

# **Transgressive Development of Coal-bearing Coastal Plain to Shallow Marine Setting in a Flexural Compressional Basin, Paleocene, Svalbard, Arctic Norway**

**Charlotta Jenny Lüthje**

University Centre in Svalbard, Department of Arctic Geology  
University of Bergen, Department of Earth Sciences



**UNIS**



**SNSK**



**RHUL**



**UiB**

**2008**

Thesis submitted in accordance with the requirements of the  
University of Bergen for the degree of Doctor in Philosophy  
Head supervisor

**Dr. Gary Nichols**

Royal Holloway University of London, Department of Earth Sciences

Co-supervisors

**Prof. Michael Talbot**

University of Bergen, Department of Earth Sciences

**Dr. John Howell**

University of Bergen, Centre for Integrated Petroleum Research

---

Charlotta J. Lüthje

**Doctor of Philosophy (Ph.D.) 2008**

Transgressive development of coal-bearing coastal plain to shallow marine setting in a flexural compressional basin, Paleocene, Svalbard, Arctic Norway

**Charlotta J. Lüthje**

University Centre in Svalbard, Department of Arctic Geology  
University of Bergen, the Faculty of Mathematics and Natural Sciences, Department of Earth Sciences

**ABSTRACT**

The most extensive Paleogene succession in Svalbard, in the Arctic north of Norway, is found in the Central Tertiary Basin of Spitsbergen. It consists of a clastic basin fill of mudstone, sandstone, coal and rare conglomerate beds. A coastal plain to shallow marine setting is suggested for the Late Paleocene Firkanten Formation, the lowermost unit of the Paleogene. This is the first comprehensive facies model, sequence stratigraphic analysis, and paleogeographic reconstruction of the Firkanten Formation, based on new borehole cores and field data.

The facies analysis reveals that sedimentation occurred in a flat relief coastal plain environment with tidal, wave, and storm influence but only minor fluvial sediment input. Previous interpretations have described the Todalen Member, the lower part of the Firkanten Formation as delta plain deposits. The detailed sequence stratigraphic analysis and paleogeographic reconstruction show that the Firkanten Formation consists of parasequences combined into parasequence sets bounded by major flooding surfaces. The succession is dominated by aggradation in a step-wise transgressive setting. The general tectonic subsidence was at all times greater than any eustatic sea level fall since there are no relative sea level falls detected in the succession. The basin was formed as a depression in front of the West Spitsbergen Fold and Thrust Belt.

Thick sections of coastal plain deposits of coal, carbonaceous shale, and other fine grained clastic sediments were deposited on the coastal plain, in mires and swamps that graded into tidally influenced lagoons. The coastal plain was protected from wave reworking by sandy barrier bars but was flooded during periods of increased relative sea level rise probably from eustatic sea level rise. The foreshore and shoreface deposits are characterised by fine grained sandstone and a few pebbly beds making up the Endalen Member, the upper part of the Firkanten Formation. The foreshore was characterised by sandy barrier bars of long shore transported fine grained sandstone. Alluvial fan deltas built out from the thrust front

transporting coarse grained material to the basin. The foreshore and shoreface show a high degree of wave and storm influence. The base of the Paleocene succession is made up by the unconformity to the Lower Cretaceous Carolinefjellet Formation, representing the lower sequence boundary characterised by poorly sorted sediment of re-deposited weathered material and vegetation.

Large, newly discovered footprints of the Pantodont '*Titanoides*' from the Todalen Member coal layers are the earliest evidence of a large mammal on the Arctic island and the northernmost discovery from the Paleocene. The traces are named *Thulitheripus svalbardii* Ign nov. isp. nov. Large Paleocene Pantodonts are previously only known from North America and their presence on Svalbard, confirms the postulated DeGeer route for migration of mammals in the Late Paleocene to Eocene.

The Central Tertiary Basin is interpreted as being of flexural origin, formed as a result of crustal shortening in West Spitsbergen due to convergence with Greenland related to the opening of the Northern Atlantic in the early Paleogene. The Late Paleozoic clasts in conglomerate beds provide evidence that there was uplift and erosion of at least 2000 m of rock in the West Spitsbergen Fold and Thrust Belt, directly adjacent to the western margin of the basin. The sand came from Mesozoic strata uplifted to the north and northwest of the basin. The deformation zone is relatively narrow and the strata are folded to vertical on the western side of the basin. The Central Tertiary Basin shows very little deformation. It is suggested that the most important factor creating the Central Tertiary Basin was compressional folding and not extension or foreland basin flexural loading as has been postulated previously. The compressional folding model suggests that the orogeny did not necessarily create a mountain belt with high elevation. The footprints suggest that there was no obstruction for migrating Pantodonts such as a seaway or elevated topography between Svalbard and Greenland /Ellesmere Island in Late Paleocene time.

## ACKNOWLEDGEMENT

This Ph.D. project was done at the University Centre in Svalbard (UNIS) in cooperation with University of Bergen (UiB) and funded by Store Norske Spitsbergen Kulkompani (SNSK) the Norwegian mining company on Svalbard. The work was partly done at UNIS and partly at the Royal Holloway University of London (RHUL).

I would like to thank Dr. Gary Nichols, my head supervisor, for help and support during this project and without whom this work would have been very different indeed. I immensely enjoyed all the interesting discussion and it was always fun to work together with the project. Your interest in the project and critical reviews improved the results. I would also like to thank everyone at the Earth Science Department at RHUL for letting me be part of the inspiring and enjoyable environment.

I would like to acknowledge Michael Talbot at UiB and John Howell at Centre for Integrated Petroleum Research (CIPR) for being co-supervisors and Jørgen Stenvold for being my contact at SNSK. SNSK is acknowledged for giving me access to the coal data and the cores. I could not have gathered all the core data without SNSK giving me permission to use the core store in Endalen, clearing the road for snow, and constantly repairing the electricity connection so I could work in above freezing temperatures and without the need of a head torch. SNSK also supported all field activity in Svea 2004-2006 in addition to providing me access to the mines for sampling and field observations at several occasions in the mines Svea Nord in Svea and Grube 7 in Longyearbyen. Arne Kristoffersen and Anna-Karin Ek at Svalbard Wildlife Service are acknowledged for letting me sample the coal seams in Grube 3. Alv Orheim at GeoArktis provided me with additional coal data sampled in the 70's to the 90's. Henrik Friis from Århus University, Denmark; Thierry Jacquin at GeoLink, France; Helen Smyth at CASP, UK; Roy Davies at Rocksource, Norway are all thanked for interesting discussions. Even if only the Central Tertiary Basin was considered in this study the Norwegian Polar Institute provided funding for fieldwork in the Cenozoic basin in Ny Ålesund in 2005, 2006, and 2008. This work has given some interesting information for understanding of the Central Tertiary Basin.

I would like to thank all the good friends I got to know during this period that has supported me to keep going. Finally the greatest thanks go to my husband for all encouragement, help, and critical reviews he has given me. Your confidence in me was the best support.

## CONTENTS

1. Introduction	1
1.1. Aim of the re-investigation of the Firkanten Formation	1
1.2. Outline of thesis	1
1.3. List of articles and contributions	3
1.4. Material and study area	4
- Core data	6
- Field data	6
- Mine data	6
- Coal and geochemistry data	7
- Reference data	8
1.5. Methodology	8
- Facies analysis	9
- Sequence stratigraphic analysis	9
- Paleogeographic reconstruction	10
2. Background	11
2.1. Paleogene setting of Svalbard	11
- Van Mijenfjorden Group	13
- Previous depositional models	16
- Basin model of transtension-transpression	21
- Basin model of a foreland basin	22
- Paleogene climate	23
- Dating of Paleogene strata	24
2.2. General coastal depositional environments	24
2.3. Peat accumulation and the prerequisite for coal deposits	27
- Coal macerals	28
- Origin of fusain	29
- Maceral of coal from Svalbard	29
2.4. General flexural formed basins	30
2.5. Questions raised	33
3. Synopsis of articles	35
3.1. Depositional environment	36
- Coastal plain	36
- Foreshore, shoreface, and offshore transition	39
3.2. Basin configuration and development	43

4. Article 1 – Coastal plain, Paleocene Spitsbergen _____	46
Lüthje, C. and Nichols, G. Submitted. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. <i>Sedimentology</i> .	
5. Article 2 – Transgressive coastal plain _____	82
Lüthje, C. and Nichols, G. Submitted. Transgressive coastal plain to shallow marine development of the Paleocene strata of Spitsbergen, Arctic Norway. <i>Journal of Sedimentary Research</i> .	
6. Article 3 – Flexural basin, Paleocene Spitsbergen _____	119
Nichols, G. and Lüthje, C. Submitted. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. <i>Basin Research</i> .	
7. Article 4 – Pantodont Titanoides, Paleocene Svalbard _____	146
Lüthje, C., Milàn, J. and Hurum, J. Submitted. Paleocene tracks of the Pantodont genus <i>Titanoides</i> in coal-bearing strata, Svalbard, Arctic Norway. <i>Proceedings of the Royal Society B</i> .	
8. Conclusions _____	163
8.1. Summary of conclusions _____	163
8.2. Answers to questions to old interpretation _____	164
8.3. Future research and limitations to this work _____	166
9. References _____	168
10. Appendix _____	175

Attachment: 1 CD

## **1. INTRODUCTION**

*In this chapter the aim and the hypothesis of this project are introduced as well as the outline of the thesis. The current status of the articles written during the project is stated. The material used in the research and the methodology are presented.*

### **1.1 Aim of the re-investigation of the Firkanten Formation**

The Firkanten Formation of Paleogene on Svalbard, Arctic Norway represents the first sediments deposited in the Central Tertiary Basin. The coal-bearing strata have been in focus for more than a hundred year within the mining industry. Nonetheless, there has previously not been made any comprehensive investigation considering the sedimentary depositional environment and coal generation in the context of basin development and sequence stratigraphic development.

A new extensive core material (drilled by SNSK since 2002 and still ongoing) provided an opportunity to do a detailed investigation of the Firkanten Formation based on modern sedimentary analysing methods. The aim of the project was to re-investigate the depositional environment in a sequence stratigraphic view to get the paleogeographical development through time. The results were evaluated in context of basin formation to get a better understanding of the regional tectonic model. The purpose was to create a comprehensive model of the depositional environment, the development of the basin, and the understanding of the formation of the basin and the depositional system. In addition the objective was to be able to predict future coal exploration more precisely.

The hypothesis was that inconsistencies in the previous interpretation had lead to incorrect conclusions. Therefore, it was important to build a comprehensive model for the basin as a whole, to be able to create a more consistent interpretation.

### **1.2 Outline of thesis**

The research results that came out of this project are presented in five articles submitted for publication in different international journals. This thesis is based on these articles with an extended introduction of the subject and a comprehensive conclusion that summaries the result of the entire work. The outline of the thesis is presented below.

1. Chapter 1 consists of a general introduction to the material and specific the methods used in the investigation.

2. It is followed by background knowledge of the Paleogene sedimentary deposits of Svalbard in Chapter 2, stating the understanding of the Firkanten Formation prior to this work. In Chapter 2 a general introduction to coastal depositional environments, coal generation and flexural basins is also found. Questions raised regarding inconsistencies in the previous interpretations are also presented in this chapter.
3. Chapter 3 provides a synopsis of the research, further presented in detail in the articles and summarises the conclusions. The questions raised in Chapter 2 are addressed and briefly discussed.

In Chapters 4 to 7 the four different articles generated from the results of this work are presented.

4. Chapter 4 focuses on the interpretation of the depositional environment from facies analysis.
5. Chapter 5 addresses the sequence stratigraphic interpretation and the paleogeographic reconstruction, which puts the results from the facies analysis in lateral distribution and development through time.
6. Chapter 6 presents the results from the regional investigation of the basin discussing the formation of the Central Tertiary Basin.
7. In December 2006 large footprints were found in the mine in outside Longyearbyen. The footprints showed to be of Pantodonts, which are described in Chapter 7.
8. The results are summarised in Chapter 8 with a conclusion of what new information and knowledge that has come out of this research project. The answers to the questions raised in Chapter 2 are summarised. Limitations and suggested work for the future are also discussed.
9. This chapter contains the references used in the thesis except for the ones in the articles, which are listed in each article respectively.
10. In this chapter the content of the Appendix is listed, which is found on the attached CD. The Appendix contains additional material such as pictures of facies and logs as well as large scale images of some of the figures in the thesis and the articles. There are also pdf versions of the articles in a large more easily readable format and a pdf version of the thesis.



### 1.3 List of articles and contributions

The contributions by the listed authors to each manuscript are summarised below:

#### Chapter 4: Article 1

Lüthje, C. and Nichols, G. *Submitted*. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. *Sedimentology*.

C. Lüthje: principal investigator and author

G. Nichols: discussions and manuscript review

Contribution by C. Lüthje: 90%

#### Chapter 5: Article 2

Lüthje, C. and Nichols, G. *Submitted*. Transgressive coastal plain to shallow marine development of the Paleocene strata of Spitsbergen, Arctic Norway. *Journal of Sedimentary Research*.

C. Lüthje: principal investigator and author

G. Nichols: discussions and manuscript review

Contribution by C. Lüthje: 90%

#### Chapter 6: Article 3

Nichols, G. and Lüthje, C. *Submitted*. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. *Basin Research*.

G. Nichols: principal investigator and co-author

C. Lüthje: principal investigator, co-author, and discussions

Contribution by C. Lüthje: 70%

#### Chapter 7: Article 4

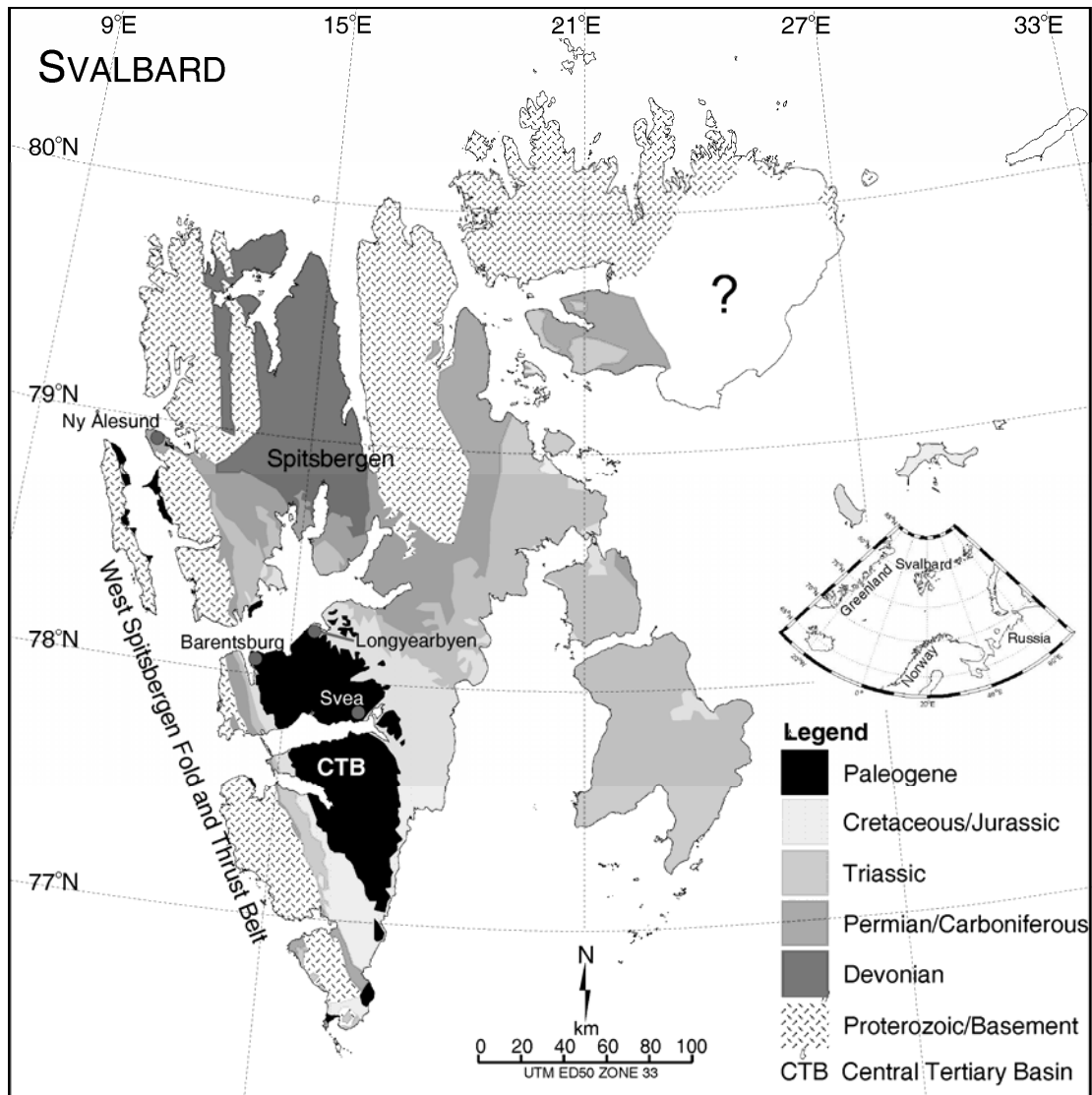
Lüthje, C., Milàn, J. and Hurum, J. *Submitted*. Paleocene tracks of the Pantodont genus *Titanoides* in coal-bearing strata, Svalbard, Arctic Norway. *Proceedings of the Royal Society B*.

C. Lüthje: field investigation, sedimentological principal investigator and co-author

J. Milàn: paleontological principal investigator and co-author

J. Hurum: field investigation, identification, and discussions

Contribution by C. Lüthje: 70%



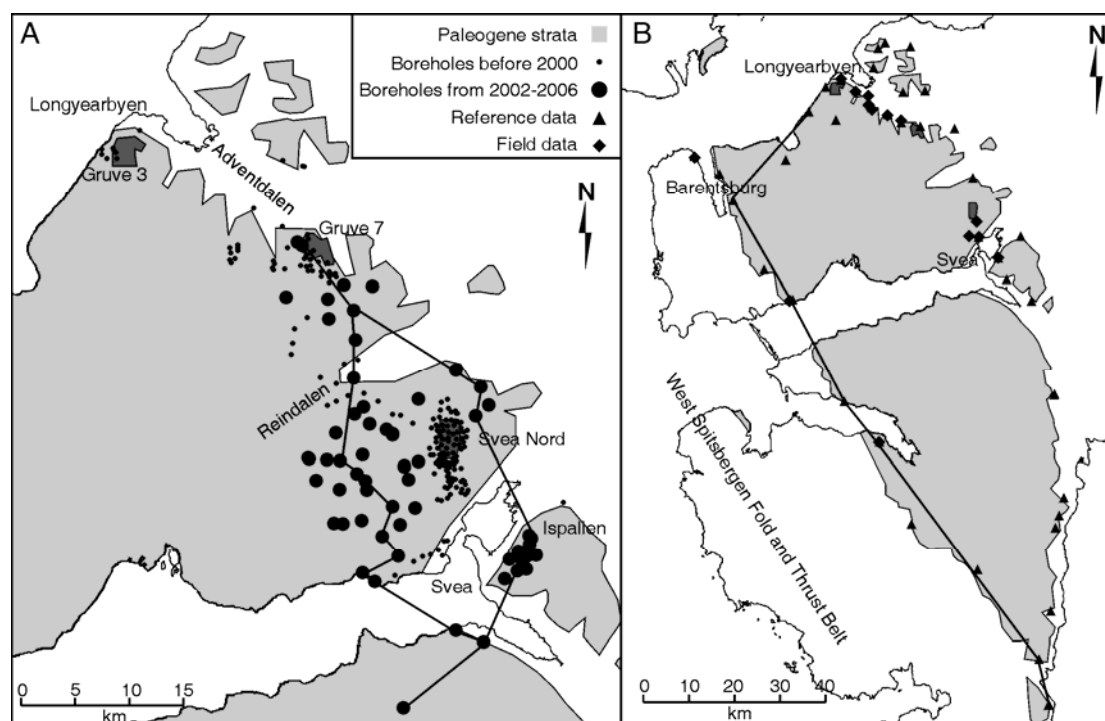
**Fig. 1.1** A simplified geological map of Svalbard. The Central Tertiary basin occupies the centre of the southern part of the main island, Spitsbergen, after (Dallmann, 1999).

#### 1.4 Material and study area

Coal has always been the most important natural resource on Svalbard. All settlements on Svalbard (Barentsburg, Longyearbyen, Pyramiden, Svea, and Ny Ålesund) originate from coal mining and all on Paleogene coal except Pyramiden, which was based on mining of Carboniferous coal. Industrial coal mining started in the beginning of the 20<sup>th</sup> century and is still the main industry followed by tourism and scientific research. The main Norwegian settlement, Longyearbyen (Fig. 1.1), is dependent on coal for all power use and heating. The largest part of the coal is exported to the power industry but since the quality of the coal is excellent some is used in steel production.

The study area was the coal-bearing Firkanten Formation of Paleogene in the Central Tertiary Basin (Fig. 1.1). There is a small section of Paleogene deposits in Ny Ålesund; the Ny Ålesund Subgroup that is similar in age and appearance to the Firkanten Formation. In addition there are two local basins of younger Paleogene deposits; the Buchananisen Group in Prins Karls Forland and the Calypsostranda Group at Skilvika/Renarodden. The Buchananisen and Calypsostrand Groups are younger sediments (suggested Late Eocene – Oligocene) than the Paleocene Firkanten Formation (Dallmann, 1999). The deposits are much coarser and the two sections are interpreted as being deposited in localised basins in the West Spitsbergen fault zone not related to the Central Tertiary Basin and they were therefore not considered in this study (Steel et al., 1985; Dallmann, 1999). The Ny Ålesund Paleogene strata are presently being investigated by the author in context of being a northern extension of the Central Tertiary Basin. However, since this is an ongoing investigation where the results are depending on fieldwork in 2008 it is not presented here.

The material used in this study was mainly the new cores and field observations. Due to inaccessibility to remote areas on Svalbard, data from reference material were used to get a better spatial coverage of the entire basin (Fig. 1.2). However, the quality of data from different sources varies greatly.



**Fig. 1.2** Detail of Figure 1.1 showing locations of the settlements, mines, boreholes, and field locations. Field data is separated into own field observations and references. The main concentration of boreholes is in the eastern part of the basin. Outlined are the cross sections of the correlations.

### ***Core data***

The Norwegian coal mining company SNSK “Store Norske Spitsbergen Kulkompanie” has drilled and cored since 2002 in the north eastern part of the Central Tertiary Basin between Longyearbyen and Svea for coal exploration (Fig. 1.1). The good coverage of boreholes and the excellent quality of the cores in this area made it possible to do a detailed study. There are about 60 cores available from 2002-2006 but not all penetrated Firkanten Formation. Unfortunately most of the older cores (predating 2002) are almost completely lost today, which also includes cores from Ny Ålesund and Russian/Soviet explorations.

The new cores were logged with a focus on the Todalen Member, the Endalen Member and the lowermost part of the Basilika Formation, at scale 1:20 and have been rescaled to 1:50 and 1:200 by using SedLog ([www.sedlog.com](http://www.sedlog.com)). Cores were picked on providing a good spatial distribution and good examples of the Todalen Member and only cores penetrating the underlying Carolinefjellet Formation were considered initially. The facies scheme is based on observations in these cores.

Overview (5 x 1 m core/picture) and detailed digital pictures (~3000) were taken during logging providing a good references material for the facies analysis. Three of the cores were sampled for thin sections (70 slides) for mineralogical analysis. The core diameter is about 4 cm and since they are not cut, all investigations were made on round surfaces.

### ***Field data***

The Firkanten Formation outcrop exposures are of various qualities and the fine grained Todalen Member is especially poor. However, field observations provided a better understanding of the spatial distribution of the facies identified from cores. Fieldwork was carried out in September 2004, July-August 2005 and August-September 2006 in the Longyearbyen and Svea areas. Numerous logs were made but due to poor exposures only 3 complete sections of the Todalen Member were possible to log. 29 samples were collected for mineralogical analysis and additional studies. During fieldwork old logs from references were re-evaluated.

### ***Mine data***

Three continuous coal sections were sampled and logged in the mines; Svea Nord, Gruve 7, and Gruve 3 (Fig. 1.2). The samples were taken for detailed coal analysis such as microstratigraphy, vitrinite reflectance, palynology, and paleoclimate studies using stable isotope analysis. Sampling a second section through the mine Svea North was scheduled to August 2006, but had to be cancelled due to the mine fire.

These samples (45 pieces) were cut and slabs prepared at Royal Holloway, University of London. The samples were scanned using a high resolution flatbed scanner giving a good overview of the initial coal analysis. The coal slabs are currently being analysed at University of Liverpool. The initial results show some variations in maceral content through the seam and some marine brackish influence (pyrite presence).

### ***Coal and geochemistry data***

SNSK sample all coal in the cores for geochemistry (ash or siliciclastic material, sulphur, and phosphor) and occasionally maceral content. The coal was analysed in bulk samples of 20 cm. The existing geochemistry data from earlier exploration cores (predating 2002) was merged with geochemistry analysis from new cores. Some of the old data from the 1970's do not have geographic location information but only notes about the collection area. In the newer sample set it was possible to get trends within the coal seams from the geochemical data. Coal samples from before 2002 was also analysed for different elements. The available data is as following:

- Ash, sulphur, phosphor, 43 elements (Al, Si, P, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, Sn, Sb, I, Ba, La, Hg, Pb, Ra, Th, U, and Pu), and coal maceral (300 samples) from borehole and field samples without geographical location data, from the 1970's
- Thickness of the main coal seam, ash, sulphur, and phosphor content (886 samples; 125 boreholes) with uncertain locations from the 1980's and 1990's
- Records of the depth of the top and the base of the coal-bearing layers (125 samples) with uncertain geographical locations, from boreholes mainly from the 1980's and 1990's
- Records of the depth of the top and the base of the coal-bearing layers with geographical locations (73 samples complete, 147 of the coal thickness) from the 1990's and 2000's
- Record of depth of stratigraphic boundaries and coal layers (28 samples) from boreholes with geographical data, from the 2000's
- Thickness of the main coal seam, ash, sulphur, and phosphor content (34 boreholes), which are displaying trends within the coal seam, with geographical location, from the 2000's
- Maceral data for 6 boreholes from the 2000's

Since this material belongs to SNSK and is confidential only the results of the analysis are presented. The material was statistically examined but the results showed that the data often was inadequate to be used for further interpretations. The specific coal seam of the samples had not always been registered and the location was often missing. However, distribution of ash, sulphur, and phosphor together with the maceral content were found to be useful in the analysis of the newer samples where depth and location of each sample were recorded. Discrepancy between the different coal seams based on the geochemistry was possible, which is also indicated by throughout geochemical analysis combined with maceral study (Orheim et al., 2007).

### ***Reference data***

To get a denser data set especially from remote areas, data from references were re-evaluated. Sedimentological logs from references from areas where field work was carried out were re-evaluated in field, according to the new facies scheme created from the boreholes.

The records of the early sedimentological investigations of the Firkanten Formation are mainly unpublished theses and reports from SNSK e.g. (Kalgraff, 1978; Steel and Dalland, 1978; Dalland, 1979; Ytreland, 1980; Tønseth, 1981; Hansen, 1982; Nøttvedt, 1982; Bruhn, 1999; Wilhelmsson, 1999; Hansen, 2004; Jochmann, 2004; Kostro, 2005). In addition there are some published papers and books e.g. (Kellogg, 1975; Steel et al., 1981; Steel and Worsley, 1984; Steel et al., 1985; Müller and Spielhagen, 1990; Michelsen and Khorasani, 1991; Nøttvedt et al., 1992; Harland, 1997; Bruhn and Steel, 2003; Cmiel and Fabianska, 2004; Nagy, 2005) and a collection of reports from the Norwegian Polar Institute e.g. (Nagy, 1966; Vonderbank, 1970; Harland, 1995). There are also reports for the different geological maps of Svalbard e.g. (Hjelle et al., 1986; Winsnes, 1988; Salvigsen et al., 1989; Dallmann et al., 1990; Dallmann et al., 1994; Major et al., 2001) whereof the data are compiled in (Dallmann, 1999). Logs, when available from these references were used in the analysis and re-evaluated in context of the new interpretation.

Even if the Firkanten Formation has been of interest for a long time due to the coal this is the first comprehensive facies and sequences stratigraphic investigation also considering paleogeography and regional tectonic basin development.

### **1.5 Methodology**

The object of this project was to investigate the sedimentary strata of the Firkanten Formation in perspective of the paleogeography and depositional environment. A sequence stratigraphic

approach was taken to analyse the spatial distribution in time of different depositional environments. To be able to do this, it was required to make a facies analysis first.

### ***Facies analysis***

The facies were originally defined from the core logs. The 44 subfacies were defined from the sedimentary appearance based on lithology, grain size, colour, lamination, structures, heterogeneity, prominent features, occurrence of clasts, organic material, root structures, bioturbation, layer boundary, thickness distribution, associated facies, and occurrence in the stratigraphy. Furthermore the subfacies were related to field observations.

The 44 subfacies were combined into 10 facies that were defined from core and field data and thereafter interpreted to a specific depositional environment. Each of the facies were identified with the same criteria as the subfacies.

The facies were further combined into facies associations representing general depositional environmental zones. The facies associations were based on the facies but identified with help of modern analogues. The analogues were chosen on the similarity to the facies assembly and other background knowledge such as climate and relative sea level change.

### ***Sequence stratigraphic analysis***

Vertical trends in sedimentary strata were identified from the facies analysis and further used in the sequence stratigraphic analysis. In general, sequence stratigraphic analysis is the basis for the correlation and understanding of horizontal relationship and thereby the lateral distribution of facies through time. This can, for example further give a better understanding in predicting the occurrence of coal subsurface. Coal-bearing deposits represent environments that are prone to react to very small changes in base level and are therefore excellent for sequence stratigraphic interpretations. Three dimensional sedimentary models and correct stratigraphic relationships can only be obtained by sequence stratigraphic interpretation. Correlation of different environments by horizontal bounding surfaces is essential to make paleogeographic reconstructions. The correlation of the Firkanten Formation was greatly revised, since previous correlations were based on lithostratigraphic models. This new sequence stratigraphic interpretation display the reality better, as is seen in the mines and outcrops and also compared to modern analogues. The modern analogues provided useful scale of extension of different zones in the depositional system but also angle of the coastline. However, different maximum and minimum scales and angles were considered.

The sequence stratigraphic model is presented in Chapter 5. The method to create the correlation was based on the result from the facies analysis combined with modern analogues. Surfaces representing base level change were identified from the facies distribution such as flooding surfaces. Nearby logs were initially correlated and then the correlation was propagated further away. The base of the Paleocene could not be used as a datum line since it is characterised by local topography. However, the coal layers showed to be useful marker horizons. The vertical sections were not de-compacted since assumptions of, for example the compaction rate and burial depth would have been necessary to make and this would have added more uncertainties.

***Paleogeographic reconstruction***

The result of the facies analysis indicated the type of depositional environment that the Firkanten Formation represents. The sequence stratigraphic analysis showed the lateral development through. By combining the results of the two analyses and evaluate it in perspective to the modern analogues, paleogeographic maps were constructed. The paleomaps gives a better visualisation of the interpretation but also verify the sequence stratigraphy. Anomalies indicated the need for ratification of the sequence stratigraphic interpretation.



