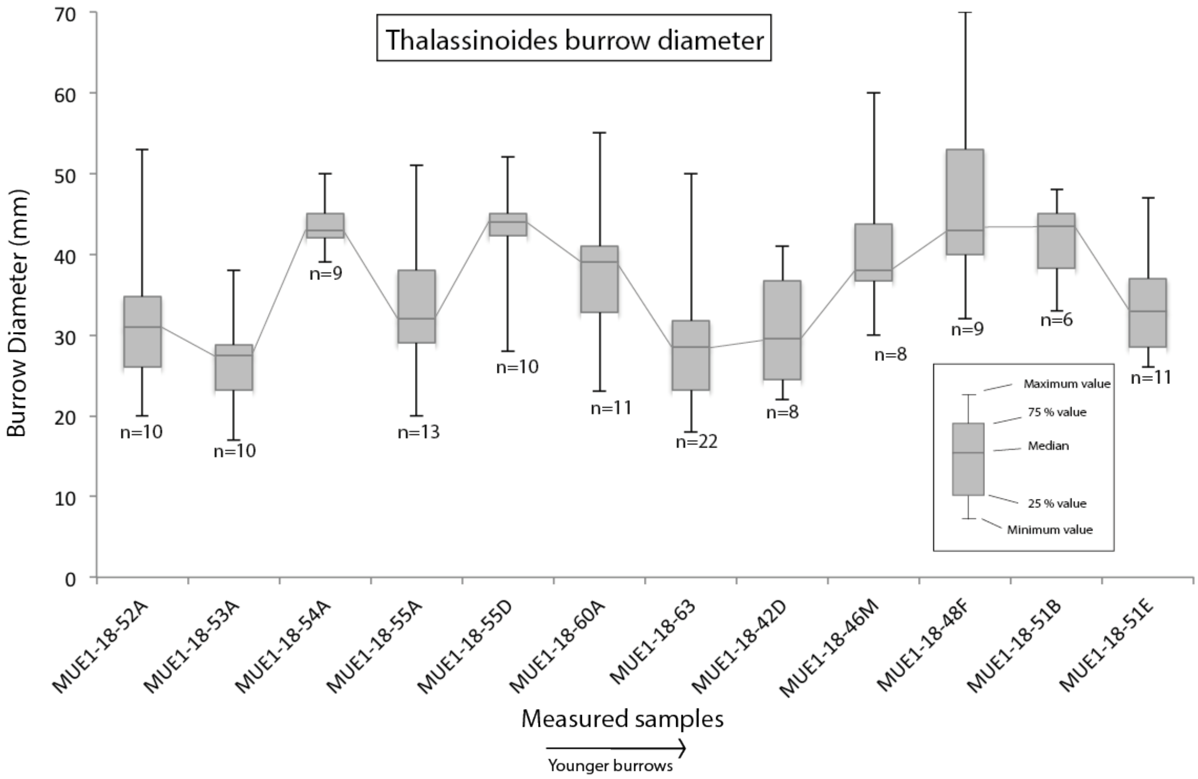


Figure 7.6: Box-plot showing the burrow diameter of *Thalassinoides* from 12 samples from the Muen Plateau (Interval 2), in total 127 pieces of trace infill. The samples are organised in stratigraphic order, from older to younger traces towards the right in the figure. The maximum, minimum, 25 %-, 75 %- and the median value for each sample is indicated in the box-plot.

In total, the diameter was measured at 127 different fragments of the trace infill. The diameter ranged from 9 to 70 mm, with an average diameter of 36.6 mm, the highest diameter was measured for sample MUE1-18-48F, while the lowest diameter was measured for sample MUE1-18-53A. The diameter seemed to be independent on the stratigraphic order, and, although the measured diameters vary, the median, ranging from 28 to 44 mm, seemed to be relatively uniform. The diameters measured for the samples MUE1-18-54A and MUE1-18-51E were most consistent, while the diameters measured for MUE1-18-48M and MUE1-18-60A varied mostly. Where the box plot is comparatively short, the overall measurements of the diameters in between the same horizontal bedding plane is relatively close, as for the sample MUE1-18-54A and MUE1-18-51E. However, if all samples are compared together, the median seems to be relatively uniform.

7.4.2 Burrow width

The burrow width was measured to determine how consistent the burrow width was throughout the succession, and if compaction had any effect on the trace infill. The box-plot presented in Figure 7.7 shows the burrow width from different samples of *Thalassinoides*. As for the diameter measurements, discussed above, the width was measured from samples collected from the Muen Plateau, Edgeøya. In total the burrow width was measured on 99 fragments of the trace infill from 11 different samples. Each sample is collected from the same horizontal bedding plane, with the same height in the stratigraphy. The samples are presented in Figure 7.7 with younger traces to the right.

The widest measured sample MUE1-18-46M was 17.5 mm, while the lowest width was measured for sample MUE1-18-60A was 3 mm. The older burrows, on the left side in Figure 7.7 seem to have a smaller burrow width compared to the younger burrows. The variations within each horizontal bed seem to be relatively low for the burrow width measurements.

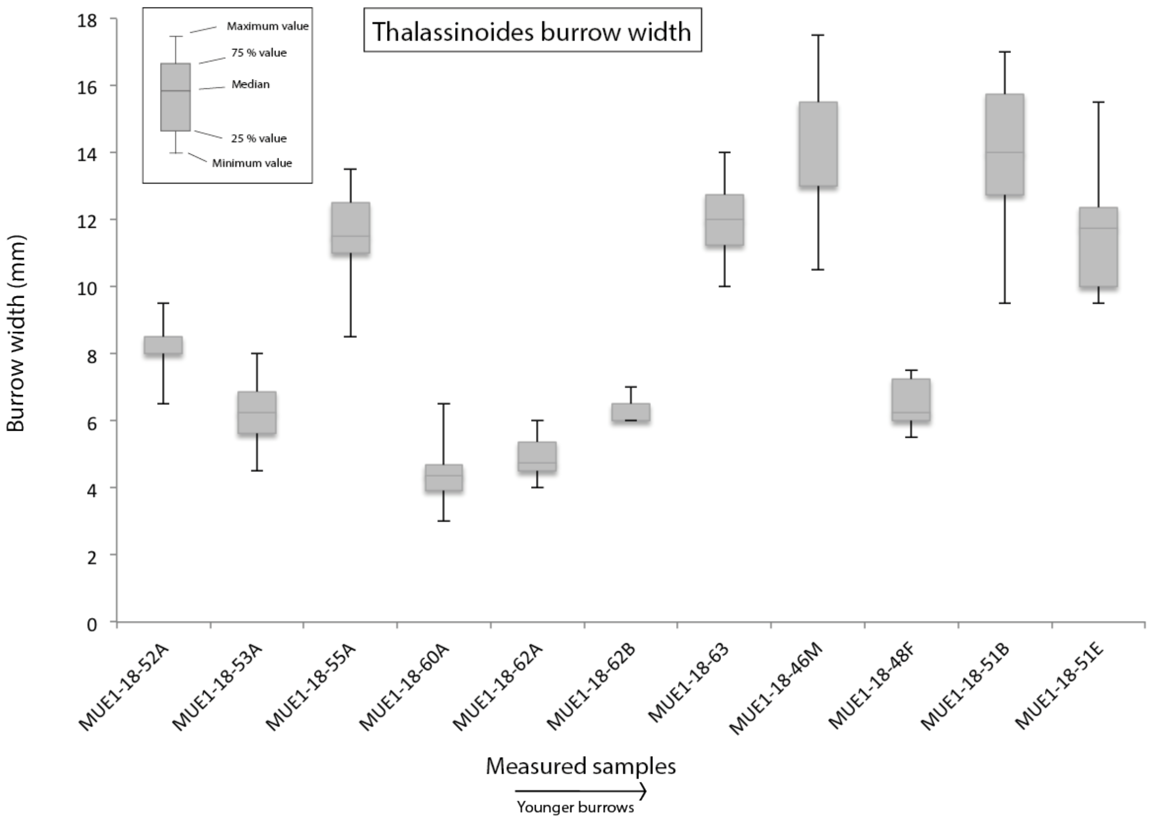


Figure 7.7: Box-plot showing the burrow width of *Thalassinoides* from 11 samples from the Muen Plateau (Interval 2), in total 99 pieces of trace infill. The samples are organised in stratigraphic order, from older to younger traces towards the right in the figure. The maximum, minimum, 25 %-, 75 %- and the median value for each sample is indicated in the box-plot.

7.5 Computed tomography scanning

Computed tomography scanning (CT-scan) is a useful tool when studying rock samples. A CT-scan can give a detailed overview of the sample and identify connected tunnels in the rock that would otherwise be inaccessible. In particular, when studying trace fossils, a CT-scan is an important tool, as it is difficult to bring well-preserved samples back from the field. CT-scans were performed for a selected number of samples (Figure 7.8). The density differences between the burrow medium and the trace infill turned out to be low. Therefore, a time-consuming segmentation process was necessary to present the results from the CT-scans as presented in Figure 7.9.

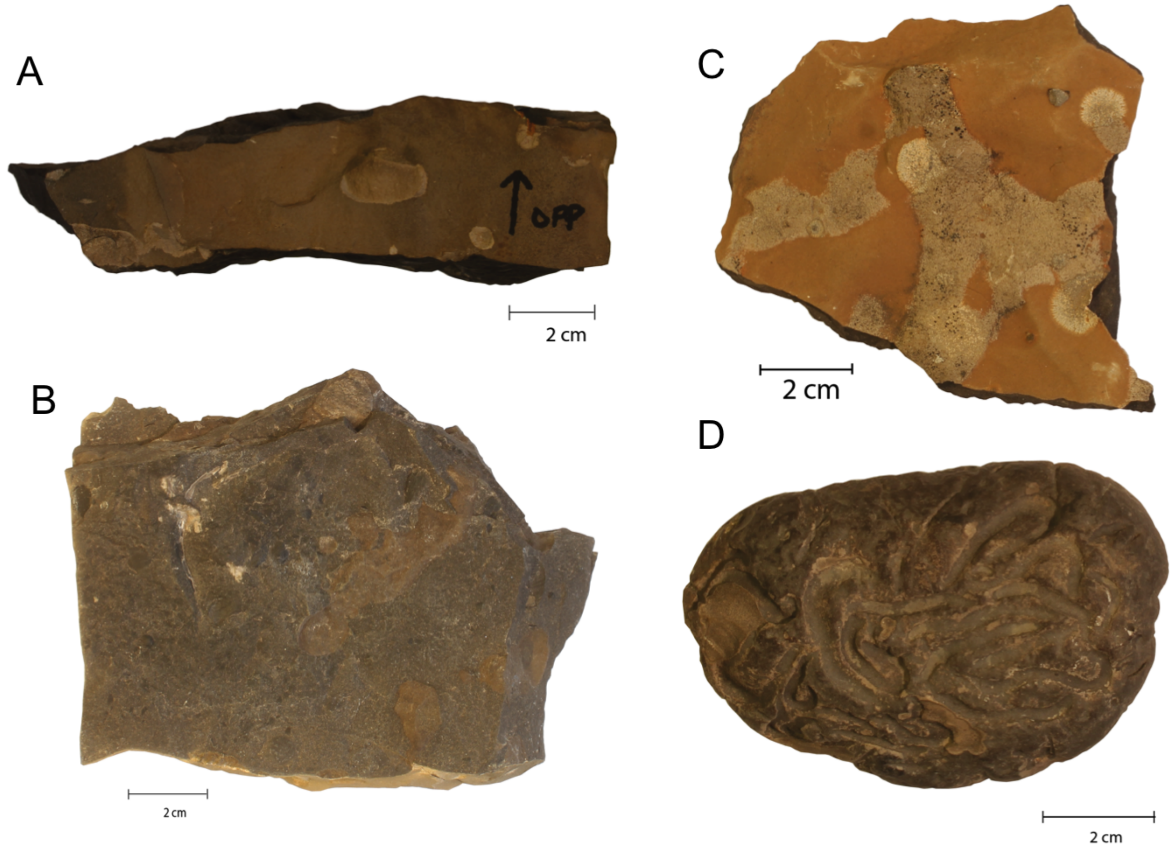


Figure 7.8: CT-scanned samples. **A)** and **B)** is a sample from the Krykkjeglupen, Edgeøya (Sample: BLA1-18-29D) **C)** Sample from the Botneheia Formation on central Spitsbergen collected by Atle Mørk and **D)** Nodule-like feature found on the Skrukkefjellet Mountain.

