Environmental changes during the Permian-Triassic mass extinction –
A palynological study of sediments from Spitsbergen

Palynofacies and palynology of two outcrops from Spitsbergen, Svalbard

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Abstract

The Permian-Triassic extinction event is regarded as the most devastating environmental crisis the Earth has experienced, having a major effect on both marine and terrestrial environments, where huge volcanic eruptions from the Siberian Traps are thought to be the cause. Palynology and palynofacies were studied on two outcrop-sections from central Spitsbergen (Deltadalen and Høgskulefjellet), in order to reconstruct paleo-environment. In addition, carbon isotope of bulk organic matter was used with the global records. Fossil records of land pollen and marine microplankton are good records for the dynamics of the mass extinction in the past, while palynofacies data help distinguish depositional environments and oxygen conditions. The palynomorph preservation was generally poor in both outcrop-sections which prevented detailed examination of species and limited biostratigraphical reconstruction. Still, the palynological analyses show that Høgskulefjellet is more marine than Deltadalen due to a higher presence of acritarchs, most notably the species Veryhachium. They also show how the low spore/pollen ratio suggests the outcrops to be a representation of the aftermath of the extinction. A negative excursion in the carbon isotope record is a global feature occurring around the extinction event, and serves as a tool for global correlation. Nevertheless, this shift is not recognized in the outcrops, suggesting that both outcrops are younger than the extinction event. This is further supported by correlation of palynofacies-patterns of the two outcrops with a core that was collected from Deltadalen, covering a continuous record of end-Permian to Early Triassic deposits. The Deltadalen outcrop section shows a peak in amorphous organic matter (AOM), which could depict an anoxic period following the extinction fitting with the suboxic to anoxic environment of Deltadalen. The combined data studied in this thesis gives an insight in how complex the study of the end-Permian extinction can be, with large differences on a small spatial setting. It is essential in the ongoing research in this field to improve correlations between sites, in order to strengthen the link with the Siberian Traps. This work shows that in addition to bulk organic carbon isotopes, palynofacies records are useful for correlating end-Permian/Early Triassic sections in boreal regions.

Keywords: Palynology, palynofacies, carbon-isotopes, Permian, Triassic, extinction, Spitsbergen.
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1 Introduction

251 million years ago, life on Earth came close to being completely extinct, resulting in vast consequences in the environment. Nearly 90% of all marine species and 70% of terrestrial vertebrate families were wiped out (Erwin, 2006). This extinction, known as the End-Permian Mass extinction has been studied greatly the last decades, with a large igneous province (LIP) in Siberia thought to be related as cause. However, the volcanic event and the biotic crisis have proven to be difficult to link, as it requires well dated and high resolution Permian-Triassic boundary successions from the Arctic region. The fossil record can help to bring forth information on the dynamics of mass extinctions in the geological past. In this thesis outcrop-sections at Deltadalen and Høgskulefjellet in Central to East Spitsbergen will be the subject of study.

1.1 Motivation

This particular event from the past has been of great interest in research and publications. There have been studies performed from this period in sections all over the world, including in several fields such as bio and lithostratigraphy, palynology chem stratigraphy, and geochemical analyses (e.g. Hongfu et al., 2001; Looy et al., 2001; Hochuli et al., 2010; Burgess et al., 2014). The huge volcanic eruptions from the Siberian Traps are the most likely source leading to the extinction (Benton and Twitchett, 2003). At the same time, there was an occurrence of widespread oceanic anoxia (Wignall and Twitchett, 1996). Mass extinctions have proven to be major drivers of evolutionary change and mark vital transitions in the history of life, such as famously how the extinction of the dinosaurs at the end-Cretaceous paved the way for mammals to thrive and massively diverse (Alroy, 1999). The feedbacks between environmental perturbation and biological response, usually occurring in short timespans, are however poorly understood (Burgess et al., 2014).

Land plants release huge amounts of pollen and spores, which are transported by wind and water to a wide range of terrestrial and marine depositional settings. By looking at the assemblage of fossil pollen and spores, it is possible to reconstruct changes in past plant communities (Traverse, 2007). A rise of spore/pollen ratio (indicative of environmental stress) before the extinction has been noted in many end-Permian successions, e.g. Looy et al. (2001).
and Hermann et al. (2010). This rise reflects a conversion from diverse woody gymnosperms to a vegetation of herbaceous lycopsids (Vascular land plants that reproduce by spores) and ferns (Looy et al., 2001). The spores also remain unseparated in their tetrad structure due to high UV radiation (Visscher et al., 2004), and advocate how stress in the environment affected their life cycle by remaining in their tetrad form (Twitchett et al., 2001). Finally, a shift in δ¹³C has been used as an important global stratigraphical tool when studying the end-Permian mass extinction (Shen et al., 2011; Burgess et al., 2014). This shift dropped approximately 5 ‰ in the global record in δ¹³C_{org} (Shen et al., 2011), and reflects major changes in the carbon cycle around the time of the crisis. It is most likely that the timing of the extinction enabled a platform for the biotic response and recovery that followed into the Mesozoic.

Figure 1.1: Map of Svalbard showing location of both outcrop sections (marked with red asterisks) and with Late Paleozoic and Early Triassic successions exposed (see legend). Modified from Dallmann (1999) and Graphics Factory (2016).
1.2 Goals of the thesis

The purpose behind this thesis is to perform both a palynological and palynofacies analysis of Permian-Triassic sediments from Spitsbergen, together with the stable C-isotopes of organic matter. The studied material comes from two outcrops at Deltadalen and Høgskulefjellet, located in Central to East Spitsbergen (Figure 1.1).

A bulk organic isotope record ($\delta^{13}C_{\text{bulkOM}}$) will be used to correlate the outcrop sections with global end Permian/Early Triassic records, and in particular, with a continuous bore section from Deltadalen covering a more extended end-Permian and Early Triassic section. Palynology will be used to study both the marine and terrestrial input in the samples. Additionally, the distribution and diversity of organic-walled microphytoplankton (acritarchs) will be studied, as they can tell of nearshore-offshore trends (Lei et al., 2012). Palynofacies analysis is another method that will be used as it is a common tool for interpretation of the depositional environment and oxygen conditions. The integration of palynofacies on studies of sections from Svalbard has only been little researched on (e.g. Mørk et al., 1999b; Mueller et al., 2014; Paterson et al., 2015). This raises the following research questions:

1. Where do the outcrop-sections fit in with the global carbon isotope record?
2. What was the depositional environment and how did oxygen conditions change in both sections?
3. What kind of changes took place in the terrestrial setting?
4. What can the microplankton tell us about past changes in the marine environment?

The study is in collaboration with a current research project involving the bio- and isotope-stratigraphy of the Permian-Triassic boundary in boreal regions at the University of Oslo. Here, palynofacies, terrestrial and marine palynomorphs and geochemical data from the previously mentioned core in Deltadalen has been studied on. The project is conducted by Postdoctoral Fellow E. E. van Soelen and supervised by Prof. Wolfram M. Kürschner from the University of Oslo. The rock samples from the outcrops were acquired and received from Prof. Richard Twitchett of the Natural History Museum London, UK (Deltadalen) and from Prof. Gunn Mangerud of the University of Bergen, Norway (Høgskulefjellet) via Valentin Zuchuat during field work for his master thesis at NTNU, Norway.
2 Background

2.1 Why use palynology?

Palynology is the study of the organic microfossils, which contain very resistant organic structures that can be preserved in sediments over very long timescales. Palynomorphs and palynofacies are the sum of all organic particles that can be found in maceration preparations of sedimentary rocks (Traverse, 2007). Maceration is generally the disaggregation and matrix dissolving of the sample that is being processed through acids. In palynological analysis the focus is on the organic microfossils, the palynomorphs. In palynofacies analysis, the range is wider including organic particles. All visible non-palynomorph palynological matter, known collectively as palynodebris, is together with the palynomorphs included in palynofacies analysis (Traverse, 2007).

2.2 Geological setting

2.2.1 General overview of Svalbard

The Svalbard Archipelago represents an uplifted and exposed part in the northwestern corner of the Barents Sea Shelf (Figure 1.1) (Faleide et al., 2008). Although this area covers about 5% of the Barents Sea, it presents the changing climate and environments that Svalbard went through as it drifted northwards to polar latitudes from the equator in the Devonian (Figure 2.1) (Worsley, 2008). This has resulted in changing sedimentary processes and depositional environments, shaping the landscape of Svalbard, disrupted during five tectonic events: the Grenvillian (Late Mesoproterozoic), the Caledonian (Ordovician-Silurian), the Ellesmerian or Svalbardian (Late Devonian), the Variscan (Middle Carboniferous) and the Alpidic (Early Cenozoic) age (Dallmann, 1999).
Figure 2.1: The northwards drift of Svalbard through time (Modified from Elvevold et al. (2007), (Lord, 2013) and (Zuchuat, 2014)).

The Hecla Hoek comprises of the oldest material formed during the Precambrian to Silurian Period (Figure 2.2). It contains largely of igneous and metamorphic rocks that has experienced folding and alteration (Caledonian Orogeny) (Elvevold et al., 2007; Dallmann, 1999). In the Devonian Period, Svalbard went through an extensive denudation where rift basin deposition of coarse clastic sequences in the lower beds occurred. In the middle and upper beds, succession of fluvial and possibly deltaic sediments took place (Johnsen et al., 2001). They are known collectively as the Old Red Sandstone, consisting of several groups in different age ranges (From Late Silurian to late in the Middle Devonian) (Worsley et al., 1986). After the deposition of the topmost units in the Old Red Sandstone, tectonic activity such as intense deformation in Late Devonian took place, giving rise to the Svalbardian Deformation (Worsley et al., 1986; Piepjohn et al., 2000).
Enter the Carboniferous Period, the tectonic regime changed. A period of extension occurred during early to middle Carboniferous. One extension during the middle Carboniferous (Variscan) happened along a few lineaments like the Billefjorden Fault Zone (BFZ in Figure 2.2), which formed the Billefjorden Graben east of it (Johnsen et al., 2001). The Billefjorden Group were deposited by non-marine environments dominated by large humid alluvial fans which built out from active fault scarps into adjacent swamps, lakes and fluvial plains (Worsley et al., 1986). That input reduced by the end of the Carboniferous. However, during the mid-Carboniferous there was a change to red clastics, sabkha evaporites and shallow marine carbonates of the Gipsdalen Group (Figure 2.2), reflecting a rise in sea-level and dry climates (Worsley et al., 1986). From there, a stable carbonate shelf started to develop. Afterwards, a
sharp change to mixed siliciclastic deposits belonging to the Tempelfjorden Group of Permian Period occurred (Blomeier et al., 2010).