## **2. BACKGROUND**

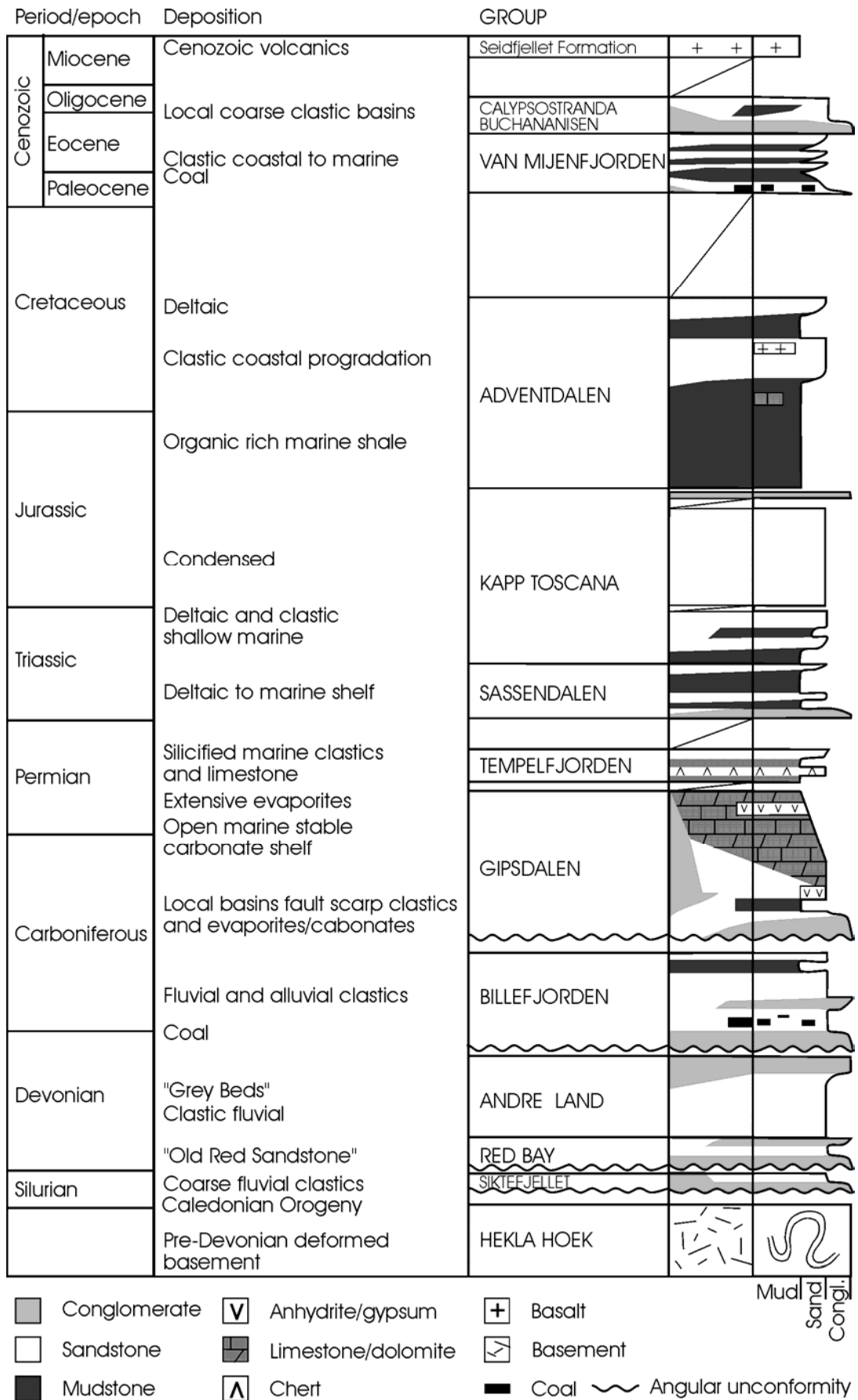
*In this chapter general background knowledge and previous interpretations of the Paleogene strata of Spitsbergen is presented. Former models are discussed and questions to the current interpretations are raised. A general introduction to coal generation in coastal depositional areas and formation of flexural basins is also found.*

Svalbard has for a long time been an area of sedimentary deposition with only one major hiatus from Albian/Aptian to Paleocene. The succession includes an almost continuous section from post-Caledonian Devonian red sandstones, found in the north, to Paleogene of the central area (Figs 1.1 and 2.1) (Steel and Worsley, 1984; Dallmann, 1999). A more complete description of the stratigraphic record on Svalbard is presented in details in Chapter 6 (Nichols and Lüthje, Submitted). The youngest Mesozoic strata exposed on Svalbard of Aptian/Albian in age are the Carolinefjellet Formation underlying the Firkanten Formation (Fig. 2.2) (Dallmann, 1999). It is a succession of mudstone and fine sandstones deposited in an open shelf environment. In the Cretaceous, Svalbard was on the margin of the Barents Shelf lying adjacent to the northern edge of Greenland and Ellesmere Island (Fig. 2.3). The whole area had been relatively stable continental crust since the Carboniferous (Harland, 1997). In the Cretaceous, however, oceanic areas started to open to the north in the Arctic Ocean and also to the south in the Northern Atlantic. Svalbard was uplifted and eroded, creating the pre-Cenozoic hiatus (Blythe and Kleinspehn, 1998). Later in the Paleocene, tectonic plate movements lead to the creation of the West Spitsbergen Fold and Thrust Belt and the Central Tertiary Basin (Fig. 2.4). Rifting and ocean floor spreading between Svalbard and Greenland is dated from Oligocene (Blythe and Kleinspehn, 1998).

### **2.1 Paleogene setting of Svalbard**

The Paleogene strata of the Van Mijenfjorden Group (Fig. 2.2) on Svalbard are mainly found in the Central Tertiary Basin that covers most of the southern half of the main island Spitsbergen (Fig. 1.1). The Paleogene sediment in the Buchananisen Group in Prins Karls Forland and the Calypsostranda Group at Skilvika/Renarodden is interpreted as not connected to the Central Tertiary Basin but deposited as local basins (Steel et al., 1985; Manum and Thronsen, 1986; Dallmann, 1999). These sections will therefore not be considered here.

The Paleogene Ny Ålesund Subgroup is being investigated as a possible northern extension of the Van Mijenfjorden Group. Based on a sequence stratigraphic concept rather than lithostratigraphy the Firkanten and Basilika Formations are related in time. Following the

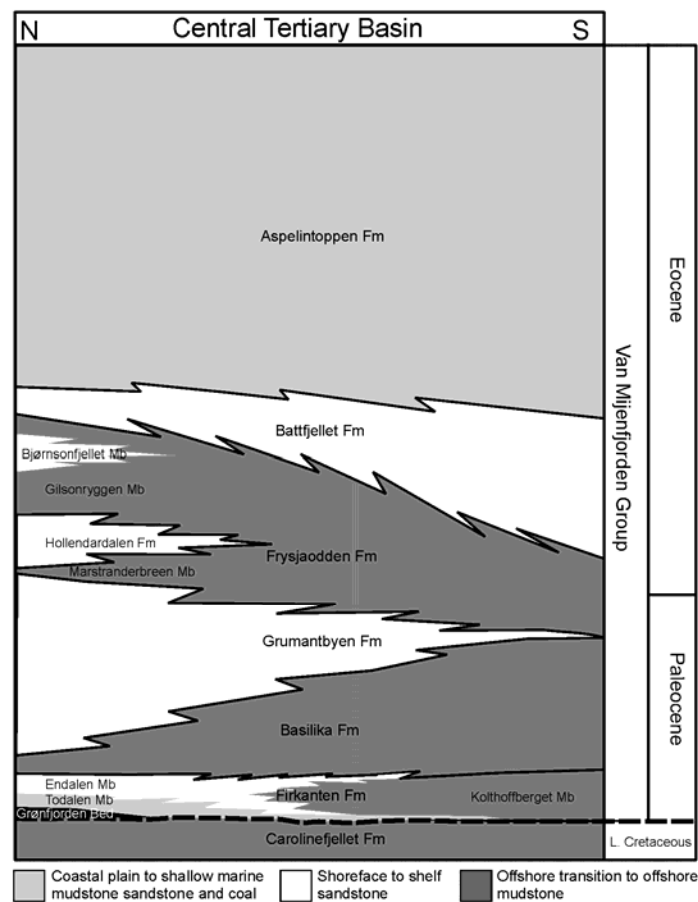


**Fig. 2.1** The stratigraphy of the sedimentary record of Svalbard, from (Nichols and Lüthje, Submitted).

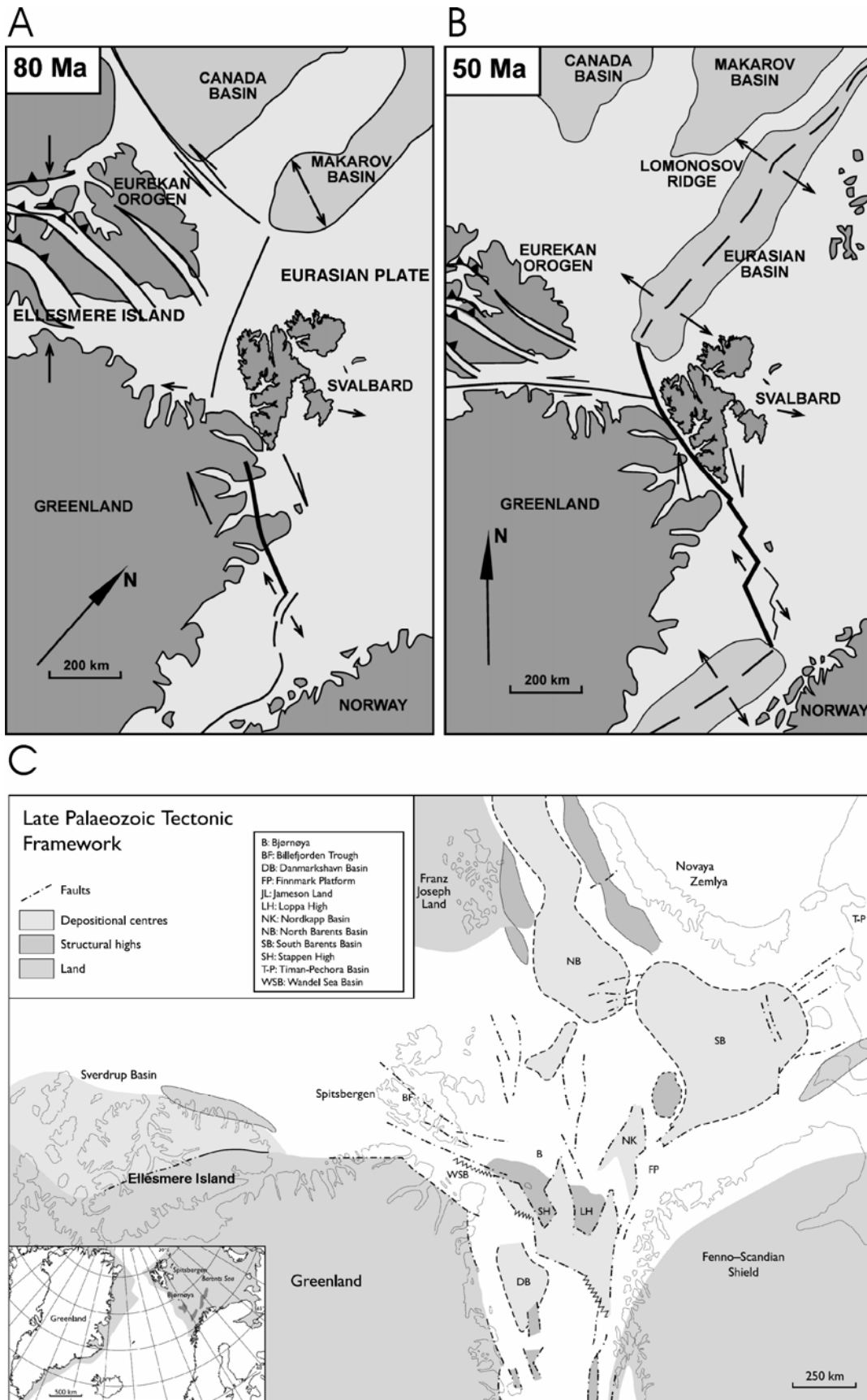
same concept Ny Ålesund coal-bearing strata could then be related to marine deposits further south. It has been suggested previously that the Ny Ålesund Subgroup is the last extension of a northwards back stepping system (Midbøe, 1985; Steel et al., 1985). The result of this ongoing investigation will not be presented here.

### *Van Mijenfjorden Group*

The Firkanten Formation is the earliest deposits in the Central Tertiary Basin (Fig. 2.2). The Todalen Member consists mainly of fine grained muddy deposits, mudstones, muddy sandstone and coal, occasionally pebbles or mudclasts conglomerate. The Endalen Member is characterised by fine grained well sorted sandstone that is often bioturbated. The Basilika Formation consists of muddy sandstone to silty mudstone with intense bioturbation.



**Fig. 2.2** The stratigraphy of the Paleogene Van Mijenfjorden Group in the Central Tertiary Basin of Spitsbergen. The focus of this study is on the lower part of the succession, the Todalen and Endalen Members of the Firkanten Formation, from (Lüthje and Nichols, Submitted a), based partly on (Steel et al., 1985; Bruhn and Steel, 2003). Geometries are based on relative thickness variations (Dallmann, 1999) over the basin.



**Fig. 2.3** Plate tectonic reconstruction model of Svalbard and Greenland from (A) Cretaceous and (B) Paleogene, after (Blythe and Kleinspehn, 1998). (C) Pre-drift reconstruction with structural element, after (Stemmerik and Worsley, 2005).

Together the Firkanten and Basilika Formations form a an initial overall transgressive succession from the continental to marginal marine deposits of the Todalen Member, through shoreface in the Endalen Member to offshore transition in the Basilika Formation (Fig. 2.2). (Steel et al., 1981; Dallmann, 1999). The Kolthoffberget Member represents laterally equivalent offshore deposits to the Todalen and Endalen Members found in the southwest. The pebbly conglomerate of the Grønfyorden Bed is only found locally on the western margin of the basin (Ohta et al., 1992).

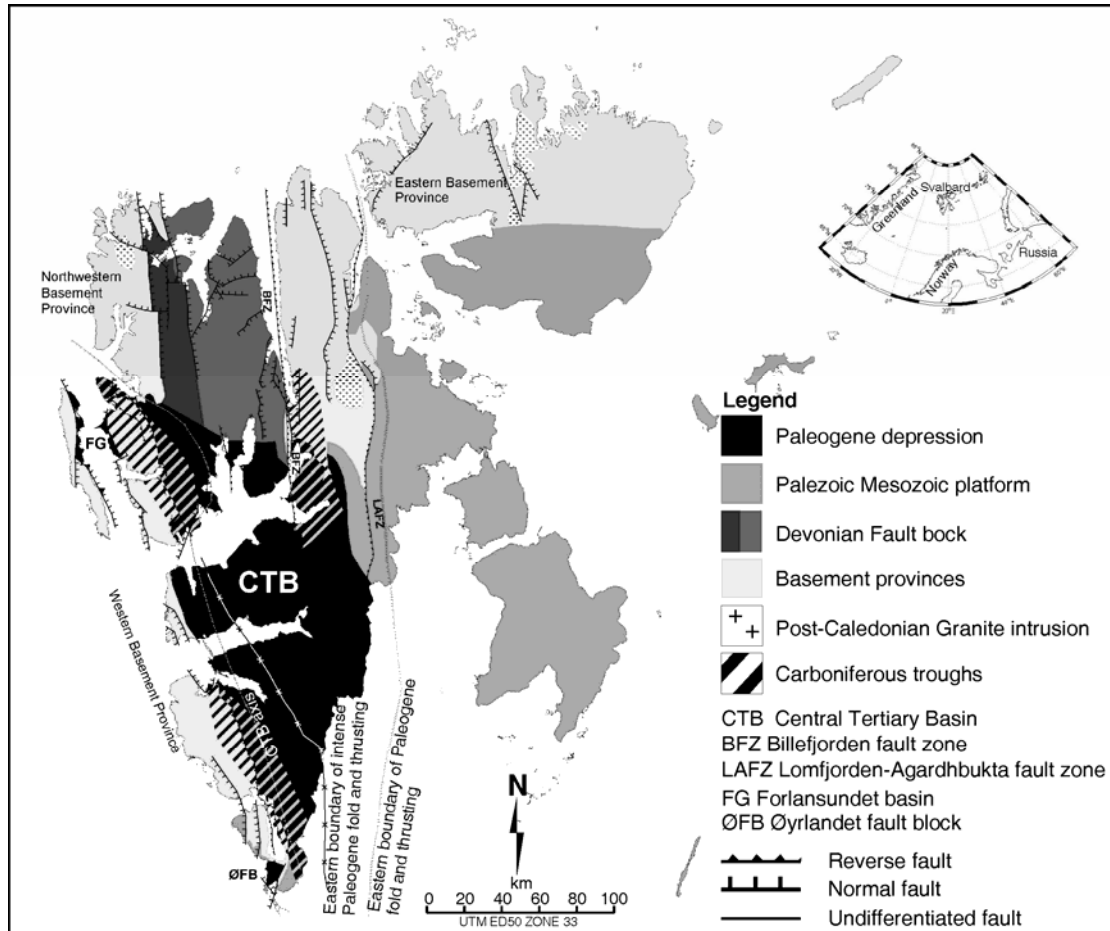


Fig. 2.4 Structural map of Svalbard, after (Dallmann, 1999).

The marine shale of the Basilika Formation is overlain by the progradational Grumantbyen Formation. The regional maximum flooding of the basin took place in the marine shale of the Frysjaodden Formation overlying the Grumantbyen Formation. The boundary between the Paleocene and Eocene is found approximately at this level (Steel et al., 1985; Manum and Throndsen, 1986; Dallmann, 1999; Nagy, 2005).

After the maximum transgression the Frysjaodden Formation marine shales were interrupted by small progradational sequences (the Hollendardalen Formation and the minor Bjørnsonfjellet Member) (Dallmann, 1999), which did not extend far into the basin. These smaller progradations preceded the large progradational section that makes the uppermost part of the sediments today. The regression covered the entire basin and extended from marine offshore (Frysjaodden Formation) through shoreface (Battfjellet Formation) and marginal marine to continental (Aspelintoppen Formation) (Dallmann, 1999). According to the calculation of overburden (1.7 km) from vitrinite reflectance, the sedimentation continued for some time in the basin and probably extended further to the east (Manum and Throndsen, 1978). However, Spitsbergen was eroded extensively during the glacial periods in the Pliocene-Holocene (Blythe and Kleinspehn, 1998).

### *Previous depositional models*

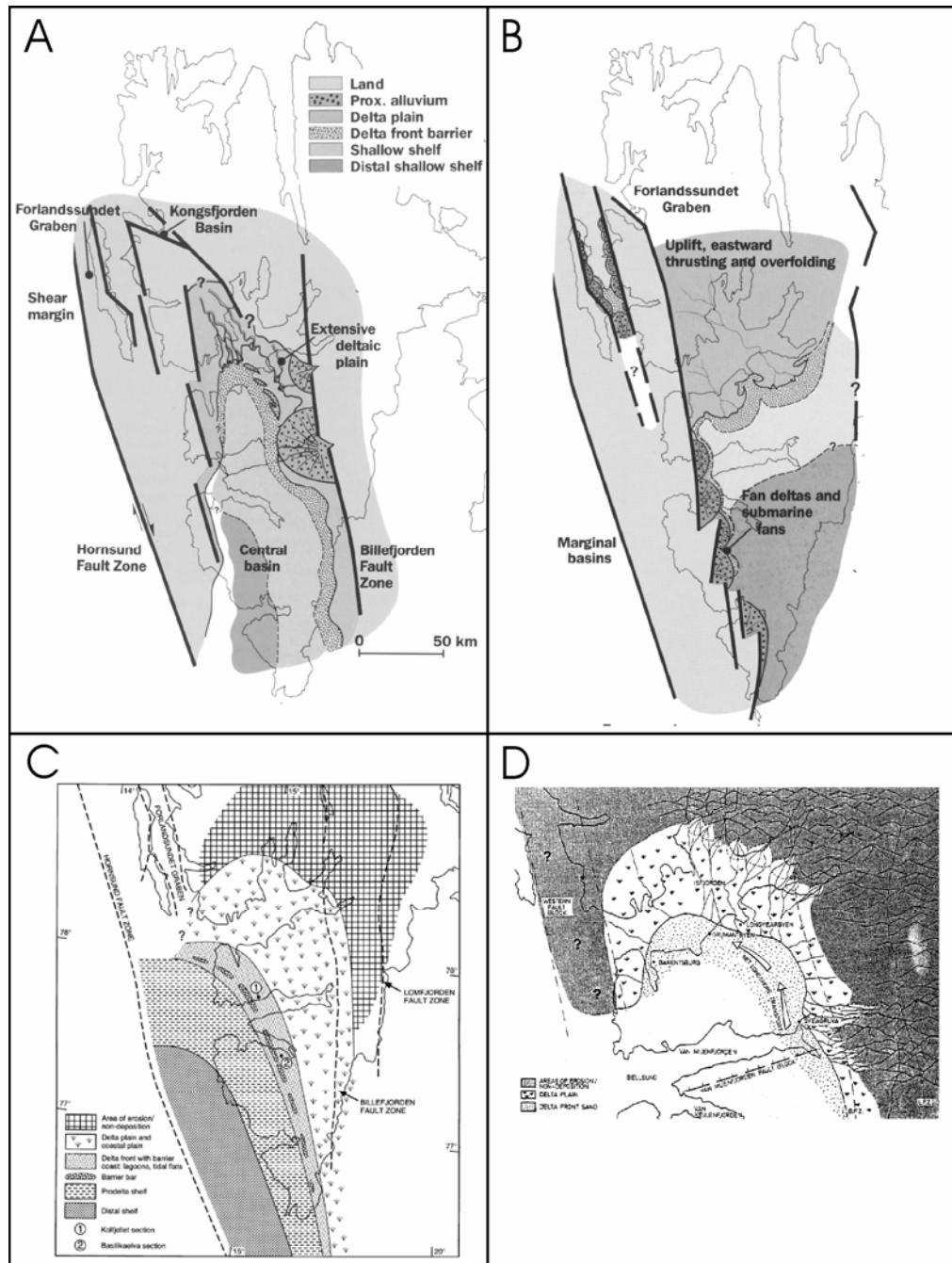
There is no single comprehensive depositional model for the Firkanten Formation regarding sediments, stratigraphy, and structural geology. In this section different previous observations and interpretations are presented. These observations raised some questions to the earlier conclusions regarding the depositional environment, which will be addressed in later chapters.

The Todalen Member mainly consists of fine grained muddy sediments and coal. The Endalen Member is made up of thick well sorted sandstone sections and the Basilika Formation is characterised by bioturbated muddy siltstones (Dallmann, 1999).

The Firkanten Formation has been described as representing a fluvial delta system building out from east-northeast where the coal-bearing strata were deposited on the delta plain represented by the Todalen Member (Steel et al., 1981). The muddy organic facies were interpreted as floodplain and interdistributary bay deposits (Fig. 2.5). Tides and waves had supposedly influenced large parts of the delta (Steel et al., 1981; Steel and Worsley, 1984) and the tidal influence on the Todalen Member has been partially recognised as extensive.

The Endalen Member was interpreted as the sandstone deposits of a wave dominated shoreline delta front (Steel et al., 1981; Steel and Worsley, 1984; Bruhn and Steel, 2003), while the shale of the Kolthoffberget Member was the lower delta front to prodelta (Fig. 2.5) (Steel et al., 1981). The interpretation was based on the stratigraphic position to the delta plain of the Todalen Member. The Basilika Formation was interpreted as offshore transition deposits (Steel and Worsley, 1984; Steel et al., 1985; Dallmann, 1999).

The collection of interpreted depositional environments of the Todalen Member reveals a complex and confusing system of fluvial, wave, and tidal influence on a coastline that was described both as retrograding and progradational at the same time e.g. (Kalgraff, 1978; Steel and Dalland, 1978; Tønseth, 1981; Nøttvedt, 1982; Hansen, 2004). Apparently the interpretation of the Todalen Member as a fluvial delta was to a large extent based on the



**Fig. 2.5** Different paleogeographic reconstructions of the Firkanten Formation raised some questions to the previous interpretations. (A) Paleocene and (B) Eocene, from (Worsley et al., 1986). (C) Firkanten Formation, from (Nagy, 2005). (D) Firkanten Formation, from (Nøttvedt, 1982).

presence of coal, indicating continental environment. It also seems that the interpretation to some extent have been influenced by the presence of the fluvial conglomerate of the Grønfjorden Bed at the base of the Todalen Member.

The presence of clasts/pebbles in the deposits were interpreted to represent a mixed braided river/low-sinuosity fluvial setting (Nøttvedt, 1982). The conglomerates were interpreted as fluvial mainly on the lack of bioturbation (Hansen, 1982), the apparently random extent, and the poor sorting (Steel and Dalland, 1978). No distinction was made between pebbly conglomerate and angular mudclasts derived from the Carolinefjellet Formation or the Firkanten Formation.

The Carbonaceous mudstone and coal have previously been interpreted as floodplain, levee, or interdistributary bay deposits on the basis of the fine grain size and the high organic content (Kalgraff, 1978; Steel and Dalland, 1978; Ytreland, 1980; Tønseth, 1981; Hansen, 1982; Wilhelmsson, 1999; Jochmann, 2004). The general floodplain interpretation of the mudstone seems to be based largely on the lack of marine observations like bioturbation and fossils (Steel and Dalland, 1978; Nøttvedt, 1982; Hansen, 2004), which are hard to identify in outcrop in the Todalen Member.

However, floodplain levee settings are normally expected to show larger input of clastic sediment than found in the Todalen Member and the extent of the mires is supposed to be limited. Peat accumulations in active delta or floodplain environments tend to be thin and irregular (McCabe, 1984).

Steel and Dalland (1978) argued that a delta plain interpretation for the lowermost section of the Todalen Member was unlikely. This conclusion was based on the marine influence on the sediments and lack of evidence for a delta succession. The thickness of the Todalen Member below the first coal seam is too thin and largely influenced by the topography, which would not make it possible for any delta to develop (Steel and Dalland, 1978). The lower part of the Todalen Member was found to be controlled by the underlying topography in the unconformity to the Carolinefjellet Formation (Steel and Dalland, 1978; Jochmann, 2004). This section was therefore argued to be a gradual transgression of the area where the fluvial impact was expected to have been minor (Steel and Dalland, 1978).

From the lithostratigraphy it is known that the Firkanten Formation is an overall transgressive succession expected to be reflected in the deposits. The delta described in the Firkanten Formation is supposed to be a fluvial dominated delta system with a later wave influenced



shoreline (Kalgraff, 1978; Steel et al., 1981). The deltaic coastal plain is described as developed during rising sea-level (Nagy, 2005) indicated by coal deposits. However, elongated fluvial deltas, as described for the Todalen Member (Kalgraff, 1978) are normally related to progradation whereas typical retrograding coastlines display tidal flats or lagoons when there has been no prior valley incision (Boyd et al., 1992). These somewhat contradicting interpretations gave rise the following two questions. These two questions and others raised in this chapter will be discussed and answered in the following chapters. The answers are summarised in Chapter 9.2.

1. *Does the Todalen Member represent a fluvial delta system?*
2. *Why are the coal-layers thick and broad and why are there no extensive fluvial channel deposits in the sections?*

The interpretation of the fine grained sediments as subaqueous levees or interdistributary bays is related to the tidal influence found in the sediments reported throughout the Todalen Member (Kalgraff, 1978; Steel and Dalland, 1978; Steel et al., 1981; Tønseth, 1981; Hansen, 1982; Wilhelmsson, 1999; Jochmann, 2004). These sediments are described as related to tidal mud flat deposits (Kalgraff, 1978; Steel and Dalland, 1978; Nøttvedt, 1982), deltaic coastal plains with lakes and swamps, or possibly related lagoons that developed during rising sea level (Kalgraff, 1978; Steel and Dalland, 1978; Wilhelmsson, 1999; Jochmann, 2004; Nagy, 2005) based on marine influence, high organic content, barren of foraminifers, and absence of calcareous taxa (Nagy, 2005). The limited evidence of macrotidal impact indicates a moderate tidal environment (Ytreland, 1980).

The tidal deposits have also been interpreted as estuaries from flooding of the fluvial valley system (Steel and Dalland, 1978; Hansen, 1982; Nøttvedt, 1982). However, there is no convincing evidence of valley incision from sea level fall described from the Todalen Member and therefore:

3. *Were there estuaries in the Todalen Member?*

Hansen (1982) argues for a back barrier bar system since the fine grained sediments deposited in tidal flat and lagoon areas in the Todalen Member indicate protection from storm and wave influence. The extent of the tidal deposits is large (Steel and Dalland, 1978) indicating a broad flat coastal plain.

The sandstone sections in the Firkanten Formation have previously been separated into two different settings; crevasse splays or fluvial channels on a delta plain in the Todalen Member and barrier bars/mouth bars of a delta front in the upper Todalen Member and in the Endalen Member (Kellogg, 1975; Steel et al., 1981; Jochmann, 2004). The crevasse splay or fluvial levee interpretations were based on the lack of shells, high content of organic debris, and occasionally rooted tops (Kalgraff, 1978; Steel and Dalland, 1978; Hansen, 1982; Nøttvedt, 1982).

Conglomerates occur in these beds as pebble filled scours and thin pebbly laminae, interpreted as crevasse splays (Steel and Dalland, 1978), fluvial chute bars (Tønseth, 1981; Nøttvedt, 1982), or related to beach deposits (Kalgraff, 1978). The sheet-like pebbly laminae were interpreted as post-storm deposited gravel lags (Nøttvedt, 1982).

Conglomeratic cross stratified bedforms are described from the Endalen Member (Bruhn, 1999). These were interpreted as braided river system but occur in otherwise foreshore/shoreface setting overlain by low angle cross laminated to plane laminated beach sandstone. The conglomerates at the boundary between the Firkanten and Basilika Formations were interpreted as fluvial deposits analogous to the Grønfjorden Bed and related to sea level fall (Kalgraff, 1978; Bruhn, 1999) but the arguments are not conclusive and therefore this question was raised.

4. *How were the conglomeratic beds deposited and where were the pebbles generated?*

Bioturbated sandstone with hummocky and swaley cross stratification, wave ripple lamination, *Ophiomorpha*, and *Planolites* has been described from the Firkanten Formation and interpreted as shoreface or upper delta front (Kalgraff, 1978; Ytreland, 1980; Nøttvedt, 1982; Bruhn, 1999; Wilhelmsson, 1999; Jochmann, 2004). In the western part of the basin the wave dominated shoreface succession is green in colour (Nagy, 2005), possibly indicating high glauconite content.