A CT-scanning was made of a sample collected from the Krykkejeglupen locality shown in Figure 7.8A and B. The result of this CT-scan is shown in Figure 7.9A and B and indicates well-preserved phosphate nodules, which is interpreted to be the trace fossil *Thalassinoides*. In total 13.2 % of the sample contains *Thalassinoides*. *Thalassinoides* and ammonoids were present in another sample (Figure 7.9C and D and Figure 7.8C). The burrows do not seem to cross the ammonoid, which is an indication that the ammonoid was first deposited, followed by the trace maker disturbing the sediment. The observable burrows shown in Figure 7.9 were not fully connected.

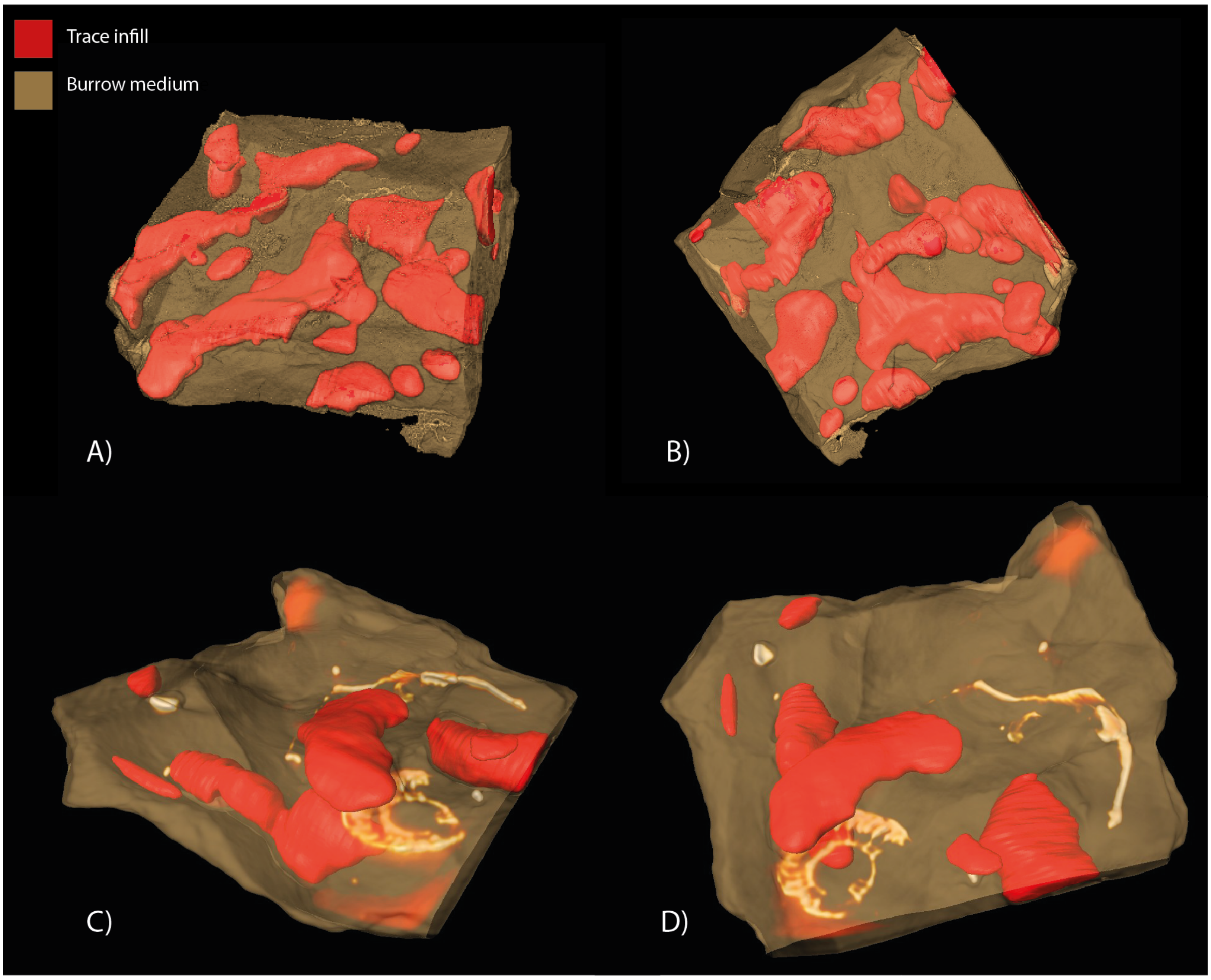


Figure 7.9: Results of the computed tomography scans from the Botneheia Formation on Svalbard. The trace infill of *Thalassinoides* is shown in red and the burrow medium a yellow weathered-siltstone is shown in brown. **A)** and **B)** is a sample from the Krykkjeglupen on Edgeøya representing 13.2 % of *Thalassinoides* **C)** and **D)** is a sample from the Botneheia Formation on central Spitsbergen collected by Atle Mørk showing the traces interacting with an ammonoid

More samples than presented here were tested in the CT-scanner. The absence of visible density differences in the rock samples, meant that not all samples could be segmented. Lack of tunnel-shaped density differences is believed to represent the absence of *Thalassinoides* trace fossil inside the specific sample. The CT-scan shown in Figure 7.10A had a visible tunnel of *Thalassinoides* in hand specimens and is the sample shown in Figure 7.1E. The cross-section of the CT-scan shown in Figure 7.10B) indicate a lack of density differences inside the rock.

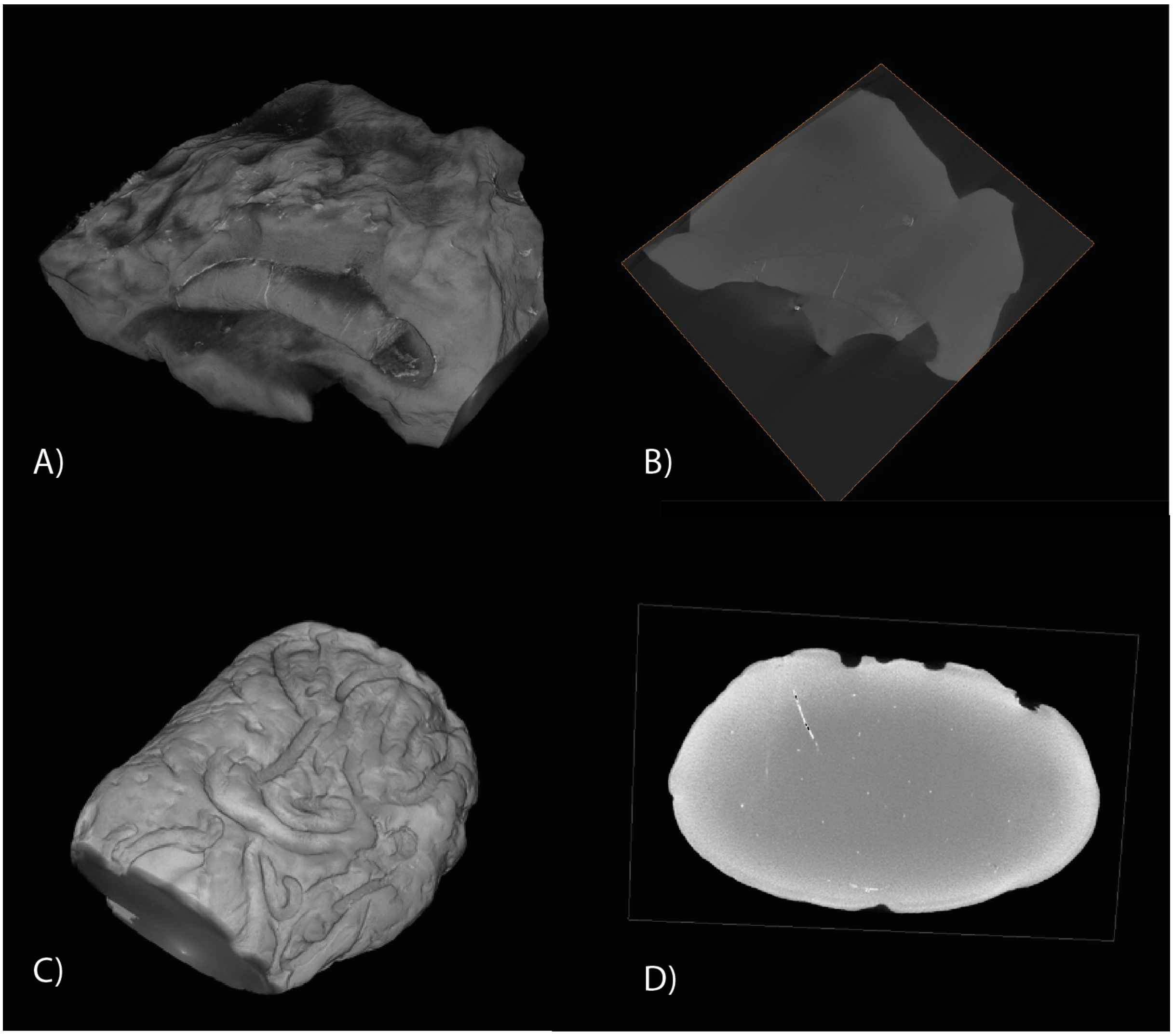


Figure 7.10: CT-scans from Skrukkefjellet, Edgeøya **A)** Sample from *Thalassinoides* visible on the rock surface **B)** Cross section of **A)** obtained from CT-scan showing no density differences **C)** Nodule-like feature with an unknown tunnel system **D)** Cross-section of the unknown tunnel system, no density differences observed.