The Mesozoic development of Svalbard is recognized by stable platform environments throughout the archipelago (Steel and Worsley, 1984). The stratigraphic record shows repeated clastic sedimentary successions, mainly delta-related coastal and shallow shelf sediments (Triassic – Early Jurassic), deeper shelf sediments (Middle Jurassic to earliest Cretaceous) and again shallow shelf/delta deposits from the west (later in the Early Cretaceous) (Dallmann, 1999; Worsley et al., 1986). The Sassendalen Group of the Lower and Middle Triassic, the Kapp Toscana Group of the Upper Triassic to middle Jurassic and the Adventdalen Group of the Middle Jurassic to Early Cretaceous are the main stratigraphic groups represented on Svalbard in this period. Late in the Cretaceous there was an opening of the Arctic Basin causing uplift in the north such as the upliftment and erosion of Spitsbergen (Steel and Worsley, 1984).

Svalbard had from Carboniferous through Cretaceous time been a part of Pangaea, where it is thought that it was connected to Greenland (Torsvik et al., 2001). When the northward extension of the North Atlantic initiated and consequently resulted in the opening of the Arctic Basin during the start of the Paleogene, Svalbard with the Barents shelf and northern Europe separated from Greenland (Harland, 1997; Torsvik et al., 2001). Prior to this event, the region was dominated by tectonic activity along the western shelf margins. It launched the formation of the compressive Tertiary orogenic belt of Spitsbergen and the northwestern shelf (Worsley, 2008). This orogeny, called the West Spitsbergen Orogeny was most visible during the folding and thrusting of Carboniferous to Early Cretaceous rocks. This extended westwards to and beyond the western coast of central and southern Spitsbergen onto the developing, depositional, Central Tertiary foreland Basin (Harland, 1997; Dallmann, 2007).

The Neogene showed the aforementioned western shelf margins being exposed to the deposition of a massive, clastic-fed wedge over and off them. This was a consequence of repeated shelf depression and uplift related to glaciers (Worsley, 2008). North-western Spitsbergen went through both Tertiary and Quaternary volcanism, most likely related to hot spots due to high geothermal gradients along the fold-and-thrust belt (Dallmann, 2007).
2.2.2 The Permian-Triassic succession of Svalbard

Permian units

From the previous subchapter, the Gipsdalen Group of Carboniferous age was defined. The group comprises of the upper part of the Wordiekammen Formation and Gipshuken Formation on top of it (Figure 2.3). The Gipshuken Formation of Lower Permian consists of evaporates and carbonates, and is normally considered as warm-water deposits of a peritidal carbonate platform. During the Permian there was a transition to dominantly fine clastics of the Tempelfjorden Group, a reflection of large-scale transgression from the mid-Permian (Worsley et al., 1986). The overlying Kapp Starostin Formation of the Tempelfjorden Group is interpreted to characterize shallow to deeper marine environments of siliceous sponge spicules in favor of deeper environments (Blomeier et al., 2010).

Figure 2.3: Permian lithostratigraphy of Spitsbergen. Modified from Dallmann et al. (1999) and Dustira et al. (2013).

The transition of Upper Paleozoic to Mesozoic sedimentary deposits from Spitsbergen represent deposition on a broad epicontinental shelf at the northeastern margin of Pangea that comprised Svalbard, parts of eastern North Greenland (Wandel Sea Basin), the Barents Sea (Finnmark Platform, Stappen High), Arctic Canada (Sverdrup Basin) and Russia (Timan-Pechora Basin) (Stemmerik and Worsley, 2005). In the Late Permian this shelf was situated at around 45° N (Stemmerik and Worsley, 2005; Cocks and Torsvik, 2007).
**Triassic units**

Moving over to the Triassic succession of Svalbard, two groups are defined: the lower to middle Triassic Sassendalen Group and the upper Triassic to middle Jurassic Kapp Toscana Group (Figure 2.4). The Triassic succession is characterized by high sedimentation rate and siliciclastic sequences. Buchan et al. (1965) defined the Sassendalen Group in west and south of Svalbard to consist of the Vardebukta and Tvillingodden Formations of Lower Triassic age. During the period of deposition of this group, there was high subsidence and sedimentation rate across the entire Barents Shelf (Vigran et al., 2014).

![Lithostratigraphy of Svalbard](image)

**Figure 2.4:** Permian and Triassic lithostratigraphy of Spitsbergen. Modified from Hounslow et al. (2008).

In central and eastern parts of the Svalbard archipelago, the Sassendalen Group is divided by Botneheia of Middle Triassic and as Mørk et al. (1999b) defined: The Vikinghøgda Formation of Lower Triassic. Vikinghøgda range in almost the same thickness from central to east, 250 m and 200-220 m respectively (Mørk et al., 1999a). The Vardebukta Formation is characterized
by sandstones with variable amounts of interbedded siltstone, shaly siltstone and shale from a shallow marine, coastal environments with prograding deltaic lobes (Buchan et al., 1965; Mørk et al., 1999a). The Vikinghøgda Formation is described as repeated siltstone and sandstone beds with hummocky lamination understood as storm influence (Mørk et al., 1999b).

On Svalbard the boundary between the Permian and Triassic Period is abrupt with highly cemented spiculitic shales situated under the non-siliceous shales of the Early Triassic Sassendalen group (Vigran et al., 2014). Previously at the end of the Permian there was a significant warming of the ocean, which has led to believe it could have been a factor to the marine extinction (Vigran et al., 2014). The cherty and glauconitic Permian sandstone representing Kapp Starostin may have contributed to erosional debris in the basal sandstones in Vikinghøgda (Vigran et al., 2014). The Permian-Triassic boundary in Spitsbergen is located in the lower Vardebuksa and Vikinghøgda formations if following the redefined P-Tr boundary by Hongfu et al. (2001). It is within these successions between the Permian and Triassic that the localities are understood to lie.

2.2.3 Localities

**Deltadalen outcrop**

The Deltadalen outcrop lies in central-east Spitsbergen in Deltadalen, hence the name (Figure 1.1), and is a part of the Sassendalen, where the transition from the Permian Kapp Starostin Formation to the Vikinghøgda Formation is exposed (Seen in Figure 1.1). The outcrop is roughly 9 m long, consisting mainly of mudstones with siltstones and sandstones, belonging to the Vikinghøgda Formation. A previous study from Mørk et al. (1999b), defined the mentioned Vikinghøgda Formation with a type section from said Deltadalen. Here, the formation was subdivided into three members: Deltadalen (mudstones with sandstones and siltstones), Lusitaniadalen (mudstones with thin siltstone beds and some limestone concretions) and Vendomdal (dark shales with dolomite interbeds and nodules) (Table 2.1). Herein, moving upwards in stratigraphy, each succeeding member becomes more distal, organic-rich and oil-prone than the one below, while overall the lithology in Vikinghøgda is characterized by being dominated by silty shale. The upper two members of Vikinghøgda contributed to forming most of the slopes and mountains surrounding the Sassendalen area (Vigran et al., 2014). As this type section is 250 m long, the outcrop-section studied for this thesis is most likely situated in the basal part.
Table 2.1: Vikinghøgda Formation and its members of the Triassic Sassendalen Group. Lithology and depositional environments. Based on Mørk et al. (1999b) and Hounslow et al. (2008).

<table>
<thead>
<tr>
<th>Vikinghøgda Fm. members</th>
<th>Lithology</th>
<th>Depositional environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>VENDOMDALEN</td>
<td>Characterized by silty, dark grey, laminated mudstones and distinct yellow-weathered ferroan dolomitic beds and nodules, which can be found in the member throughout central Spitsbergen.</td>
<td>Distal shelf deposits, below wave base, with accumulation of marine derived organic material in a low oxic environment.</td>
</tr>
<tr>
<td>Base: Dark grey shale with rare calcite concretions, lacking the yellow-weathered dolomitic concretions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUSITANIADALEN</td>
<td>Middle and Upper: Rich in calcite concretions. Topmost part has almost 1 m thick ferroan dolomite cemented silty-sandstone with interbeds of gray mudstone.</td>
<td>Lower: Transgressive development from the underlying member towards a distal shelf environment.</td>
</tr>
<tr>
<td>Base: Interval of dark-gray laminated silty mudstone with a few thin sandstone or siltstone beds.</td>
<td>Overall: Represents a moderately deep shelf deposition, distal to the deltaic input from the west.</td>
<td></td>
</tr>
<tr>
<td>No erosional contact to mark a transition, but is rather marked by a decrease of the number of sandstones within the silty-mudstone succession.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELTADALEN</td>
<td>Moving upwards: Silty shale with intervals dominated by siltstone or very fine-grained sandstones, often with hummocky cross lamination</td>
<td>Repeated occurrence of siltstone and sandstone beds with hummocky lamination indicates storm influence on a shelf above storm wave base.</td>
</tr>
<tr>
<td>Lower: Abundant sandstone and siltstone interbeds. The sandstone lays on an erosional surface of partly silicified siltstones of the Permian Kapp Starostin Formation.</td>
<td>Sediment supply from the deltaic coast in the west may have been built up above storm wave base, where sheet sand bodies were laterally spread out on the seafloor.</td>
<td></td>
</tr>
</tbody>
</table>
Høgskulefjellet outcrop

The outcrop at Høgskulefjellet was as mentioned previously studied by Valentin Zuchuat for his thesis in 2014. Høgskulefjellet lies in central Spitsbergen. The outcrop depicts 17 m of altered, soft, finely laminated silty shales and shales, interbedded with thin rippled siltstone beds (up to 10 cm thick) (Zuchuat, 2014). Where the silt content decreases, the boundary between the Kapp Starostin and Vikinghøgda Formations have been placed, approximately 9.8 m in the log. Here there is a change in colour to darker tinges. It should be noted that the placement of the boundary has been differentiated based on sharp colour changes as no identifiable index fossils have been collected and as the silt content of the shales diminished vertically within the succession.

2.3 The end-Permian mass extinction

2.3.1 Dating the extinction

Dating the boundary has proven to be a challenge with several dates quoted up through the years. This prevented scientists to determine whether the decline of life at that period was a long process or an instant event (Benton and Twitchett, 2003). Performing geochronological studies on million-year-old rocks to the thousand enables thorough evaluation of patterns in change in climate, how the response is to distresses in the environment, and evolution in deep time (Burgess et al., 2014). Bowring et al. (1998) performed an analysis of uranium/lead (U-Pb) zircon data from Late Permian and Early Triassic rocks in south Chinese sections. The data place the Permian-Triassic boundary at 251.4 ± 0.3 million years ago. A later study performed by (Shen et al., 2011) with U-Pb dating reveal the peak of the extinction to be just before 252.28 ± 0.08 million years ago. However, the most recent study by Burgess et al. (2014) of the Permian-Triassic boundary in the same Chinese sections, puts the occurrence of the extinction to be between 251.941 ± 0.037 and 251.880 ± 0.031 million years ago, with an interval of 60 ± 48 thousand years for the extinction to take place, where the boundary is defined by the first appearance datum of the conodont, Hindeodus parvus.