The intensively bioturbated sandstone was interpreted as lower delta front or prodelta/offshore transition wave influenced setting (Kalgraff, 1978; Ytreland, 1980; Hansen, 2004; Jochmann, 2004). The interpretation of the distal sections of the Firkanten Formation as prodelta was based on the relation to the interpreted delta plain of the Todalen Member. However, as a consequence of question 1:

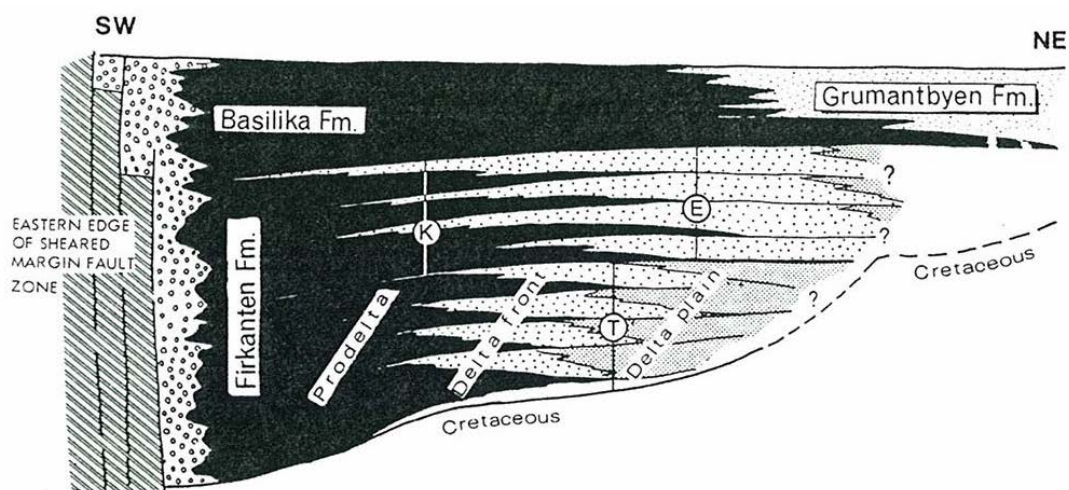
5. *If the Todalen Member does not represent a delta plain setting, then what do the Endalen Member and the Basilika Formation represent?*

***Basin model of transtension-transpression***

In the late Cretaceous, Svalbard was located adjacent to North Greenland and Ellesmere Island (Fig. 2.3) (Blythe and Kleinspehn, 1998). The West Spitsbergen Fold and Thrust Belt (Fig. 2.4) was created due to plate shortening in connection to the opening of the Northern Atlantic (Lyberis and Manby, 1993; Harland, 1997).

The previous model (transtension-transpression) of the formation of the Central Tertiary Basin was based on the stratigraphic record of transgressive-regressive cycles (Steel et al., 1981) and missing evidence for extensive uplift in the west in early the Paleocene (Steel et al., 1985). According to this model the basin was initially formed during a period of transtension (Steel et al., 1985) represented by the initial transgressive succession in the Paleocene, the section from the unconformity at the base of the Firkanten Formation to the top of the Grumantbyen Formation (Fig. 2.2). This early phase of the basin was believed to be characterised by delta progradation from east towards south-southwest (Fig. 2.6) (Steel et al., 1985). However, there are no indications of substantial uplift and erosion east of the basin of the Mesozoic strata therefore:

6. *Where did the sediments in the Firkanten Formation come from?*



**Fig. 2.6** Extension model during the early basin development. T is the Todalen Member, E the Endalen Member, and K the Kolthoffberget Member, from (Steel et al., 1981). The early transgressive phase represents the transtensive phase and the overlying progradation is the transpressive part.

According to Steel et al. (1985) the basin configuration changed to transpressional in the Eocene and was characterised by two regressive phases in the succession from the base of the Frysjaodden Formation to the top of the Aspelintoppen Formation (Steel et al., 1985). The progradation was at this point from west to southeast. The drainage reversal was interpreted as evidence for a late onset of the thrust belt after the formation of the basin (Steel et al., 1985). In the late Eocene and early Oligocene the plate movement was oblique slip before the rifting and sea floor spreading started in the Oligocene (Steel et al., 1981; Steel et al., 1985). This model raised the question:

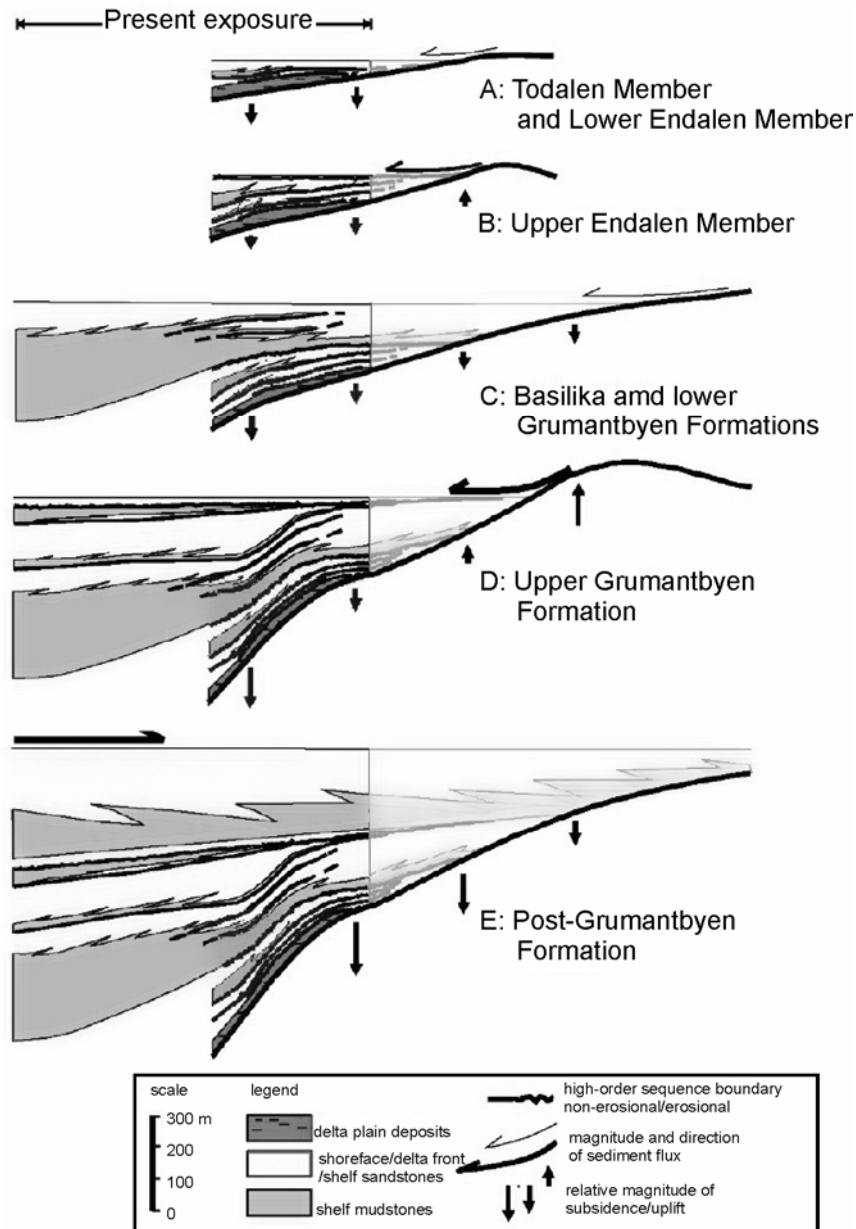
7. *How was the basin formation related to the thrust belt?*

***Basin model of a foreland basin***

The newer model (foreland basin flexural loading) suggests that the Central Tertiary Basin was formed as a flexural depression in front of the fold and thrust belt (Bruhn and Steel, 2003). Recognition of compressional structures throughout the Paleocene and Eocene succession indicates overall compression during basin formation, with no initial extension, but with a strike-slip component (Braathen et al., 1995; Bergh et al., 1997; Braathen et al., 1999). A foreland basin, with an adjacent peripheral bulge, was suggested to have been created by flexural loading of the crust in connection to plate shortening in the thrust belt (Bruhn and Steel, 2003). The deformation might have been influenced and bounded by the Billefjorden and Lomfjorden-Agardhbukta fault zones to the east (Fig. 2.4) (Bergh et al., 1997). The sediment source during the early transgressive succession was from the peripheral bulge (Fig. 2.7) and not until later did the thrust belt start to shed sediments (Bruhn and Steel, 2003). However, in general the uplift of a foreland bulge is relatively minor compared to the thrust belt in a foreland basin setting and therefore:

8. *Could the peripheral bulge have been a source of sediments for the Firkanten Formation?*

Before the sea floor spreading started in the Oligocene there was a period of extension (Braathen and Bergh, 1995; Blythe and Kleinspehn, 1998; Braathen et al., 1999). The Miocene was characterised by denudation while the glaciation in late the Cenozoic efficiently eroded the area (Blythe and Kleinspehn, 1998).



**Fig. 2.7** Development of depositional the architecture in the Firkanten, Basilika and Grumantbyen Formations, after (Bruhn and Steel, 2003).

### *Paleogene climate*

The climate at Spitsbergen in the Paleocene and Early Eocene based on fossil plant material has been interpreted to be warm-temperate with a high humidity equally distributed over the year (Golovneva, 2000) even if the latitude has been reconstructed to 65-68° N (Cepik and Krutzsch, 2001). The temperature rarely reached 0 °C (Schweitzer, 1980). In the Late Eocene the climate changed to almost cool-temperate (Golovneva, 2000). From the Paleocene to Eocene there is recorded a general climatic change in the northern hemisphere towards a colder climate (Wolfe, 1980). The climate seems to have been favourable in the Paleocene on

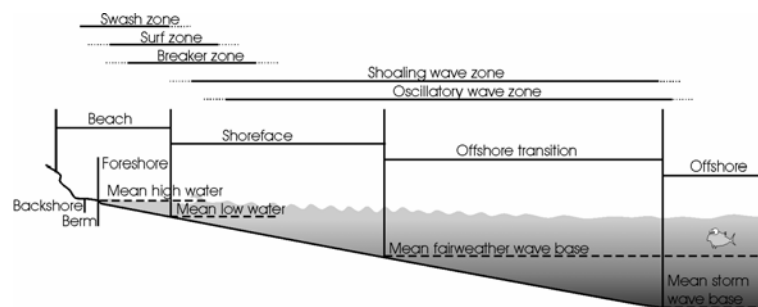
Spitsbergen for mammal plant eaters like Pantodonts, of which there are found traces (Lüthje et al., Submitted).

### ***Dating of Paleogene strata***

The Tertiary coal bearing strata on Svalbard are described as of Paleocene age (Michelsen and Khorasani, 1991; Cmiel and Fabianska, 2004). Dating the Paleogene strata on Svalbard is complicated due to the poor fossil record from the sediments and the extensive cementation, which makes it difficult to gain any material for dating. However, from sparse material of palynology, spores, plant fragments, and molluscs a Paleocene age can be concluded for the Firkanten Formation (Livsic, 1974; Schweitzer, 1980; Manum and Throndsen, 1986; Nagy et al., 2000; Nagy, 2005). Late Paleocene calcareous nannofossils are described from the Firkanten Formation in the southern part of the basin (Cepek, 2001). The boundary with the Eocene is above the Grumantbyen Formation in the shale of the Frysjaodden Formation (Fig. 2.2) (Livsic, 1974; Steel et al., 1981)

## **2.2 General coastal depositional environments**

A depositional coastline consists of an inner continental section, a marginal marine, a shallow marine, and a marine section. The marine sections are divided according to the amount of wave, storm and tidal energy working on the sediments (Fig. 2.8) (Reading and Collinson, 1996). The most marine zone (below the mean storm wave base) is the offshore. This is separated from the shoreface (above mean fair-weather wave base) by the offshore transition or the lower shoreface. The foreshore is above the mean low water mark, representing a zone of high energy with breaking waves washing up on the beach. The beach represents the



**Fig. 2.8** Classification of a coastline into different environmental zones, according to water depth and the energy regime acting on the coast; wave, storm, and tidal, after (Reading and Collinson, 1996).

subaerial part of the coast. The foreshore consists of the break, the surf and the swash zone, of which the breaker zone extends out to the upper shoreface (Reading and Collinson, 1996). On the coastal side of the foreshore are the un-vegetated backshore and the continental area. The different zones of the near shore are characterised by:

- *Offshore*

Below the storm wave base, sedimentation is dominated by hemipelagic settling but coarse sediment can be transported out by large storms or turbidity currents. The bioturbation in this zone can be intense.

- *Offshore transition*

The sediments in the section above the storm wave base but below fair-weather wave base is dominated by storm deposits with hummocky and swaley cross bedded sand interrupting the otherwise fine grained hemipelagic mud. The section is characterised by shifting high and low energy intervals.

- *Shoreface*

Closer to the shore, at the shoreface, the sand layers become thicker and more amalgamated. Normally oscillatory and shoaling waves act on the shoreface breaking in the upper part. This is also a zone of intense bioturbation during periods of fair-weather. Strong, wave or tidally induced currents can have a large effect on sediment transportation and shaping of the shoreface. During storms the shoreface can be largely eroded, and coarse material can be washed up on the beach or transported further out into the offshore.

- *Foreshore*

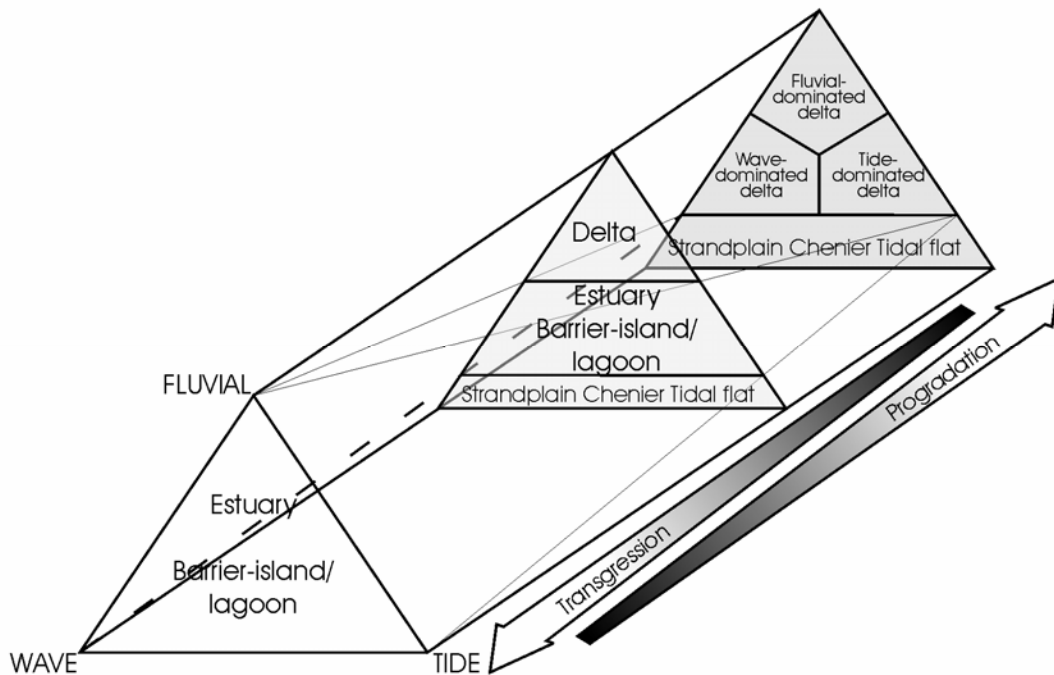
The foreshore, which includes the beach, often display well-sorted sandy sediments washed by waves. However, all coastal deposition depends on the source of sediment and type of material available for deposition, which will also influence the shape of the coast.

- *Backshore*

The backshore can be mud prone since it is an area of much lower energy level than the foreshore since it is protected from wave energy by the barrier bars and islands built up on the foreshore. In the coastal backshore areas there can be extensive mud tidal flats, swamps, marshes, and further inland on the coastal plain peat bogs (Reading and Collinson, 1996).

Depositional coastlines have been classified according to the dominant energy regime configuring the coast and the general development of the depositional basinal setting (Fig. 2.9). The three energy regimes are fluvial, wave or tidal influence (Boyd et al., 1992). A coast will often be influenced by all three energy regimes but with one dominant part. In addition coastal areas dominated by the same energy regime will show different development if the base level is rising or falling, that is, if the system is retrograding or prograding. A wave dominated coastline in a retrograding or rising base level setting will develop barrier bars and islands and adjacent lagoons. However, during base level fall a wave dominated coast will be characterised by strandplains and cheniers. Fluvial dominated coastlines are in general prograding since the high sediment supply forces the coastline to prograde even during rising sea level. During increased base level the river mouth would drown and develop into an estuary. This general division of the coast gave rise to the following question.

9. What type of depositional coastline is represented in the Firkanten Formation?



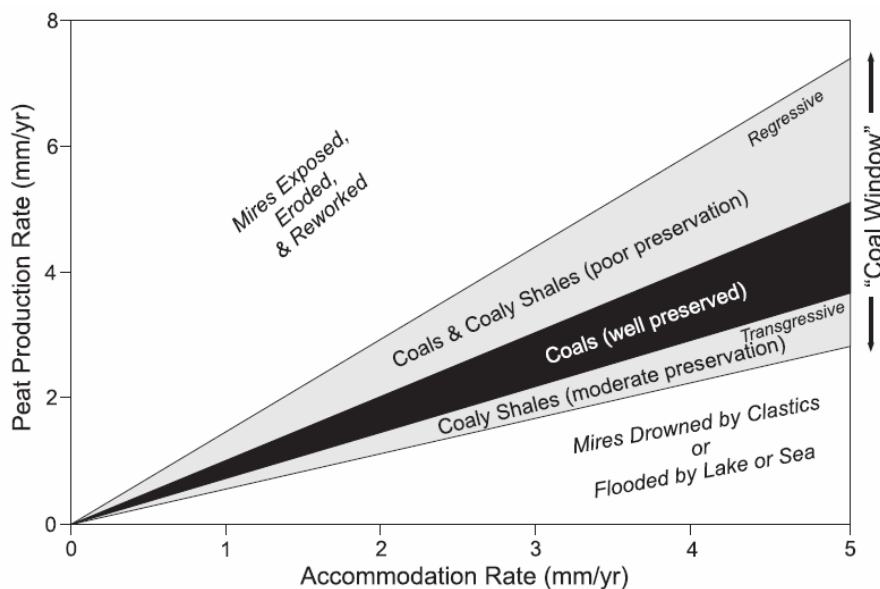
**Fig. 2.9** Coastal classification scheme of the relation of coastal depositional environment to relative sea level changes separated according to dominant energy/sediment input, fluvial wave or tidal and to the general basin development, prograding or retrograding, after (Boyd et al., 1992).



### 2.3 Peat accumulation and the prerequisite for coal deposits

Peat, the precursor to coal, accumulates typically in environments where there is substantial vegetation growth, sufficient standing water to reduce degradation, an absence of inorganic sediments, and creation of accommodation space (Fig. 2.10) (Ward, 1984; Bohacs and Suter, 1997). The paleoflora is among other things influenced by the geological age, physiographic setting, climate, and nutrient availability. Climate, which includes temperature, humidity, and seasonal fluctuations influences the decomposition and is itself controlled by the paleogeography (Ward, 1984). Degradation depends on, among other things, water table level and fluctuations of this.

The paleoecological parameters of the mire, like water depth, chemistry and nutrient supply control the type of peat accumulated, which in turn will influence the coal characteristics (Nichols, 1995). Nichols (1995) summarizes the work by (Teichmuller, 1958) into four different mire type reconstructions for Cenozoic coals: the reed mire; the Nyssa-Taxodium forested swamp; the brush mire; and Sequoia forest, based on modern analogues and represented by different hydrologic environments. The peat production rate is controlled by climate, type of flora, and supply of water and nutrients. Preservation of organic plant material takes place when oxidation and decay by bacterial and/or fungal activity are limited, for example, below the groundwater table.



**Fig. 2.10** The coal window, representing where peat can be accumulated and preserved, is where the rate of organic production is in balance with the rate of accommodation space created, from (Davies et al., 2005) after (Bohacs and Suter, 1997). If too much accommodation is created the mire will be drowned and if too little it will be denuded. The grey areas are conditions where organic-rich sediments are deposited with various contents of siliciclastics and organic material.

The creation of accommodation space is controlled by eustacy, tectonic, and general subsidence from compaction. As stated, coal accumulations are found in basins with little or no clastic input and where the base level (mostly groundwater table) and organic production are in pace (Teichmuller, 1989), or where the peat production rate and the creation of accommodation space are in balance (Bohacs and Suter, 1997). Even if the sediment input of inorganic clastic material is too high there can still be organic material deposited. However, these sediments will not form proper coal seams (Fig. 2.10).

The organic material is altered during the peatification process to form peat. Coal is produced by diagenesis of organic material such as peat during burial, called coalification. During the coalification process peat is converted into coal with increasing rank from peat, lignite (brown coal), sub-bituminous, bituminous, and anthracite. The rank of the coal is determined by the level of geochemical alteration that has taken place. This is controlled by pressure and temperature, where temperature is the most important factor. An increased temperature leads to increased rank and thereby increased carbon content, vitrinite reflectance, and calorific value (kcal/kg) e.g. (Teichmuller, 1987; Teichmuller, 1989). There is in addition an increase in loss of water and volatile matter.

Peat accumulating environments can be rheotrophic or ombrotrophic, which will influence the grade of the peat and the coal. Rheotrophic environments (swamps) can be fresh or brackish (limnic or paralic respectively) but commonly the water supply comes from groundwater, precipitation, and surface runoff. In ombrotrophic environments (bogs) the main water supply is from precipitation and the bog surface is often domed (Scott, 1987).

Different types of peat are formed by vascular plant (humic) and algal (sapropelic) material (McCabe, 1984; Scott, 1987). Banded humic coal consists of a heterogeneous mixture of plant debris, while non-banded sapropelic coal is made up of homogeneous spores and algal material (Ward, 1984).

### ***Coal macerals***

The main coal maceral groups are vitrinite, liptinite, and inertinite. The maceral composition reflects the coal/peat composition and is therefore related to the depositional environment, tectonic setting, paleoflora, paleoclimate, and paleogeography (Ward, 1984; Teichmuller, 1989; Shearer et al., 1995; Bohacs and Suter, 1997; Scott, 2002; Moore and Shearer, 2003) but also depends on several other parameters, such as degradation, alteration, and diagenesis (Wüst et al., 2001). There is no direct connection to any single factor but is an interacting relationship.

Vitrinite is the most common maceral in most coal. Vitrinite is derived from cell wall material (woody tissue) of plants, which are chemically composed of the polymers, cellulose and lignin, detrital material, and gels e.g. (Ward, 1984; Teichmuller, 1989; Scott, 2002). The cellulose is degraded during peatification/coalification, while the lignin is more resistant. The cell structures are often preserved (Scott, 2002). Liptinite, which is a diverse group (Scott, 2002) is derived from waxy and resinous parts of hydrogen-rich plants and decomposition products (Teichmuller, 1989). The inertinite macerals, which is a controversial group, are derived from plant material that has been strongly altered. Several different origins of inertinite have been discussed and have often been referred to in the literature as an indication of desiccation, oxidation, and fungal degradation, which in turn would indicate a raised bog (Sweet and Cameron, 1991) or falling base level (groundwater).

### ***Origin of fusain***

Inertinite is often represented by fusain. Scott (1989) discusses the origin of fusain (fusinite and semifusinite) as representing fossil charcoal. Jones and Chaloner (1991) argue, based on comparison of experimentally produced charcoal and fossil material that the origin of typical fusain is fossil charcoal. Only fire has been proven to create fusain by the charring process (Scott, 1989). To form charcoal burning with limited access to oxygen (Scott, 1989) as created in a charcoal stack, is needed. Therefore, it can be concluded that charring is rather the opposite of the oxidation by desiccation.

Fusain is mainly made of wood and fibres. Lignin rich plants like gymnosperms are more easily charred since lignin is more prone to produce charcoal than other plant materials such as herbaceous plants, and might therefore be overrepresented in fusain (Scott, 1989). However, this does not exclude that other macerals of the inertinite group could have an origin other than fire.

A possible connection between low water table and high inertinite content could be that an area of low water table is more prone to burn. However, Scott (1989) shows that modern wildfires can occur in waterlogged areas and do not have to be preceded by long periods of drought.

### ***Maceral of coal from Svalbard***

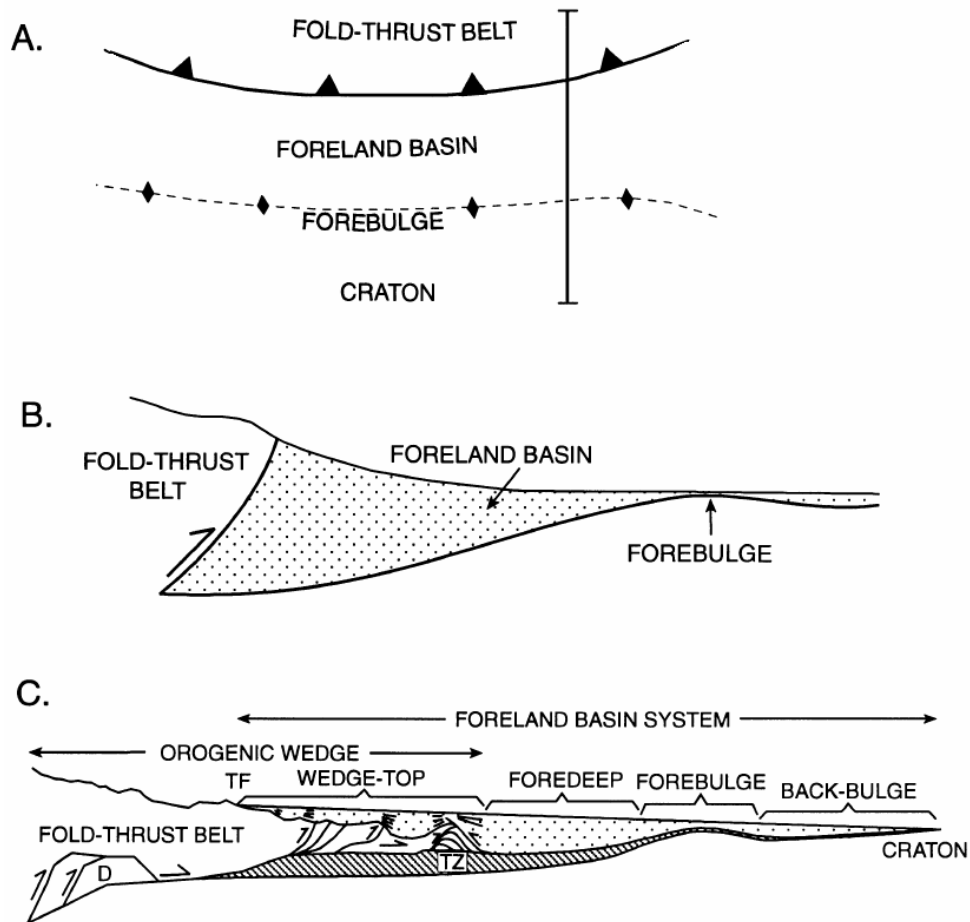
There is a noticeable difference in the inertinite maceral content between the lower and upper main coal seams of the Paleocene coal on Svalbard (Michelsen and Khorasani, 1991; Cmiel and Fabianska, 2004; Orheim et al., 2007). Globally, Paleocene coal is often high in inertinite while Eocene coal has low inertinite content (Shearer et al., 1995).

The Paleocene record of the Firkanten Formation on Svalbard contains traditionally five coal seams; Svea, Todalen, Longyear, Svarteper, and Askeladden. The Svea seam is high in inertinite (> 10 %, mostly 30-50 %) like other Paleocene coals while the upper main coal seams (Longyear seam) show particularly low inertinite content similar to Eocene coal (< 10 %) (Michelsen and Khorasani, 1991; Cmiel and Fabianska, 2004; Orheim et al., 2007). The other three minor seams are also low in inertinite content similar to the Longyear seam (Orheim et al., 2007).

#### **2.4 General flexural formed basins**

Flexural basins are formed from flexural response of the crust to stress. Foreland basins are a common type of flexural basins and are formed under compression (Allen et al., 1986; DeCelles and Giles, 1996). They can be divided further into 1. The Alpine type peripheral foreland basins related to continent-continent collision and 2. The Laramide type retro-arc foreland basins related to lithospheric subduction (Dickinson, 1974; Catuneanu, 2004). The basin represents a potential depositional centre for sedimentary accommodation that can be separated into, counting from the thrust belt; wedge-top, foredeep, forebulge, and back-bulge areas (Fig. 2.11) (DeCelles and Giles, 1996).

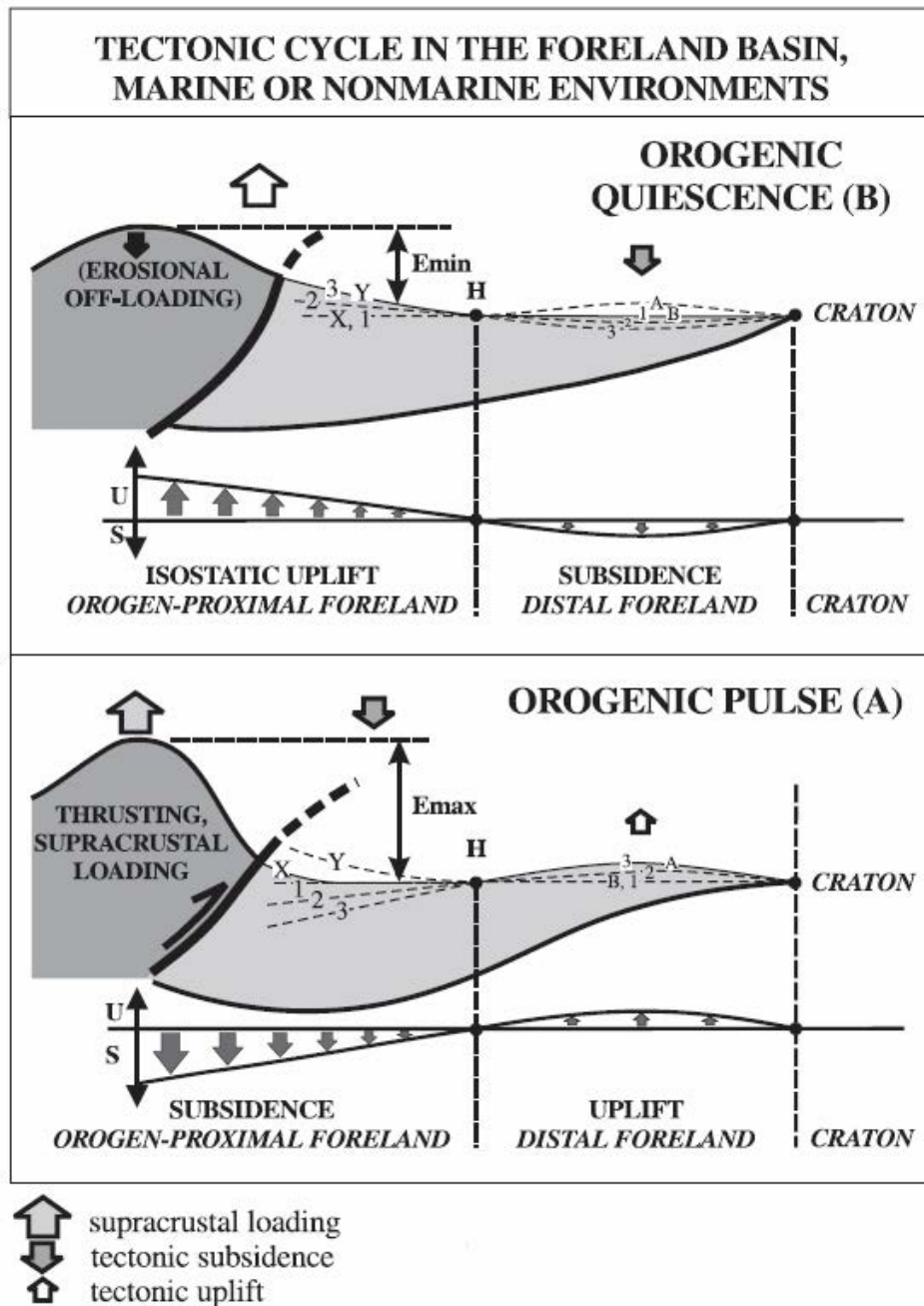
The formation of the foreland basin is largely controlled by the properties of the lithosphere. When the crust is topographically loaded in the fold and thrust belt, the increased weight will make the crust flexure and bend down forming a basin in front of the thrust front (DeCelles and Giles, 1996). The load and therefore the subsidence will be greatest closest to the fold and thrust front (Fig. 2.12) (Catuneanu and Sweet, 1999). Narrow steep foreland basins have been suggested to form from plastic compressional folding of the crust rather than simple loading (Fig. 2.13) (Zhang and Bott, 2000). Depending on the rigidity of the crust it will bend in a sinusoidal waveform of anticlines and synclines of progressively decreasing wavelength, which decay away from the fault zone. The foreland bulge is the first anticline but is mostly not a prominent high. The sediment accumulation in the basin will lead to further subsidence (DeCelles and Giles, 1996). During periods of tectonic quiescence the mountain belt is eroded, which will lead to uplift of the basin (Fig. 2.12) (Catuneanu and Sweet, 1999). The different stages of the development are recorded in the sedimentary strata (Heller et al., 1988) and therefore the sedimentary pattern can be used for understanding the basin formation.