Two nodule-like features with the same type of tunnel systems were found as scree on the Skrukkefjellet mountain in the Botneheia Formation (see Figure 7.8D). These tunnels could not be identified, and do not share many similarities with trace fossils observed in the Botneheia or the Bravaisberget Formations. One of these nodules was CT-scanned to investigate if tunnels were present inside the rock (see Figure 7.10A). Figure 7.10B shows a cross-section of the rock, which do not show any density differences. The identified tunnels on the surface of the samples seem to be caused by some trace making animals, or some bioturbation occurring while the rock was still soft enough to deform.

8. Discussion

The following chapter presents and evaluates the main findings from this work in light of the established literature (see Chapter 2 and 3). First spatial and temporal variations of *Thalassinoides* are discussed, followed by the origin of phosphate nodules and their relation to the burrow infill of *Thalassinoides*. Then the trace fossils in the Middle Triassic on Edgeøya are discussed considering their size, global distribution, tiering and facies distribution. Finally, palaeo-environmental conditions are considered.

8.1 Spatial and temporal variations

In this work, sedimentary logs were produced from six localities on Edgeøya to describe occurrences of trace fossils. To further investigate how the trace fossils vary laterally in the Blanknuten Member on Edgeøya, log correlations were made and presented in Figure 8.1. From Skrukkefjellet located in the north, to Muen, located further south on Edgeyøa the distance was approximately 42 km. The purple siderittic nodules at the base of the Tschermakfjellet Formation were used as a datum to correlate the sedimentary logs.

Correlating *Thalassinoides* across the field localities was challenging for a number of reasons including poor outcrop quality, lack of burrows and local fluctuations in the bottom environment. The outcrops were in general steep, and cliff-forming and easily accessible bedding surfaces were limited at many localities. *Thalassinoides* were mostly observed in several beds at Muen, which made it almost impossible to correlate with the other localities where limited findings of these burrows were made. Absence of well-exposed bedding surfaces seems to be the main cause for the lack of observation at the other localities. Local fluctuations in the bottom environments across the different localities could cause *Thalassinoides* to be deposited at different levels in the stratigraphy or lacking due to limited oxygen availability.

At all localities, siltstone beds (LF-3) were present at different stratigraphic intervals. Some of these siltstone beds were easily correlated across the closely spaced field localities (see Figure 8.1). Most accurate correlations of the siltstone beds were between Blanknuten NW Valley and Krykkjeglupen, as the distance between these localities is only 3.5 km. It requires more energy to transport silt particles compared to clay, and the siltstone beds were interpreted to represent episodes of higher erosion rates and higher energy caused by storm-events which brought pulses of oxygen to the dysoxic-anoxic basin (Mørk and Bromley, 2008). The Middle Triassic lasted for a period of approximately 10 Ma, and it is not unlikely that several storm-events and pulses of oxygen occurring during this time as event-beds are relatively common from a geological perspective. Not all the siltstone beds from the different sedimentary logs can be fully correlated, which could be related to inconsistency in the wind- and current directions operating in the basin through time. Other factors affecting pulses the of oxygen and deposition of siltstone beds across the basin could be related to the ocean wave height which is dependant on wind speed, length of fetch and the duration of the wind (Johnson and Baldwind, 2006). The algae *Botryococcus* spp. have been found from cores of the Botneheia Formation drilled close to Kong Karls Land described by Vigran et al. (2014). The *Botrycoccus* spp. is widely distributed in aquatic environments, especially in lakes and brackish lakes (Vigran et al., 2014; He et al., 2018). This could indicate sedimentary provenance not far from the shelf. According to Brekke et al. (2014) the Botneheia Formation contains sedimentary organic matter with transported terrestrial fractions in addition to autochthonous marine organic matter.

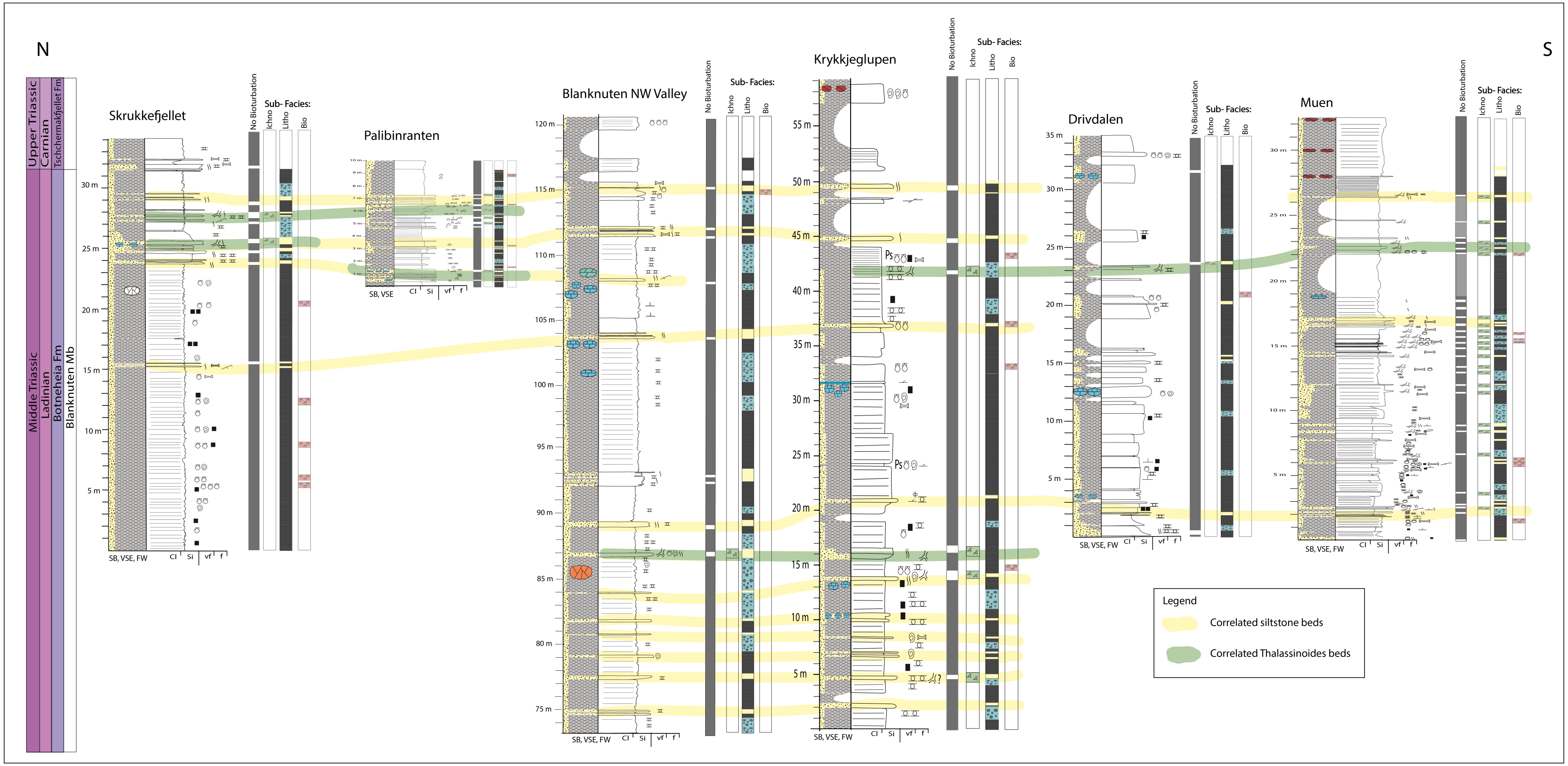


Figure 8.1: The sedimentary logs from visited localities on Edgeøya. Yellow marks indicate correlated siltstone beds, green indicate correlated *Thalassinoides*.

Maps showing the distribution of *Thalassinoides* through the Ladinian succession on Edgeøya have now been produced based on field observations, spatial and temporal variations of the trace fossil (Figure 8.2). The ichnogenus *Thalassinoides* dominated the succession on Edgeøya and only a few observations of *Chondrites* and *Planolites* were made. Most of *Thalassinoides* were observed at Muen, while a few were observed at Blanknuten NW Valley, Drivdalen, Krykkjeglupen, Palibinranten and Skrukkefjellet.

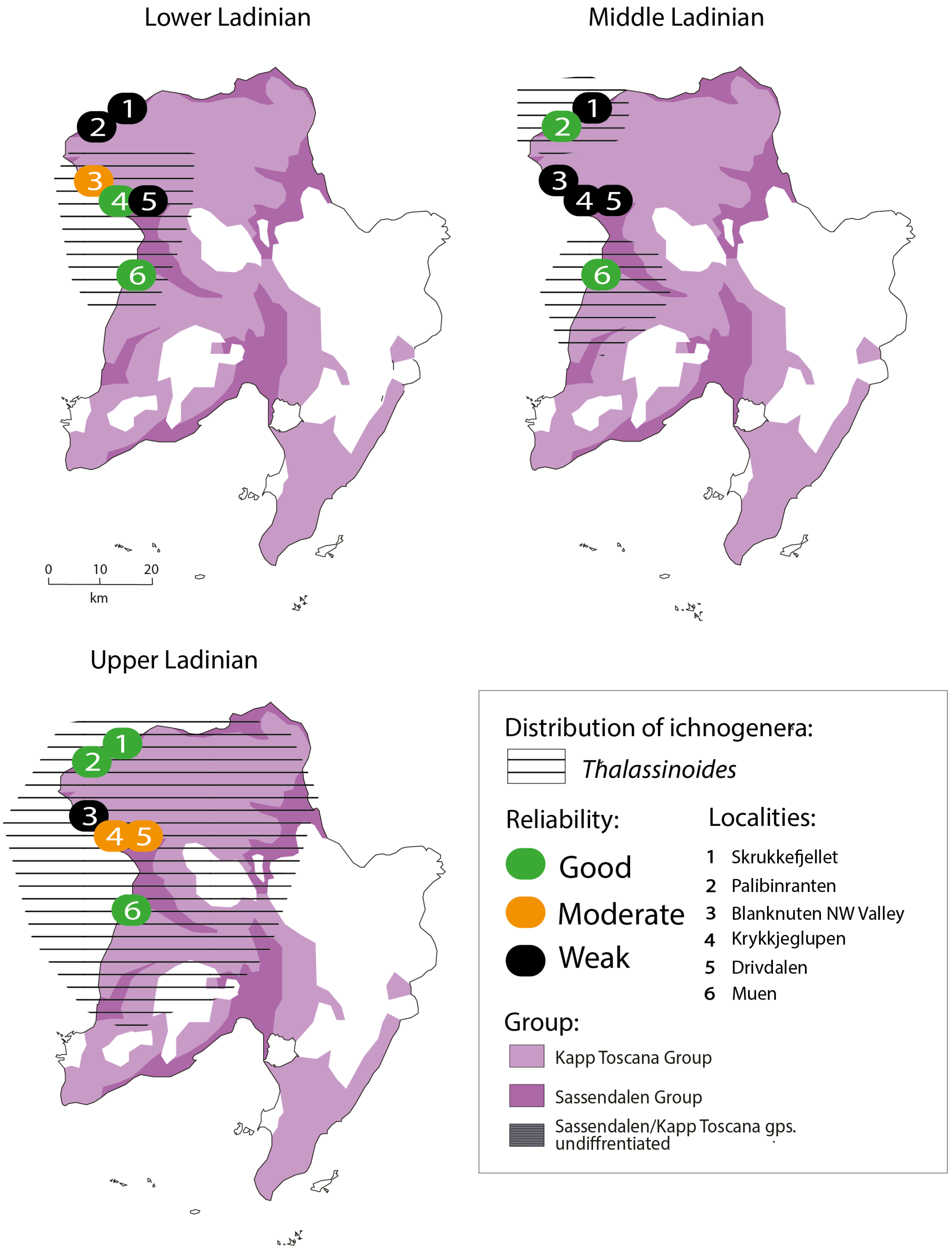


Figure 8.2: Maps showing the distribution of *Thalassinoides* through the Ladinian succession on Edgeøya. The data are from the different localities marked with numbers (1-6), and the reliability marked with the colours showing good (green), moderate (orange) and weak (black).