2.3.2 Causes

One of the theories behind the cause of the end-Permian mass extinction is by impact. This is due to presence of extra-terrestrial noble gases found in cage-like molecular structures of fullerenes, which are large molecules of carbon arranged as hexagons around a hollow ball, at
the Permian-Triassic boundary in China (Becker et al., 2001). However, there have also been studies against this suggestion, making the entire impact theory weak (Benton and Twitchett, 2003).

On the other hand, a more accepted theory is that the massive volcanic eruptions occurring in Siberia played an important part in the end-Permian extinction (Benton and Twitchett, 2003). These eruptions caused by the Siberian Traps, composed of basalt that has built up many thick layers over thousands of years. The result is a distinguished morphology where the different lava flows erode back over time, creating a staircase-like appearance (Benton and Twitchett, 2003). The rich amount of basalt helped release volumes of CO$_2$ that was passing through thick sequences of coal (Marshall and Jacobs, 2009). This type of setting caused global warming that lowered the oxygen content in the oceans, and generated H$_2$S in the deep oceans (Meyer and Kump, 2008). Dating has set the eruption to the Permian-Triassic boundary, and increased the importance of the eruption as a significant part of the end-Permian extinction (Bowring et al., 1998). Shen et al. (2013) explained how these volcanic eruptions could affect the microplankton. For instance, volcanic ash can disperse thousands of kilometres away from the eruption source, which in turn can have an effect where it lands.

The end-Permian extinction event from the latest dating though, indicates that it happened over a sudden time, 60 ± 48 thousand years. This is a period shorter than previous estimations of the length of the magmatism in the Siberian Traps, and it has been suggested that a single pulse of magmatism generated the most severe change in the Permian-Triassic environment (Burgess et al., 2014).
3 Materials and methods

3.1 Samples

The study area for this thesis encompasses Late Permian to Early Triassic sediments from outcrops in central to east Spitsbergen, Svalbard. The two locations studied are situated in central and east Spitsbergen: Deltadalen (78°17'26.4''N, 16°55'20.8''E) and Høgskulefjellet (78°32'02.2''N, 15°53'51.8''E) (Figure 1.1) with the main purpose of analyzing the Permian-Triassic boundary. Prof. Richard J. Twitchett from the Natural History Museum in London, UK collected 35 samples from an outcrop in Deltadalen mainly consisting of mudstones and silty shale. Valentin Zuchuat in work for his master thesis at NTNU, Norway (Zuchuat, 2014) collected 19 samples which were indented for palynological analyses at a later stage from an outcrop in a narrow water stream on the east slope of Høgskulefjellet. This section consists of silty shales and shales, interbedded with thin rippled siltstone beds. The Deltadalen outcrop is about 9 m long, and the outcrop at Høgskulefjellet is roughly 17 m long. 12 samples from Deltadalen and 8 samples from Høgskulefjellet were taken for palynological analyses (see Appendix B for full list of sample data). In addition, a total of 54 samples from both outcrops were sent to Iso-Analytical Limited in the UK for further isotope analysis, such as TOC and δ¹³C content (see Appendix C for full list of data).

3.2 Slide preparation

Processing of the palynological samples and the slide preparation were both conducted at the Palynological Laboratory of the Department of Geoscience at the University of Oslo following standardized palynological processing techniques (Kuerschner et al., 2007; Traverse, 2007). Sediments weighing between 3 to 8 g were washed and crushed into fragments of 5 mm> in a disaggregation process to prepare them for acid treatment. This is performed by using a clean mortar and pestle. To each sample a tablet of Lycopodium marker spores (avg. of 12,077 spores) was added. The marker spores were added in order to give quantification of the palynomorph counts. Afterwards, they were treated first with hydrochloric and then with hydrofluoric acids to eliminate carbonate and silicate minerals respectively, in order to remove carbonates and silicates (e.g. sand). Later, they were sieved with a 7 µm nylon mesh sieve in order to remove clay minerals and small particles. The residues were then mounted on slides for microscopic analysis. The same procedure was conducted for the samples from Høgskulefjellet.
3.3 Bulk carbon isotope analysis

Analyses of palynology and palynofacies can be significantly improved when used together with geochemical proxies such as organic matter content (TOC) and stable carbon isotopes ($\delta^{13}$C). These proxies can give suggestions of the environment, and also be used as comparative data and quality control of the analyses. A total of 54 samples (35 samples from the Deltadalen outcrop and 19 samples from the Høgskulefjellet outcrop) were analysed for $\delta^{13}$C. To achieve this 1 g of sediment was crushed to powder, treated with 1M hydrochloric acid and left for 24h to eliminate all inorganic carbon. The samples were then neutralized with water and oven dried at 60 ºC. Subsequently, the samples were then analyzed with an Elemental Analyser – Isotope Ratio Mass Spectrometry (EA-IRMS), where the isotope ratios are stated in the standard $\delta$ notation in per mil (‰) versus the Vienna PDB. To get analytical precision, routine analysis of internal laboratory reference materials has to indicate a standard deviation of less than 0.08‰ for the bulk carbon isotope values. For reference material, IA-R001 (wheat flour) was used: $\delta^{13}$C$_{V-PDB} = -26.43$‰. The standard deviation of the standard was 0.05. The measurements were performed by Iso-Analytical Limited in the UK.

3.4 Analysis

Each slide was analyzed for both palynofacies and palynology with the use of a light microscope by identifying and counting minimum 300 organic particles for palynofacies analysis and if possible minimum 300 palynomorphs for the palynological analysis (Explained in more detail in Sections 3.5 and 3.6). Palynomorphs represent both terrestrial and marine input.

The result of the analyses can be presented as relative (%) abundance where one uses the different components’ percentages of the total sum. They can also be presented as the concentration of pollen per gram dry sample, the absolute (g$^{-1}$) abundance. This is calculated by using the Lycopodium marker spores. However, the Lycopodium spore counts were excluded from the total palynomorph counts. Photos were taken with an AxioCam E Rc 5s camera connected to a computer using software Zen AxioVision Rel. 4.8.2. The results were calculated and plotted in diagrams by using the software C2, Tilia, PAST (Hammer et al., 2001) and Microsoft Office Excel, while all figures and graphs were made through Adobe Illustrator.
3.5 Palynofacies

Not only palynomorphs are present in the maceration residue slide as mentioned in section 2.1. This has triggered studies on all particulate organic matter (POM), both the palynodebris and palynomorphs, to make an attempt to classify them. However, the attempts have normally been subjective with a scientific objective, resulting in a number of different classifications (Traverse, 2007). Powell et al. (1990) defined palynofacies as “distinctive assemblage of palynoclasts whose composition reflects a particular sedimentary environment”, where palynoclasts involves all organic components in a palynological preparation, which is broadly similar to POM. Mendonça Filho et al. (2012) added to that with the total assemblage of microscopic organic constituents that remain after maceration using normal palynological preparation methods. Conclusively, the total assemblage of POM in a slide is called palynofacies.

Table 3.1: Classification of sedimentary organic matter. See subsections 3.5.1 to 3.5.3 for detailed descriptions. Based on Tyson (1995).

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>CONSTITUENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURED</td>
<td></td>
</tr>
<tr>
<td>Phytoclasts</td>
<td>Opaque phytoclasts&lt;br&gt;Translucent phytoclasts:&lt;br&gt;- Wood remains&lt;br&gt;- Plant remains&lt;br&gt;Fungal debris&lt;br&gt;Reduviasporonites</td>
</tr>
<tr>
<td>Green algae</td>
<td>Prasinophytes</td>
</tr>
<tr>
<td>Palynomorphs</td>
<td></td>
</tr>
<tr>
<td>Sporomorphs</td>
<td>Spores&lt;br&gt;Pollen</td>
</tr>
<tr>
<td>Marine microplankton</td>
<td>Acritarchs</td>
</tr>
<tr>
<td>STRUCTURELESS</td>
<td></td>
</tr>
<tr>
<td>Amorphous organic material</td>
<td>Degraded terrestrial organic matter&lt;br&gt;Degraded aquatic organic matter</td>
</tr>
</tbody>
</table>
For this study the classification and methodology of palynofacies has been modified after Tyson (1995) (Table 3.1) (see sections 3.5.1 to 3.5.3 for further details). The POM was subdivided into terrestrial and aquatic derived particles, and amorphous organic matter (AOM). Terrestrial POM includes both translucent and opaque phytoclasts (wood, plant cuticles, charcoal, fungal debris), pollen, broken bisaccate pollen grains and spores, while the aquatic POM solely in this thesis consists of acritarchs.

### 3.5.1 Phytoclasts

According to Tyson (1995), phytoclasts are remains and debris from higher plants. From there we can divide them in two key categories: Translucent and opaque.

In the translucent phytoclast category one can find the constituents: wood remains, and plant debris and cuticles. The wood remains are as the name implies, derivers of wood. More precisely woody tissue of land plants (Tyson, 1995). They usually have a biostructure in the shape of holes or stripes, and are of brown, translucent colour. Plant tissue is from the cellulose, non-woody part of the plant, while most cuticles and their fragments come from leaves (Tyson, 1995). They are both distinct by their cellular structure, but have brown, translucent colour and light, translucent colour, respectively. For this thesis they have been counted as one category.

Other constituents of translucent phytoclasts related to this thesis are fungal tissues and *Reduviasporonites*. Fungal tissues consist of fragments of a very thin or fine thread or fiber, known as hyphae (Tyson, 1995). They appear like thin, branching, tubular, structures of indeterminate length which can be 1-30 µm in width, and often with relatively dark, matte brown colour despite their thin appearance (Tyson, 1995). *Reduviasporonites* is of fungal origin (Visscher et al., 1996). Researchers have previously been unsure as to whether *Reduviasporonites* were a type of fungus or algae. However, a study from Sephton et al. (2009) classifies it as fungi after carbon and nitrogen analyzation. They have robust-walled single cells and appear as multicellular chains.

Opaque phytoclasts are defined as oxidized or carbonized woody tissues and include charcoal (Tyson, 1995). Charcoal is produced in high temperatures under conditions of very low oxygen and appear as entirely black.

In this thesis the analysis has focused mainly on these constituents, that’s why the focus has been on them in this subsection.
3.5.2 Amorphous organic matter

Amorphous organic matter (AOM) are of terrestrial and aquatic origin, and have their origin in biodegraded cellular remains, algal material and disintegrated faecal pellets from zooplankton and bacteria (Lewan, 1985; Tyson, 1995; Batten, 1996). Under the microscope AOM appears completely structureless with irregular and diffuse outlines, and a fluffy, translucent mass.

3.5.3 Palynomorphs

Fossil palynomorphs are comprised of poropollenin, chitin, or pseudochitin little modified from their original composition (Traverse, 2007). In short, they represent all organic microfossils where their constituents have originated from plants or animals such as sporomorphs (spores/pollen), acritarchs, and algae and algae remains.