**Fig. 2.11** Schematic view and cross section of a foreland basin, after (DeCelles and Giles, 1996). (A) Structural map of a foreland basin. The vertical line indicates the orientation of the cross section shown in B. (B) Simplified cross section of a foreland basin, with the fold and thrust belt, foreland basin and bulge. Not to scale. (C) Revised concept of a foreland basin system, with wedge-top, foredeep, forebulge, and back-bulge depositional centres.

Foreland basins are elongated and have an asymmetrical pattern, which is displayed in the sedimentary record across the basin.

The peripheral foreland basin can be characterised by two types of development: 1. The Pyrenean type formed on full continental crust with an initial continental or shallow marine sedimentation often with axial inflow of sediments (Hirst and Nichols, 1986) and 2. The true Alpine type with initial deep marine sedimentation (Covey, 1986) formed on an initial thinned crust. The Alpine foreland basins are sometimes referred to as going from an underfilled flysch stage with deep marine sedimentation to a filled or overfilled molasse stage of terrigenous sedimentation (Allen et al., 1986; Sinclair, 1997).

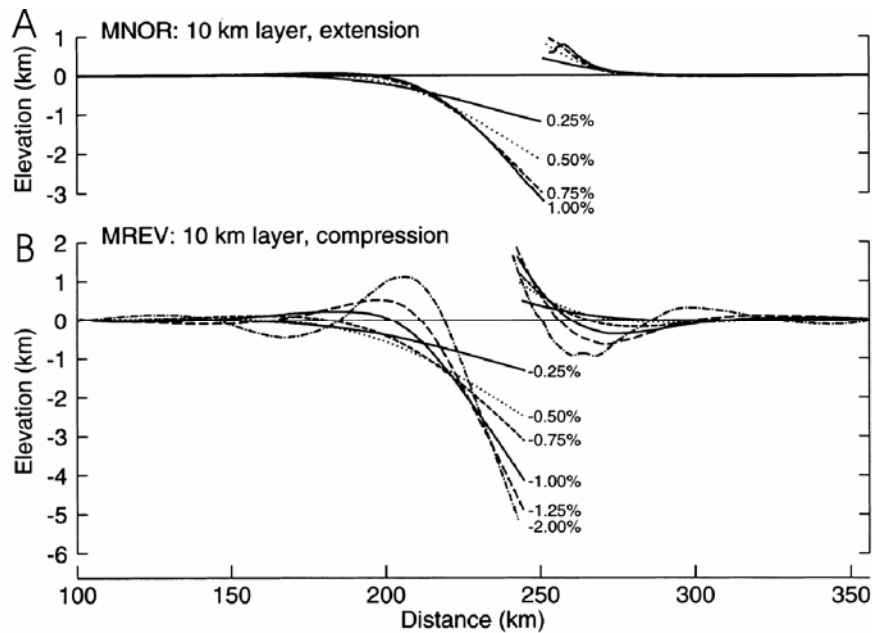


**Fig. 2.12** Flexural model of a foreland basin showing the uplift and subsidence during (A) orogenic pulse and (B) tectonic quiescence, after (Catuneanu and Sweet, 1999). The vertical scale of the distal foreland or bulge is exaggerated for clarity.  $E_{min}$  and  $E_{max}$  are minimum and maximum difference in elevation between sediment source area and the proximal surface profile.  $X$  is the topography at the end of the pulse stage while  $Y$  is the surface profile at the end of the quiescence stage. 1 is the horizontal plane at the beginning of the respective periods and 2 and 3 show the evolution in time.  $U$  is uplift and  $S$  subsidence where  $H$  is the hingeline between the two.

The Central Tertiary Basin formation was formed as a foreland basin related to the West Spitsbergen Fold and Thrust Belt (Bruhn and Steel, 2003). The fold and thrust belt was formed due to convergence between Svalbard and Northern Greenland (Manby and Lyberis,

2000). This indicates that the Central Tertiary Basin could be classified as an Alpine type foreland basin. The Firkanten Formation represents the first deposits in this basin and is characterised by clastic continental and shallow marine deposits. The Central Tertiary Basin is therefore expected to have formed as a Pyrenean type of peripheral foreland basin to investigate this further the following question was raised.

#### 10. How did the Central Tertiary Basin form?



**Fig. 2.13.** Modelled basin profiles of (A) extensional normal faulted model versus (B) compressional 10-km-thick reverse faulted model development. The stacked flexure profiles compare the evolution to increased stretching (0.25% to 1.00% strain) respectively shortening (-0.25% to -2.00% strain), after (Zhang and Bott, 2000).

### 2.5 Questions raised

The questions raised to the previous interpretation address the type of depositional environment the Firkanten Formation represents and how it developed through time. They also indicate that there are inconsistencies in the interpretation of the formation of the Central Tertiary Basin. There are uncertainties in understanding the sediment drainage and where to find the provenance area of the sediments. These are the specific questions:

1. Does the Todalen Member represent a fluvial delta system?
2. Why are the coal-layers thick and broad and why are there no extensive fluvial channel deposits in the sections?
3. Were there estuaries in the Todalen Member?

4. How were the conglomeratic beds deposited and where were the pebbles generated?
5. If the Todalen Member does not represent a delta plain setting, then what do the Endalen Member and the Basilika Formation represent?
6. Where did the sediments in the Firkanten Formation come from?
7. How was the basin formation related to the thrust belt?
8. Could the peripheral bulge have been a source of sediments for the Firkanten Formation?
9. What type of depositional coastline is represented in the Firkanten Formation?
10. How did the Central Tertiary Basin form?

Subjects related to the depositional environment, questions 1-5 and 9 are discussed in Chapter 4. Questions 3, 5, and 9 relate to the development of the basin and are addressed in the sequence stratigraphic discussion in Chapter 5. Chapter 6 concerns the structural formation of the basin and addresses questions 4, 6-8, and 10.



### 3. SYNOPSIS OF ARTICLES

*In this chapter a synthesis of the results of the research that form the basis of the articles presented in Chapters 4-7 is presented. The questions raised to the previous interpretation are discussed but are addressed in more details in the individual articles.*

This research on the Firkanten Formation resulted in three articles regarding the depositional environment, the paleogeographic development, and the basin formation and configuration. These articles are presented in Chapter 4-6 respectively. In addition tracks of mammal Pantodonts were discovered in Gruve 7. The result from this work is presented in Chapter 7. Below the synopsis of the main discussion and results is found.

The Firkanten Formation is the lowermost deposit in the Central Tertiary Basin on Spitsbergen representing the main deposit of Paleogene strata on the island (Figs 1.1 and 2.2). It rests on the low angle unconformity to the Lower Cretaceous Carolinefjellet Formation (Steel et al., 1981; Dallmann, 1999).

The systematic investigation of the facies of the Todalen and Endalen Members, based on new cores and field data resulted in a new model for the depositional environment. It recognises that the fluvial impact on the sedimentation was more limited than previously anticipated for the Todalen Member, previously described as representing a fluvial delta system e.g. (Steel et al., 1981; Steel et al., 1985; Dallmann, 1999). The Todalen Member is more correctly described as a wave dominated coastal depositional system with microtidal influence.

The facies model was developed in combination with the sequence stratigraphic interpretation and paleogeography in a three dimensional view through time. According to this model the Todalen Member represents the coastal zone and the Endalen Member the adjacent shoreface and foreshore (Lüthje and Nichols, Submitted a). Stratigraphically, the Endalen Member is situated above the Todalen Member, which indicates a retrograding succession confirmed by the sequence stratigraphic model (Lüthje and Nichols, Submitted b). The system showed a normal aggrading pattern interrupted by retrograding back-stepping events. The coastline followed the outline of the basin limited to the north, west, and east, opening up towards the south (Figs 1.1 and 2.4). The sediment source was the fold and thrust belt in the west and the uplifted northern area. The basin was limited for sedimentary accumulation to the east, possibly by an uplifted foreland bulge or an area of no subsidence, and therefore no accommodation space was created. This foreland bulge has previously been suggested as

provenance for the Firkanten Formation (Bruhn and Steel, 2003). However, the forebulge alone cannot be considered responsible for the relief to provide the source area for the sediments and there is furthermore, not discovered any major uplift and erosion in the Lower Cretaceous succession to the east. Uplift of a forebulge is less than one tenth of the subsidence in a foreland basin (Allen and Allen, 2005).

The sedimentary depositional model and the provenance of the sediments from the fold and thrust belt and uplifted northern area provided further implications for the interpretation of the tectonic basin development (Nichols and Lüthje, Submitted). The previously suggested models for the Central Tertiary basin development; the transtension/transpression (Steel et al., 1981) and the foreland basin flexural loading model (Bruhn and Steel, 2003), were considered. The new model suggests formation mainly through compressional folding, which would explain the size and configuration of the basin.

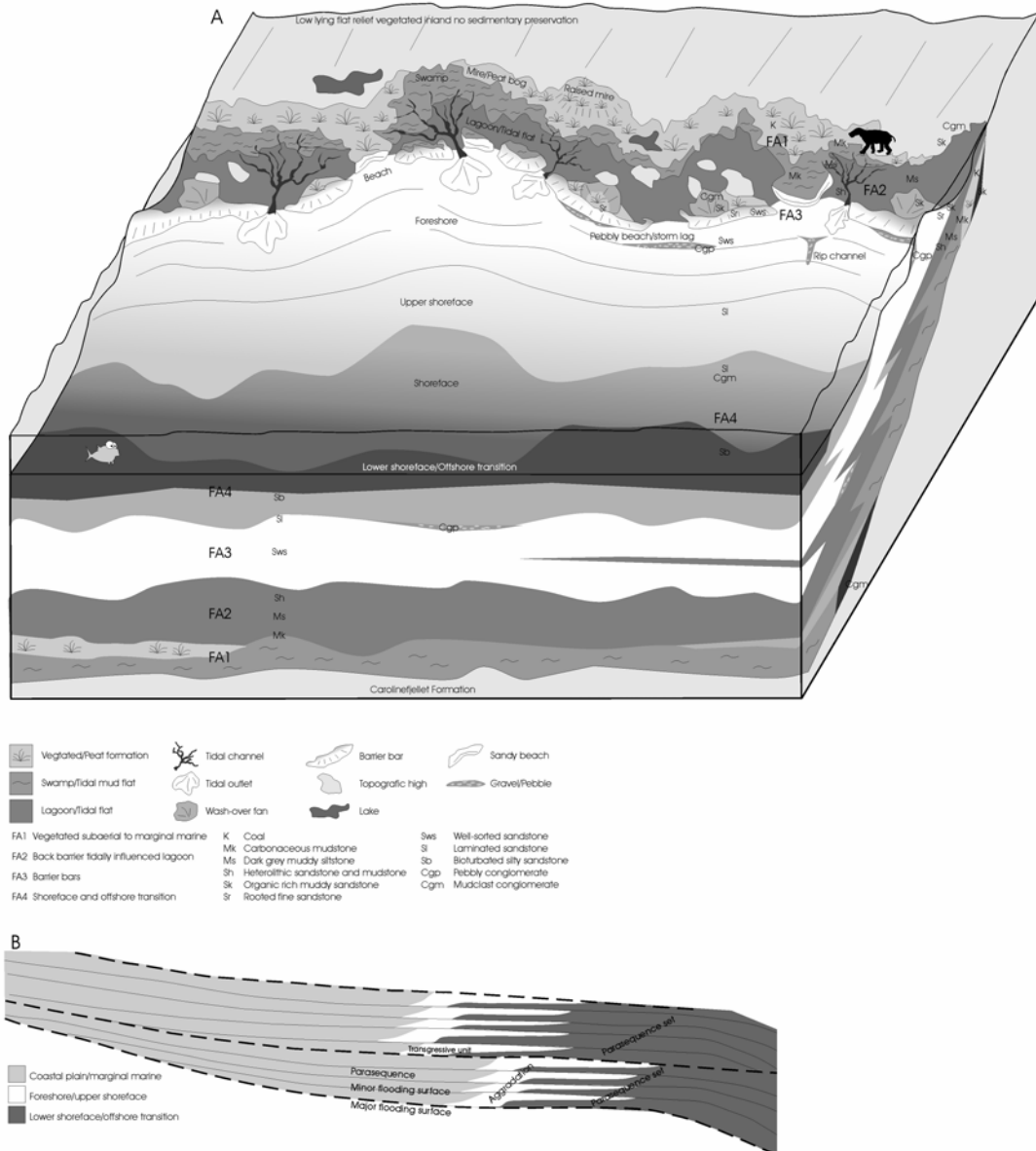
### **3.1 Depositional environment**

The depositional environment in the Firkanten Formation was a wave energy dominated coast. The conceptual model of the depositional environment from the facies analysis is presented in Fig. 3.1. The fine grained muddy and carbonaceous deposits of the Todalen Member represent the costal plain and the well sorted sandstones of the Endalen Member represent the foreshore and shoreface. The lower shoreface and offshore transition is represented by muddy bioturbated sandstone of the Endalen Member and the Basilika Formation. The facies analysis resulted in definition of numerous subfacies that were combined into ten facies. These were further interpreted as representing four different environmental zones, the facies associations; the vegetated subaerial to marginal marine, back barrier tidally influenced lagoon, barrier bars, and shoreface and offshore transition (Lüthje and Nichols, Submitted a).

#### ***Coastal plain***

The costal plain was characterised by muddy deposits often with high organic content. The tidal reworking of the sediments indicates that large areas were influenced by tides. However, the typical tidal evidence indicated a low energy regime since no signs of macrotidal impact were found, such as large tidal channels. This implies a low gradient coast where even a small tidal range would have impact on a large area.

On the coastal plain, large peat mires developed into raised mire complexes, developing into thick coal layers. These coal layers are mined in several places on Svalbard today where the



**Fig. 3.1** (A) Conceptual diagram of the depositional environment and the distribution of facies and facies associations in the Firkanten Formation, after (Lüthje and Nichols, Submitted a). (B) Conceptual diagram of the sequence stratigraphic model. The parasequences are minor prograding sections bounded by flooding surfaces. They build up parasequence sets bounded by major flooding surfaces. The parasequence sets sometimes have a retrograding lower unit and a dominant aggrading upper section, from (Lüthje and Nichols, Submitted b).

larger coal seams are up to 5 metres thick. Considering the compaction of peat to coal this suggest that several tens of metres of peat accumulated in the mires. Single continuous mires could have a diameter of more than 5 km. The mires extended within a zone from the coast towards the inland with a width of approximately 10 km. The great extent of the mire

complexes confirms a low gradient. In this environment there are found tracks of Pantodonts, a large omnivore/herbivore mammal that is previously only known from the Paleocene of Northern America (Lüthje et al., Submitted). The dense vegetation was attractive to grazing animals.

The thick coal layers developed when the vegetation growth was in pace with relative sea level rise or creation of accommodation space for a longer period indicating long term stable conditions. The eastern side of the basin tends to show thicker coal sections than in the west. Close to the thrust front the subsidence and the clastic sediment input was higher (Fig. 2.12), limiting the coal accumulation resulting in thin and divided coal seams. The most favourable area for coal formation seams to have been on the eastern margin of the basin. The mires developed into raised mires that occasionally acted as natural dikes for the marine transgression, which increased the thickness of the coal layer further. The coal is mostly ombrotrophic coal but sapropelic coal is found as thin layers on top of the coal seams. This indicates that the coal was formed in mires or peat bogs but occasionally the mires were flooded probably by raised ground water table preceding the marine transgression transforming the mire into swamps. Muddy coal and carbonaceous mudstone adjacent to coal layers were found in association to marine transgression indicating that the mires developed close to the marine realm on the coastal plain.

The muddy tidally influenced sediments were deposited as broad shallow marine lagoon and tidal flat complexes, characterised by organic-rich heterolithic mud and sandstone with mud drapes and herringbone structures. Microtidal influence on clastic deposits is diagnostic in the Todalen Member with no specific variation over the basin or in time. These sediments were bioturbated and trace fossils found are *Planolites*, *Teredolites*, but also larger non-specified sand-filled ones. *Teredolites* are formed by marine bivalves that burrow down into flooded organic material. Surprisingly few macrofossils of marine shells or carbonate microfossils like foraminifers are found in the deposits (Nagy, 2005). In thin sections, carbonates are almost absent indicating that carbonate might have been dissolved. The coastal mires could have generated acids that influenced the deposits through the ground water. With high yearly precipitation this can affect large areas outside the mire and also the nearby marine realm (McCabe, 1984).

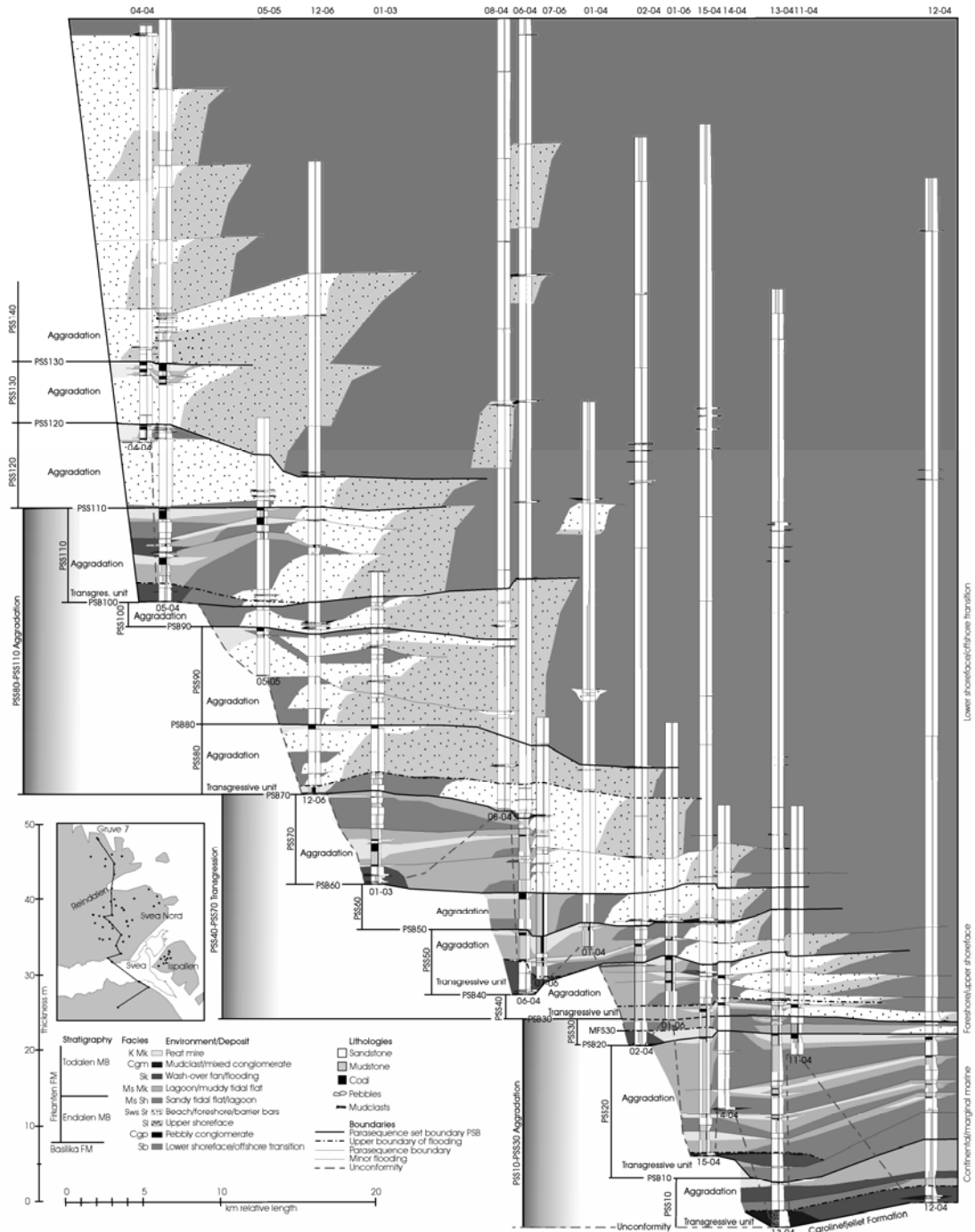
At the base of the Todalen Member there is often found a mudclasts conglomerate in association with unsorted organic-rich sandstone. This is interpreted as the initial flooding of vegetated and weathered areas. The character of the sediment shows that it was dumped quickly with no depositional structures. Roots and, possible but not identified, continental

trace fossils are associated with these layers indicating subaerial exposure. The basal unconformity is not isochronal. The flooding and initiation of sedimentation in new areas took place in steps during the major flooding events. The mudclasts were probably generated from the underlying Carolinefjellet Formation. The sequence stratigraphic correlation indicates an inherited relief in the underlying unconformity of less than twenty metres. Highs were left as local areas of non deposition on the coastal plain. The relief was filled in during the first stage of deposition (Lüthje and Nichols, Submitted b) and by the time the retrogradation progressed as far as the foreshore environment nearby all relief was filled in (Fig 3.2).

The Danish Wadden Sea was put forward as a modern analogue for the Todalen Member. There are several similar characteristics such as; a low relief broad coastal plain, a peat forming environment, a transgressive coast, a microtidal regime, and an extensive area of lagoon and tidal flat complexes protected by sandy barrier bars (Fig. 3.3). There are found no evidence of any large fluvial system in the Todalen Member. The sequence stratigraphy reveals an overall transgressive back-stepping environment, not symptomatic for delta systems. The general shape of the strata is very flat with no incisions. The fluvial input to the Todalen Member was probably restricted to the western side of the basin where the highest rate of subsidence was found close to the thrust front. Any fluvial drainage system would naturally follow the depressions and areas of greatest subsidence. The configuration of the fine grained organic-rich rich deposits indicates a broad flat environment interpreted as coastal plain rather than delta plain. The presence of lagoons and tidal flats in a retrograding succession also indicate a coastal plain. The tidal deposits are not likely to have been generated as estuaries since there was no initial valley incision. The coal layers are extensive and thick, neither indicative for fluvial plain deposits since the clastic input would be expected to be too large to generate extensive peat deposits. A paleogeographic reconstruction of the depositional environment of Firkanten Formation is presented in Fig. 3.4.

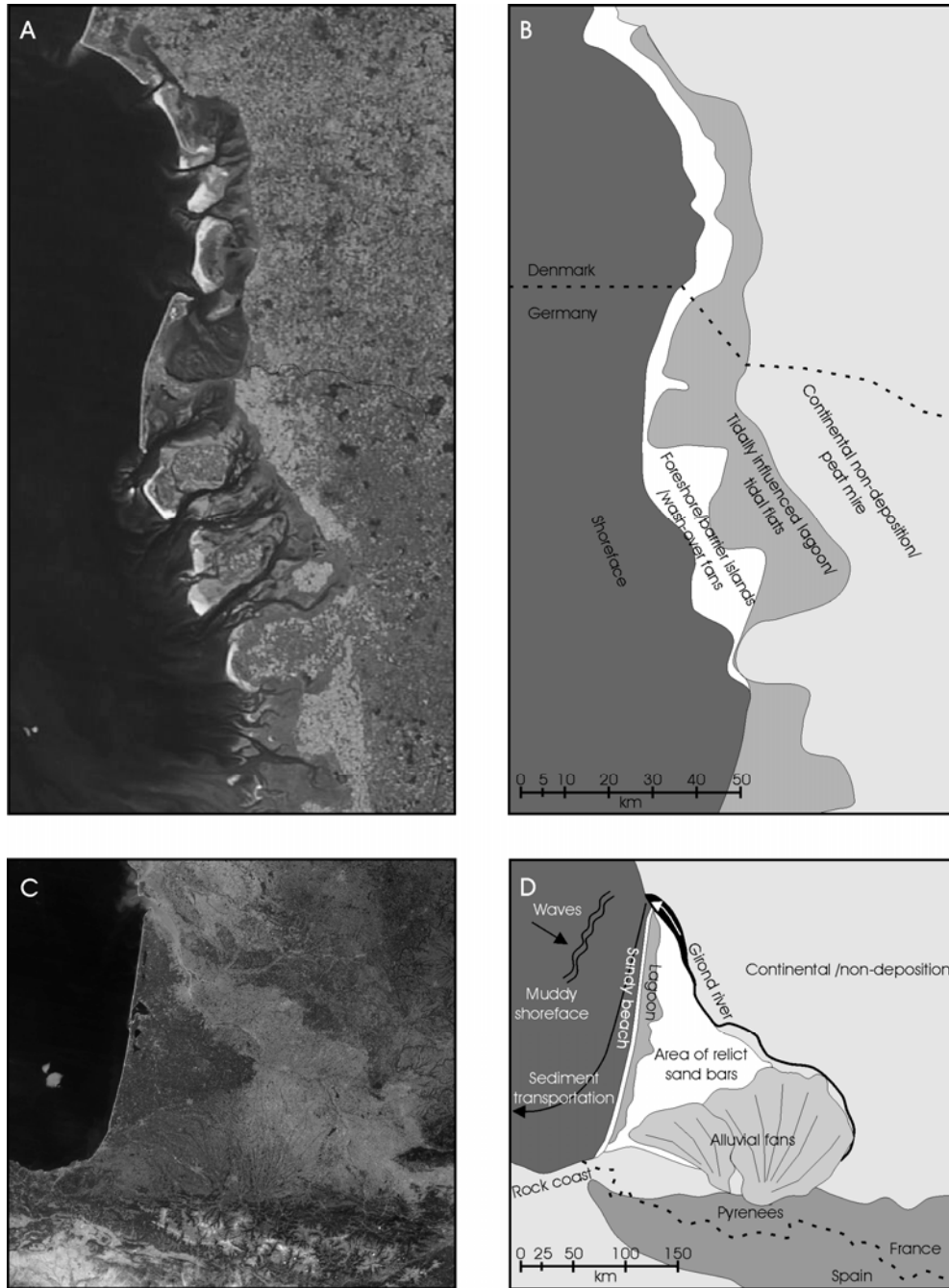
#### ***Foreshore, shoreface, and offshore transition***

The coastal plain was protected from waves and storms by barrier bars and islands represented by the Endalen Member well sorted sandstone. The shoreface deposits are characterised by large scale hummocky cross-stratification bioturbated during periods of quiescence. Typical trace fossils are *Ophiomorpha* and *Thalassinoides* (Lüthje and Nichols, Submitted a). The lower shoreface and the offshore transition is characterised by muddy intensely bioturbated sandstone. There is a wide range of trace fossils among which the following were identified *Ophiomorpha*, *Thalassinoides*, *Helminthopsis*, *Planolites*, *Paleophycus*, *Terebellina*, and *Teichichnus*.



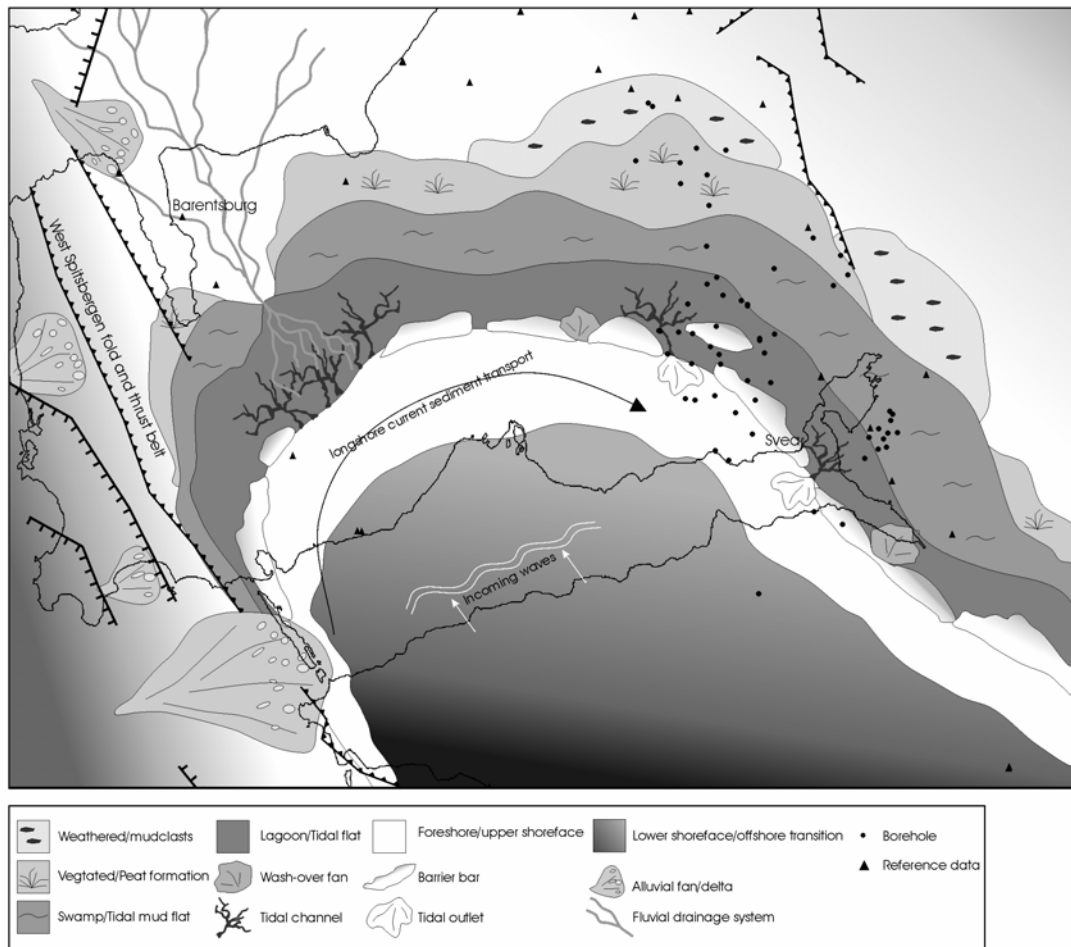
**Fig. 3.2** Correlation panel of the Firkanten Formation from the eastern side of basin from south of Svea to Reindalen to Longyearbyen, from (Lüthje and Nichols, Submitted b).