As *Thalassinoides* were not present over the whole succession on any of the visited localities, but in certain beds, the maps presented include, in some areas, interpolation and interpretation in order to provide a more meaningful overall schematic. Therefore, the reliability of the observations were taken into account and marked with different colours. In the upper Ladinian succession, occurrences of *Thalassinoides* are most frequent. Figure 1.2 shows a map of the trace fossil assemblages in the Middle Triassic on Svalbard produced by Mørk and Bromley (2008). On Edgeøya, the map shows a dominance of the *Thalassinoides* assemblages consisting of the ichnogenus *Taenidium*, *Polykladichnus*, *Rhizocorallium* and *Thalassinoides* (Mørk and Bromley, 2008). In this work, no observations of *Taenidium*, *Polykladichnus* and *Rhizocorallium* were made, and the succession is dominated only by the ichnogenus *Thalassinoides*. The ichnogenera marked to be present on Edgeøya by Mørk and Bromley (2008) is not in consistent with the results presented in this work. In Mørk and Bromley (2008) more detailed data were presented of the proximal Bravaisberget Formation compared to the distal Botneheia Formation, and as a consequence, the lack of detailed information led to some over-interpretation regarding the trace fossil assemblages on Edgeøya. The map presented in Figure 8.2 in this work gives an updated and more precise view of the trace fossils on Edgeøya.

8.2 *Thalassinoides* vs. phosphate nodules?

The observed burrow systems in the upper Blanknuten Member on Edgeøya belongs to the ichnogenus *Thalassinoides*. The remaining evidence of these burrow systems was the network of phosphate nodules which were visible on the bedding surfaces. Body fossils or scratches were not found preserved in association with the burrow system. The expression of both connected and un-connected phosphate nodules in the outcrop, addresses the issue of how these burrows was preserved.

The observations from the Middle Triassic succession on Edgeøya indicated that some of the phosphate nodules were fillings of the trace fossil *Thalassinoides*. On all localities, the phosphate nodules were frequently found in the succession and had variable size and shape. The nodules were present either as phosphorite conglomerate, occasionally incoherent nodules or as lags of phosphate nodules. Most of the phosphate nodules observed were not associated with the trace fossil *Thalassinoides*, this based on the wide range in size of the nodules and the lack of clear connection between them. Krajewski (2000, 2008) did not link all the phosphate nodules in the Botneheia Formation to be infills of the trace fossil *Thalassinoides*. Although, the lack of well-exposed bedding surfaces reduced the chance to observe the horizontal burrow systems, it is unlikely that all the phosphate nodules in the Blanknuten Member were formed by *Thalassinoides* burrows as stated by Mørk and Bromley (2008) as discussed in Section 1.1.1. In the literature, only a few studies correlate the formation of phosphate nodules to the fillings of *Thalassinoides* burrows (Fürsich, 1973; Mørk and Bromley, 2008). Fürsich (1973) investigated the *Thalassinoides*-rich limestone beds in the Upper Jurassic, Corallian Bed, in Southern England. The study indicated that the nodules were infills of *Thalassinoides* traces (Fürsich, 1973). The mechanisms responsible for the formation of nodules in the limestone were suggested to be a combination of early infill and cementation of the *Thalassinoides* burrows, burrow density and compaction (Fürsich, 1973). The similar mechanisms, as shown in Figure 8.3, help explain the correlation between *Thalassinoides* and some of the observed phosphate nodules in the Blanknuten Member on Edgeøya.

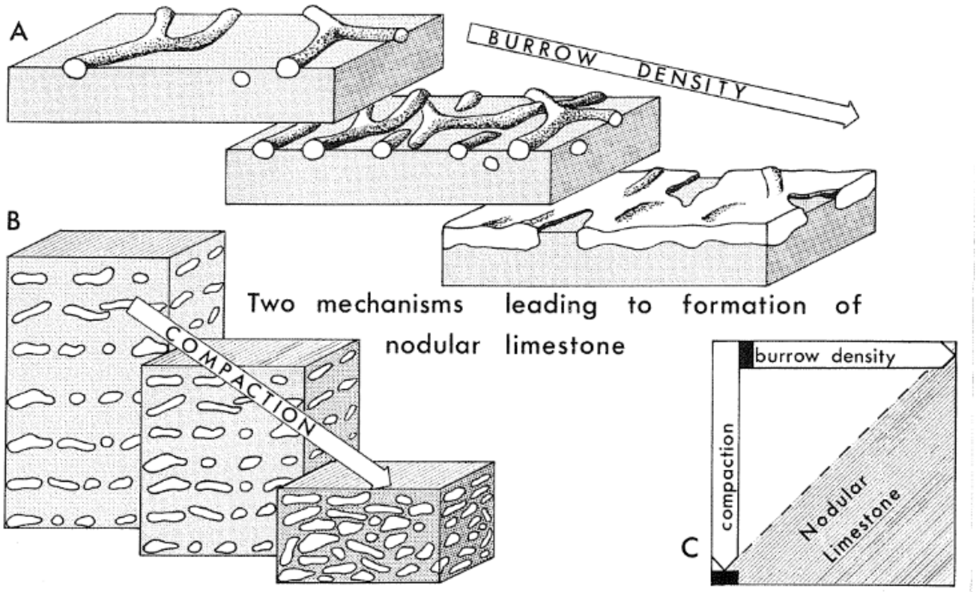


Figure 8.3: The two mechanisms burrow density and compaction leading to formation of nodules. Figure from Fürsich (1973).

There was no findings of body fossils or scratches associated with the *Thalassinoides* burrow system. Crustaceans in the fossil record are usually sparse (Whicher et al., 2016). Burial by diagenesis cause dissolution and decomposition of the cuticule which is the lightly skeletal materials of the crustaceans (Schäfer, 1972). The Botneheia Formation is deposited in a low-energy environment with fluctuating anoxic, dysoxic and oxic conditions. Preservation of light skeletal organisms is usually effective in this type of low-energy environments (Seilacher et al., 1985). However, experiments by Allison (1988) showed that anaerobic processes are effective means of decay and light skeletons can easily be broken down giving them a low preservation potential. In addition, the seafloor is usually abundant with abandoned burrows as the trace maker usually leave their burrow after construction and do not return (Whicher et al., 2016).

Based on the observations made from this work and from the literature, a conceptual model through time from the formation of *Thalassinoides* burrows to the present connected phosphate nodules in the silty shale of the Blanknuten Member succession was made and is shown in Figure 8.4. First, organic-rich soft sediment was deposited. The crustacean deposit feeder burrowed into the sediment in order to search for food, producing horizontal burrow systems where oxygen-rich water was brought in to the burrow for respiration (Waslenchuk et al., 1983). To stabilise the burrows, organic matter and fine-grained material was decomposed and later cemented through the secretion of mucus by the Crustaceans (Dworschak, 1983; Vaugelas and Buscail, 1990). At the burrow wall, exchange of solutes between the burrow water and the sediment was likely to occur (Aller et al., 1983; Vaugelas and Buscail, 1990). The high concentration of solutes in the burrow wall enhanced the reaction with phosphorous which was present in the burrow water (Waslenchuk et al., 1983; Krajewski, 2000). From experiments of modern *Thalassinoides* burrows, no major changes in the burrow shape were observed, but the burrow wall underwent constant changes (Dworschak, 1983). During early diagenesis processes precipitation of carbonate apatite reacted with the decomposed organic matter and the mucus in the burrow wall which contributed to form the characteristic phosphate infill which eventually preserved the *Thalassinoides* burrows (Mørk and Bromley, 2008). The burrow infill was influenced by compaction, which contributed to modify the trace infill and produced the nodular appearance (Fürsich, 1973). In 3D view/vertical view, lags of non-connected phosphate nodules were visible in outcrop but difficult to recognise as the trace fossil *Thalassinoides*.