Acritarchs

The acritarchs are hollow, organic-walled, single-celled organisms who their biological affinity is unknown (Armstrong and Brasier, 2005). They are thought to have originated from algae, and some believe they are the resting cysts of marine algae. Acritarchs are marine although non-marine specimen have been reported in Recent strata, and also they occur as brackish- and freshwater species (Armstrong and Brasier, 2005; Traverse, 2007). They usually have a smooth, spherical shape, either of large or small types, and types with long or short spines.

The most common acritarch genera during Late Permian to Early Triassic were Dictyotidium, Leiosphaeridia, Veryhachium and Micrhystridium, all representing four different morphological types (Shen et al., 2013). Smooth, spherical shape, either of large types (Dictyotidium) or small types (Leiosphaeridia), and types with long spines (Veryhachium and some species of Micrhystridium) or short spines (Micrhystridium) are the differences that separate them.

Sporomorphs

Sporomorphs is the collective term for terrestrial spores and pollen (Tyson, 1995). They are produced in the life cycle of embryophytic plants (also known as land plants) that generate real embryos, where spores are produced by the low-lying bryophytes and ferns, and pollen by seed plants such as the conifers (gymnosperms) and angiosperms (Armstrong and Brasier, 2005;
Identification of their morphology is used to differentiate the pollen and spores in palynological analyses.

The morphology of spores is described according to their shape, apertures, wall structure and size. The main distinct feature is their ridge on the surface called laesurae, also known as “scar” (Armstrong and Brasier, 2005). As the spores are initially in a tetrad shape after dispersing from their mother cell, they split up in 4 only to be distinguished by their scar which is the contact between them. Monolete, trilete and alete are the 3 different subdivisions of spores based on their scar (Traverse, 2007).

Pollen grains can be divided by their shape. However, they are quite varied in their morphology and their shape is usually a result of their ability to disperse and pollinate. The air sacs and their form and weight contribute mostly to wind pollination (Armstrong and Brasier, 2005). The sacs which can be monosaccate or bisaccate are a result of increased buoyancy for long-distance transport by wind (Armstrong and Brasier, 2005). Those pollen grains that lack sacs disperse in other ways. For the palynofacies analysis the pollen grains have been divided in pollen (bisaccate and non-bisaccate) and bisaccate half (sacci).

**Algae**

Algae and algae remains can be of both marine and freshwater origin. In this thesis, the marine prasinophyte of the genus *Tasmanites* was the one of interest. It has a distinct, thick wall with a round shape and a light colour under the microscope.

**3.5.4 Palynofacies analysis**

The total assemblage of all organic matter observed and how it is distributed on a slide is the base for palynofacies analysis. Subsequently, analysis of palynofacies can be used interdisciplinary, such as with sedimentological data, enabling paleoenvironment interpretation (Tyson, 1995). For instance, in anoxic marine conditions where the input of terrestrial material is gone, palynofacies are usually the organic group of dominance (Batten, 1996).
Figure 3.1: A ternary APP-diagram (Amorphous organic matter-palynomorph-phytoclasts). See Table 3.2 for description of fields. Modified from Tyson (1995) and Rustad (2013).

The relative abundance of the different groups can help to determine distinct palynofacies. A high relative and absolute amount of AOM can indicate relatively low oxygen, a high preservation rate, and high nutrient values in the original water during time of deposition (Tyson, 1993; Tyson, 1995; Traverse, 2007). These features are also representable for a distal depositional environment (Tyson, 1995). Most phytoclasts are derived from the terrestrial flora. If the relative values phytoclasts are high, the input of terrestrial organic matter is of large immensity indicating close proximity to fluvio-deltaic sources. Here, the TOC content is medium to high due to high dilution of sediments, and reveal a mixed phytoclast composition (Tyson, 1993; Tyson, 1995). The percentage of phytoclasts, being small and opaque, is also often high in oxidizing situations, where the other components are selectively destroyed and the TOC content is low (Tyson, 1995). The interpretation of high relative values of palynomorphs on the other hand, are dependent on the composition of palynomorph assemblages. If the assemblage is dominated by sporomorphs, it indicates of an oxidizing environment with low AOM values, and moderate proximity to a fluvio-deltaic source, or it can indicate of an hypersaline environment with low production of plant debris and plankton (Tyson, 1995). Also, if buoyant or wind-blown pollen, especially bisaccates are dominant, the
environment is distal and stably stratified (Tyson, 1995). There is also a possibility that the assemblage is dominated by plankton. This indicates high productivity, low AOM preservation and oxidized environment. It is inversely related to that of sporomorphs, as poorly vegetated adjacent land areas (i.e. distal shelf areas) removed from river inputs have high values.

The relative abundances between the different parameters in an assemblage can be plotted against each other in a ternary APP-diagram (AOM, phytoclasts and palynomorphs), developed by (Tyson, 1995) (Figure 3.1). The diagram plots the POM-assemblages into fields for the purpose of depositional environments (relative proximity to terrestrial organic matter sources and proximal-distal changes), and the redox status of the depositional environments that control AOM preservation (see Table 3.2) (Tyson, 1993).

Table 3.2: Palynofacies field in relation to the APP-diagram (Figure 3.1).
   Modified from Tyson (1995).

<table>
<thead>
<tr>
<th>Palynofacies field</th>
<th>Environment</th>
<th>Microplankton</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Highly proximal shelf or basin</td>
<td>Very low</td>
</tr>
<tr>
<td>II</td>
<td>Marginal dysoxic-anoxic basin</td>
<td>Very low</td>
</tr>
<tr>
<td>III</td>
<td>Heterolithic oxic shelf (proximal)</td>
<td>Common to abundant Dinocysts dominant</td>
</tr>
<tr>
<td>IV</td>
<td>Shelf to basin transition</td>
<td>Very low-low</td>
</tr>
<tr>
<td>V</td>
<td>Mud-dominated odic shelf (distal)</td>
<td>Common to abundant Dinocysts dominant</td>
</tr>
<tr>
<td>VI</td>
<td>Proximal suboxic-anoxic shelf</td>
<td>Low to common Dinocysts dominant</td>
</tr>
<tr>
<td>VII</td>
<td>Distal suboxic-anoxic shelf</td>
<td>Moderate to common Dinocysts dominant</td>
</tr>
<tr>
<td>VIII</td>
<td>Distal dysoxic-oxic shelf</td>
<td>Low to moderate dinocyst dominant % prasinophytes increasing</td>
</tr>
<tr>
<td>IX</td>
<td>Distal suboxic-anoxic basin</td>
<td>Generally low, prasinophytes often dominant</td>
</tr>
</tbody>
</table>
3.6 Palynology

3.6.1 Taxonomic identification

Spores and pollen are results of different plant taxa, and therefore have morphological distinctions. Due to the preservation state of the palynomorphs, which was average to poor, the level of identification was kept to the major morphological groups in pollen, spores and acritarchs, with some genus representing the group. As work progressed it became quite clear how the pyritisation caused difficulties during the identification process (see Appendix A, Plate 5 for examples). If achievable sporomorphs and/or acritarchs were identified to its species/taxa.

The major morphologic groups chosen are based and modified on the work of Hochuli et al. (2010) in the Southern Barents Sea and are displayed in Table 3.3.

Table 3.3: List of the morphological groups applied in this thesis with description and their affinity. Based on Hochuli et al. (2010)

<table>
<thead>
<tr>
<th>Affinity</th>
<th>Morphological Group</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lycopsids</td>
<td>Cavate Trilete spores</td>
<td>Spore wall with clearly separated layers (cavate)</td>
</tr>
<tr>
<td></td>
<td>Uvaesporites Group</td>
<td>Spore wall thickened around whole equator</td>
</tr>
<tr>
<td>Ferns, but also Lycopsids</td>
<td>Other Trilete spores</td>
<td>Spore wall without separated layers</td>
</tr>
<tr>
<td></td>
<td>Spore Tetrads</td>
<td>Spores in its original three-dimensional tetrad from Cordaites</td>
</tr>
<tr>
<td>Cordaites</td>
<td>Florinates Group</td>
<td>Bilateral pollen with a single saccus.</td>
</tr>
<tr>
<td></td>
<td>Monosaccate Pollen</td>
<td>Pollen with a single saccus</td>
</tr>
<tr>
<td>Pteridosperms</td>
<td>Vittatina Group</td>
<td>Pollen with numerous taeniates and intervening thinner areas</td>
</tr>
<tr>
<td></td>
<td>Taeniate Bisaccates excl.</td>
<td>Pollen with two sacci, and more than one taeniate</td>
</tr>
<tr>
<td></td>
<td>Lueckisporites Group</td>
<td>Pollen with two sacci, and one taeniate</td>
</tr>
<tr>
<td></td>
<td>Non-taeniate Bisaccate Pollen</td>
<td>Pollen with two sacci, but no taeniates</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Pteridosperms/Conifers</td>
<td>Bisaccate undifferentiated</td>
<td>Sacci and undeterminate bisaccate pollen due to preservation or orientation on slide</td>
</tr>
<tr>
<td>Microplankton</td>
<td>Micrhystridium</td>
<td>Acritarch with processes (long and short)</td>
</tr>
<tr>
<td></td>
<td>Baltisphaeridium</td>
<td>Acritarch with processes (long, thin, and short, thin)</td>
</tr>
<tr>
<td></td>
<td>Veryhachium</td>
<td>Two dimensional acritarch with 3-5 processes</td>
</tr>
<tr>
<td></td>
<td>Leiosphaeridium</td>
<td>Acritarch with no processes</td>
</tr>
</tbody>
</table>

### 3.6.2 Palynological analysis

Spores and pollen are produced in vast numbers, and are distributed widely as they can travel through wind or water. This means that they can settle on the bottom of ponds, lakes, rivers and oceans (Armstrong and Brasier, 2005). Consequently, palynology can be used for biostratigraphy and as a tool for correlation of marine and terrestrial sections (Cirilli, 2010). Where the ecology of the parent plant is known, spores and pollen can be used for palaeoecological and palaeoenvironmental studies (Armstrong and Brasier, 2005). A ternary plot like the microplankton-spore-pollen plot (Figure 3.2), helps indicate onshore-offshore depositional environments and transgressive-regressive trends. This is based on the total palynomorph assemblage.
Figure 3.2: Ternary diagram for describing total palynomorph assemblages (Microplankton-spore-pollen as parameters in plot). Arrow marks theoretical regressive trend. From Tyson (1995).

Another factor to consider is how the different morphologies can have an impact in the spreading range of sporomorphs. Bisaccate pollen grains for instance have an increased buoyancy. This enables them to travel even farther into an offshore depositional setting. As a result, this can distort the assemblages and is known as the “Neves Effect” (Tyson, 1995).