The glauconite content of the sandstone indicates low sedimentation rate on parts of the shelf. The foreshore was relatively narrow and the well sorted fine grained sand was deposited from longshore wave and tidal induced currents (Lüthje and Nichols, Submitted b). The deposits were sourced from the west and the north where the most uplifted and eroded areas were



**Fig. 3.3** Modern analogues (A) Satellite image of the Danish Wadden Sea, a modern analogue for the depositional environment in the Firkanten Formation (MODIS image from NASA Visible Earth, <http://visibleearth.nasa.gov>). (B) The coast is characterised by a wide tidally influenced lagoon and tidal flat areas protected from wave action by barrier bars/islands with well sorted foreshore sand deposition, from (Lüthje and Nichols, Submitted a). (C) Satellite image of the Bay of Biscay, a modern analogue for the sediment transportation in the Firkanten Formation (MODIS image from NASA Visible Earth, <http://visibleearth.nasa.gov>). (D) The coast is characterised by longshore current transportation. Fine grained sandstone is deposited in a narrow zone on the foreshore. The shoreface is muddy with glauconite production, from (Lüthje and Nichols, Submitted b).

situated (Nichols and Lüthje, Submitted). The sand entered the basin close to the thrust front. The French coast of Bay of Biscay has a similar sediment transportation character (Fig. 3.3B). Sediment input is restricted to the outlet of the Gironde River to the north and is transported along the shore. The foreshore is characterised by fine grained sands in a narrow zone. The shoreface is muddy, even at a shallow water depth and there is glauconite production. The paleowater depth in the Endalen Member could therefore have been misinterpreted as deeper than the actual depth.



**Fig. 3.4** Regional paleogeographic reconstruction of the Central Tertiary Basin showing sedimentary transportation pattern, fluvial drainage, and interpretation of the environmental setting, from (Lüthje and Nichols, Submitted b).

On the foreshore and the shoreface pebbly layers deposited by storms were found. These pebbles were generated from the thrust belt to the west of the basin. The size of the pebbles in the fluvial deposits of the Grønfjorden Bed is much larger than found otherwise in the Firkanten Formation indicating sorting of the sediments along the coast. Occasionally storms washed over the barrier bars and deposited wash-over fans of unsorted sediments and pebbly



layers in the lagoons. The fluvial Grønfjorden Bed is only found locally in the west close to thrust front. It is interpreted to represent alluvial fans/deltas generated off the thrust front.

Aeolian dunes have not been identified in the succession. They may be expected in a regressive succession where sand deposited on the foreshore and shoreface would have been exposed for re-depositing by wind during sea level fall similar to the Bay of Biscay. However, the barrier bars in the Firkanten Formation are sometimes rooted especially when overlain by coal.

A new depositional model and paleogeographic reconstruction is suggested for the Firkanten Formation (Fig. 3.4). Sandy sediments entering the basin close to the thrust front from the uplifted northern section was re-deposited in the basin as sandy beaches on the foreshore. Inland of the foreshore large tidally influenced lagoons and tidal flats gradually developing into coastal plain swamps and peat mires were found. Some minor fluvial channels were probably present but insignificant for the sedimentary record. Coarse grained pebbly sediments were shed into the basin from the thrust front, indicated by the provenance of pebbles and the alluvial fan delta of Grønfjorden Bed. These pebbles were sorted while being transported in the basin. The pebbles were deposited on the foreshore and washed-over into the lagoons during storms. The coast was dominated by wave and storm influence.

### **3.2 Basin configuration and development**

The Central Tertiary Basin was structurally limited to the west by the fold and thrust belt, to the north by uplift, and to the east by restricted accommodation space respectively (Figs 1.1 and 2.4). The basin formation was connected to the fold and thrust belt and formed as a depression in front of the thrust front. The Firkanten Formation is overall transgressive, showing a gradual back-stepping coastline with no relative sea level falls.

The conceptual model for the sequence stratigraphy is presented in Fig. 3.1B. The section is built up of minor prograding parasequences that are stacked in a general aggrading trend. The parasequences are bounded by minor flooding events. The parasequences are combined into parasequence sets, with an aggrading stacking pattern in a general retrograding succession, bounded by major flooding surfaces. The parasequence sets occasionally have a lower retrograding unit deposited during flooding.

The aggrading sections were deposited in periods when relative sea level rise (accumulation space created) were in pace with the sedimentation. The transgression and flooding of areas

took place in steps when the relative sea level rise increased and outpaced the sedimentation. This probably reflected eustatic variations (Lüthje and Nichols, Submitted b). In the well correlation the aggrading successions of parasequence sets and the overall general retrograding trends stand out clearly (Fig. 3.2). The detailed well core correlation from south of Svea to Longyearbyen indicate that the parasequence sets can be combined further into higher level order of aggrading and retrograding successions.

The lowermost section consists of tidally influenced coastal plain deposits. The infilling of any relief in the underlying unconformity is covered by this section. This aggrading coastal plain section is followed by a retrograding succession. The seawards side of the shoreline was dominated by sandy beach and foreshore to shoreface deposits. Within this transgressive succession there are thinner aggrading units where extensive coastal plain deposits accumulated. The major flooding surfaces that separate the parasequence sets show much larger offset in depositional environment than the minor ones.

The relative sea level rise was probably controlled by a combination of several factors of which tectonic subsidence dominated. The basin subsidence was from compressional folding with an additional effect of flexural loading and isostasy when the basin started to fill with sediments (Nichols and Lüthje, Submitted). The smaller variations in relative sea level change were caused by eustasy (Lüthje and Nichols, Submitted b). The sediment supply to the basin seems to have been uniform during the Firkanten Formation since there is no change in depositional environment.

Uplift of the fold and thrust belt was prior to deposition of the Firkanten Formation since the sediments that were generated from older deposits, which must have been uplifted and exposed prior to erosion. Pebbles were generated from the thrust front and the sand was from the eroded Mesozoic strata in the north. The extensional model (Steel et al., 1981; Steel et al., 1985) does not give any mechanism for this uplift and therefore a compressional model for the generation of the basin is preferable (Bruhn and Steel, 2003) in accordance with the recognition of compressional structures (Braathen et al., 1995; Bergh et al., 1997; Braathen et al., 1999).

The Central Tertiary Basin formed as a depression in front of the thrust front. The mechanism has been considered to be better explained as compressional folding (Nichols and Lüthje, Submitted) than flexural loading as suggested previously (Bruhn and Steel, 2003). Vertical strata close to the thrust front at Festningen indicate that the basin is the down fold of the crust, rather than formed as a regular foreland basin in connection to loading from thrusting.

If it was formed from general thrusting there would have been indications that the thrust belt moved considerably during deformation and more sign of thrusting in the basin. Even thick continental crust can be extensively folded by compressional folding (Zhang and Bott, 2000). The mountain range was probably not extensively elevated. The newly discovered presence of Pantodonts on Svalbard also indicates a relatively low mountain belt since it could otherwise have limited migration from Northern America where they known from in Paleocene. This is in consistent with compressional folding rather than flexural loading since no great mountain belt is needed to create the depression.

The uplifted northern area and the western fold and thrust belt was the provenance of the sediments. From the western entry point the sediments were transported eastwards in the basin by longshore currents (Fig. 3.3). The subsidence on the western side seems to have been larger than in the east, indicating an asymmetrical basin. The flexural origin of the basin also indicates that it would probably have been asymmetrical. The thinner and heterolithic coal seams that are found on the western side indicate a higher sediment influx. High sediment influx is also indicated by the fluvial/alluvial fan systems on this side, the Grønfjorden Bed (Fig. 3.4).

**4. ARTICLE 1 – COASTAL PLAIN, PALEOCENE SPITSBERGEN**

**Article 1**

**Coal Formation in a Coastal Plain Setting, Paleocene,  
Spitsbergen, Arctic Norway**

**Charlotta Lüthje**

University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway.

**Gary Nichols**

Department of Earth Sciences, Royal Holloway University of London, Egham,  
Surrey, TW20 0EX, UK

Submitted to Sedimentology

Citation: Lüthje, C. and Nichols, G. *Submitted*. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. Sedimentology

# Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway

CHARLOTTA LÜTHJE <sup>1</sup> and GARY NICHOLS <sup>2</sup>

<sup>1</sup> University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway, e-mail: lott@lythje.com

<sup>2</sup> Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK

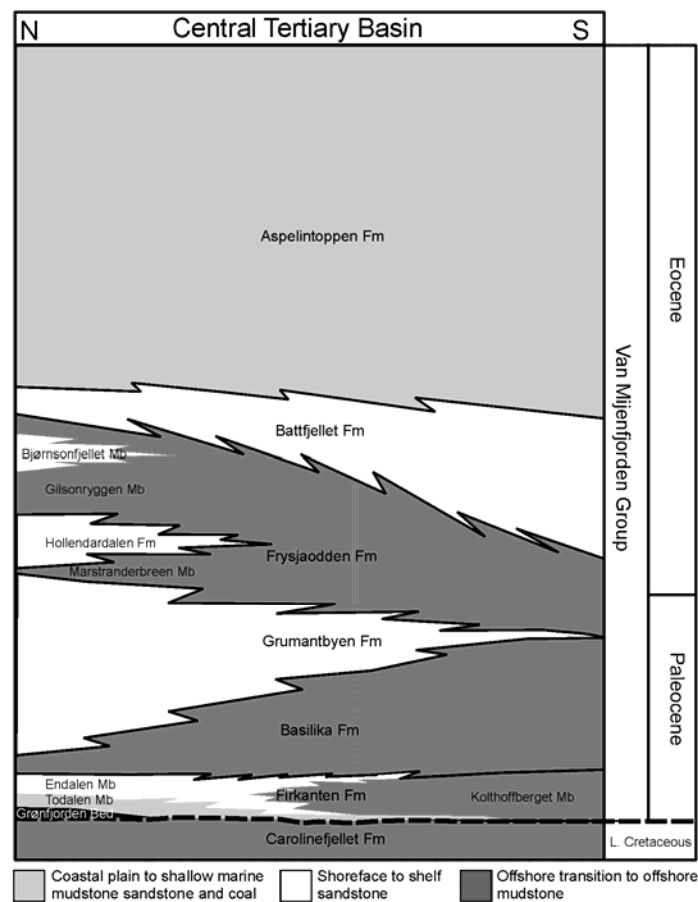
## ABSTRACT

The Central Tertiary Basin of Spitsbergen contains the most extensive Paleogene succession in the Svalbard archipelago in the Arctic north of Norway. It consists of a clastic basin fill of mudstone, sandstone, coal and rare conglomerate beds. A coastal plain to shallow marine setting is suggested for the Paleocene Firkanten Formation, the lowermost unit of the Paleogene whereas previous interpretations have described the Todalen Member, the lower part of the Firkanten Formation as delta plain deposits. This is the first detailed facies analysis of the Firkanten Formation, based on new borehole core and field data. It reveals that sedimentation occurred in a flat relief coastal plain environment with tide, wave, and storm influence but only minor fluvial sediment input. Coal, carbonaceous shale, and other fine grained clastic sediments were deposited on the coastal plain, which was an area of mires and swamps grading into tidally influenced lagoons. The coastal plain was protected from wave reworking by sandy barrier bars. The foreshore and shoreface deposits are characterised by fine grained sandstone and a few pebbly beds making up the Endalen Member, the upper part of the Firkanten Formation. These facies show a high degree of wave and storm influence.

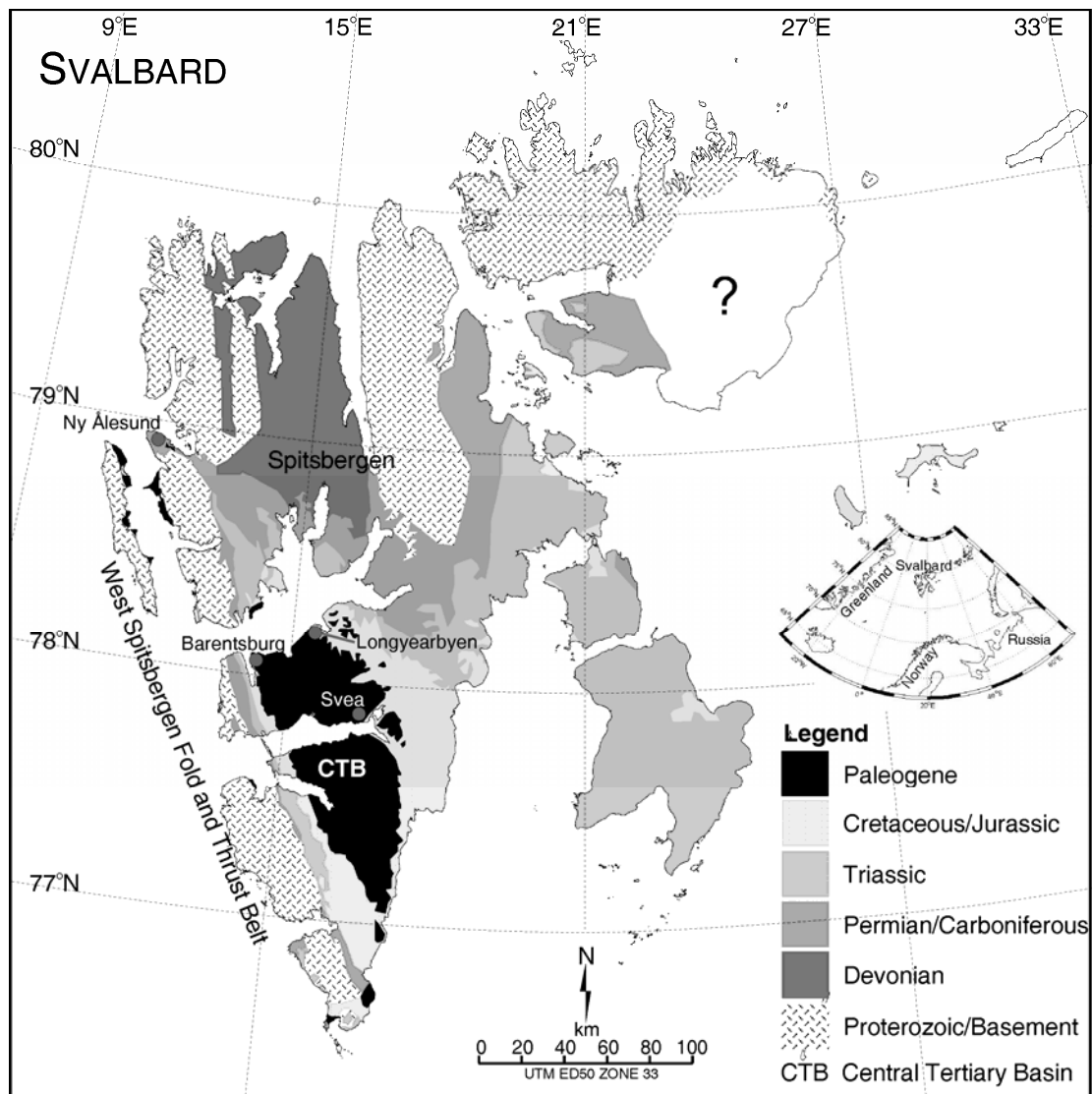
**Keywords:** *Spitsbergen, Cenozoic, facies analysis, coal, coastal plain*

## INTRODUCTION

The commercially important coal on Svalbard is found in the Paleocene Todalen Member of the Firkanten Formation in the Central Tertiary Basin (Fig. 1), which covers the central part of the main island Spitsbergen (Fig. 2). The basin consists of 1900 m of Paleogene clastic deposits (Dallmann, 1999), of which the Todalen Member is the lowermost section that represents the initial phase of sedimentation in the basin. The most recent interpretations of the Central Tertiary Basin describe it as a foreland basin formed during the Cenozoic thrusting due to plate shortening between Greenland and Svalbard in connection to the opening of the North Atlantic (Bergh *et al.*, 1997; Braathen *et al.*, 1999; Bruhn and Steel, 2003; Nichols and Lüthje, Submitted).



**Fig. 1** The stratigraphy of the Paleogene Van Mijenfjorden Group in the Central Tertiary Basin of Spitsbergen. The focus of this study is on the lower part of the succession, the Todalen and Endalen Members of the Firkanten Formation. Based partly on (Bruhn and Steel, 2003; Steel *et al.*, 1985), geometries are based on relative thickness variations over the basin (Dallmann, 1999).

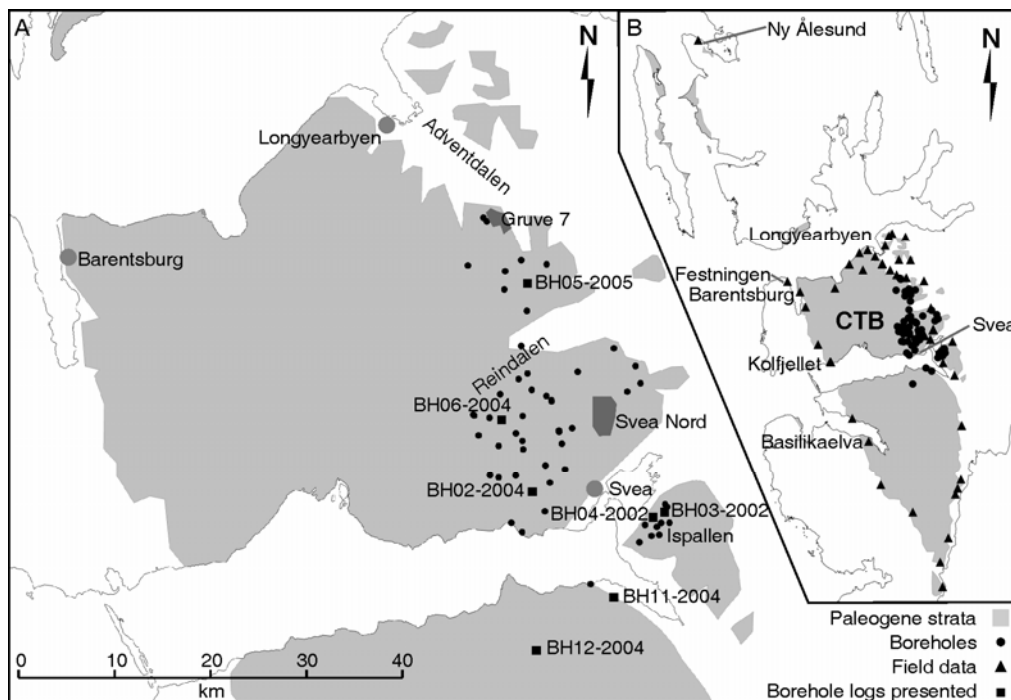


**Fig. 2** A simplified geological map of Svalbard, after (Dallmann, 1999). The main Paleogene strata are found in the Central Tertiary basin that occupies the centre of the southern part of the main island, Spitsbergen.

The Paleogene deposits of the Central Tertiary Basin rest unconformably on the Carolinefjellet Formation which is of Albian-Aptian age (Dallmann, 1999). The general lithostratigraphic pattern in the Cenozoic strata (Fig. 1) shows an initial overall transgressive succession from the continental to marginal marine deposits of the Todalen Member, through shoreface in the Endalen Member to offshore transition in the Basilika Formation (Dallmann, 1999). The Kolthoffberget Member represents laterally equivalent offshore deposits to the Todalen and Endalen Members found in the south western part of the basin. The conglomerate of the Grønfjorden Bed, described as a pebbly fluvial deposit, is only found at the western margin of the basin in the location Grønfjorden and further south (Ohta *et al.*, 1992). The Basilika Formation is overlain by the progradational Grumantbyen Formation and the regional maximum flooding of the basin took place in the marine shales of the

Frysaodden Formation overlying the Grumantbyen Formation. The boundary between the Paleocene and Eocene is found approximately at this level (Steel *et al.*, 1985; Manum and Thronsen, 1986; Dallmann, 1999; Nagy, 2005).

Previous interpretations of the Todalen Member of the Firkanten Formation have considered the facies to represent a deltaic setting of deposition e.g. (Steel *et al.*, 1981; Steel *et al.*, 1985; Dallmann, 1999). However, this new detailed facies analysis, based on the new extensive core data and additional field observations, has shown that the depositional environment may be better interpreted as the deposits of a coastal plain. This investigation is primary based on the new set of core data available from the Norwegian mining company SNSK, drilled since 2002 and still ongoing (Fig. 3). The main target area for coal exploration is between Longyearbyen and Svea, which is where most cores were drilled. The excellent core quality made it possible to in detail investigate the softer fine-grained sediments that mostly are covered in field. The field work, carried out in the areas that were the least difficult to access in the vicinity of Svea, in Adventdalen and nearby valleys, at Ispallen, and in



**Fig. 3** Detailed section of Fig. 2 showing locations of the settlements, mines, boreholes, and field locations. (A) The main concentration of boreholes is in the eastern part of the basin, where the largest mine, Svea Nord is situated. Several boreholes were drilled in the seventies and eighties but almost all of the cores are lost today. This study was mainly based on the cores from 2002 and forward, locations of these are shown on the map. The borehole numbers refer to presented logs (Figs 5-6 and 8-9) (B) The entire Paleogene strata remaining on Svalbard, from (Dallmann, 1999). The map shows locations of field and core data used in the study. Field data is represented by both own field observations and references.



Reindalen for comparison to the cores. Field data were also collected at Festningen, Kolfjellet, and Basilikaelva (Fig. 3). For information on the facies assemblages of the southern and western part of the basin selected references were used e.g. (Nagy, 1966; Kellogg, 1975; Kalgraff, 1978; Ytreland, 1980; Dallmann, 1999; Nagy, 2005).

## **FACIES DESCRIPTION AND INTERPRETATION**

Ten facies have been defined based on 44 subfacies, details of which are shown in Table 1, and are grouped into four facies associations. The lower section of the Firkanten Formation, the Todalen Member, consists of heterolithic alternating very fine sandstone, organic-rich sandstone, siltstone, mudstone, and coal (represented by facies Sh, Sk, Sr, Ms, Mk, and K). In the western part of the basin the Todalen Member is preceded by fluvial conglomerate of the Grønfjorden Bed (Dallmann, 1999) (facies Cgp). The Endalen Member, the upper part of the Firkanten Formation, consists mainly of homogeneous fine grained sandstone of up to several tens of metres thickness. The prominent sandstone cliffs of the Endalen Member are made of facies Sws, Sl, and partly Sb (well sorted, laminated and bioturbated sandstones). Only the lower part of the Basilika Formation has been included in this study and is mainly represented by varieties of facies Sb.

### **Facies K: Coal**

This facies includes coal, muddy silty coal, and carbonaceous silty mudstone (Figs 4 and 5). Beds are homogeneous or plane parallel laminated, and the bed thickness varies from a few centimetres to several metres. The thickest coal deposits are almost five metres in the mine Svea Nord (Fig. 3) where there is an ongoing extraction of a coal layer that extends over tens of square kilometres. The eastern side of the Central Tertiary Basin shows generally thicker and more extensive coal seams.

Due to the soft character of the coal this facies is often scree covered and poorly exposed in the field. The siliciclastic material found splitting the coal seam consists of laterally extensive but thin layers of muddy siltstone or muddy carbonaceous very fine sandstone. The coal is high volatile bituminous (Manum and Throndsen, 1978) and is in general is low in ash and sulphur content (< 2 % sulphur when ash is < 10 %) but with large variations. The sulphur content normally increases with ash content typically at bottom and top of the coal layers. The colour is black or very dark brown and it is mostly humic coal.

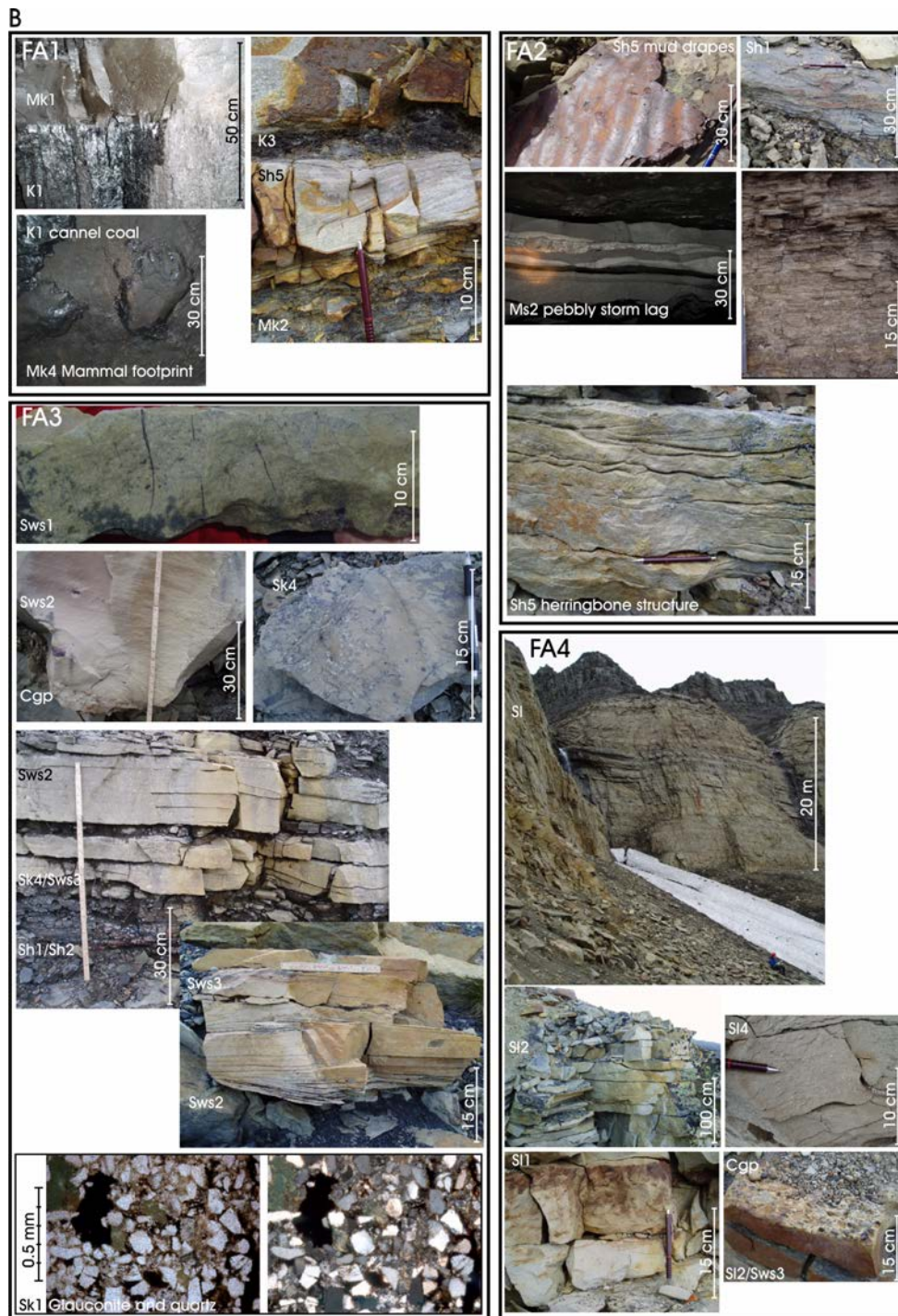
4. Article 1- Coastal plain, Paleocene Spitsbergen

**Table 1** Facies, subfacies and facies associations recognised in the Todalen and Endalen Members of the Firkanten and lower part of the Basilika Formation, with interpretations of the depositional environment compared to previous interpretations (see text for references).