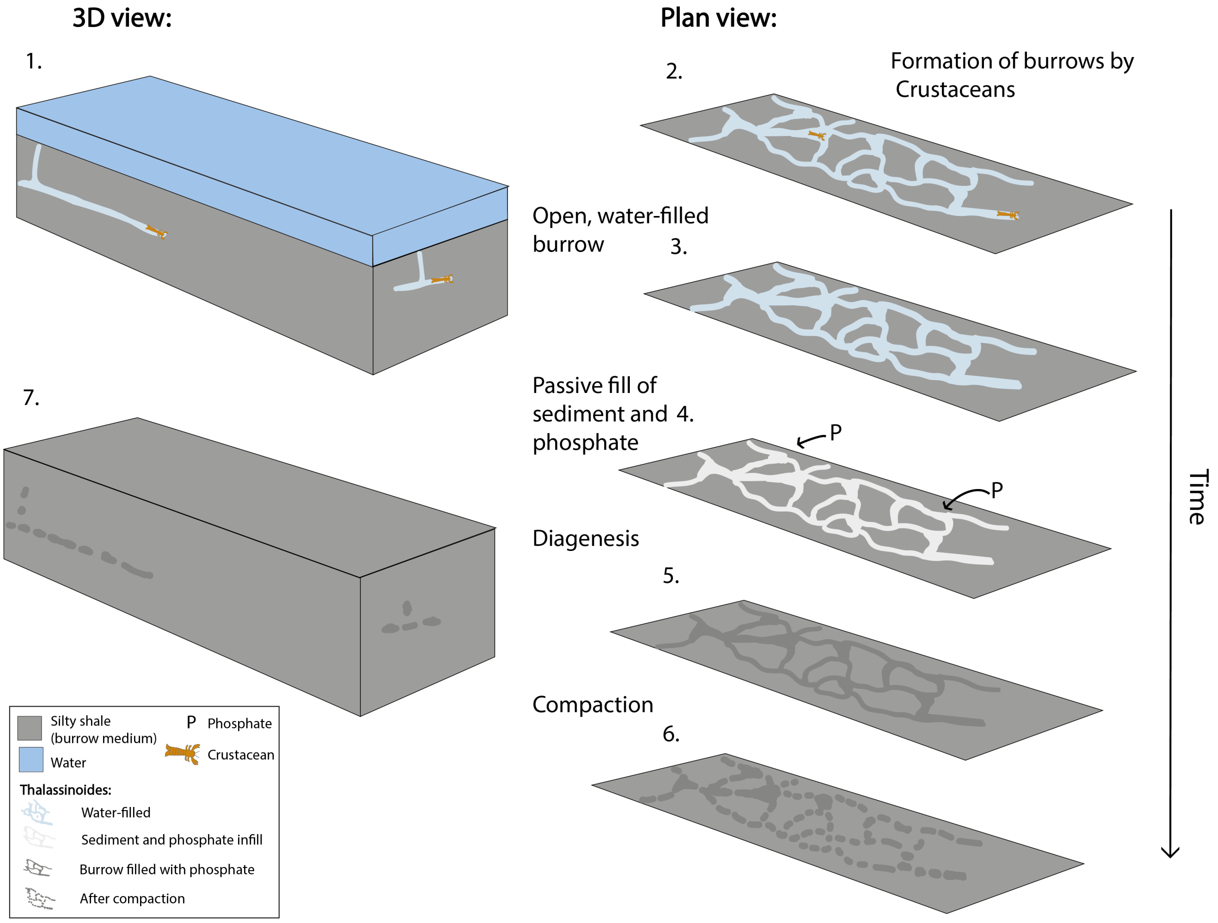


Figure 8.4: A conceptual model of the formation of *Thalassinoides* traces and the later formed phosphate infill in the silty shale of the Middle Triassic succession on Edgeøya.

8.3 Trace fossils in the Middle Triassic

8.3.1 Ichnofacies

Thalassinoides were found to be monospecific, and the lack of other ichnotaxa made it almost impossible to incorporate them in to the established ichnofacies *Teredolites*, *Glossifungites* or *Cruziana*. Instead, it was decided to classify the ichnofacies in the Blanknuten Member as the sub-facies *Thalassinoides* (IF-1) in this work. The ichnofacies *Teredolites* are usually present in borings of wood-ground (Pemberton and Wightman, 1992; Buatois and Mángano, 2011), which do not match with the deposits and burrows in the Blanknuten Member. The *Glossifungites* ichnofacies are known to have horizontal *Thalassinoides* burrows and are common in high-energy environments (MacEachern et al., 1992, 2007). A high-energy environment is unlikely for the Botneheia Formation which have been interpreted to be deposited in an open shelf environment (Mørk et al., 1982; Worsley, 2008; Krajewski, 2008). The *Cruziana* ichnofacies have dominantly horizontal burrows and are deposited in moderate to low energy conditions (MacEachern and Pemberton, 1992; MacEachern et al., 1999; Buatois and Mángano, 2011). The horizontal burrows of *Thalassinoides* and the low-energy conditions seem to fit for the burrows in the Botneheia Formation. As the findings from Edgeøya mainly include *Thalassinoides*, the ichnodiversity is too low to confidently incorporate the burrows in the Blanknuten Member to the *Cruziana* ichnofacies.

8.3.2 Lack of tiering in the Blanknuten Member

It was expected to find a well preserved tiering structure in the Middle Triassic succession on Edgeøya based on the work of Mørk and Bromley (2008). In addition to the ichnogenus *Thalassinoides*, minor findings of *Chondrites* and *Planolites* were found, but not preserved in a tiered structure. The lack of other ichnotaxa and tiering structures suggests poor living conditions in the sediment, probably caused by the low oxygen content in combination with a soupy substrate consistency (Martin, 2004; Gingras et al., 2011). The tiering model can only be applied to beds which are distinctly burrowed (Savrda and Bottjer, 1989b). The beds filled with *Thalassinoides* in the succession on Edgeøya are interpreted to indicate short-term oxygenation periods, where the primary strata are thin with a lack of cross-cutting relationships, indicating there was not sufficient time to establish a tiering structure in the sediment during the short-term oxygenation period (Savrda and Bottjer, 1989b; Martin, 2004).

Usually, biogenic structures are difficult to recognise or are not preserved in mudstones or shale (Wetzel, 1998). Wet weather during fieldwork contributed to making the observations of trace fossils even more difficult. In addition, compaction, weathering or low contrasting colour difference between trace medium and trace infill further inhibited identification (Wetzel, 1998). Diagenetic processes could have contributed to masking imprints in the sediment.

The lack of observations of a tiering structure and other ichnotaxa on Edgeøya indicate that the previously constructed tiering model presented by Mørk and Bromley (2008) is not valid on Edgeøya. However, the tiering model is probably valid further west, in the Bravaisberget Formation, where more distal deposits are present giving better living conditions for a more diverse ichnofauna (Mørk and Bromley, 2008).

8.3.3 Global trace fossil diversity

Figure 8.5 shows the global distribution of trace fossil assemblages from the Middle Triassic reported from South China (Feng et al., 2017b,a; Luo et al., 2016), southern Poland (Chrząstek, 2013; Kowal-Linka and Bodzioch, 2011; Jaglarz and Uchman, 2010), south Israel(Korngreen and Bialik, 2015) and the Germanic basin (Knaust, 2007, 2013) including the new findings from this thesis.

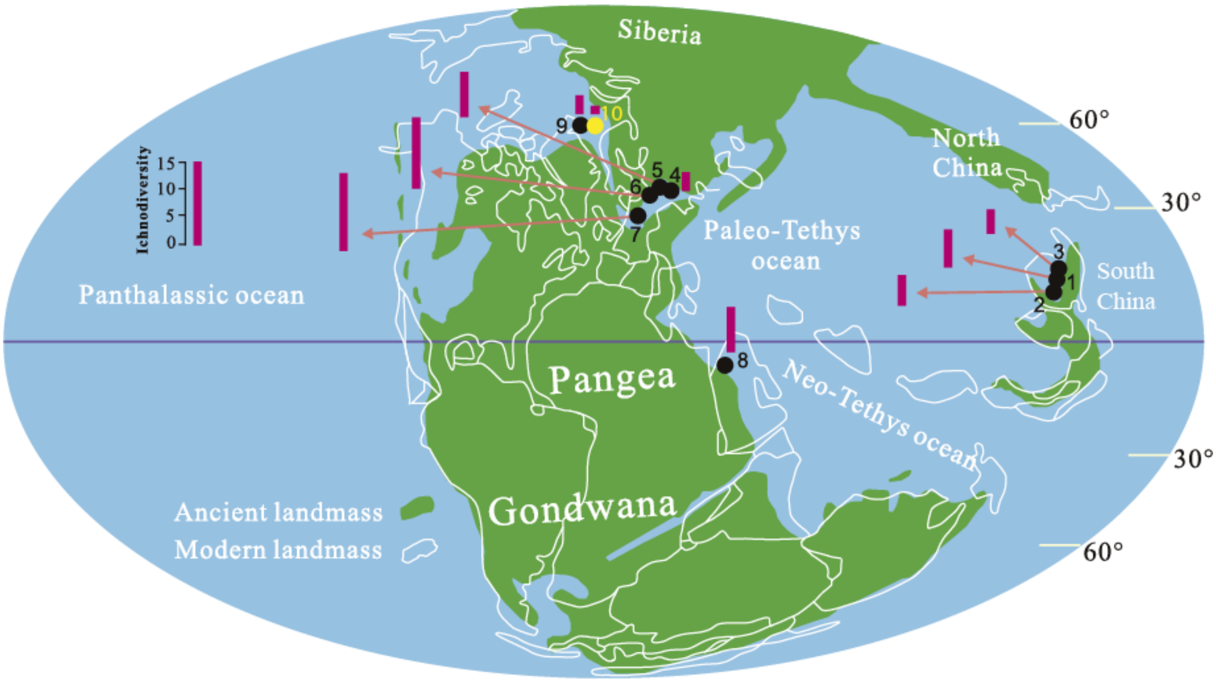


Figure 8.5: Global distribution of the trace fossil diversity during the Middle Triassic (mainly Anisian), modified from Feng et al. (2017b). Pink colour representing ichnogenera. 1: Boyun, Yunnan Province, South China (Feng et al., 2017b) 2: JMC, Yunnan Province, South China (Feng et al., 2017b) 3: TSQ, Yunnan Province, South China (Luo et al., 2016) 4: Upper Silesia, South Poland (Kowal-Linka and Bodzioch, 2011) 5: Tatra Mountains, South Poland (Jaglarz and Uchman, 2010) 6: Raciborowice Gòrne, South Poland (Jaglarz and Uchman, 2010) 7: Central Germany (Knaust, 2013) 8: Levant Basin, South Israel (Korngreen and Bialik, 2015) 9: Bravaisberget Formation, Western Svalbard (Mørk and Bromley, 2008) 10: Botneheia Formation, Edgeøya, Svalbard (this thesis).

The majority of the ichnofauna found in the Middle Triassic have a low to moderate ichnodiversity (Feng et al., 2017b). Svalbard is currently the area with the lowest ichnodiversity of the Middle Triassic successions worldwide, though more studies are needed to cover all exposed areas. The Bravaisberget Formation on Eastern Svalbard shows a higher ichnodiversity compared to the more distal deposits in the Botneheia Formation on Edgeøya, as the Bravaisberget Formation are interpreted to consist of delta-top and shallow sea settings with better living conditions for the trace making organisms (Mørk and Bromley, 2008). The

Boyun succession in South China consist of limestone deposited in an inner-ramp environment, while the older JMC succession consist of limestone and tempestites indicating a mid-ramp setting (Feng et al., 2017b). In the succession from the Tatra Mountains from southern Poland the deposits are carbonates deposited on a restricted carbonate ramp below the fair-weather base (Jaglarz and Uchman, 2010).

8.3.4 Trace fossil size distribution

This is the first time a trace fossil size analysis has been performed in the Middle Triassic succession on Edgeøya. The presented trace fossil size distribution found in this thesis has an average diameter of 36.6 mm, with a range from 17 to 70 mm. The relative burrow diameter is a proxy for the size of the burrowing organism.