Microplankton assemblages are also of use when analysed. Their distribution can indicate paleoecological environments, as acritarchs and their assemblages are used to suggest proximal-distal variations in hydrodynamic energy, water depth and proximity to fluvial inputs (Tyson, 1995).
4 Results

4.1 Palynofacies

Between 303 - 449 (avg. 364) particulate organic matter (POM) in total from the Deltadalen outcrop and between 317 - 420 (avg. 346) POM in total from the Høgskulefjellet outcrop were identified and counted for each slide (see Appendix D for the complete list of data). The results are displayed in Figure 4.1 to Figure 4.5.

4.1.1 Deltadalen

In the samples from Deltadalen the amorphous organic matter (AOM) is dominating the samples with clear peaks throughout the outcrop. They range between 16 and 82 % (avg. 45 %) of the total sum. The phytoclasts are the next group in abundance with wood remains as the biggest contributor with 4 - 39 % (avg. 18 %) within this group. Plant remains contribute with 0.4 - 30 % (avg. 6 %), charcoal contribute with 0 - 6 % (avg. 2 %) and other phytoclasts with 0 - 20 % (avg. 5 %) of the total sum. Colour on the POM was mostly light yellow to yellow in AOM, light to dark brown on wood and plant remains and other phytoclasts, and black on charcoal in all the samples. Also, clusters of pyrite and pyritasation of TPOM was present in all of the samples.

The palynomorphs vary greatly in their relative abundance throughout the Deltadalen outcrop where they range from 11 - 53 % (avg. 22 %). The terrestrial ones are the group that dominates with up to 19 % in some samples of the total sum. Here the group is split by pollen grains and broken pollen grains, usually with only the sacci intact, with 2 - 19 % (avg. 7 %) and 3 - 18 % (avg. 8 %) respectively. Another group that is contributing to the terrestrial palynomorphs, is spores with 0 - 13 % (avg. 2 %). The relative abundance of the marine palynomorphs is between 2 - 12 % (avg. 6 %) of the total sum. Within this group the acritarchs are the only contributors, therefore they reflect the entire group.
Figure 4.1: Diagram of the relative distribution of palynofacies stacked in groups correlated with palynomorphs of Deltadalen. Percentages are relative to total palynofacies. The cluster analysis was used to divide the distribution in palynofacies zones.
Figure 4.2: Diagram of the relative distribution of palynofacies stacked in groups correlated with palynomorphs of Høgskulefjellet. Percentages are relative to total palynofacies. The cluster analysis was used to divide the distribution in palynofacies zones.
As seen in Figure 4.1 and Figure 4.4, the basal part of the palynofacies (0.2 – 1.3 m) is characterised by fluctuations of AOM and high amounts of phytoclasts, where there is an overall dominance of wood remains (avg. 22 %). AOM is clearly most abundant with an average relative abundance of 49 %. Phytoclasts rise to 63 % in their highest peak throughout the section at 0.6 m. This reverses moving upwards to 1.3 m. Of the palynomorphs the terrestrial ones are the majority with 12 % in this section. The marine/terrestrial ratio drops, before experiencing a peak, indicating of increased marine input.

The following meters up to 4.4 m, the AOM continues to dominate, where they experience a global peak of 82 %. The phytoclasts remain stable with the other phytoclasts as the main representative, but decrease dramatically down to about 5 %. At the same point the terrestrial and aquatic palynomorphs experience also a drop. However, the marine input increases to its highest peak at the same point, corresponding to the peak of AOM.

Following this point, the AOM decreases intensely up to 7.4 m. On the other hand, the terrestrial input increases with spores, pollen (especially broken sacci) and phytoclasts increasing. As a consequence, the marine/terrestrial ratio decreases. Towards the very top, it can be observed an increase in AOM, together with plant and wood remains.

### 4.1.2 Høgskulefjellet

Høgskulefjellet samples shows a similar variety in the relative abundance of the palynomorphs as Deltadalen ranging from 29 - 56 % (avg. 43 %).

However here, the marine palynomorphs represented by acritarchs is the dominating group ranging between 26 - 52 % (avg. 40 %), while the terrestrial palynomorphs vary between 0.6 - 8 % (avg. 2.9 %) contributing little to the total sum. As in the Deltadalen samples the terrestrial palynomorph group here consists of pollen grains and sacs of bissacate pollen with 0 - 5 % (avg. 1.6 %) and 0.6 - 3 % (avg. 1.3 %) respectively. Spores also contribute with 0 - 2.4 % (avg. 0.3 %) where they were only identified and counted in one of the slides.

AOM is clearly the most dominating group throughout the Høgskulefjellet outcrop, ranging between 20 - 52 % (avg. 37 %). The second most abundant is wood remains with 5 -22 % (avg. 16 %), then plant remains at 0.6 - 5 % (avg. 2 %), charcoal at 0 - 1 % (avg. 0.1 %), and other phytoclasts at 0 - 0.3 % (avg. 0.04 %) as minor contributors to the total sum.
Figure 4.3: Palynofacies data plotted in the APP-diagram (AOM-Phytoclast-Palynomorph). Modified from Tyson (1995).

Table 4.1: Explanation of the different palynofacies fields noted in Deltadalen and Høgskulefjellet. From Tyson (1995).

<table>
<thead>
<tr>
<th>Palynofacies field</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVa</td>
<td>Dysoxic-suboxic shelf to basin transition</td>
</tr>
<tr>
<td>IVb</td>
<td>Suboxic-anoxic shelf to basin transition</td>
</tr>
<tr>
<td>V</td>
<td>Mud-dominated oxic shelf (&quot;Distal shelf&quot;)</td>
</tr>
<tr>
<td>VII</td>
<td>Distal suboxic-anoxic shelf</td>
</tr>
<tr>
<td>VIII</td>
<td>Distal dysoxic-oxic shelf</td>
</tr>
</tbody>
</table>
Charcoal and other phytoclasts were only identified in one of the slides. The colour on the POM was quite similar as in the samples from Deltadalen, and also the samples from Høgskulefjellet experienced the presence of pyritization.

Up to 6.8 m, Høgskulefjellet is characterised by the dominance of aquatic palynomorphs represented by acritarchs, especially at 3.8 m with a peak and global maximum of 53 % (Figure 4.2 and Figure 4.5). Terrestrial palynomorphs average at 5 %, a global maximum (spores are registered only in this section). AOM decreases from the base to 3.8 m before increasing towards 8.4 m with 42 %. The marine/terrestrial ratio decreases as the terrestrial input increases.

Moving up to the top in Figure 4.2 and Figure 4.5, AOM keeps increasing with the exception of a small drop at 9.6 m, to a global peak of 52 % at 11.5 m. The phytoclasts decrease towards 8.4 m where wood remains are the only constituent left and therefore the major phytoclast. Terrestrial palynomorphs decrease and remain at very low values to the top (avg. 2 %). On the other hand, the aquatic palynomorphs continue at high values before decreasing at 10.3 m but remain the highest constituent of the palynomorphs towards the top. The marine/terrestrial ratio is the highest at same depth as the global peak of AOM. Afterwards, the ratio decrease rapidly and is low through the final meters of the section.

No fungal remains, rediviasporonites or algae was located in any sample from both outcrops. Furthermore, a ternary APP-diagram where the AOM, palynomorphs and the phytoclasts were plotted against each other after Tyson (1995) (Figure 4.3). The diagram shows how the samples of Deltadalen range between fields IVa, IVb, VII, VIII and two outliers in field V, while the samples from Høgskulefjellet are situated in fields V and VII.
Figure 4.4: Diagram of relative amount of particulate organic matter with TOC content, bulk carbon isotope data, marine/terrestrial ratio and cluster analysis zones from Deltadalen outcrop.
Figure 4.5: Diagram of relative amount of particulate organic matter with TOC content, bulk carbon isotope data, marine/terrestrial ratio and cluster analysis zones from Høgskulefjellet outcrop.
4.2 Palynology

Overall, 147 - 383 (avg. 316) palynomorphs and microplankton from the Deltadalen outcrop and 316 – 391 (avg. 341) from the Høgskulefjellet outcrop were counted and identified for each slide (See Appendix E for complete list of data). Two slides did not have the ideal amount of counts (300), due to inadequate of palynomorphs and microplankton. The preservation of the palynomorph was generally poor in both outcrop samples’ slides which prevented detailed examination of species. Pyritisation made it difficult for identification in all slides. Lycopodium marker spores were counted as well, and the resulting calculated absolute concentration is displayed in Figure 4.8 and Figure 4.9.

The major morphological palynomorphs and microplankton groups that were present and able for identification are listed in Table 4.2. The relative abundance can be displayed in Figure 4.6 to Figure 4.7. The genera have been used as groups for this study, where they were systematically described (Appendix F). A cluster analysis was calculated in the software Tilia, enabling to divide the relative abundances in 5 zones for Deltadalen and 3 zones for Høgskulefjellet (Figure 4.6 to Figure 4.7).

Table 4.2: List of the major morphological groups in Deltalen and Høgskulefjellet outcrop-sections.

<table>
<thead>
<tr>
<th>Spores</th>
<th>Pollen</th>
<th>Acritarchs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deltoidospora</td>
<td>Lueckisporites</td>
<td>Micrystridium</td>
</tr>
<tr>
<td>Uvaesporites</td>
<td>Lunatisporites</td>
<td>Baltisphaeridium</td>
</tr>
<tr>
<td>Protohaploxyypinus</td>
<td>Leiosphaeridium</td>
<td></td>
</tr>
<tr>
<td>Vittatina</td>
<td></td>
<td>Veryhachium</td>
</tr>
</tbody>
</table>
Figure 4.6: The relative distribution of the major palynological groups from Deltadalen. The cluster analysis was used to divide the distribution in zones.
Figure 4.7: The relative distribution of the major palynological groups from Høgskulefjellet. The cluster analysis was used to divide the distribution in zones.
4.2.1 Palynomorph zones

Deltadalen (Figure 4.6)

Zone A (0 – 3 m)

The basal palynomorph zone is characterised by dominance of undifferentiated bisaccates and their broken sacci (avg. 57 %). They also have their global maximum in the middle of the zone with a relative abundance of 69 % before decreasing towards the top. Vittatina Group (avg. 2 %), taeniate bisaccates (avg. 4 %) and non-taeniate bisaccates (avg. 5 %) of the pollen groups represents the largest amount of the remaining pollen. All of them show a decrease towards the top. The spores are quite poorly represented in this zone; there are a few cavate trilete spores at the base and at the top of the zone (avg. 0.1 %), and other trilete spores (avg. 2%) located in the entire zone with peaks at base, middle and top. The acritarchs are quite abundant, especially *Micrhystridium*, that increases towards the top from 15 % to a global maximum of 52 %. Leiosphaeridium Group is a minor contributor (avg. 1 %). The spore/pollen ratio fluctuate and has a peak at the top of the zone. Corresponding with this peak is a peak of the marine/terrestrial ratio of the palynomorphs.