Facies association	Facies	Subfacies	Grain size	Description	Depositional environment	Previous interpretation	
FA1	K	K1	coal	Bituminous coal	Peat bog, raised mire, or marsh	Vegetated floodplain or delta plain	
		K2	cl.-si.	Muddy coal, homogeneous or plane laminated	Swamp or marsh		
		K3	si.	Carbonaceous laminated siltstone	Swamp, lake, lagoon, or proximal tidal flat		
	Mk	Mk1	cl.-si.	Carbonaceous mudstone with root structures	Tidal flat, lagoon, or swamp	Floodplain, levee, interdistributary bay, or lagoon	
		Mk2	cl.-si.	Muddy siltstone with organic content and sand stringers	Tidal flat, lagoon, or lake		
		Mk3	cl.-v.f.s.	Carbonaceous muddy sandy siltstone weakly laminated	Lagoon, or tidal flat		
		Mk4	cl.-v.f.s.	Carbonaceous muddy sandstone weakly laminated	Lagoon, or tidal flat		
	FA2	Ms	Ms1	cl.-si.	Silty bioturbated mudstone, sandfilled burrows	Tidal mud flat, lake or lagoon	Interdistributary bay, crevasse splays, tidal flat or lagoon
			Ms2	cl.-si./v.f.s.	Heterolithic lenticular bedded siltstone	Tidal flat	
			Ms3	cl.-v.f.s.	Sandy muddy siltstone homogeneous	Tidal flat or lagoon	
Sh		Sh1	cl.-si./v.f.s.	Heterolithic ripple laminated bioturbated sandstone, wavy bedding	Tidal sand flat	Tidal influenced interdistributary bay, subaqueous levee or estuary	
		Sh2	cl.-si./v.f.s.	Heterolithic ripple laminated bioturbated sandstone flaser bedding	Distal tidal sand flat		
		Sh3	cl.-si./v.f.s.-f.s.	Heterolithic bioturbated sandstone with mudclasts and organic debris	Distal wash-over fan or lagoon		
		Sh4	cl.-si./v.f.s.-f.s.	Heterolithic ripple laminated bioturbated sandstone with mudclasts and organic debris	Distal wash-over fan or lagoon		
		Sh5	f.s.-m.s.	Ripple laminated sandstone with organic material and mud drapes	Tidal channel, tidal flat, wash-over fan		
		Sh6	v.f.s.-f.s.	Bioturbated muddy sandstone with organic material	Tidal channel, tidal flat, wash-over fan		
FA3		Sk	Sk1	cl.-v.f.s.	Silty muddy sandstone with organic debris weak lamination	Wash-over fan or flooded erosion surface	Crevasse splays, fluvial channel, or barrier mouth bars
			Sk2	cl.-v.f.s.	Homogeneous rooted silty muddy sandstone with organic debris	Vegetated wash-over fan or flooded erosion surface	
			Sk3	cl.-v.f.s./gr.	Homogeneous silty muddy sandstone with mudclasts	Lagoon, distal swamp, or wash-over fan	
			Sk4	f.s.-m.s./gr.	Weakly ripple laminated sandstone with organic material, mudclasts and bioturbation	Lagoon, wash-over fan, flooded erosion surface	
		Sr	Sr1	cl.-si./c.s.-v.c.s.	Purple siltstone with scattered very coarse sand	Subaerially weathered paleosol	Abandoned fluvial channel point bars
	Sr2		si.-f.s.	Rooted white muddy sandstone	Vegetated subaerially weathered paleosol possible barrier bar		
	Sr3		si.-v.f.s.	Muddy silty sandstone with bioturbation	Paleosol possible nest possible barrier bar		
	Sws	Sws1	v.f.s.-m.s.	Rooted well sorted sandstone with low angle cross lamination	Vegetated beach or backshore possibly of barrier bar	Delta front or barrier mouth bars	
		Sws2	v.f.s.-f.s.	Plane to low angle cross laminated sandstone well sorted	Beach, backshore, or foreshore		
		Sws3	f.s.-m.s.	Ripple laminate or trough cross laminated sorted sandstone	Foreshore or beach		
		Sws4	v.f.s.-f.s.	Nicely ripple laminated well sorted sandstone with bioturbation	Foreshore		
		Sws5	v.f.s.-f.s.	Bioturbated cross laminated sorted sandstone	Tidal channel or outer foreshore		
		Sws6	v.f.s.-f.s.	Laminated bioturbated sorted sandstone with plane to low angle cross lamination	Outer foreshore to upper shoreface		
		Sws7	v.f.s.-f.s.	Very well sorted ripple laminated sandstone	Upper shoreface or lower foreshore normal wave deposits		
Sws8		v.f.s.-f.s.	Very well sorted unstratified sandstone	Upper shoreface			
FA4	Sl	Sl1	v.f.s.-f.s.	Well sorted sandstone with typically <i>Ophiomorpha</i>	Shoreface	Delta front or shoreface	
		Sl2	v.f.s.-f.s.	Very well sorted hummocky/swaley cross stratified sandstone	Shoreface storm deposits		
		Sl3	v.f.s.-f.s.	Well sorted sandstone with mudclasts or faecal pellets	Shoreface storm deposits		
		Sl4	f.s.	Sorted bioturbated sandstone	Middle to lower shoreface		
		Sl5	v.f.s.-f.s.	Muddy bioturbated sandstone	Middle to lower shoreface		
	Sb	Sb1	f.s.	Very heavily bioturbated sandstone	Middle to lower shoreface	Lower delta front	
		Sb2	si.-v.f.s.	Silty homogeneous bioturbated sandstone	Middle to lower shoreface		
		Sb3	cl.-v.f.s.	Muddy homogeneous bioturbated sandstone	Lower shoreface		
		Sb4	si.-v.f.s.	Silty bioturbated sandstone with weak plane lamination	Lower shoreface storm deposits		
		Sb5	cl.-v.f.s.	Muddy homogeneous heavily bioturbated sandstone	Lower shoreface		
FA3, FA4 occasionally FA2	Cg				No differentiation, fluvial channel lag or storm deposits		
Cgm	Cg1	gr.-pb.	Mudclast conglomerate, subangular to angular clasts	Storm lag, eroded mudflats or underlying Cretaceous			
Cgp	Cg2	gr.-pb.	Extra formational rounded clasts	Storm lag, beach, or current deposits			
	Cgm, Cgp	Cg3	gr.-pb.	Mixed mud- and extra formational clasts	Storm deposits		

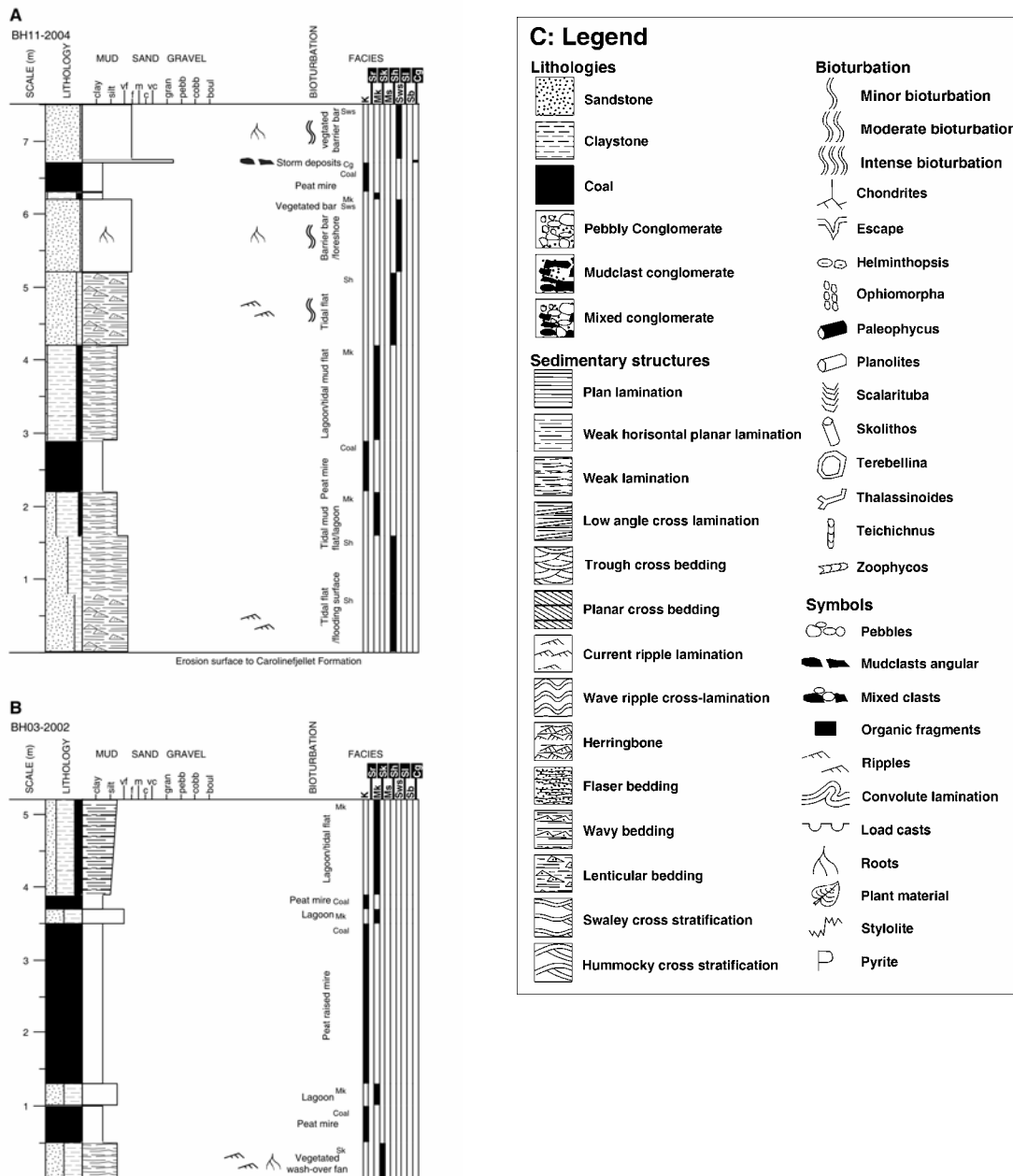


**Fig. 4** (A) Core photographs representing the facies recognised in the study area, grouped by facies associations. FA1 vegetated subaerial to marginal marine; variations of muddy coal and carbonaceous mudstone. All coal is sampled at the drill site for geochemical analysis. FA2 back barrier tidally influenced lagoon; variations of tidal deposits and different conglomerate. Notice sandfilled centimetre scale burrows. FA3 barrier bars; foreshore/upper shoreface well sorted sandstone, different related conglomerates, paleosol represented by Sr2 rooted sandstone, and Sk4 organic-rich sandstone wash-over/flooding surface. FA4 shoreface and offshore transition; range of sandstone from storm deposited well sorted shoreface to muddy bioturbated lower shoreface with large scale *Ophiomorpha*.



**Fig. 4 (B)** Field photographs representing the facies recognised in the study area, grouped by facies associations. FA1 vegetated subaerial to marginal marine; coal in the mine and field. Mammal footprints of possible *Pantodont* in cannel coal from Gruve 7, Longyearbyen. FA2 back barrier tidally influenced lagoon; different tidal features mud drapes, herringbone structures and flaser bedding. Pebbly storm lags in Ms2 muddy siltstone indicating wash-over fans on a tidal flat. FA3 barrier bars; well sorted sandstone vegetated, homogeneous, low angle cross-stratified and bioturbated. Photomicrograph of glauconitic quartzitic sandstone of facies Sk organic-rich sandstone of wash-over fans. FA4 shoreface and offshore transition; sandstone with typical hummocky cross-stratification. Sl4 laminated sandstone with bioturbation like *Planolites* and *Terebellina*. Conglomerate representing beach storm deposits/flooding surface.

Sapropelic (cannel) coal is found at the top of some coal beds in association with pyrite. The boundaries are sharp or graduals depending on the associated facies, typically transitional from finer grained facies below and sharp or erosive when overlain by sandstone deposits. Facies K is associated with facies Mk, Ms, and Sr (carbonaceous mudstone, muddy siltstone, and rooted fine sandstone).



**Fig. 5** Logs of FA1 vegetated subaerial to marginal marine, representing peat mire, lagoon, paleosol, and muddy tidal flat. (A) Facies Mk carbonaceous mudstone. (B) Facies K coal. (C) legend for logs in Figs 5-6 and 8-9.

### *Interpretation of facies K*

Peat, the precursor to humic coal, accumulates typically in environments where there is substantial vegetational growth, sufficient standing water to reduce degradation, absence of inorganic sedimentation, and creation of accommodation (Ward, 1984; Bohacs and Suter, 1997). Thick coal deposits with a large lateral extent, as in the Firkanten Formation, are therefore derived from peat accumulating environments with limited clastic input during moderately rising base level in pace with the mire growth (McCabe, 1984). Raised mires, which typically preserve thick layers of peat can develop in coastal areas and are known to divert clastic input (McCabe, 1984) due to elevation. They will therefore typically have an interior undisturbed from clastic and marine input. The low ash content indicates that the clastic input to the mire was low and the low sulphur values suggest that there was a limited marine influence (McCabe, 1984). However, the fluctuating sulphur values are consistent with a paralic depositional environment close to the shore.

The thickest pure coal sections probably represent raised mires (ombrotrophic) complexes. The coal primarily contains material from vascular plants, like conifers *Cupressaceae Taxodiaceae* and rare *Podocarpaceae* of wet forested mire (Cmiel and Fabianska, 2004). Angiosperms, ginkgoes and rare ferns are also described from Paleogene Svalbard (Golovneva, 2000). Dispersed organic matter is suggested to originate from algal/bacterial production (Cmiel and Fabianska, 2004). Thin coal beds, with high ash and sulphur contents would have formed at the marine influenced outer rim of the mire or in poorly developed mires, more correctly described as marsh or swamp (rheotrophic) environments. Sapropelic coal is produced by algal, bacterial, or fungal organic production in stagnant swamps under anaerobic conditions (McCabe, 1984) as indicated by the observed pyrite content. The occurrence of sapropelic coal on top of the humic coal indicates initial stage of flooding of the mire complex. Facies K is suggested to have accumulated in mire complexes in a near-shore coastal plain wetland.

### **Facies Mk: Carbonaceous mudstone**

Carbonaceous muddy silt- and sandstone of facies Mk occur associated with facies K. The beds are often plane parallel laminated or homogeneous and the colour is dark brown to black due to the very high organic content (Figs 4 and 5). Organic material also occurs as fragments of pure coalified clasts and root structures. The beds vary from a few centimetres thick to more than a metre. The sulphur content is normally not particularly high for these organic-rich mudstones (< 10 % sulphur). The lowest sulphur values are in the mudstone beds with

very high ash content (> 90 % ash), whereas the highest sulphur content (~15 % sulphur) occurs mainly in beds with medium ash content (25-35 % ash).

#### *Interpretation of facies Mk*

On coastal plain environments such as lagoons, lakes, and tidal flats, thick successions of organic-rich sediments may be preserved during periods of rising sea level. The association with coal suggests that facies Mk was deposited in an environment close to peat accumulation, but where the terrigenous clastic input was too high to generate coal (Bohacs and Suter, 1997). The muddy character suggests a low energy level for deposition of facies Mk while the sulphur content indicates marine influence. The characteristics of facies Mk correspond well to vegetated supratidal swamps and marshes protected by barrier bars from waves, tides and storms but still influenced by marine or brackish water (Reading and Collinson, 1996).

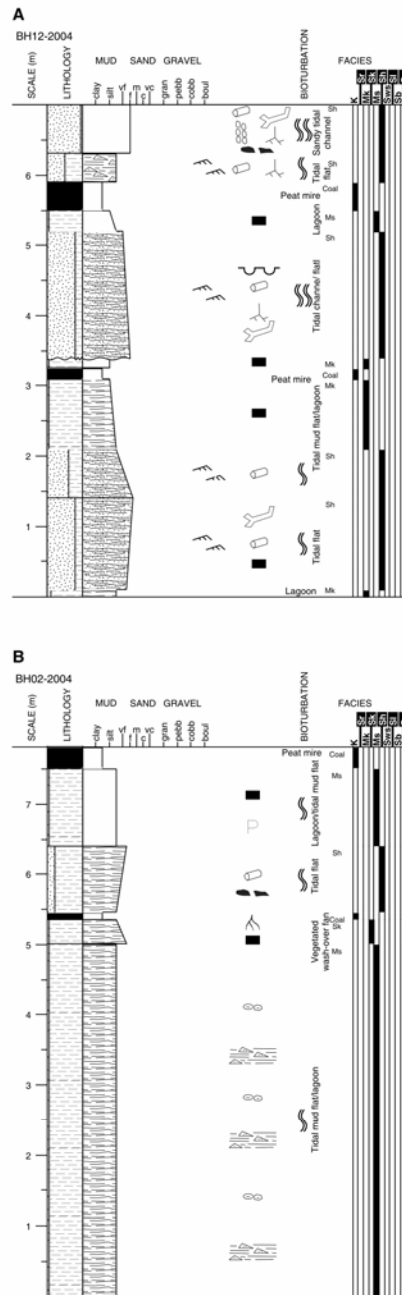
#### **Facies Ms: Dark grey muddy siltstone**

This dark grey sandy muddy siltstone is often associated with facies Sh (heterolithic sandstone and mudstone). The beds are mostly homogeneous with bioturbation in places in the form of large (cm scale) sand-filled burrows (Figs 4 and 6), but can also be plane laminated. The colour is grey to dark grey with lenses and strings of sandstone forming lenticular bedding which shows ripple cross lamination. The beds are only a few centimetres thick when interbedded with facies Sh (heterolithic sandstone), but are otherwise up to a metre in thickness. The organic content is low but this facies is found in association with the organic-rich Mk.

#### *Interpretation of facies Ms*

The fine grain size indicates a low energy conditions which may be found in the proximal part of tidal mudflats, sheltered lagoons, or in lakes on the coastal plain (Reinson, 1992). The lenticular bedding and sand-filled burrows indicate the variable energy of a tidally influenced environment. Flocculation of the clay minerals leads to semi-lithification of the mud flats which may then be burrowed, with the burrows later filled with sand during the rising tide. The low organic content and relatively sparse bioturbation observed suggests a restricted, brackish environment, possibly influenced by acidic groundwater from adjacent mires. However, the homogeneity suggests that the deposits may also be completely burrowed throughout but the traces are not identified due to the intensity and small sizes. Mudstone with low organic content has also previously been described from the Firkanten Formation by

Nagy (2005), who, based on the restricted foraminifer fauna, interpreted these as lagoon deposits.



**Fig. 6** Logs of FA2 back barrier tidally influenced lagoon representing bioturbated muddy sections of tidal flat and lagoon. (A) Facies Sh heterolithic sandstone and mudstone. (B) Facies Ms dark grey muddy siltstone.



### **Facies Sh: Heterolithic sandstone and mudstone**

Facies Sh comprises a large range of subfacies of heterolithic interbedded sandstone and mudstone with flaser, wavy and lenticular bedding (Table 1). Along with Ms, Sh is the most common facies in the Todalen Member and can make up beds of up to several metres thickness. The sand is well sorted, very fine to fine, rarely coarser, and it is often bioturbated with sand filled burrows (Figs 4 and 6), while root structures occur more rarely. *Teredolites* (Fig. 7) was observed in Gruve 7 (Fig. 3) in a bed overlying the coal. In places the primary structures are disturbed by bioturbation, loading, and soft sedimentary deformation but ripple lamination occurs frequently. Herringbone structures with mud-drapes are observed both in core and field and mudclasts and organic debris are present. The boundaries are sharp between the lamina of mud and sand but gradual from one subfacies to another. Facies Sh occurs associated with both Mk and Ms.



**Fig. 7** *Teredolites* trace fossil from the roof in Gruve 7 in wash-over fan deposits.

#### *Interpretation of facies Sh*

The alternation of sand and mud indicate the rapidly changing energy level of a tidal environment. Sand is deposited during high energy episodes with current ripple lamination and is later covered with mud from suspension (Reineck and Wunderli, 1968; Dalrymple, 1992). Herringbone structures that signify the opposite flow direction are generally diagnostic for tidal deposition, and mud-drapes are also a strong indicator for a tidal environment. Organisms will be active in the mud during quiet periods and later the burrows get filled with sand during the rising tide. *Teredolites* are created by marine burrowing and dwelling

bivalves that typically bore into organic deposits that have been flooded (Pemberton *et al.*, 1992).

The wide range of subfacies represents different zones in the tidal flat environment characterised by different energy levels and water depths. Mud deposits are normally expected to represent the more landward setting whilst the grain size or the sand/mud ratio increases gradually seawards (Dalrymple, 1992). The less muddy sections possibly represent minor tidal channels and tidal bar complexes. It is possible that some of the changing energy level was caused by episodic events of storms, but the deposits show little evidence of storm deposition such as erosive surfaces. Tidal influence is a very common feature of the fine-grained deposits of the Firkanten Formation.

### **Facies Sk: Organic-rich muddy sandstone**

Facies Sk is made up of predominantly grey to dark grey very fine sandstone which is very poorly sorted and mixed with mud, silt, and organic debris. The different subfacies of Sk vary in amount of mud and organic debris content (Table 1). Primary structures are mostly absent or disturbed, but weak planar and ripple lamination occur. The dominant feature of this facies is the poor sorting and presence of organic debris (Figs 4 and 8). The facies is sometimes overlain by coal.

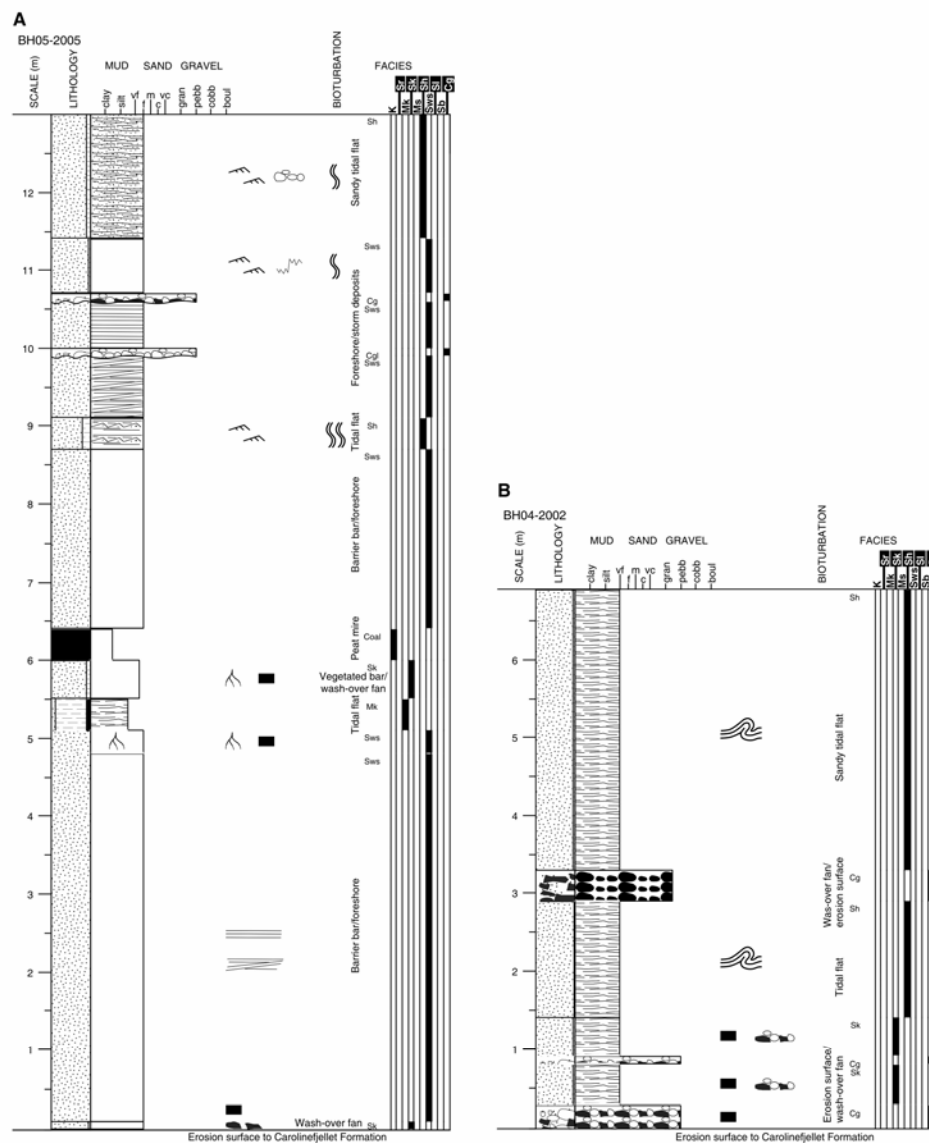
Specific trace fossils are rarely identified other than root structures but the sediments appear biogenically reworked in places; possible *Thalassinoides* and *Scalarituba* have been observed in field. Since this facies is often covered by scree the geometrical shape of the deposit is hard to recognise but it is probably sheet-like. The beds are up to 2 m thick but normally less than 0.5 m. Facies Sk occurs most frequently at the base of Todalen Member in association with the previously described facies K, Ms, or Sh and mudclasts conglomerate (facies Cgm). In thin section this facies show primary glauconite. The glauconite shows no oxidation and is pressed between other grains indicating that they were still soft during early compaction (Fig. 4B).

#### *Interpretation of facies Sk*

The marine indications (trace fossils and glauconite) together with the continental influence (high organic content) suggest a mixed origin of a continental to marginal marine environment, possibly a vegetated area. Glauconite forms in marine environments with low clastic sediment input (Prothero and Schwab, 1996) and is concentrated during periods of sea level rise (Johnson and Baldwin, 1996). The glauconite grains were probably re-worked and incorporated into this facies but since the grains show no signs of oxidation, their origin was

probably in a contemporaneous marine environments and it is not likely that the glauconite was reworked from the underlying Carolinefjellet Formation.

The mudclast conglomerate (Cgm) associated with facies Sk contains rip-up clasts from the underlying Lower Cretaceous Carolinefjellet Formation. Facies Sk is primarily but not exclusively found at the base of the Paleocene succession situated on the unconformity and especially where there is evidence of some relief on the unconformity surface. The top surface of the underlying Carolinefjellet Formation does not show any signs of weathering. However, prior to Cenozoic deposition the area was probably covered by weathered material formed during the prolonged period of uplift and exposure in the upper Cretaceous that



**Fig. 8** Logs of FA3 barrier bars representing well sorted sandstone of foreshore/upper shoreface and wash-over fans/erosive flooding surface. (A) Facies Sws well-sorted sandstone. (B) Facies Sk organic-rich muddy sandstone.

created the unconformity, but the material must have largely been eroded prior to or during flooding. This suggests that some of facies Sk deposits are related to the marine flooding of the area by the initial transgression when the previously weathered material was eroded, reworked and deposited. The raised base level created accommodation and the sections of facies Sk deposits could be considered to be ravinement facies.

The geometry, bed thickness and general sedimentary character of facies Sk combined with the association to mudclasts/pebbly conglomerate beds suggest that occurrences of facies Sk could represent deposits from storm events such as wash-over fans (Reinson, 1992), lobe-shaped, sheet-like deposits that built into the lagoon (Reinson, 1992). These deposits are often bioturbated between storm events and can also be vegetated (Reinson, 1992; Reading and Collinson, 1996), leaving the organic-rich sheet sandstone overlaid by thin coal (Reinson, 1992) an association found in the Todalen Member.

#### **Facies Sr: Rooted fine sandstone**

Facies Sr is typically made of silty very fine to fine sandstone with some organic material and scattered coarser grains: beds are grey, purple, yellow, white, or brown in colour. The layering is disturbed by abundant root structures and although there are no identified trace fossils, bioturbation is present (Figs 4 and 8). Bed thicknesses are less than 0.5 m and the lower boundary is often transitional from facies Sk or Sws (well sorted sandstone). Facies Sr is rare but when present it is always overlain by coal.

#### *Interpretation of facies Sr*

The leached appearance of facies Sr, roots, and association with coal beds suggest that it represents a paleosol. Bleached horizons overlain by coal have been termed gleyed soils associated with paludization (Retallack, 2001), formed as a hydric soil which represents a water saturated anaerobic surface upon which the coal forming vegetation grew (Huddle and Patterson, 1961; Collinson, 1996). Leaching can also be caused by the acids from the mire (McCabe, 1984). The original process of deposition of facies Sr is difficult to recognise because the layering is disturbed but the close association with Sk and Sws (well sorted sandstone) facies suggests that Sr might have originally formed in a similar way.

### **Facies Sws: Well-sorted sandstone**

Facies Sws is made of well sorted sandstone of very fine to fine grain size, with sharp bed boundaries. It is characterised by the grey to light grey clean sandstone with almost no structures (Figs 4 and 8) except poorly developed ripple lamination, low angle cross lamination, and plane parallel lamination. The grains are predominantly quartz, but fresh, unweathered glauconite can make up to 5% of the sediment. Pebbles, mudclasts, and organic material are limited but occur in places. Root structures occur only in the uppermost part of some beds, associated with facies Sr. Beds are occasionally bioturbated showing *Skolithos* ichnofacies like *Ophiomorpha* (with well developed lining) and *Planolites*. Facies Sws is found predominantly in the upper part of the Todalen Member and throughout the Endalen Member.

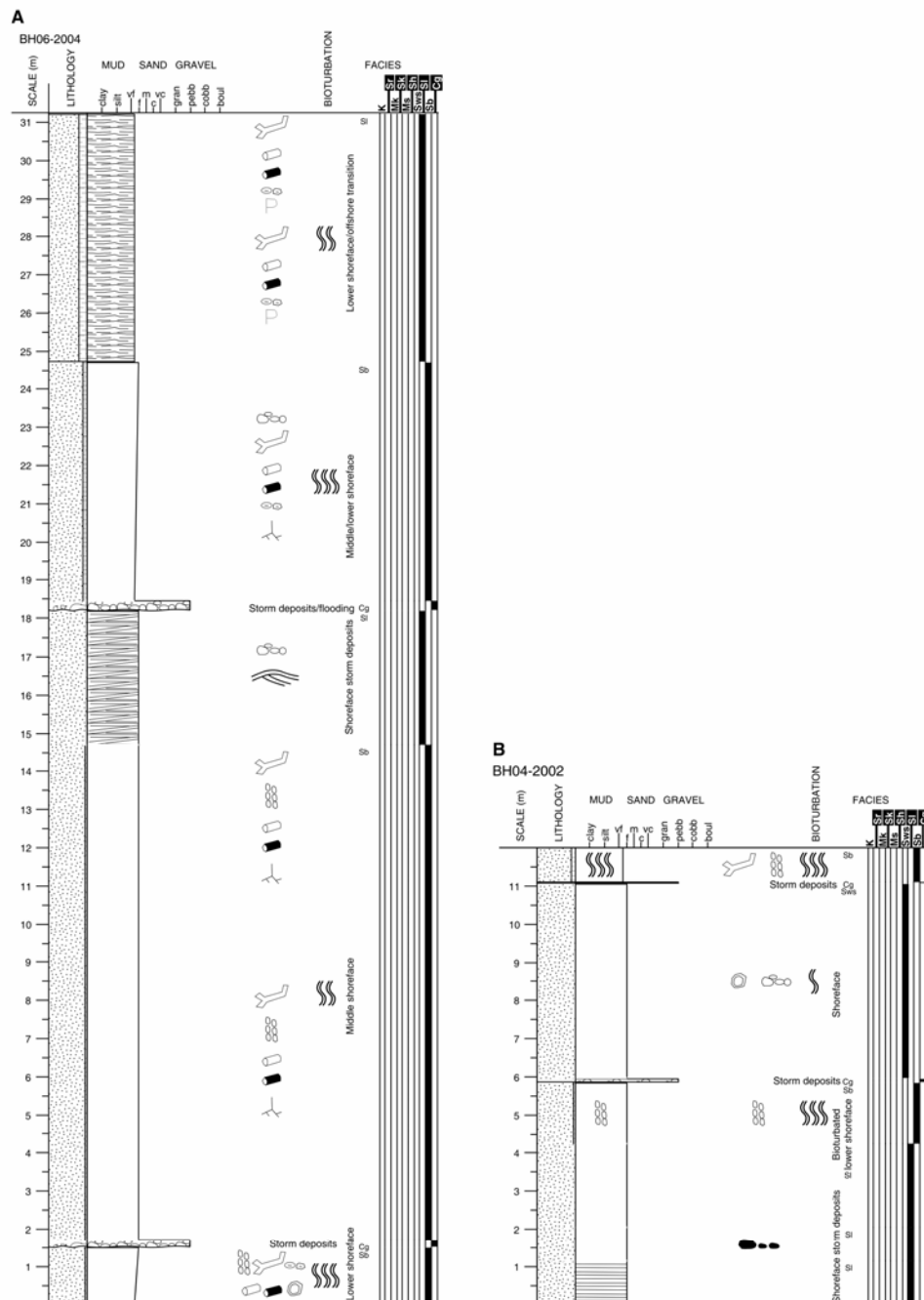
#### *Interpretation of facies Sws*

The well sorted and mature character of the sandstone beds indicates deposition in a moderate to high energy shallow marine environment with extensive sorting. A marine environment is also indicated by the fresh grains of glauconite. The somewhat restricted structures in facies Sws are typical for foreshore/beach/backshore and the uppermost part of the shoreface (Walker and Plint, 1992; Reading and Collinson, 1996). Plint and Norris (1991) interpreted similar deposits as beach to backshore deposits. The *Skolithos* ichnofacies is typical of the upper shoreface (Pemberton *et al.*, 1992) and the lining of the burrows indicates a soft, sandy substrate. In this depositional setting normal fair-weather wave action results in well-sorted sand, while storm events will occasionally bring in coarser sediments and cause localised erosion of the coastline. The presence of roots indicates vegetation on a beach and facies Sws is therefore interpreted as the deposits of a beach with adjoining barrier bars/islands and foreshore deposits.

### **Facies Sl: Laminated sandstone**

This light grey to grey sandstone is very well sorted with weak lamination. The form of the lamination seen in the cores indicates the presence of hummocky and swaley cross-stratification, current ripple lamination, and planar lamination (Figs 4 and 9). The interpretation of the laminae seen in cores as components of hummocky or swaley cross-stratification are confirmed by field observations where these structures are sometimes overlaid by wave ripple lamination. The beds are laterally continuous in the field. Mudclasts occur scattered, occasionally with pebbles and granules and as subrounded mudclasts or

possible faecal pellets in distinct laminae. Glauconite is present within many beds. The beds are often bioturbated, typically by *Ophiomorpha*, *Thalassinoides*, *Planolites*, *Paleophycus* and *Terebellina*, with some of the traces showing evidence of mud lining of the burrows.



**Fig. 9** Logs of FA4 shoreface and offshore transition representing shoreface to lower shoreface of well sorted sandstone to muddy bioturbated sandstone. (A) Facies Sb bioturbated sandstone. (B) Facies S1 laminated sandstone. Notice half scale compared to Figs 5-6 and 8.

#### *Interpretation of facies S1*

The presence of hummocky and swaley cross-stratification indicates deposition in high-energy marine conditions associated with storm activity (Leckie and Walker, 1982). The presence of mudclasts reflects erosion during storm events and deposition as laminated storm deposits (Reineck and Singh, 1972). The trace fossil assemblage (*Skolithos ichnofacies* – Pemberton *et al.*, 1992) is typical of moderate to high energy shallow marine environments, including storm-influenced shelf settings (Ekdale *et al.*, 1984) and the clay lining of the burrows indicates a soft, sandy substrate (Pemberton *et al.*, 1992). This association of characteristics suggest that this facies was deposited in a lower shoreface to offshore transitional setting below fair-weather wave base (cf. Walker and Plint, 1992). However, Plint and Norris (1991) considered similar sand-rich facies to be middle to upper shoreface deposits. The high degree of bioturbation probably reflects periods of low sedimentation rate whilst the intensity of hummocky and swaley cross-stratification indicates high storm influence that would overprint any fair-weather deposits. The horizons of mudclasts/faecal pellets are probably storm-generated (Reineck and Singh, 1972).