Trace fossil size distribution from *Thalassinoides* traces found in the Anisian in the Boyun and JMC succession in south-western China by Feng et al. (2017b) had a mean diameter of 14.2 mm and a maximum diameter of 22 mm. Figure 8.6 shows the burrow size for *Thalassinoides* worldwide from Early Triassic, Anisian and the studied locality on Edgeøya. The burrow diameter measured by Feng et al. (2017b) from the Anisian is lower compared to the burrow diameters of *Thalassinoides* in the Ladinian succession on Edgeøya. According to Feng et al. (2017b), the mean burrow size of *Thalassinoides* found worldwide increased significantly from the Early Triassic to the Anisian as shown on Figure 8.6. The increase was higher for *Rhizocorralium* compared to *Thalassinoides*. The comparisons between the burrow sizes presented in Figure 8.6 are limited to a certain extent in that the data from this thesis concerns measurements from *Thalassinoides* only, whereas the measurements from other localities is from all burrows including both *Thalassinoides* and *Rhizocorallium*.

Size measurements of *Thalassinoides* from the Early Jurassic TNL member in the Fonte Coberta section in Portugal from the Early Jurassic reveal a diameter which varies between 10 and 34 mm, with an average of 22 mm (Rodríguez-Tovar et al., 2017). The measurements by Rodríguez-Tovar et al. (2017) from the Early Jurassic is lower compared to the Ladinian measurements from Edgeøya.

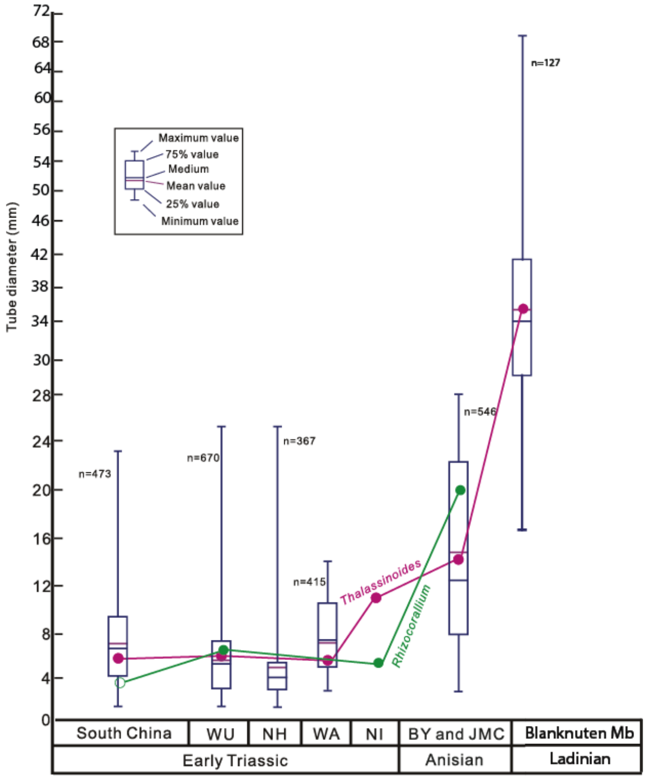


Figure 8.6: Burrow size of trace fossils from localities worldwide from the Early Triassic to Middle Triassic, including the size measurements from *Thalassinoides* from the Middle Triassic succession on Edgeøya. Modified from Feng et al. (2017b).

The size measurements of *Thalassinoides* from the Botneheia Formation on Edgeøya have been influenced by diagenetic processes which could have affected the trace fossil size. After influence of compaction, the burrow infill could have been stretched out, increasing both the original burrow diameter and burrow width. Another limitation of this trace fossil size analysis is that the data is only from one locality, the Muen Plateau. A greater quantity of measurements would have been preformed if several bedding planes with *Thalassinoides* were available for study, this would have given a more confidence to the data and the results would have been more representative for several areas on Edgeøya. In general though, it is clear that the diameter of *Thalassinoides* burrows from the Upper Blanknuten Member in the Ladinian succession are higher compared to other diameter measurements of *Thalassinoides* from the Early Triassic, Anisian and the Early Jurassic.

8.4 Palaeoenvironmental interpretations

8.4.1 Palaeo-oxygenation

The trace fossils found either in silty shale or in siltstone in the Blanknuten Member gives information of the bottom water conditions during the time the organisms burrowed in the sediment. When detailed vertical sedimentary analysis are available, as on the Muen Plateau (see Section 6.1), relative palaeo-oxygenation curves can be constructed. Figure 8.7 shows the sedimentary log of the Muen Plateau with an interpreted palaeo-oxygenation curve.

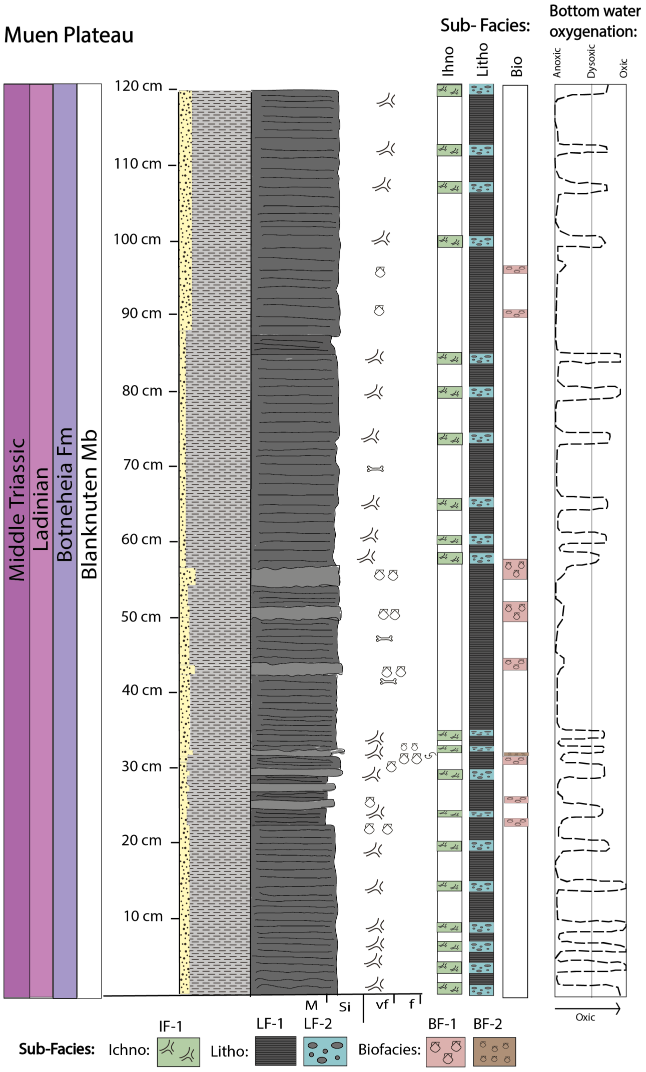


Figure 8.7: The sedimentary log of the Muen Plateau with a detailed paleo-oxygenation curve construction based on the observation of *Thalassinoides*.

The beds rich in *Thalassinoides* burrows were interpreted to reflect a dysoxic to oxic bottom environment, and where laminated black silty shale dominates, the bottom water was interpreted to be anoxic (Figure 8.7). During short intervals, the bottom water changed from anoxic to oxic, reflecting a short-term improvement of the bottom water. The lack of cross-cutting relationships and other ichnogenera in combination with relatively thin primary strata on the Muen Plateau indicate short oxygenation events rather than extended oxygenation events (Savrda and Bottjer, 1989b). The phosphate nodules, which are the trace infills of *Thalassinoides* in the Botneheia Formation, are another indicator of oxic/dysoxic conditions, as there are few examples of phosphate nodules from anoxic/euxinic conditions (Krajewski, 2011). A previous study of an Eocene oil shale in Jordan had similar observations (Hussein et al., 2014). The oil shale had intervals with abundant assemblages of the trace fossil *Thalassinoides* separated by organic-rich sediment, which suggested changes in the bottom water from an oxygenated to an oxygen-depleted system (Hussein et al., 2014).

On all visited localities on Edgeøya, *Thalassinoides* were present in siltstone beds. The isolated siltstone beds rich in *Thalassinoides* in the successions can be explained by the doomed pioneer model presented by Grimm and Föllmi (1994) and FöIlmi and Grimm (1990). The doomed pioneer model is based on field observations from the siliciclastic Oligocene-Miocene San Gregorio Formation in Mexico and the Miocene Monterey Formation of California, where isolated horizons of *Thalassinoides* occur in event-siltstone beds. Gravity flow transports animals from nearshore well-oxygenated settings to anoxic settings. The transported animals are called "doomed pioneers". The allactonous doomed pioneers burrows into the anoxic sediment and die rapidly by the lack of oxygen. The trace maker of *Thalassinoides*, crustaceans, have the potential to survive this type of transport and short periods under anoxic conditions (Grimm and Föllmi, 1994; Buatois and Mángano, 2011). Figure 8.8 shows a modified version of the doomed pioneer model, made suitable for the *Thalassinoides*-rich siltstone beds on Edgeøya. The difference between the original model by Grimm and Föllmi (1994) and FöIlmi and Grimm (1990) and the updated version is shown in Figure 8.8 is that silt and crustaceans are transported to dysoxic rather than anoxic conditions.

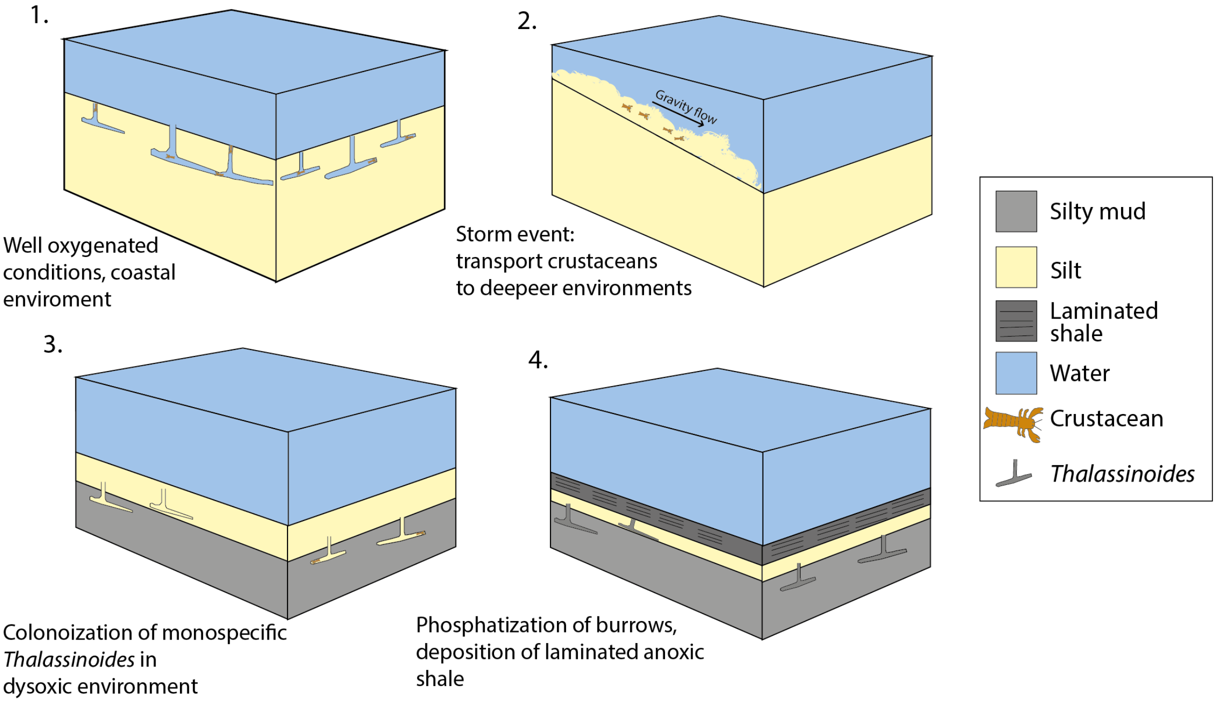


Figure 8.8: Conceptual model of how the trace maker of *Thalassinoides*, crustaceans, are transported together with silt by gravity flow to dysoxic environments **1:** Established community of crustaceans in a well oxygenated coastal environment. **2:** Storm-event causing transport of silt and crustaceans to deeper dysoxic environments. **3:** The colonisation of the trace making crustaceans in the dysoxic environment and formation of *Thalassinoides* takes place. **4:** *Thalassinoides* burrows get phosphatized, overlaid by laminated shale indicating anoxic conditions. The figure is based on the doomed pioneer model after Grimm and Föllmi (1994) and FöIlmi and Grimm (1990).