Zone B (3 – 6.7 m)

The second zone is characterised by an increase of undifferentiated bisaccates and sacci at the lower boundary to a local maximum at 63 % moving up before decreasing again at the upper boundary. Monosaccate pollen Group witness a small peak and global maximum of 5 % in the middle of the zone. Taeniate bisaccate Group drop from zone A to B, but have a local maximum of 6 % moving up in the stratigraphy. Lueckisporites Group has an average of relative abundance of 0,5 %, and Non-taeniate bisaccate Group drop at the lower boundary before a slight increase toward the top. Spores have extreme low abundances with only Other trilete spore Group as a contributor at the upper boundary with <1 %. Micrhystridium Group at the lower boundary maintains a stable value around 31 % before a sudden drop to 18 %. However, at the upper boundary the group has a local maximum of 52 %. Leiosphaeridium Group still averages 1 % throughout the zone. The marine/terrestrial ratio drops before increasing again to the top of the zone. The spore/pollen ratio is very low.
Zone C (6.7 – 9.4 m)

The final and topmost palynomorph zone is characterized by a clear predominance of undifferentiated bisaccates and sacchi and Micrhystridium Group, average of relative abundance of 52 % and 30 % respectively. The spores increase to 3 % at the very top, but overall are quite few. The remaining pollen groups are minor contributors averaging at <1 %, with the exception of Taeniate Bisaccate Group that has a local maximum at the base of the zone, before dropping and peaking at the top. At the very top, the section has its highest peak in spore/pollen ratio, while the marine/terrestrial ratio decrease in the beginning of the zone before increasing.

Høgskulefjellet (Figure 4.7)

Zone A (0 – 7.3 m)

The first palynomorph zone of Høgskulefjellet is characterised by the Micrhystridium Group that is dominating without a doubt (avg. 70 %). Undifferentiated bisaccates and sacchi show a small decrease in the zone from 10 % to 7 % of the major pollen groups, while the rest of the groups are minor contributors. The same trend is observed in spores. The other trilete spores have a global maximum at the base (3 %) before decreasing, Cavate trilete spores average at 1 %. Besides Micrhystridium Group, the Veryhachium Group increases to 8 %, a global maximum at the top, while undifferentiated acritarchs have an average of relative abundance of 12 %. The spore/pollen ratio is at its highest in the beginning of this zone, but experience a steadily drop towards the top. The marine/terrestrial ratio of the palynomorphs has a small increase and remain stable through the zone.

Zone B (7.3 – 10 m)

The second palynomorph zone observes a rise in the Leiosphaeridium Group to 9 %, a local maximum, while the Micrhystridium Group maintains a dominant abundance. Here it has a global maximum of 74 %. Veryhachium Group decreases moving up in the zone. The undifferentiated bisaccates and sacchi continues to drop stepwise, this time to 5 %. In this zone, the marine/terrestrial ratio is at its highest, while the spore/pollen ratio has a major decrease.
Zone C (10 – 14.5 m)

The final and topmost palynomorph zone of Høgskulefjellet is characterised by the presence of the Vittatina Group (avg. <1 %) and very small accumulations of taeniate bisaccates (avg. <1 %), Lueckisporites Group (<1 %), and non-taeniate bisaccates (avg. 2 %). Undifferentiated bisaccates and sacci Group has a rise to a global maximum of 14 %. There is a slight decrease in the Micrhystridium Group to ca. 50 %, but is stable in the entire zone. Veryhachium Group peaks at the bottom before decreasing to the top to <1 %. Leiosphaeridium Group increases dramatically from the previous zone all the way to the upper boundary to a global maximum (27 %). The spore/pollen ratio has a small peak at the beginning, before dropping. The ratio increases towards the top. The marine/terrestrial ratio is considerably lower and remain stable throughout the zone.

4.2.2 Absolute abundances of Deltadalen and Høgskulefjellet

The absolute abundances for both outcrop sections was calculated in Tilia and overlain by the relative abundances, and correlated with the marine/terrestrial ratio (Figure 4.8 to Figure 4.9). The relative and absolute abundance curves follow each other mostly. Spores, a minor contributor in both Deltadalen and Høgskulefjellet are amplified together with the pollen of Høgskulefjellet, while the pollen of Deltadalen is reduced. The acritarchs are reduced in both sections, although in Deltadalen there are sections that are not quite following the relative curve. The same applies for sections of the spores. However, these irregularities are usually fitting with the lycopodium spike.
Figure 4.8: The sample mass, lycopodium concentration, lycopodium spike (the number of counted lycopododium spores) plotted against the relative and absolute abundances of spores, pollen and acritarchs, and the marine/terrestrial ratio of Deltadalen.
Figure 4.9: The sample mass, lycopodium concentration, lycopodium spike (the number of counted lycopodium spores) plotted against the relative and absolute abundances of spores, pollen and acritarchs, and the marine/terrestrial ratio of Høgskulefjellet.
4.3 Bulk carbon isotope

Overall, the carbon-isotope profile shows a positive trend in Deltadalen outcrop (Figure 4.4), while it depicts a negative trend throughout the Høgskulefjellet outcrop (Figure 4.5). For complete list of bulk carbon isotope data, see Appendix C.

4.3.1 δ¹³C

Deltadalen

The bulk carbon isotope record is measured from 35 samples ranging from 0.2 – 9.4 m in the outcrop. They show more or less a steady value increase from -32.85 to -29.18 ‰. At the base, the δ¹³C profile has a stepwise increase with no particular major deviations. Continuing upwards, δ¹³C-values increase from -32.70 to -30.95 ‰, reflecting a steady, but small positive excursion. From 3.6 m it has a few fluctuations towards -29.98 ‰, while from 6.1 to 8.3 m, the δ¹³C fluctuates around -30 ‰ with clear peaks and lows. In the final meters the δ¹³C begins to rise positively with a small fall at the end, conclusively representing an upwards rising trend in the section.

Høgskulefjellet

In Høgskulefjellet, 19 samples ranging from 0.5 – 16 m were measured for bulk carbon isotope values. The results show a steady decrease from -25.88 to -28.33 ‰. All the way from the bottom to 6.8 m, the δ¹³C-content displays a declining trend from -25.94 to -27.23 ‰ with a rather larger decrease at the base. The following meters to 10.3 m, the δ¹³C remains stable around -27 to -28 ‰ with a small negative low of -28.03 ‰. Lastly, in the final meters, δ¹³C values showcases a stable negative excursion trend in the zone.

4.3.2 Carbon content (TOC)

In the Deltadalen outcrop, the TOC-content increases very little, staying stable through the first meter up to 1.3 m. Up to 3.6 m, the TOC-content fluctuates more, but is still around a stable percentage, until it decreases rapidly down from 1.26 to 0.37 %. After this rapid decrease, the TOC has its highest value throughout the section jumping immediately up to a peak of 2.53 % at 3.8 m. Afterwards, the content decreases and maintains a more or less stable value to 6.8 m. Here the value drops below 1 %, as it keeps falling towards the top. Just before the top, the
TOC has its lowest value (0.17 %) of the entire section at 9.2 m.

The Høgskulefjellet section depicts more stable values throughout the outcrop, with no significant peaks or lows. The TOC content is below 0.50 % in the entire section. At the base, the value decreases from 0.45 % to remaining somewhat stable around 0.30 % up to 8.4 m. Here the values rise to its highest (0.47 %) before decreasing in the following meter down to 0.15 %, the lowest value of the section. Finally, the TOC-content in the topmost interval (10.3 m – top) is characterized by fluctuations around 0.20 – 0.36 %.
5 Discussion

5.1 Correlating the outcrops with the global records

In addition to the extinction itself, excursions in isotopic composition ($\delta^{13}C$) of marine carbon is the key information about the environmental disturbance at the transition between the Permian and Triassic (Payne et al., 2004). Therefore, a negative carbon isotope shift near the Permian-Triassic boundary acts as an important stratigraphical tool. Near the base of the Vikinghøgda Formation in the Deltadalen core such an excursion occurs, where values change from -24.5 to -32.7 ‰ (Figure 5.2 to Figure 5.3). This is consistent with organic isotope records from other boreal settings (e.g., East Greenland (Twitchett et al., 2001) and other studies from central Spitsbergen, Dickson Land (Dustira et al., 2013) and western Spitsbergen, Festingen (Grasby et al., 2015)). A similar shift in the bulk carbon isotope composition however, is not present either in the Deltadalen nor in the Høgskulefjellet outcrop-sections. The omission of this excursion can suggest that both are younger than the extinction event.

5.1.1 Deltadalen

The $\delta^{13}C$ profile recorded in Deltadalen has values from -32.7 ‰ and shifting positively to -24.5 ‰, which do not represent a distinct excursion. A core drilled nearby the outcrop in Deltadalen was correlated with instead (van Soelen et al., in prep.). The borehole core (DD1) is almost 100 m deep and penetrates the Triassic Vikinghøgda Formation and the Permian Kapp Starostin Formation. As the core is continuous and and covers a longer interval, it was chosen for comparison for better resolution. The $\delta^{13}C$ profile record from the outcrop is exposed at the core from 85 m to 75 m with a similar trend, and approximately at the same depth interval as the outcrop (Figure 5.1). TOC values from the core and the outcrop show similar trends. A 2.51 % peak is found at 81.7 m in the core and a similar peak is observed at +3.8 m (2.53 %) in the outcrop. The TOC peaks together with isotope profiles supports the Deltadalen outcrop is younger than the extinction event. This large positive fluctuation was also noted by Payne et al. (2004), which further describes that due to the longer stratigraphic interval of the excursion, the development must have been more slowly in time scale. AOM and palynomorph relative abundances from the palynofacies analysis from both studies uncover correlating trends (Figure 5.2). The negative excursion is not present, suggesting that the Deltadalen outcrop-section represents a more recent interval.
5.1.2 Høgskulefjellet

The section from Høgskulefjellet has a decreasing δ¹³C profile (-25.88‰ to -28.33‰), in the δ¹³C profile, contrary to the positive trend in Deltadalen. There was not recorded a negative excursion shift here either. This could probably place this section even higher up in the stratigraphy, as the δ¹³C values in the core also have a similar trend (Figure 5.3). The AOM is quite dominant (20-40 %) in this part of the core, fitting with the dominance of AOM at Høgskulefjellet. On the other hand, the overall organic carbon content is low, with TOC values ranging between 0.15 % to 0.47 %, fitting with a possible response in the aftermath of the extinction. There is also low TOC content in the core where the section from Høgskulefjellet may fit.
Figure 5.2: Correlation between the core (van Soelen et al., in prep.) and Deltadalen outcrop-section. The red line seen in the core-figure is an illustration of the placement of the Deltadalen outcrop. Here the records of TOC, δ¹³C, AOM and palynormorphs fit.
Figure 5.3: Correlation between the core (van Soelen et al., in prep.) and Høgskulesfjellet outcrop-section. The red lines seen in the core-figure is the records of TOC and δ¹³C from the outcrop placed to illustrate fitting trends. AOM, phytoclast and palynomorphs are also present in both sub-figures for higher resolution.
5.2 Paleoenvironmental interpretation

Palynofacies analysis is a useful tool for interpretation of the depositional environment and the oxygen conditions, both discussed further in subsections 5.2.1 and 5.2.2.