#### **Facies Sb: Bioturbated silty sandstone**

Facies Sb typically occurs overlying facies S1 and is found in the upper part of the Endalen Member and in the Basilika Formation. This facies comprises muddy silty grey sandstone that is homogeneously mixed by intense bioturbation identified as *Ophiomorpha*, *Thalassinoides*, *Helminthopsis*, *Planolites*, *Paleophycus*, *Terebellina*, *Teichichnus* (Figs 4 and 9), leaving only weak indications of the original lamination. In the cores the form of the primary structures indicates planar lamination but hummocky and swaley cross-stratification was also found in the field. Pebbles and granules occur scattered within beds but also as thin laminae of sub-rounded mudclasts. In the field this facies forms layers of considerable lateral extent.

#### *Interpretation of facies Sb*

The muddy character and high intensity of bioturbation of the beds indicate that this facies was deposited in an environment where deposition alternated with periods of quiescence. Although extensively bioturbated some primary structures indicate the influence of storm activity (hummocky and swaley cross-stratification). Facies of this character are considered to be lower shoreface to offshore transition deposits (Plint and Norris, 1991) formed between the fair-weather and storm wave bases (Reading and Collinson, 1996). During storms coarser sediments are eroded from the coast and re-deposited further out in the basin (Hart and Plint, 1989; Reading and Collinson, 1996) and semi-lithified mud deposited during fair-weather

conditions is ripped up and deposited as laminae of mudclasts. A lower shoreface setting is also indicated by the *Skolithos* to *Cruziana* trace fossil assemblage (Ekdale *et al.*, 1984; Pemberton *et al.*, 1992; Pemberton and MacEachern, 1995).

Between storms, burrowing activity was favoured by oxygenated bottom condition and low sedimentation rates. The bioturbated muddy siltstone and fine sandstones of the Kolthoffberget Member (Fig. 1) (Dallmann, 1999; Nagy, 2005) could possibly be the finer version of facies Sb and the Basilika Formation similarly becomes muddier further up in the stratigraphy (Dallmann, 1999) reflecting deepening of the basin. Sb is interpreted as the deposits of middle to lower shoreface environment.

### **Facies Cgp and Cgm: Conglomerate**

Beds and layers of conglomerate occur throughout the Firkanten Formation. There are two types of conglomerate clasts; round to subrounded extrabasinal clasts form facies Cgp and angular to subangular, largely intrabasinal mudrock clasts form Cgm (Fig. 4) (Kostro, 2005). Type Cgp is typically found in thick beds (> 20 cm) at the top of the Todalen and Endalen Members, but also occurs as thin layers and as the fill of shallow scours in other parts of the Firkanten Formation (Fig. 4). The second type, Cgm is more common at the base of the Todalen Member in the eastern part of the basin where thicker beds of up to 0.5 m occur. There are also conglomerates made up of both types of clasts. The lithology of the extrabasinal clasts is typically chert, vein quartz, grey quartzitic sandstone and metamorphic quartzite. The clasts sizes range from granules to pebbles in both conglomerate types.

#### *Interpretation of facies Cgp*

Beds of extrabasinal rounded clasts of facies Cgp occurring at the base of the Firkanten Formation in the western part of the basin form the Grønfjorden Bed and are interpreted as fluvial deposits (Kellogg, 1975; Nichols and Lüthje, Submitted). The sandstone and conglomerate beds in the Grønfjorden Bed show trough-scale cross-bedding and occur in fining-up successions typical of the fill of a bedload-dominated river channel (Nichols and Lüthje, Submitted). These characteristics have not been observed to be associated with conglomeratic facies elsewhere in the Firkanten Formation. The clast types indicate that their provenance is in the fold and thrust belt in the west or from the north of the Central Tertiary Basin (Nichols and Lüthje, Submitted) (Fig. 2). The conglomerates of the Grønfjorden Bed were therefore probably deposited as fluvial or alluvial fan deposits restricted to the western side of the basin. The deposits of facies Cgp formed in this setting display both larger clasts



and greater variety of sizes than Cgp facies elsewhere: scattered pebbles and thin layers of facies Cgp found elsewhere in the basin are exclusively granule to pebble size.

The beds of facies Cgp associated with marine facies Sws, Sl and Sb show indications of wave reworking. At the shoreline gravel may be deposited by rip currents, longshore currents and wave action to form beds of conglomerate (Hart and Plint, 1995). Scour fills of facies Cgp, observed at the base of sandstone beds, are interpreted as wave or tidal induced erosive current features such as beach lags or storm deposits (Hart and Plint, 1995). The transportation of the facies Cgp pebbles from the western source area to other parts of the basin was by marine processes such as currents induced by shoaling waves moving coarse sediment along shore (Hart and Plint, 1995). Waves also move coarse sediment onshore and fine sediment offshore during fair weather (Hart and Plint, 1989) while during storms the coarse sediments are moved from the shore and deposited offshore. Storms can also bring coarse material into the lagoons as wash-over fans. Longshore currents are a major agent for transportation of gravel on the upper shoreface (Hart and Plint, 1995) and are known from the south coast of England at Chesil Beach to be able to sort grain sizes exceptionally well (Carr, 1971; Hart and Plint, 1989).

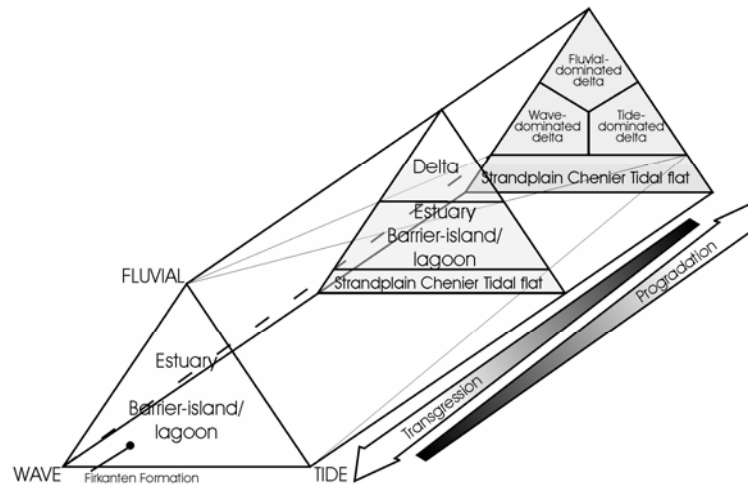
#### *Interpretation of facies Cgm*

The mudrock clasts of the Firkanten Formation can be both intraformational, generated from within the Firkanten Formation or extraformational derived from underlying strata of the Carolinefjellet Formation. The clasts in the conglomerate at the base of the Todalen Member are mainly derived from the underlying Carolinefjellet Formation. Since the clasts are mostly angular they were not transported very far but are expected to come from a local high in the relief of the unconformity (Jochmann, 2004; Kostro, 2005). The scattered mudrock clasts in the Firkanten Formation probably originate from mudflat deposits where material deposited on tidal flats and around lagoons can become semi-lithified. These mudflat areas would have been eroded during storms and re-deposited as intraformational clasts. The angular clasts are not likely to have been transported very far, while the sub-rounded clasts could have been moved somewhat further from the shoreline.

## **FACIES ASSOCIATIONS**

The facies described above have been grouped into four facies associations representing different depositional environment. Boyd *et al.* (1992) classified coastal depositional settings by the dominant process acting on the coast, with three end members: fluvial, tidal, or wave dominated. These coastal types were further classified according to whether they are in

progradational or retrogradational settings (Fig. 10). The facies in the Firkanten Formation are considered to be associated with wave and storm dominated near shore marine environments but with some tidal influence (Fig. 11).

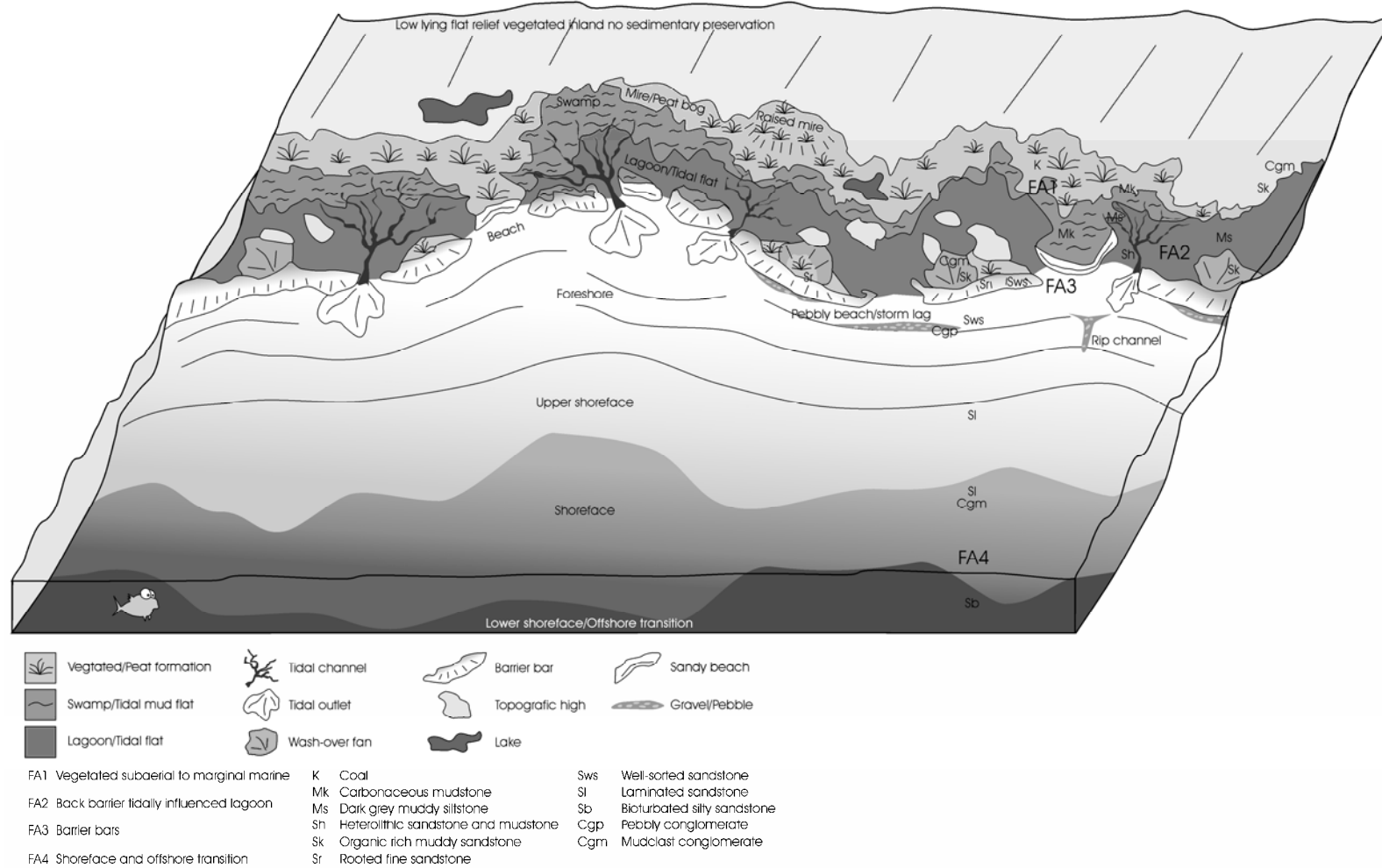


**Fig. 10** Coastal classification scheme of the relation of coastal depositional environment to relative sea level changes separated according to dominant energy/sediment input, fluvial wave or tidal, after (Boyd *et al.*, 1992). The depositional setting of the Firkanten Formation is dominated by waves but with some tidal influence deposited during a general sea level rise.

#### FA1: Vegetated subaerial to marginal marine

Facies association FA1 consists of the carbonaceous facies K and Mk that represent a vegetated continental to marginal marine sheltered environment, above the mean high water level and flood tide level and within the supralittoral zone (Fig. 11). Facies Ms and Sr are closely related but have a marine origin. The close association with marine facies suggest that the coal (Facies K) was deposited in a near shore environment such as a coastal plain close to a tidal flat or lagoon (Fig. 11). This facies association occurs over a large area in a close relationship with marine facies suggesting that there was a broad low gradient coastal plain environment where even minor fluctuations in sea level would affect large areas. The apparent absence of fluvial facies in the central and eastern parts of the basin indicates that the coarser, fluvial deposits of the Grønfjorden Bed were confined to the western side of the basin.

This interpretation of the continental facies as coastal plain deposits contrasts with the previous interpretation of the Todalen Member as a delta plain succession (Steel *et al.*, 1981). Most active delta environments today do not seem to have any major potential for peat accumulations (McCabe, 1984) and peat accumulations in environments with a high clastic input tend to be thin and discontinuous. The thick and extensive coal seams are therefore not



**Fig. 11** Conceptual diagram of the depositional environment and the distribution of facies and facies associations in Firkanten Formation. Facies codes are related to Table 1.

typical of deposition in a delta setting. Peat accumulated in a coastal plain is limited to the shore by the marine influence and inland by desiccation. Subsidence and eustatic sea level changes determine the position of the shoreline and hence the extent of the coastal plain and coal deposit. The gradient of a coastal plain will affect the extent of the coal accumulation (Bohacs and Suter, 1997).

Paralic peat normally varies greatly with distance to the shoreline (Greb *et al.*, 2002). Under stable conditions, when organic production is in pace with subsidence, raised mire complexes will build up in the most landward part of the mire. This ombrotrophic zone is situated above high water mark and can be desiccated, although ombrotrophic mires are known to generate a raised ground water table (McCabe, 1984). The ombrotrophic zone gradually changes seawards into an intermittently submerged mesotrophic zone and a completely submerged distal rheotrophic zone (Greb *et al.*, 2002). This pattern is displayed in the facies distribution in the Todalen Member by the carbonaceous mudstone facies (Mk) which has a variable ratio of mud and organic material: the clastic input and marine influence on the sediments gradually increase seaward while the amount of organic material decreases. This transition is also found in the Todalen Member in the vertical sedimentary record of transgressive successions representing gradual flooding of the mire areas (Figs 4 and 5). The thick mudstones preserved suggest a protected coastal plain in the Todalen Member, developed with raising base level, which would create the required accommodation.

Raised mire can only form in environments where the annual rainfall is higher than annual evaporation resulting in a high water table keeping the coastal plain “fresh”. The low sulphur content of the Todalen Member coal could be an indication of high precipitation and thereby high fresh water input forcing the saltwater/freshwater interface seawards. The climate in the Paleocene is interpreted as temperate humid with annual rainfall distributed equally over the year (Golovneva, 2000; Cepek and Krutzsch, 2001).

#### **FA2: Back barrier tidally influenced lagoon**

Facies association FA2 comprises the heterolithic fine grained strata of facies Ms and Sh interpreted as the deposits of tidally influenced environments. There is a gradual seawards transition from the vegetated coastal plain with mires and swamps (FA1), becoming more and more marine influenced on the tidal flats and in lagoons (FA2) (Fig. 11). The association with FA3 barrier bars (see below) indicates that FA2 deposits were protected by barrier islands and hence represent the fine grained sediments of a back barrier system. The Firkanten Formation is interpreted to have been deposited in a combined tidal and wave influenced environment (Figs 10 and 11) with the tidal flats and lagoons acting as a buffer zone for the vegetated areas

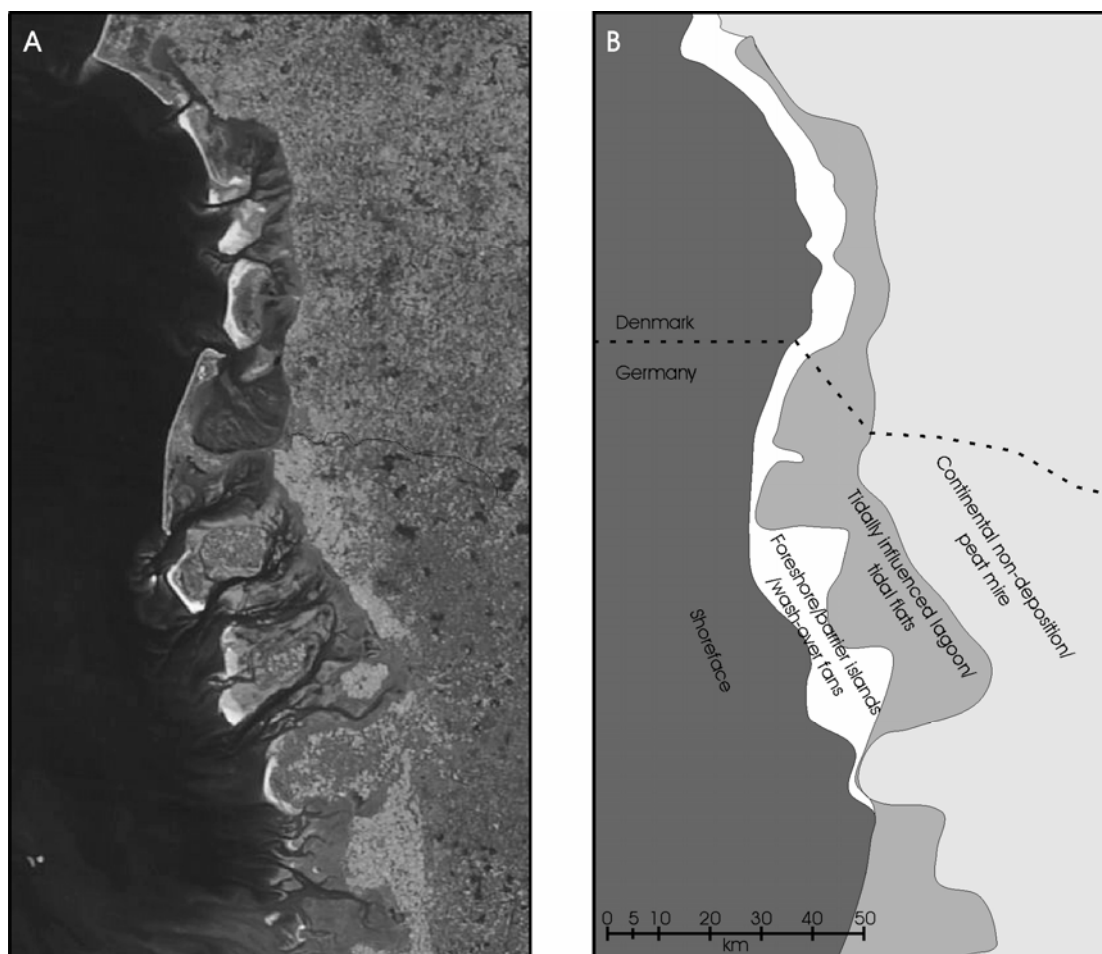
protecting them from the marine influence. This facies assemblage suggests a low angle relief dissipative coast, with mixed tidal flat and lagoon facies.

The normal fair-weather waves would not have had much influence on the lagoons since they would have been sheltered by the barriers (Reinson, 1992), but storms could have a great erosive effect on both tidal flats and lagoons. The mudrock clast conglomerates found in the Todalen Member are possibly generated from erosion of mudflats. Tidal inlets and wash-over fans along the barrier bar would also have brought coarse material into the lagoons (Reinson, 1992).

The lack of evidence of well developed meso/macrotidal influences (e.g. see Dalrymple, 1992; Reading and Collinson, 1996) indicate a microtidal setting for the Firkanten Formation. However, the tidal influence on the coastline can be significant even in a microtidal environment where a low gradient of the coastline means that even a small tidal range would involve movement of a large volume of water over a large area. The low sulphur content of the coal could be an indication that the tidal range was not high enough to affect the mire areas.

A modern analogue for the fine grained tidal deposits of the Firkanten Formation, the Todalen Member, could be the southeast coast of the North Sea; the Danish Wadden Sea (Fig. 12). This area shows a gradual decrease from mesotidal to microtidal range from the west (Holland < 3 m) to the east (Denmark 1-0.5 m). The coast is in addition overall transgressive, wave dominated with some storm influence and is situated in a temperate climate zone, all features similar to the environment of deposition of the Todalen Member. The climate at Spitsbergen in Paleocene based on fossil plant material has been interpreted to be warm-temperate with a high humidity equally distributed over the year (Golovneva, 2000; Cepek and Krutzsch, 2001). There are, however, some large tidal channels on the southern North Sea coast despite the low tidal range so the tidal range in the Todalen Member may have been even lower.

Raised mires are normally very acidic influencing the area outside of the mire and nearby deposits (McCabe, 1984). The absence of calcareous foraminifer taxa (Nagy, 2005) and carbonate shells in the Firkanten Formation could be due to dissolution caused by the acid from the mire waters. Calcareous nanofossils have only been described once from the Firkanten Formation, a dissolution-resistant species indicating that dissolution of other forms had probably taken place (Cepek, 2001). High precipitation on the coastal plain pushes the saltwater interface seawards and leads to a larger area influenced by the acids from the mire, including penetrating into underlying sediments. The restricted fauna found in the Todalen Member (Nagy, 2005) could also be caused by the brackish environment in the lagoon created by fresh water run-off mixed with marine saltwater, creating an environment occupied only by a restricted fauna.



**Fig. 12** (A) Satellite image of the Danish Wadden Sea, a modern analogue for the depositional environment in the Firkanten Formation (MODIS image from NASA Visible Earth, <http://visibleearth.nasa.gov>). (B) The coast is characterised by a wide tidally influenced lagoon and tidal flat areas protected from wave action by barrier bars/islands with well sorted foreshore sand deposition. The inland of the lagoon is recognised by peat mires in a flat relief low-lying area. Notice that the barriers are cut by several tidal channels even if the area is microtidal.

### FA3: Barrier bars

Facies Sk, Sr, Sws and parts of Cgm and Cgp are combined into facies association FA3 representing a wave and storm induced near shore environment. This environment includes all parts of the shoreline including beach (foreshore and backshore), the barrier bars and islands, back barrier sandy wash-over fans and tidal deltas as well as possibly the uppermost part of the shoreface (Fig. 11). This barrier bar complex is a widespread zone where waves build up the barriers, behind which back barrier lagoon and coastal plain environments (FA1 and FA2) developed. The good sorting of the sandstone in facies of FA3 is due to wave action at the

shoreline. Every shoreline has an equilibrium line that is dependent on grain size, wave condition, and slope: on the landward side of the equilibrium line sediments are moved onshore and seawards of the line sediments move offshore. The result is that finer grained sediments are transported offshore while coarser grained sediments move onshore.

From FA2 it is clear that tides have at least had some influence on the Firkanten Formation. Tidal currents break through barriers and create tidal inlets and even tidal deltas, probably represented by parts of the sandy sections of FA2. The Endalen Member and the Basilika Formation show extensive storm and wave influence and lack convincing tidal evidence, indicating that they represent the seawards side of the barrier islands and a marine setting where storm and wave action makes it harder to recognise tidal effects. Root horizons show that the barriers were vegetated during fair-weather (Fig. 11) and these vegetated barriers were probably eroded during storms and gave rise to the organic-rich wash-over deposits. The thin pebbly storm lags also indicate storm action on the coastline as material was reworked by wave action and transported by longshore currents (Hart and Plint, 1995). Some of the thicker conglomerates in the Firkanten Formation are probably related to pebbly deposits on the beach (Fig. 11).

#### **FA4: Shoreface and offshore transition**

Facies S1 and S<sub>b</sub> represent the deposits of deeper water between the upper shoreface and offshore transition zones. These sediments are characterised by sand deposition from storms and mud during quiescence. Burrowing organisms colonized the substrate in between storms and the bioturbation can be intense, mixing the sediments completely: the bioturbation increases with water depth, and decreases with at higher rates of sedimentation. The bioturbation and grain size normally reflect the water depth but in the Todalen Member the sedimentation rate was probably relatively low due to low sediment input, suggested by the glauconite content. This would be reflected in more bioturbation than expected at a certain water depth. The sediment in the Endalen Member is also coarser than would be expected for the water depth indicated by the bioturbation. Therefore it is suggested that the water depth in this facies association in the Firkanten Formation represents middle to lower shoreface.

## **A COASTAL DEPOSITIONAL ENVIRONMENT FOR THE FIRKANTEN FORMATION**

The sediment input and the energy regime (waves, storms, and tides) control coastal environments that can be classified by the dominant processes (Boyd *et al.*, 1992). The three end members – wave, tidal, and fluvial – interact to shape the coastline (Fig. 10), whilst the sea level change and rate of sediment supply will give rise to regressive/progradational or transgressive/retrograding coastlines with different character (Boyd *et al.*, 1992). The facies of the Firkanten and Basilika Formations indicate a transgressive environment and there is no evidence for valley incision or sea level fall in the succession. Transgression and low sedimentation rates in a wave-dominated setting typically result in a barrier bar and lagoon system (Boyd *et al.*, 1992), as seen in the Firkanten Formation. Some tidal influence and fluvial input may be present, but is of minor importance for the coastal system. Tidal dominated shorelines do not have well-developed barriers as the tides help to maintain a low relief of the coastline, whilst fluvial dominated coastlines are characterised by deltas and show stronger evidence for progradation (Fig. 10).

The Todalen Member is characterised by muddy fine grained sediments with a high organic content deposited in a marginal marine environment. The foreshore and shoreface deposits of the Endalen Member consist predominantly of well sorted sand. At a coast with low fluvial sediment input and a general rising sea level, the fine sediment will tend to be trapped onshore in the back barrier system where there will be available accumulation space. In transgressive systems less sediment are transported and deposited further out into the basin (Johnson and Baldwin, 1996) as the sediment is trapped in near coastal systems (shoreline to inshore environment) such as beach barrier systems (Fig. 11). However, at the foreshore and shoreface the sediments are reworked and winnowed by waves and storms and therefore no mud is found, only well sorted sand. During normal wave conditions on the shoreface, sands build up barrier islands (Hart and Plint, 1995). Wash-over fans are an important process and are likely to be preserved in the stratigraphic record (Reinson, 1992), which is found in the Firkanten Formation (Facies Sk).

The tidal range of the Firkanten Formation is thought to be microtidal on the basis of the absence of features typical high tidal influence, such as tidal sand ridges, tidal sand banks, and tidal channel deposits (Johnson and Baldwin, 1996; Reading and Collinson, 1996). There is no indication of incision that could indicate that any of the marginal marine sediments could represent estuary deposits and hence the finer grained sediments are interpreted as the deposits of a tidally influenced lagoon or combined lagoon/tidal flat area (Fig. 11).



## COMPARISON WITH PREVIOUS INTERPRETATIONS

This study is the first comprehensive facies analyses of the Firkanten Formation to be published. Previous sedimentological investigations of the Firkanten Formation include many unpublished thesis and reports, and the published interpretations e.g. (Kellogg, 1975; Steel *et al.*, 1981; Steel *et al.*, 1985; Harland, 1997; Dallmann, 1999; Bruhn and Steel, 2003; Nagy, 2005) are largely based on facies descriptions from them. Some of the observations and interpretations in the previous work are consistent with the new facies model, but they come to a different conclusion regarding the overall depositional setting.

This new facies analysis of the Todalen Member indicates that deposition occurred in a coastal plain environment and not in a fluvial delta setting, as suggested previously. Fine grained carbonaceous sediments were deposited on a broad low relief vegetated coastal plain, transitional into lagoon and tidal flat environments. The coastline was protected from waves and storms by barrier islands and on the foreshore the sand was winnowed by waves. The conglomeratic beds are mainly associated with marine facies and were deposited as gravelly lags in beach, foreshore, and shoreface settings. Overall the system was transgressive, which is consistent with the depositional environment (Figs 10 and 11).

The previous general interpretation was that the Todalen Member was formed in a fluvial dominated delta plain environment (Steel *et al.*, 1981; Steel *et al.*, 1985; Bruhn and Steel, 2003) and this was partially based on the assumption that the conglomeratic beds in the Firkanten Formation are related to the fluvial Grønfjorden Bed. However, the Grønfjorden Bed is described only from the western side of the basin (Kellogg, 1975; Nichols and Lüthje, Submitted) and in this study an important distinction has been made between the extrabasinal clast and mudrock clast conglomerates (Cgp and Cgm) and the depositional settings in which they formed. The Endalen Member has been interpreted by previous authors as a delta front succession (Steel *et al.*, 1981; Steel and Worsley, 1984; Bruhn and Steel, 2003) based on its stratigraphic position relative the Todalen Member, which was considered to be a delta plain succession. The key differences between the present and previous interpretations are summarised below (Table 1).

### **Flood plain vs. coastal plain**

Carbonaceous mudstone and coal of the Todalen Member (equivalent to facies Mk and K) have previously been interpreted as floodplain or interdistributary bay deposits (Steel *et al.*, 1981) on the basis of the fine grain size and the high organic content. Mudstone beds similar to facies Ms and Mk have been described as non-marine, flood basin and levee accumulations

(Nøttvedt, 1982) where the coal was deposited in areas of low clastic input. However, in floodplain settings input of clastic sediment usually inhibits peat accumulation and the extent of the mires is expected to be limited and irregular (McCabe, 1984). In contrast, observations of deposits of the Todalen Member indicate that the mires were extensive and received little clastic input. In the most recent study of the Todalen Member (Nagy, 2005) it is suggested that the mudstone of facies Mk and Ms were deposited in lakes, swamps and lagoons during rising sea level based on marine influence, high organic content and barren foraminifer. This is consistent with the conclusions of the present study.

#### **Tidally influenced lagoon vs. estuary or tidally influenced delta plain**

Heterolithic mudstone and sandstone similar to facies Sh have been interpreted as tidally influenced submarine levees or interdistributary bays of a delta with limited tide and wave influence (Steel *et al.*, 1981; Steel and Worsley, 1984). Beds equivalent to facies Mk and Ms have been described as tidal mud flat deposits (Nøttvedt, 1982) or lagoons (Nagy, 2005). The tidally influenced sections have also been considered to be estuary deposits (Nøttvedt, 1982), however, this is considered unlikely since we have found no evidence for valley incision or associated fluvial deposits.

#### **Barrier bars vs. crevasse splays**

The sandstone beds in the Firkanten Formation have previously been separated into two different settings; crevasse splays or fluvial channels on a delta plain in the Todalen Member and barrier bars/mouth bars of a delta front in the Endalen Member (Kellogg, 1975; Steel *et al.*, 1981). Poorly sorted sandstone with organic material (facies Sk and Sr) have been described as crevasse splay or fluvial levee deposits on a delta plain (Nøttvedt, 1982) but they can also be interpreted as parts of a lagoonal succession (Nagy, 2005). The well sorted sandstone sections with pebbly lamina (similar to FA3) were interpreted as fluvial channel fill in the Todalen Member, with the presence of *Ophiomorpha* indicating a marginal marine setting (Nøttvedt, 1982). In this present study and in Nagy (2005) these facies are considered to be the deposits of beach/barrier bars.

### **Foreshore vs. fluvial channel**

The delta interpretation was based on the close relationship to non-marine facies of FA1 and the presence of pebbles interpreted as channel lag (Nøttvedt, 1982). Conglomerate beds were interpreted as fluvial partly on the basis of comparison with the Grønfjorden Bed. However, the pebbly layers occur in many parts of the succession as part of tabular beds, and occur not only at the bases of the beds. These thin pebbly laminae were interpreted as crevasse splays or fluvial chute bars (Nøttvedt, 1982) but they have a similar appearance to gravelly foreshore/shoreface deposits described by (Hart and Plint, 1989; Hart and Plint, 1995; Hart and Plint, 2003). Furthermore, no distinction was made between conglomerate beds composed of extrabasinal clasts and beds of angular mudrock clasts (Steel *et al.*, 1981).