After storm-events, it is expected that higher mixing of the water column will occur, which thus helps to supply the bottom water with oxygen (Oschmann, 1988). The storm-events contributed to better living conditions for crustaceans to colonise and burrow in the sediment for a limited period. The duration of the oxygenated episode seem to be limited, as undisturbed and laminated shale often overlies the event bed. The organisms colonised the sediment for a limited amount of time before they died due to the insufficient amount of oxygen available. This model provides an explanation of the higher oxygenation periods, the absence of other trace fossils and the lack of a well preserved tiering structure in the Middle Triassic succession on Edgeøya.

In addition to trace fossil analysis, several other methods can be used as to provide an estimated proxy of the palaeo-oxygenation, e.g. TOC, trace elements, biomarkers and presence of certain elements (Demaison and Moore, 1980; Powell, 1988; Tribovillard et al., 2006). For example, under anoxic conditions, higher concentrations of U, Cu, MO, Ni, P and S are typical in the sediment (Demaison and Moore, 1980). In this work, TOC was available from

Blanknuten NW Valley and Muen. In general, the TOC content was decreasing with the presence of trace fossils, especially where the trace fossils were present in siltstone beds. The TOC was ranging from 1.5 to 12 wt.% in the successions. The TOC works as a proxy for palaeo-oxygen content since organic matter is higher under anoxic than oxic conditions (Demaison and Moore, 1980). TOC and lamination are expected to increase with a decreasing infauna and oxygen levels (Potter et al., 2005). The changes in TOC were higher in siltstone beds compared to the silty shale. The influx of silt material contributes to a higher dilution of organic matter (DeReuil and Birgenheier, 2018). The decreased TOC value observed do not necessarily have to be caused by the presence of *Thalassinoides* itself, but rather a combination of a higher dilution of the organic matter, more oxygen and, as a consequence, better living potential for the trace making organisms.

8.4.2 Lithostratigraphical units and relative sea level correlations

Krajewski (2008) divided the Botneheia Formation into nine lithostratigraphic units based on geochemical data, XRD and thin sections. Correlating these lithostratigraphic units with ichnological data is work that, previous to this study, something that has not previously been presented. Figure 8.9 shows these units and a relative sea level curve from Krajewski (2008, 2013) correlated with the sedimentary log from Muen from this work, based on the height profile from Krajewski (2008) investigations on Muen. The logged succession on Muen covers the middle, upper and top of the Blanknuten phosphorite-bearing unit, the units 7, 8 and 9 respectively.

Unit 7 was deposited during a period of high organic productivity, euxinic bottom conditions and a high relative sea level associated with the maximum flooding of the Barents Sea (Krajewski, 2013). Figure 8.9C indicate the typical euxinic bottom environment with intermittently oxygenated periods during unit 7. Unit 8 was described by Krajewski (2008) as black shale with uniformly distributed phosphate nodules and beds of coqina and reptilian fragments. According to Krajewski (2008, 2013), the unit is interpreted to be a regressive phase with a falling sea level. Figure 8.9D shows Krajewski (2013) interpretation of the bottom environment during unit 8, which were oxic-to-dysoxic, with some reworking by bioturbation. Few storm-events occurred during unit 8, but in general, the bottom environments were more oxygenated. Both unit 8 and 9 show a regressive trend, with oxic-dysoxic bottom environments (Krajewski, 2008).

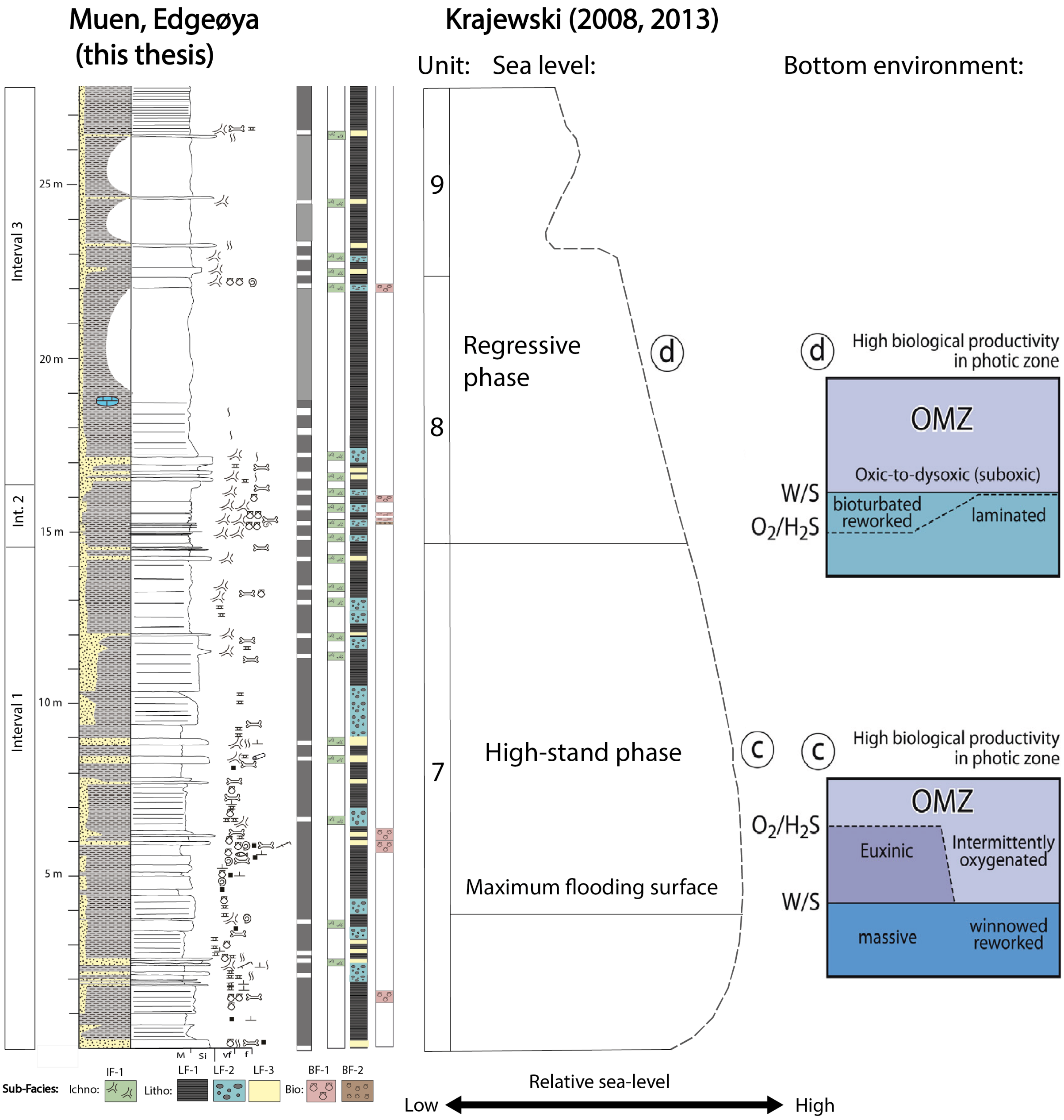


Figure 8.9: Sedimentary log of the Muen locality correlated with Krajewski (2008, 2013)

Unit 7, correlates to the Interval-1 on Muen shown in Figure 8.9. Interval-1 consisted of 10 beds of *Thalassinoides* burrows present in the siltstone beds, which were interpreted to be transported to the basin by storm-events. The transport of crustaceans and silt by storm-events indicate periods of oxygenated conditions. The storm-events corresponds well with Krajewski (2013) interpretation of intermittently oxygenated bottom water conditions. Interval-2 (Muen Plateau) and parts of Interval-3 of the logged succession on Muen correlates with unit 8 (see Figure 8.9). The Muen Plateau had 20 beds of *Thalassinoides* inter-bedded with dark shale and coqina beds indicating bottom water conditions fluctuating from anoxic/dysoxic to oxic. The data from this work were interpreted to be more dysoxic compared to Krajewski (2013) interpretation of the bottom water oxygenation. Overall, the bottom water conditions from this work seem to correlate relatively well with Krajewski (2008, 2013) work.

It is not appropriate to use the information of *Thalassinoides* burrows to produce relative sea level curves, as *Thalassinoides* itself is not a good indicator of water depth. *Thalassinoides* is known from shallow to deep marine environments and so represents a broad range of bathymetric depths (Ekdale, 1992). The presence of *Thalassinoides* indicate that oxygen was present in the bottom-water, but a specific depth could not be distinguished based on this data. The relative sea level curve on Figure 8.9 indicates a high-stand phase during unit 7 and a regressive phase during unit 8 and 9. In unit 7, the burrowers could not survive in the silty shale, due to the lack of oxygen caused by the high-stand. Instead, storm-events transported the burrowers to the more dysoxic areas during the high-stand in unit 7. During the shallower, regressive phase in unit 8 and 9 the living conditions were better, and the burrowers could rework the silty shale. The higher energy from storm-events transport the silt particles further out on the shelf where lower energy conditions close to the storm-wave base prevail. At a water depth approximately half the wavelength, there is no motion in the water. The storm-wave base rarely exceeds a water depth of 200 metres (Johnson and Baldwind, 2006).