5.2.1 Depositional environment

Based on the high abundance of AOM together with the occurrence of marine microplankton in both sections, it is interpreted that the sediments were deposited primarily in a more distal shelf marine setting. Worsley et al. (1986) indicates, based on paleoenvironmental reconstructions, that the location of Spitsbergen was in a shallow to deeper marine shelf setting (Figure 5.4). In the Deltadalen and Høgskulefjellet outcrop-sections, the assemblages of POM have a varied and fluctuating composition. The POM assemblages are represented by a generally high percentage of AOM, low to medium percentages of phytoclasts and terrestrial palynomorphs and low to high percentages of marine microplankton (Figure 4.1 to Figure 4.2). Høgskulefjellet had especially high percentages of marine microplankton. The ternary APP-diagram shows how the samples of Deltadalen indicate fields IVa, IVb, VII, VIII and two outliers in field V (Figure 4.3), indicating variations of shelf to basin transition or shelf environment (Table 4.1) environment (Tyson, 1995). The samples from Høgskulefjellet are situated in fields V and VII (Figure 4.3), supporting a shelf setting (Tyson, 1995). In assemblages of high AOM, abundances of palynomorphs are low, because the palynomorphs are primarily controlled by the extent of AOM or phytoclast dilution (Tyson, 1993).
Figure 5.4: A: Late Permian paleoenvironment reconstruction with localities marked with red asterisks. B: Early Triassic paleoenvironment with localities marked with red asterisks. Modified from Worsley et al. (1986).

Another ternary diagram plotting AOM vs. Terrestrial vs. Marine shows the difference in both sections (Figure 5.5). In general, Høgskulefjellet has a tendency towards more marine particles in the samples due to a high abundance of acritarchs. However, there is a slight increase of the phytoclast content towards the top in Deltadalen (Figure 4.1). Together with a minor rise of terrestrial palynomorphs it implies an environment more proximal a fluvio-deltaic source (Tyson, 1995).
5.2.2 Oxygen conditions

The oxygen supply is helpful when determining the depositional environment. The APP-diagram from Figure 4.3, also indicates the oxygen supply in the water column. The dominance of AOM throughout the section, especially below 6.5 m in Deltadalen (Figure 4.1), is interpreted to reflect the creation of suboxic to anoxic conditions during deposition, matching mostly with the distal “suboxic-anoxic shelf” and “suboxic-anoxic basin” fields of Tyson (1995) (Figure 4.3). Høgskulefjellet displays all samples in fields V and VII (Figure 4.3), suggesting a slightly more oxic environment. Pyrite inclusions was observed in most samples from both outcrop-sections during microscope analysis. The presence of pyrite inclusion corroborates an anoxic and clastic environment (Tyson, 1995; Batten, 1996). The high AOM in both sections and presence of pyrite could link them to an anoxic period (Wignall and Twitchett, 1996) following the biotic crisis. How organic matter is preserved relies on the duration of exposure to oxygen and can be altered by changes in organic matter input, sedimentation rate, or bottom-water oxygenation (Tyson, 2005). Further variations in AOM can be a result of sea-level change, or variations in water column oxygenation.
5.3 Ecosystems

When studying mass extinctions, ecosystems and their collapse following a biotic crisis are often looked upon as well. Twitchett et al. (2001) defined ecosystem collapse as a dramatic change in community structure due to the vanishing of dominating plant, animal and trace-fossil taxa, and changes in the relative proportions of surviving taxa.

5.3.1 Palynomorph records - Terrestrial

The composition of terrestrial palynomorphs in Deltadalen and Høgskulefjellet display little diversity in pteridosperms and conifers.

Deltadalen

The Deltadalen assemblages reveal a great dominance of undifferentiated bisaccates and sacci (Figure 4.6). They are most likely of pteridosperm or conifer pollen affinity as these groups were distinguishable in the section. The palynomorphs that were identifiable were represented of Vittatina Group and taeniate bisaccates (Pteridosperms) and non-taeniate bisaccates and *Lueckisporites* (Conifers) throughout the sections, but in low abundances compared to undifferentiated bisaccates and sacci. These assemblages together with *Florinites* and monosaccate pollen of Cordaites affinity are generally considered as common in Permian (Hochuli et al., 2010). Spores are sparsely represented in Deltadalen, resulting in low spore/pollen ratios, which confirms a reduced role of lycopsids. The palynomorph assemblages suggest a setting in the period following the extinction. This setting matches the isotope records (Section 5.1). Due to environmental stress, lycopsid species as *Uvasporites* that are commonly intact as tetrads increase when the Late Permian gymnosperms collapsed resulting in a turnover (Twitchett et al., 2001). In the aftermath higher pollen ratio would be expected, and a slow increase as recorded in East Greenland of Early Triassic taeniate pollen grains (Twitchett et al., 2001). Further studies (Mangerud and Konieczny, 1993), notes a same shift from gymnosperms to lycopsids in palynological assemblages, while other studies (Hochuli et al., 2010; Grasby et al., 2015) document the same rise of spores in the Late Permian.

This shift shows how the gymnosperms and their ecosystem collapsed, paving the way for a short-lived recovery of lycopsids and bryophytes and constituents of Early Triassic shrubland communities due to response of environmental stress (Twitchett et al., 2001; Hochuli et al., 2010). In the studies from Twitchett et al. (2001) and Hermann et al. (2010), the $\delta^{13}C$ excursion
occurred after the collapse of both marine and terrestrial ecosystems. Thus, the terrestrial and marine (loss of chert-forming siliceous sponges) ecosystems happened synchronously across northwestern Pangea (Grasby et al., 2015).

**Høgskulefjellet**

This section shows minor abundances of spore and pollen taxa, with the undifferentiated bisaccates and sacci as the most abundant one. Of the identifiable ones, non-taeniate bisaccates are the highest represented. Strong fluctuations in the relative dominance of microplankton together with low numbers of spores and pollen, imply that this section is most likely marine/offshore, further supported by the ternary APP-diagram (Figure 5.5) and microplankton-spore-pollen plot (Figure 5.6).

![Figure 5.6: Microplankton-spore-pollen ternary plot. The line indicates theoretical regressive trend with the possible environmental interpretations shown filed in the plot. Modified from Tyson (1995).](image)

Also, the lack of finding spores in their tetrad shape, may relate to the sections being after the extinction. Around the end-Permian mass extinction, the regular presence of unseparated
spore tetrads, are the most possible evidence for massive environmental stress acting on plants (Visscher et al., 2004).

### 5.3.2 Acritarch record changes – Marine

Acritarchs found in Deltadalen outcrop are represented mainly by *Leiosphaeridium* and *Micrhystridium* with *Baltisphaeridium* present in one section. At Høgskulefjellet, the same groups are represented, but *Veryhachium* is also found throughout the section. The species *Micrhystridium breve* (short spines) was most abundant in both sections, indicating nearshore environments. Other species of *Micrhystridium* together with *Veryhachium* that have longer spines, are more common in open marine environments, moving from nearshore to deep shelf (Figure 5.7) (Lei et al., 2012). The spherical acritarchs exemplified with *Leiosphaeridium*, is typical for open marine environments from the shelf to the basin, while larger types of spherical acritarchs are common in environments interpreted to be of shallow water (Figure 5.7) (Lei et al., 2012). The acritarchs were most abundant and diverse in shelf and upper-slope settings (Lei et al., 2012).

![Figure 5.7](image)

**Figure 5.7:** The relative abundances of the major acritarch groups relative to all aquatic palynomorphs and their sedimentary facies. The triangles indicate the different sections studied from Lei et al. (2012). Modified from Lei et al. (2012).
As Figure 5.8 shows, there is a clear dominance of *Micrhystridium* dominates in both outcrops with a high relative abundance. Correspondingly as Lei et al. (2012) mentions, *Micrhystridium* is distributed widely, from nearshore setting in shallow water to offshore settings in deeper water. In Deltadalen at 0.2 m and 3.6 m some *Micrhystridium* are identified with longer spines indicative of an open marine environment. This fits well as the small, spherical and deeper water *Leiosphaeridium* is identified throughout the section. However, due to the dominance of *M. breve* it is difficult to draw conclusions of *Leiosphaeridium* and *Micrhystridium* (long spines) alone.

*Micrhystridium breve* with short spines are the most abundant in this section, interpreted as nearshore environments. The presence of *Veryhachium* and more relative abundance of spherical *Leiosphaeridium* in Høgskulefjellet puts it slightly more towards the open marine than Deltadalen (Figure 5.8). Further, the omission of large spherical forms in Deltadalen and Høgskulefjellet, indicates that both sections are at a younger stage than the extinction. Large spherical forms disappear entirely at or close to the end-Permian mass extinction (Shen et al., 2013).

**Figure 5.8**: Relative abundance of the different aritarch groups of total acritarchs from both sections correlated in different sedimentary facies. DD = Deltadalen. HØG = Høgskulefjellet. Modified from Lei et al. (2012).
When it comes to diversity, Lei et al. (2012), showcased that a pattern of 2-4 acritarch species with 1-3 genera each is usually found in nearshore environments and basinal facies. Also, the genera *Veryhachium* occurs on the shelf and towards the basin, suggestive of an open marine environment. This correlates well with the identified groups. There was little diversity within the groups during identification, with 1-2 species per group. Shen et al. (2013) recorded how the diversity of acritarch from Late Permian decreased significantly into the Early Triassic, where the big spherical ones were the most affected. On the other hand, the short-spined forms experienced a rather steady diversity (Shen et al., 2013). Because short-spined forms endured in the inner shelf, but not the long-spined and spherical forms of the deeper environments, a suggestion is that the nearshore environments served as shelter during times of extreme environmental crises in the Early Triassic (Shen et al., 2013).

Acritarch assemblages that have low diversity and high abundance, and composed of spherical forms and short-spined forms are typical of inshore-shallow water facies (Tyson, 1995). Yet, deep water assemblages are also characterized by low diversity. Therefore, in general one has to be cautious when interpreting due to similarities and limited knowledge of Late Permian/Early Triassic acritarch distribution (Dustira et al., 2013).

### 5.4 Correlation with other studies

Palynology and palynofacies studies in Deltadalen are sparse, limiting the correlation ability. However, there are some discussed below.