9. Conclusions

This thesis aimed to further understand the formation, preservation, spatial and temporal variations of the trace fossils in the Blanknuten Member on Edgeøya, Svalbard. By sedimentological fieldwork and ichnological analysis, the results of this thesis have led to the following conclusions:

- Ichnological analysis of the Blanknuten Member on Edgeøya on Svalbard reveals monospecific occurrences of the ichnogenus *Thalassinoides*.
- An updated map of the trace fossil distribution on Edgeøya has been produced based on temporal and spatial variations.
- The previously published *Thalassinoides* assemblages consisting of ichnogenus *Taenidium*, *Polykladichnus*, *Rhizocorallium* and *Thalassinoides* indicated to be present in the Middle Triassic succession were not found in the studied successions.
- From detailed sedimentary logging on the Muen Plateau, 20 beds filled with *Thalassinoides* were found to alternate with laminated shale and coqina beds indicating bottom water conditions fluctuating between anoxic, dysoxic and oxic.
- The absence of other ichnotaxa with cross-cutting relationships do not support previous findings of a tiering structure on Edgeøya. The beds filled with *Thalassinoides* indicate short-term oxygenation periods where there was no enough time to establish a tiering structure.
- *Thalassinoides* burrows were preserved in siltstone beds and silty shale as connected phosphate nodules in the succession, best visible on horizontal bedding surfaces. Presence of *Thalassinoides* in siltstone beds was interpreted to be a result of storm-events redepositing silt and trace makers to a less oxygenated bottom water

environment and supplying oxygen to the basin.

- Phosphate nodules are common in the Botneheia Formation and were formed in both *Thalassinoides* burrows or inconsistently in the succession. Not all phosphate nodules were infills of *Thalassinoides*.

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A. Abbreviations

AM Atle Mørk

BF Biofacies

CT Computed tomography

FM Formation

FT Frida Tronbøl

FW Fredrik Wesenlund

IF Ichnofacies

LF Lithofacies

MB Member

NHM Natural History Museum

NTNU Norwegian University of Science and Technology

SAG Sten-Andreas Grundvåg

SB Sofie Bernhardsen

TOC Total organic carbon

UNIS University Centre In Svalbard

UIT University of Tromsø

VSE Victoria Sjøholt Engelschiøn

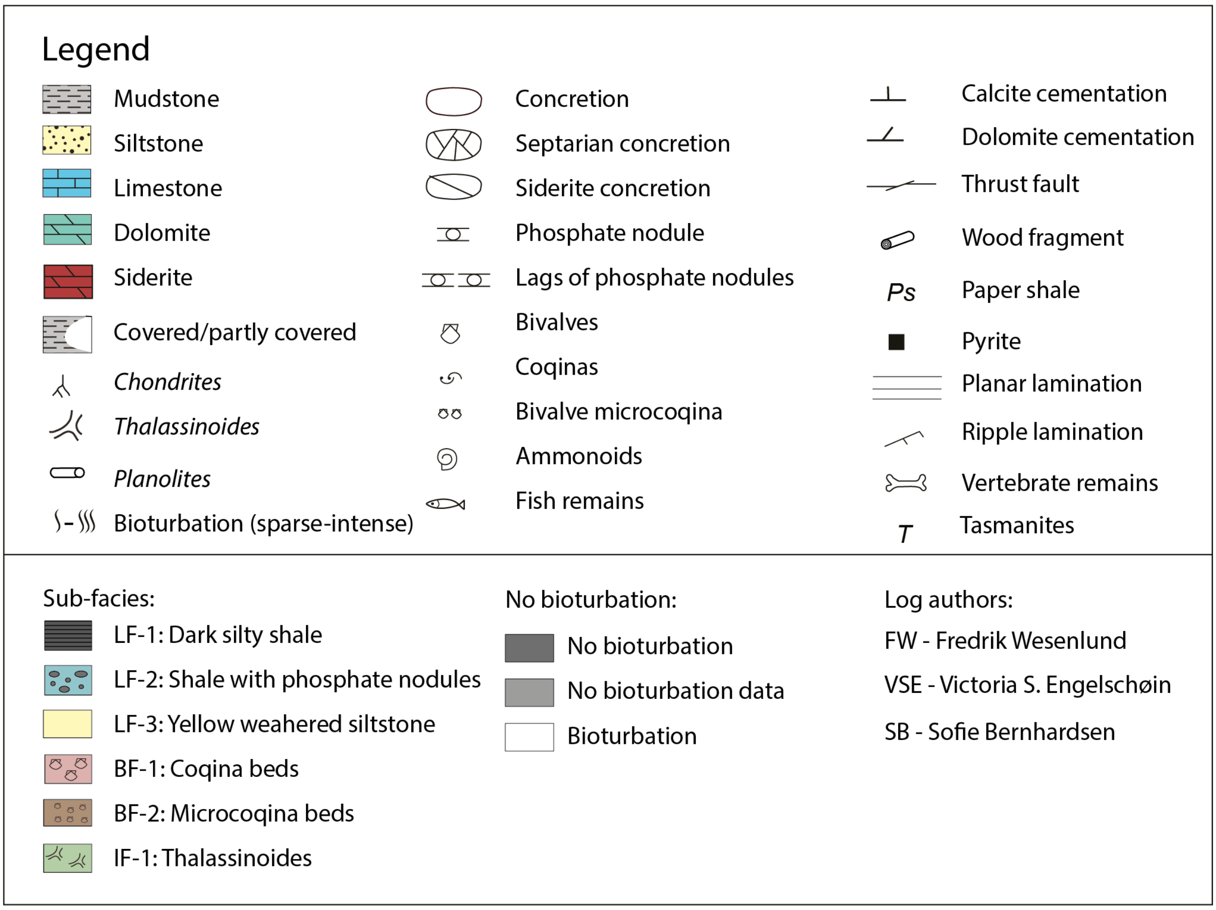
B. Appendix

B.1 GPS coordinates from logged sections

Table B.1: Overview of logged sections, GPS-points and number of samples collected at Edgeøya, 2018

Locality:	Log name:	Date:	GPS (start):	m a.s.l. (start):	GPS (end):	m a.s.l. (end):	Nb. of Samples:
Drivdalen	DRI1-18	01.08.18	35X 0371013 8662228	82	35X 0370808 8662090	112	33
Krykkjeglupen	BLA1-18	31.07.18, 07.08.18	35X 0368004 8661453	27	35X 0367927 8661530	93	48
Muen	MUE1-18	08.08.18, 10.08 - 14.08.18	35X 0367850 8645056	116	35X 0367473 8644646	133	233
Blanknuten NW Valley	BLA2-18	03.08 - 05.08.18	35X 0365223 8664391	38	35X 0365448 8664535	141	101
Palibinranten	PAL-1-18	19.08.18	35X 0364764 8682139	129	35X 0364765 8682139	134	42
Skrukkefjellet	SKR1-18	30.07.18 - 16.08.18	35X 0367911 8683037	152	35X 0368113 8683118	181	149
Skrukkefjellet East	No log	20.08.18					42

B.2 Legend for logged sections



Legend

Mudstone
Siltstone
Limestone
Dolomite
Siderite
Covered/partly covered
Chondrites
Thalassinoides
Planolites
Bioturbation (sparse-intense)

Concretion
Septarian concretion
Siderite concretion
Phosphate nodule
Lags of phosphate nodules
Bivalves
Coqinas
Bivalve microcoqina
Ammonoids
Fish remains

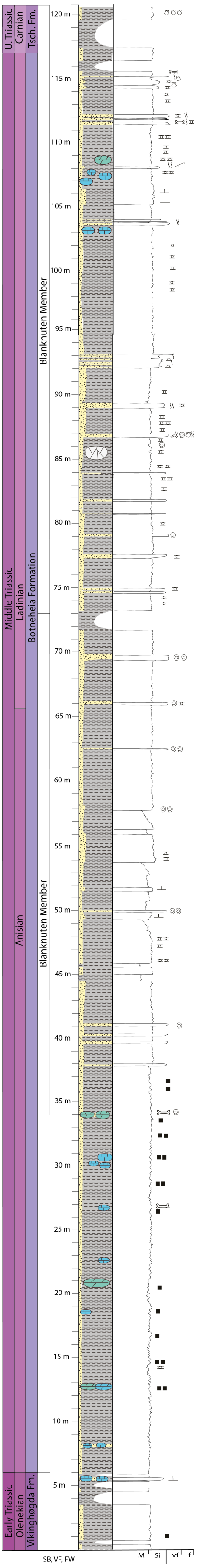
Calcite cementation
Dolomite cementation
Thrust fault
Wood fragment
Ps Paper shale
Pyrite
Planar lamination
Ripple lamination
Vertebrate remains
T Tasmanites

Sub-facies:
LF-1: Dark silty shale
LF-2: Shale with phosphate nodules
LF-3: Yellow weahered siltstone
BF-1: Coqina beds
BF-2: Micrococqina beds
IF-1: Thalassinoides

No bioturbation:
No bioturbation
No bioturbation data
Bioturbation

Log authors:
FW - Fredrik Wesenlund
VSE - Victoria S. Engelschøin
SB - Sofie Bernhardsen

B.3 Sedimentary log: Blanknuten NW Valley



B.4 Carbonate staining

Table B.2: Results of carbonate staining of thin sections from different localities on Edgeøya. Thin sections exposed to Altzarin red s sodium salt (0.1 g) and 0.2 % HCl. Pink staining indicating carbonate, colourless indicating dolomite.

Carbonate staining of thin sections					
Locality	**Sample Number:**	**Meters (in log)**	**Carbonate (pink staining):**	**Dolomite (no staining):**	**Comment:**
Blanknuten Valley	BLA2-18-47-C	87		x	
Skrukkefjellet	SKR1-18-VS23	15,2		x	
Skrukkefjellet	SKR1-18-VS33	27,2	(x)	x	Siltstone grains colourless, microcouqina slightly pink coloured.
Skrukkefjellet	SKR1-18-VS34	27,8	(x)	x	Siltstone grains colourless, microcouqina slightly pink coloured.
Drivdalen	DRI1-18-14A	13	(x)	(x?)	Microcoquina slightly coloured
Muen	MUE1-18-26A	8,8	(x)		Microcoquina slightly coloured
Muen	MUE1-18-24B	14,2	(x)		Microcoquina slightly coloured
Muen	MUE1-18-26B	14,2	(x)		Microcoquina slightly coloured

B.5 List of presentations

Bernhardsen, S., Engelschiøn, V.S., Mørk, A - Occurrences of *Thalassinoides* isp. within an organic rich hydrocarbon source rock; the Botneheia Formation, Edgeøya, Svalbard (oral presentation)

Engelschiøn, V.S., Bernhardsen, S., Wesenlund, F., Hammer, Ø., Hurum, J.H., Mørk, A - Palaeontology of the Middle Triassic dysoxic succession of the Botneheia Fm., Svalbard (poster presentation)

Engelschiøn, V.S., Bernhardsen, S., Wesenlund, F., Hammer, Ø., Hurum, J.H., Mørk, A - Geobiosphere of the Middle Triassic of Svalbard - linking biofacies to geochemistry (poster presentation)

Wesenlund, F., Engelschiøn, V.S., Bernhardsen, S., Røstad, J. - Investigating the Middle to Late Triassic Successions on Edgeøya, Svalbard – A Multidisciplinary Approach (poster presentation)