The palynofacies results of Deltadalen from this study does not display the negative excursion in the carbon record. Therefore, a correlation with the core (DD1) has been attempted (section 5.1). Mørk et al. (1999b) studied the Vikinghøgda Formation in Deltadalen. They found a high abundance of marine plankton in the basal part, together with a high presence of flakes/sheets (AOM), resembling the Deltadalen outcrop-section (Figure 5.9). This is further strengthened by the core (Figure 5.9B). The Deltadalen outcrop-section also had palynomorphs such as *Lueckisporites virkiae*, *Vittatina* spp. and plankton comprising most notably of *Micrhystridium*, even though most of them were indefinable due to mineral growth. These features are also found in the basal part of the palynofacies of Mørk et al. (1999b), suggesting a similar age. Although forms such as *Vittatina* and *Lueckisporites virkiae* are typical for late Permian strata, they are seen in equivalent to similar transitional microflora of Permian-Triassic layers (Utting, 1994; Looy et al., 2001).
Moving up in the stratigraphy, Mørk et al. (1999b) identified an abundance of pollen, spores and plankton (*Micrhystridium*), well-fitting with Deltadalen outcrop-section in this study. *Lunatisporites* is present in both studies. Roughly in the middle of its section, the Deltadalen outcrop also has a peak of AOM. Here the phytoclasts are really low, which could represent a condensed section. This drop in phytoclast and peak of AOM correlates with Mørk et al. (1999b). Additionally, after the AOM peak, acritarch, spores and pollen increase while the phytoclasts become less abundant (Figure 5.9). This change in POM is also noted by Mørk et al. (1999b).

The Høgskulefjellet section has a peak in the marine/terrestrial ratio of the palynofacies (Figure 4.5). Together with a high spore/pollen ratio this suggests that Høgskulefjellet is higher up than Deltadalen outcrop-section compared to the core (Figure 5.10). Another correlating factor is the presence of *Veryhachium* in the core and in Høgskulefjellet at this stage of the section. *Veryhachium* was present in almost the entire section from Høgskulefjellet, but in minor relative abundances, same as from the core. Both findings of *Veryhachium* had 3 processes as their feature. At the top of Deltadalen Member of the Vikinghøgda Formation, Mørk et al. (1999b) notes regular to abundant values of *Veryhachium* in the palynofacies analysis with a large dominance of *Micrhystridium*. This fits with Høgskulefjellet and the core, and marks an environmental change from below.
Figure 5.9: Correlation between Mørk et al. (1999b) (A), the core (van Soelen et al., in prep.) (B) and Deltadalen (C).
Figure 5.10: Correlation between the Høgskulefjellet outcrop-section and the core (van Soelen et al., in prep.) based on marine/terrestrial ratios and spores/pollen ratio. Mørk et al. (1999b) records has been added to provide correlation with Høgskulefjellet. Blue line indicates the presence of *Veryhachium*. 
6 Conclusions

The palynological and palynofacies analyses, together with the isotope results of the retrieved samples from Deltadalen and Høgskulefjellet section generated the following conclusions:

1. The carbon-isotope records do not show the negative excursion associated with the end-Permian mass extinction. After correlation with the core from Deltadalen, both outcrops are suggested to be of a younger age.

2. Both outcrops had high abundance of AOM, indicating of depositions in a more distal shelf marine setting. By the use of ternary APP-diagram, Deltadalen depicts variations of shelf to basin transition or shelf environment, while Høgskulefjellet is located on a distal shelf. However, variations in sea level can also alter the AOM composition.

3. Deltadalen is deposited under suboxic to anoxic conditions, supported by the APP diagram and high abundance of AOM. Høgskulefjellet is suggestive of more oxic environment. The presence of pyrite inclusions in both sections corroborates with a more anoxic condition following the biotic crisis.

4. A low spore/pollen ratio in Deltadalen is a possible representation of the period after the extinction. This also correlates with the interpretation of the isotope records.

5. The acritarch records studied, indicates a predominantly abundance, but low diversity. *Micrhystridium* is clearly the most abundant and hardiest, indicative of a nearshore environment.

6. The presence of namely the acritarch genera *Veryhachium* and more relative abundance of spherical *Leiosphaeridium* in Høgskulefjellet, helps to indicate this section to be slightly more open marine than Deltadalen.

7. Through correlation with other studies from Deltadalen area (Mørk et al., 1999b), the outcrop-section from Deltadalen can be distinguished to be at basal part of the Vikinghøgda Formation as AOM abundances and notion of certain palynomorphs were identified.

8. The Høgskulefjellet section is suggested to be placed even younger than Deltadalen, because peaks in the marine/terrestrial ratio and spore/pollen ratio are corresponding with
the core. This is further implied with the presence of *Veryhachium* with 3 processes in both sections, additionally as well in the study from Mørk et al. (1999b).
7 References


PIEPJOHN, K., BRINKMANN, L., GREWING, A. & KERP, H. 2000. New data on the age of the uppermost ORS and the lowermost post-ORS strata in Dickson Land
(Spitsbergen) and implications for the age of the Svalbardian deformation. *Geological Society London, Special Publications* 180, 603-609.


RUSTAD, T. 2013. Palynofacies and palynology of the Cenomanian-Turonian deposits in ODP 174AX Bass River core, New Jersey - Depositional environment, vegetation history, petroleum potential and climate changes during the Oceanic Anoxic Event 2. Master, University of Oslo, Department of Geosciences


A. Plates
Plate 1

1. Undifferentiated trilete spore. Deltadalen (+7.4 m)

2. Undifferentiated trilete spore. Deltadalen (+2.6 m)

3. *Deltoidospora* sp. Høgskulefjellet (10.3 m)
Plate 2

1. Undifferentiated bisaccate pollen. Deltadalen (+4.4 m)

2. Undifferentiated bisaccate pollen. Deltadalen (+5.2 m)

3. *Lunatisporites* sp. Deltadalen (+6.2 m)

4. Undifferentiated monosaccate pollen. Deltadalen (+7.4 m)
Plate 3

1. *Micryhystridium breve* (semi-long spines) (Jansonius, 1962). Deltadalen (+0.2 m).


4. *Baltisphaeridium* sp. (short spines). Deltadalen (+3.6 m)
Plate 4

1. *Veryhachium* sp. Høgskulefjellet (3.8 m)


3. *Leiosphaeridium* sp. Høgskulefjellet (8.4 m)

4. Cluster. *Micrhystridium. breve* (short spines) and undiff. non-taeniate pollen. Høgskulefjellet (3.8 m)
Plate 5

1. Undiff. taeniate bisaccate pollen due to pyritization. Høgskulefjellet (6.7 m)

2. Undiff. non-taeniate bisaccate pollen due to pyritization. Høgskulefjellet (6.7 m)

3. Broken undiff. bisaccate pollen. Høgskulefjellet (10.3 m)
B. Sample data
## DELTADALEN

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81
## HØGSKULEFJELLET

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D. Palynofacies data
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E. Palynological data
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<td>3</td>
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F. Systematic description
Spores

Genus: *Deltoidospora* (Miner, 1935)
*Deltoidospora* sp.
Plate 1, Figure 4
Description: Laevigate trilete spore with a triangular outline. The apices may be rounded or convex and the sides concave or convex.

Genus: *Lycopodiumsporites* (Delcourt et al., 1955)
*Lycopodiumsporites* sp.
Not illustrated
Description: Coarsely reticulate trilete spore with short laesurae and rounded-triangular equatorial contour.

Genus: *Uvaesporites* (Döring, 1965)
*Uvaesporites* sp.
Not illustrated
Description: Broadly, circular, trilete spore with distinct laeaeae. Proximally flat, distally weak area where element indiscriminately forming kidney shape bunch, irregular.

Undifferentiated trilete spores
Plate 1, Figures 1-2
Description: Any trilete spore with distinctive laesurae but further identifying impossible.

Monosaccates

Genus: *Florinites* (Schopf et al., 1944)
Not illustrated
Description: Bilateral monosaccate pollen.

Undifferentiated monosaccates
Plate 2, Figure 4
Description: Indistinguishable pollen grains with a single saccus.
Bisaccates

**Genus: Protohaploxypinus** (Samoilovich, 1953)

*Protohaploxypinus* sp.
Plate 2, Figure 1

**Description:** Taeniate bisaccate pollen, haploxylonoid, suboval shape. Variable number of taeniate, each 3 to 7 \( \mu m \) wide.

**Genus: Lueckisporites** (Potonié and Klaus, 1954)

*Lueckisporites* sp.
Not illustrated

**Description:** Saccate pollen. Bisaccate. Diploxylonoid in outline. Body is circular, showing two longitudinal ribs in polar view. The sacci are more or less semi-circular in shape.

**Genus: Lunatisporites** (Leschik) emend. (Scheuring, 1970)

*Lunatisporites* sp.
Plate 2, Figure 3

**Description:** Bisaccate, oval, haploxylonoid, central body distinct, bears 3 taeniae on the proximal face; sulcus wide.

Undifferentiated taenitae bisaccates
Plate 2, Figures 1-2. Plate 5, Figure 1 (pyritization), Figure 3 (Broken)

**Description:** Bisaccate pollen grains that were indistinguishable

Sulcate (nonsaccate) pollen

**Genus: Vittatina** (Jansonius, 1962)

*Vittatina* sp.
Not illustrated

Description: Striate pollen without sacci (sometimes with).

Acritarchs

**Genus: Micrhystridium** (Deflandre, 1937) emend. (Sarjeant and Stancliffe, 1994)
Micrhystridium breve (Jansonius, 1962)
Plate 4, figures 1-3

**Description.** The vesicle is ellipsoidal to spherical in outline. The wall is thin and consists of a single layer, and has a yellow to brown color. Along the surface of the vesicle, there are numerous spines (20-30). They are short in some species, hollow, simple and pointed. Other have long spines. Vesicle and processes are smooth.

**Genus:** Baltisphaeridium (Eisenack, 1958) (Eisenack, 1969)
*Baltisphaeridium* sp.
Plate 4, figure 4
**Description:** Spherical to oval vesicle, with numerous hollow and unbranched processes. Apices are rounded, wall is thin (less than $\frac{1}{2}$ µm).

**Genus:** Leiosphaeridium (Staplin, 1961)
*Leiosphaeridium* sp.
Plate 5, Figure 4
**Description:** Vesicle is ellipsoidal to circular in outline. Smooth wall, thin to moderate thick, folding minor to prominent.

**Genus:** Veryhachium (Deunff, 1954) (Sarjeant and Stancliffe, 1994)
*Veryhachium* sp.
Plate 5, Figure 1
**Description:** Triangular vesicle in outline, 2 processes along each angle and one attached on central body. 1 process is broken. Thin and long processes. Wall is thin and single layered.

*Veryhachium hyalodermum* (Cookson, 1956) (Schaarschmidt, 1963)
Plate 5, Figure 2
**Description:** Vesicle is triangular in outline, with 3 processes along each angle and one attached on central body. The processes are simple and long. The wall is thin and single layered.

Undifferentiated acritarchs

Not illustrated

**Description:** Acritarchs that were undistinguishable.