Channel geometries are rarely observed in the field, and where there are lenticular packages of beds they display wave ripple and low angle cross lamination, hummocky and swaley cross-stratification, or evidence of tidal influence. They are therefore considered to be deposits of an otherwise foreshore/shoreface setting (cf. Hart and Plint, 1989; Hart and Plint, 1995; Hart and Plint, 2003).

### **Shoreface vs. delta front**

Bioturbated sandstone with hummocky and swaley cross stratification similar to facies S1 and Sb of FA4 has been described from the Firkanten Formation and interpreted as shoreface or upper delta front (Nøttvedt, 1982; Bruhn and Steel, 2003; Nagy, 2005). The bioturbated sandstone was interpreted as lower delta front or prodelta/offshore transition based on the relation to the interpreted delta plain of the Todalen Member. However, intense bioturbation and glauconite are possible indications of low sedimentation rates and not commonly associated to delta front deposits.

## **CONCLUSIONS**

The new facies analysis provides a simple depositional model for the Firkanten Formation (Fig. 11).

- A transgressive wave dominated coastline for the entire Firkanten and Basilika Formations is suggested, rather than the previous models involving a fluvial delta system transitional to a wave dominated coast.

- The overall transgressive low relief coastal environment was dominated by wave influences in a microtidal regime.
- The coal and carbonaceous mudstone of the Todalen Member were deposited on the sheltered coastal plain in mires and swamps which gradually extended into lagoons and tidal flats.
- The fluvial input to this system is suggested to have been minor and only occurring in the western part of the basin (the Grønfjorden Bed).
- The paralic environment was protected by barrier bars from wave and storm influence and the sand dominated foreshore and beach at the seaward side of the bars show typical wave and storm influence.
- Gravelly material was mainly deposited as part of storm events that also brought material into the lagoons to form wash-over fans.
- The Endalen Member and the Basilika Formation show a progression from shoreface to offshore transition on a storm and wave dominated shelf.

#### ACKNOWLEDGMENTS

SNSK (Store Norske Spitsbergen Kulkompani) are thanked for providing access to their data records, core store facilities and the mines in Longyearbyen and Svea Nord. Charlotta Lüthje would also like to thank SNSK for providing funding for a PhD project carried out at UNIS, Royal Holloway University of London and at the University of Bergen. Rikke Bruhn is acknowledged for critical comments on an early version of the manuscript and M. Lüthje for careful reading of the manuscript.

#### REFERENCES

- Bergh, S.G., Braathen, A. and Andresen, A.** (1997) Interaction of basement-involved and thin-skinned tectonism in the Tertiary fold-thrust belt of central Spitsbergen, Svalbard. *AAPG Bull.*, **81**, 637-661.
- Bohacs, K. and Suter, J.** (1997) Sequence stratigraphic distribution of coaly rocks: Fundamental controls and paralic examples. *AAPG Bull.*, **81**, 1612-1639.
- Boyd, R., Dalrymple, R. and Zaitlin, B.A.** (1992) Classification of clastic coastal depositional environments. *Sed. Geol.*, **80**, 139-150.
- Braathen, A., Bergh, S.G. and Maher, H.D.** (1999) Application of a critical wedge taper model to the Tertiary transpressional fold-thrust belt on Spitsbergen, Svalbard. *Geol. Soc. Am. Bull.*, **111**, 1468-1485.

- Bruhn, R. and Steel, R.** (2003) High-resolution sequence stratigraphy of a clastic foredeep succession (Paleocene, Spitsbergen): An example of peripheral-bulge-controlled depositional architecture. *J. Sed. Res.*, **73**, 745-755.
- Carr, A.P.** (1971) Experiments on longshore transport and sorting of pebbles - Chesil Beach, England. *J. Sed. Pet.*, **41**: 1084-1104.
- Cepek, P.** (2001) Paleogene calcareous nanofossils from the Firkanten and Sarsbukta Formations on Spitsbergen. In: *Intra-continental fold belts; Case 1: West Spitsbergen, Geologisches Jahrbuch; Polar Issue No. 7* (Eds F. Tessensohn), pp. 535-547. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
- Cepek, P. and Krutzsch, W.** (2001) Conflicting Interpretations of Tertiary biostratigraphy of Spitsbergen and new palynological results. In: *Intra-continental fold belts; Case 1: West Spitsbergen, Geologisches Jahrbuch; Polar Issue No. 7* (Eds F. Tessensohn), pp. 551-599. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
- Cmiel, S.R. and Fabianska, M.J.** (2004) Geochemical and petrographic properties of some Spitsbergen coals and dispersed organic matter. *Int. J. Coal Geol.*, **57**: 77-97.
- Collinson, J.D.** (1996) Alluvial sediments. In: *Sedimentary Environments: Processes, Facies and Stratigraphy* (Ed. H.G. Reading) 3rd edn, pp. 232-280. Blackwell Science, Oxford.
- Dallmann, W.K.** (1999) *Lithostratigraphic lexicon of Svalbard*. Norsk Polarinstitut, 318 pp.
- Dalrymple, R.W.** (1992) Tidal depositional systems. In: *Facies Models: response to sea level change* (Eds R.G. Walker and N.P. James), p. 409. Geological Association of Canada, St Johns, Newfoundland.
- Ekdale, A.A., Bromley, R.G. and Pemberton, S.G.** (1984) Ichnology The use of trace fossils in sedimentology and stratigraphy. *SEPM Short Course Notes*. **15**, 317p.
- Golovneva, L.B.** (2000) Palaeogene climates of Spitsbergen. *GFF The Geological Society of Sweden*, **122**, 62-63.
- Greb, S.F., Eble, C.F., Hower, J.C. and Andrews, W.M.** (2002) Multiple-bench architecture and interpretations of original mire phases - Examples from the Middle Pennsylvanian of the Central Appalachian Basin, USA. *Int. J. Coal Geol.*, **49**, 147-175.
- Harland, W.B.** (1997) *The Geology of Svalbard*, Geol. Soc. London Mem., **17**, 521 pp.
- Hart, B.S. and Plint, A.G.** (1989) Gravelly shoreface deposits: a comparison of modern and ancient facies sequences. *Sedimentology*, **36**, 551-557.
- Hart, B.S. and Plint, A.G.** (1995) Gravelly shoreface and beachface deposits. In: *Clastic Facies Analysis - a Tribute to the Research and Teaching of Harold G. Reading* (Eds A.G. Plint), *IAS Spec. Publ.*, **22**, 75-99
- Hart, B.S. and Plint, A.G.** (2003) Stratigraphy and sedimentology of shoreface and fluvial conglomerates: insights from the Cardium Formation in NW Alberta and adjacent British Columbia. *Bull. Can. Petrol. Geol.*, **51**, 437-464.
- Huddle, J.W. and Patterson, S.H.** (1961) Origin of Pennsylvanian underclay and related seat rocks. *Geol. Soc. Am. Bull.*, **72**, 1643-1660.
- Jochmann, M.** (2004) *The geology of the Ispollen area, Svalbard, with emphasis on the coal bearing Firkanten Formation*, Diploma. Ludwig Maximilians Universität, München, 88 pp.
- Johnson, H.D. and Baldwin, C.T.** (1996) Shallow clastic seas. In: *Sedimentary Environments: Processes, Facies and Stratigraphy* (Ed. H.G. Reading) 3rd edn, pp. 232-280. Blackwell Science, Oxford.
- Kalgraff, K.L.** (1978) *Aspects of Sedimentation in Firkanten Formation, Tertiary, Svalbard*, Universitetet i Bergen, Bergen, 178 pp.

- Kellogg, H.E.** (1975) Tertiary stratigraphy and tectonism in Svalbard and continental drift. *AAPG Bull.*, **59**: 465-485.
- Kostro, F.** (2005) *Character of the basal unconformity of the Paleocene successions in the Central Basin, Svalbard*. Diploma, University of Freiberg, Freiberg, 106 pp.
- Leckie, D.A. and Walker, R.G.** (1982) Storm-dominated and tide-dominated shorelines in Cretaceous Moosebar-Lower Gates interval - outcrop equivalents of deep basin gas trap in Western Canada. *AAPG Bull.*, **66**, 138-157.
- Manum, S.B. and Thronsdén, T.** (1978). Rank of coal and dispersed organic matter and its geological bearing in the Spitsbergen Tertiary. *Norsk Polarinstitutt. Aarbok 1977*, 159-177.
- Manum, S.B. and Thronsdén, T.** (1986) Age of Tertiary formations on Spitsbergen. *Polar Res.*, **4**, 103-131.
- McCabe, P.J.** (1984) Depositional environments of coal and coal-bearing strata. In: *Sedimentology of coal and coal-bearing sequences*. (Eds R.A. Rahmani and R.M. Flores), *IAS Spec. Publ.*, **7**, 13-42.
- Nagy, J.** (1966) Preliminary report on the geology of Eastern Torell Land, Vestspitsbergen. *Norsk Polar institutt årsbok*, 1964, 69-72.
- Nagy, J.** (2005) Delta-influenced foraminiferal facies and sequence stratigraphy of Paleocene deposits in Spitsbergen. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **222**, 161-179.
- Nichols, G. and Lüthje, C.** (Submitted) Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. *Basin Research*.
- Nøttvedt, A.** (1982) *Characteristics and evolution of the Askeladden deltaic sequence (Paleocene) on Spitsbergen - with comparison to the Ravenscar Group deltaic sequence (Bajocian) of Northeast England*. Dr.Scient, University of Bergen, Bergen, 137 pp.
- Ohta, Y., Hjelle, A., Andresen, A., Dallmann, W. and Salvigsen, O.** (1992) Isfjorden, Svalbard 1:100 000. Temakart nr. 16. Norwegian Polar Institute.
- Pemberton, S.G. and MacEachern, J.A.** (1995) The sequence stratigraphic significance of trace fossils in examples from the Cretaceous of Alberta. In: *Sequence Stratigraphy of Foreland Basin Deposits - Outcrop and Subsurface Examples from the Cretaceous of North America* (Eds J.A. Van Wagoner and G.T. Bertram). *AAPG Mem.*, **64**, 429-475.
- Pemberton, S.G., MacEachern, J.A. and Frey, R.W.** (1992) Trace fossil facies models: Environmental and allostratigraphic significance. In: *Facies Models: response to sea level change* (Eds R.G. Walker and N.P. James), 47-72. Geological Association of Canada, St Johns, Newfoundland.
- Plint, A.G. and Norris, B.** (1991) Anatomy of a ramp margin sequence: facies successions, paleogeography, and sediment dispersal patterns in the Muskiki and Marshybank formations, Alberta Foreland Basin. *Bull. Can. Petrol. Geol.*, **39**, 18-42.
- Prothero, D.R. and Schwab, F.** (1996) *Sedimentary geology: an introduction to sedimentary rocks and stratigraphy*. W.H. Freeman and Company, New York, 575 pp.
- Reading, H.G. and Collinson, J.D.** (1996) Clastic coasts. In: *Sedimentary Environments: Processes, Facies and Stratigraphy* (Ed. H.G. Reading) 3rd edn, pp. 154-231. Blackwell Science, Oxford.
- Reineck, H.E. and Singh, I.B.** (1972) Genesis Of Laminated Sand And Graded Rhythmites In Strom-Sand Layers Of Shelf Mud. *Sedimentology*, **18**: 123-128.
- Reineck, H.E. and Wunderli, F.** (1968) Classification and origin of flaser and lenticular bedding. *Sedimentology*, **11**: 99-104.

- Reinson, G.E.** (1992) Transgressive barrier island and estuarine systems. In: *Facies Models: response to sea level change* (Eds R.G. Walker and N.P. James), 179-194. Geological Association of Canada, St Johns, Newfoundland.
- Retallack, G.J.** (2001) *Soils of the past: an introduction to paleopedology*. Blackwells, Oxford, 404 pp.
- Steel, R., Dalland, A., Kalgraff, K.L. and Larsen, V.** (1981) The central Tertiary basin of Spitsbergen - sedimentary development in a sheared margin basin. In: *Geology of the North Atlantic Borderlands* (Eds J.W. Kerr and A.J. Fergusson). *Can. Soc. Petrol. Geol. Mem.*, **7**, 647-664.
- Steel, R., Gjelberg, J., Helland-Hansen, W., Kleinspehn, K., Nøttvedt, A. and Rye-Larsen, M.** (1985) The Tertiary strike-slip basin and orogenic belt of Spitsbergen. *SEPM Spec. Publ.* **39**, 339-359.
- Steel, R. and Worsley, D.** (1984) Svalbard's post-Caledonian strata - an atlas of sedimentological patterns and palaeogeographic evolution. In: *Petroleum Geology of the North European margin*, (Eds Spencer, A.M. *et al.*) pp. 109-135. Graham & Trotman, London.
- Walker, R.G. and Plint, A.G.** (1992) Wave- and storm-dominated shallow marine systems. In: *Facies Models: response to sea level change* (Eds R.G. Walker and N.P. James), 219-238. Geological Association of Canada, St Johns, Newfoundland.
- Ward, C.R.** (1984). *Coal geology and coal technology*. Blackwell Scientific Publications, Oxford. 345 pp.
- Ytreland, G.K.** (1980) *Sedimentation along the Western margin of the Central Tertiary Basin, (Firkanten Formation), Spitsbergen*. Cand.Scient., University of Bergen, Bergen, 183 pp.

**5. ARTICLE 2 – TRANSGRESSIVE COASTAL PLAIN**

**Article 2**

**Transgressive coastal plain to shallow marine development  
of the Paleocene strata of Spitsbergen, Arctic**

**Charlotta Lüthje**

University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway.

**Gary Nichols**

Department of Earth Sciences, Royal Holloway University of London, Egham,  
Surrey, TW20 0EX, UK

Submitted to Journal of Sedimentary Research

Citation: Lüthje, C. and Nichols, G. *Submitted*. Transgressive coastal plain to shallow marine development of the Paleocene strata of Spitsbergen, Arctic Norway. J. of Sed. Res.



# TRANSGRESSIVE COASTAL PLAIN TO SHALLOW MARINE DEVELOPMENT OF THE PALEOCENE STRATA OF SPITSBERGEN, ARCTIC NORWAY

CHARLOTTA LÜTHJE<sup>1</sup> and GARY NICHOLS<sup>2</sup>

<sup>1</sup> University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway

E-mail: lott@lythje.com

<sup>2</sup> Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK

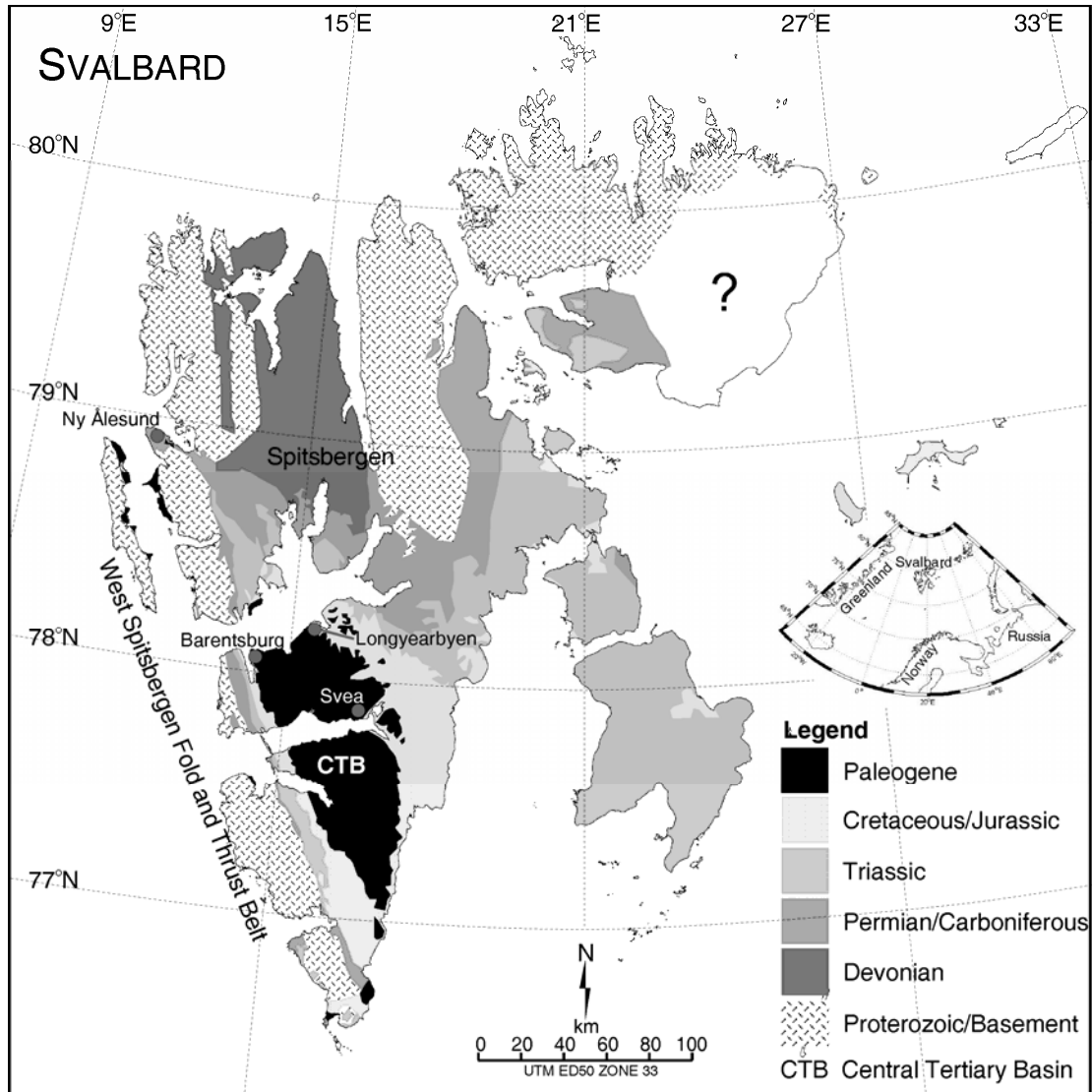
## ABSTRACT

The first detailed sequence stratigraphic analysis and paleogeographic reconstruction for the Paleocene Firkanten Formation of the Central Tertiary Basin in Spitsbergen, Arctic Norway is presented based on new core data. This succession is the lowest unit of the basin fill and shows an overall step-wise transgressive pattern of beds. It consists of parasequences bounded by minor flooding surfaces that are combined into parasequence sets bounded by major flooding surfaces. There is no evidence for relative sea-level falls within the succession and it is suggested that the tectonic subsidence exceeded rates of eustatic sea level fall. Aggradation is the dominant pattern in the strata building up thick successions of coastal plain deposits of coal and mudstone when sediment supply and organic production were in balance with tectonic subsidence and eustatic sea level change. During periods of increased relative sea level rise the coastal plain was flooded. The base of the Paleocene succession is marked by an unconformity with the Lower Cretaceous Carlinefjellet Formation, representing the lower sequence boundary. The basal transgression left a unit of poorly sorted sediment of re-deposited weathered regolith and vegetation on the unconformity surface. Paleogeographic reconstructions show a gradual back stepping coastline with a low-relief wave-induced coastal plain environment from marginal to shallow marine with only minor fluvial sediment input. The foreshore was characterised by sandy barrier bars of long shore transported fine grained sandstone. In the marginal marine setting tidally-influenced lagoons dominated and on the coastal plain peat was deposited in extensive raised mire complexes. Coal seams formed from these mires could be used as a basis for correlation using differences in the maceral content.

*Keywords: coastal plain, coal, transgression, Paleocene, Spitsbergen*

## INTRODUCTION TO THE PALEOGENE OF SVALBARD

The Paleogene strata on Spitsbergen, the main island of the Svalbard Archipelago are mainly found in the Central Tertiary Basin (Fig. 1). The basin comprises 1900 m of Paleogene clastic deposits (Dallmann 1999). The Todalen and Endalen Members of the Firkanten Formation are the lowest part of the succession and represent the initial phase of sedimentation in the basin (Fig. 2), resting on the Lower Cretaceous rocks of the Carolinefjellet Formation.

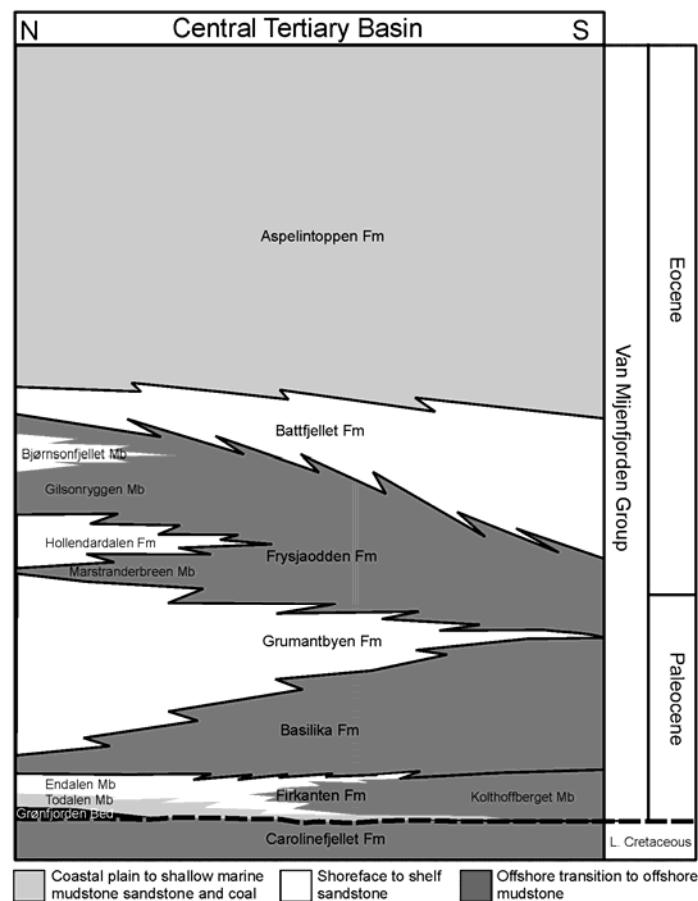


**Fig. 1** A simplified geological map of Svalbard, after (Dallmann 1999). The main Paleogene strata are found in the Central Tertiary basin that occupies the centre of the southern part of the main island, Spitsbergen.

Recent interpretations of the Central Tertiary Basin describe it as a flexural basin formed during the Cenozoic thrusting due to plate shortening between Greenland and Svalbard in connection to the opening of the North Atlantic (Bergh et al. 1997; Braathen et al. 1999;

Bruhn and Steel 2003; Nichols and Lüthje Submitted). The basin was constrained by a thrust front in the west and an uplifted area in the north (Fig. 1). In the east there are several old lineaments and fault zones that might have been reactivated during the compression and the formation of a suggested foreland bulge (Bruhn and Steel 2003). The most marine facies are found in the south.

The general lithostratigraphic interpretation of the Paleogene deposits (Fig. 2) shows an initial overall transgressive succession through the Firkanten and Basilika Formations from continental to marginal marine deposits through shoreface and offshore transition (Dallmann 1999). The Basilika Formation is overlain by the progradational Grumantbyen Formation. The regional maximum flooding of the basin took place in the marine shale of the Frysjaodden Formation, which is overlying the Grumantbyen Formation. The boundary between the Paleocene and Eocene is found approximately at this level (Steel et al. 1985,



**Fig. 2** The stratigraphy of the Paleogene Van Mijenfjorden Group in the Central Tertiary Basin of Spitsbergen. The focus of this study is on the lower part of the succession, the Todalen and Endalen Members of the Firkanten Formation, from (Lüthje and Nichols Submitted), based partly on (Steel et al. 1985; Bruhn and Steel 2003), geometries are based on relative thickness variations (Dallmann 1999) over the basin.

Manum and Throndsen 1986; Dallmann 1999). Small progradational units (the Hollendardalen Formation and the Bjørnsonfjellet Member) within the Frysjaodden Formation marine shale precede the large progradational section that makes the uppermost part of the succession (Dallmann 1999). This regression from the marine offshore Frysjaodden Formation through shoreface and marginal marine in the Battfjellet Formation, to continental deposits of the Aspelintoppen Formation covered the entire basin (Dallmann 1999). There are indications that a substantial amount of the succession above the Aspelintoppen Formation has been eroded during the later part of the Cenozoic (Manum and Throndsen 1978).

Previous interpretations of the Todalen Member of the Firkanten Formation have considered that the facies represent a deltaic setting (Steel et al. 1981; Steel et al. 1985; Dallmann 1999). Recent detailed investigation of the facies assemblages suggests the depositional environment may be more correctly interpreted as the deposits of a low relief coastal plain that was wave-dominated but with some tidal influence and only minor fluvial input (Fig. 3) (Lüthje and Nichols Submitted). Fossil plant material indicates that the climate in the Paleocene and Early Eocene was warm-temperate, with a high humidity equally distributed over the year (Golovneva 2000) even though plate reconstruction places Spitsbergen at 65-68° N at this time (Cepek and Krutzsch 2001).

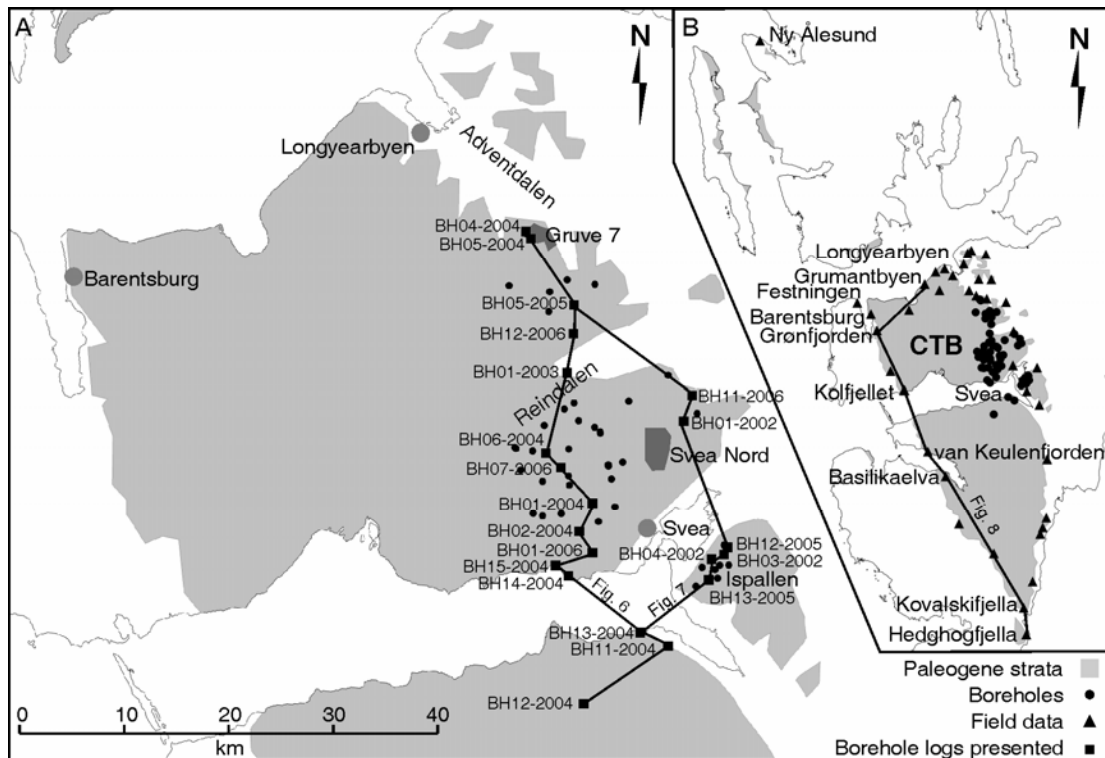
The Todalen Member coal seams have been informally named and correlated by the local Norwegian coal company (SNSK). Traditionally it is considered to contain five seams named from bottom to top the Svea, Todalen, Longyear, Svarteper, and Askeladden coal seams. These are found in the area from Svea (the lowermost two) to Longyearbyen (Todalen and Longyear) and to the north of Longyearbyen (the upper two). The Svea seam is mainly mined in Svea and the Longyear seam in Longyearbyen (Fig. 1). The Todalen seam is not very well developed and the upper two have high sulphur and ash content. A sequence stratigraphic approach to correlation was taken here for the purposes of gaining a better understanding of the development of the basin and prediction of the distribution of coal seams.

#### *Material and Study Area*

The sequence stratigraphic analysis presented here, as well as the facies analysis (Lüthje and Nichols Submitted), was primarily based on the new set of core data available from the Norwegian mining company SNSK, drilled since 2002 (and still ongoing) and additional field



The study area covers the entire Central Tertiary Basin with a more detailed local study in the area of good core coverage. This area in the northeast of the basin was also relatively easily accessed for additional field observations and shows some of the best exposures of the Firkanten Formation. Additional data from the western part of the basin were also collected. In the centre of the basin the Firkanten Formation is approximately 1000 m below current sea level (Dallmann et al. 1990) and is only known from the cores. For information on the facies assemblages of the southern part of the basin selected references were used (Nagy 1966; Kellogg 1975; Kalgraff 1978; Ytreland 1980; Dallmann 1999; Nagy 2005). The facies assemblages show remarkable little variation over the entire basin, which indicate a similar environment over the area.



**Fig. 4** Detail of Fig. 1 showing locations of the settlements, mines, boreholes, and field locations. (A) The concentration of boreholes is in the eastern part of the basin. Outlined are the cross sections in Figures 6-7 and 9. (B) The Paleogene strata remaining on Svalbard, from (Dallmann 1999). The map shows locations of field and core data used in the study. Field data is represented by both original field observations and reports by other authors. Outlined is the cross section in Figure 8.

## **FACIES MODEL**

The new interpretation of the facies suggests a wave-dominated coastline for the entire Firkanten and Basilika Formations (Lüthje and Nichols Submitted) in a transgressive setting. The facies scheme from (Lüthje and Nichols Submitted; Table 1) is adopted here (Fig. 3). The low relief coastal environment was dominated by waves in a microtidal regime. The coal and carbonaceous mudstone (Facies association FA1; Facies K coal and Mk carbonaceous mudstone) of the Todalen Member were deposited on the sheltered coastal plain in mires and swamps. Peat accumulated in extensive raised mires to form bituminous coal which has been mined at several places on Svalbard. The coastal plain gradually extended seawards into the wetlands of tidally influenced lagoons and tidal flats (Facies association FA2). Although it was a microtidal environment, large areas were influenced by the tides due to low relief across the area. The fluvial input to the basin was limited (Lüthje and Nichols Submitted). In the lagoons and on the tidal flats muddy siltstone (Facies Ms) and heterolithic sandstone (Facies Sh) were deposited (Fig. 3).

The paralic environment was protected from wave and storm action by barrier bars (Facies association FA3). The well sorted sandstone of the foreshore and beach deposits on the seaward side of the barrier bars/islands show intense wave and storm influence (Facies Sr rooted sandstone and Sws well sorted sandstone). Storms broke the barriers sometimes and brought coarse material into the lagoons as wash-over fans (Facies Sk organic-rich sandstone and Cgm/Cgp conglomerate). Some gravels and pebbles were deposited in current scours and as storm lags on the foreshore and upper shoreface (Facies Cgp and Cgm). The shoreface and offshore transition (Facies association and FA4) are storm dominated with hummocky cross stratification (Facies Sl) in the Endalen Member and the Basilika Formation. The lower shoreface (Facies Sb bioturbated sandstone) was muddy and intensively bioturbated (Lüthje and Nichols Submitted) (Fig. 3).

## **CRITERIA FOR CORRELATION**

The sequence stratigraphic model for the Firkanten Formation was developed from the facies model (Lüthje and Nichols Submitted) (Fig. 3), which provided the framework for the correlation. The coverage of boreholes in the area between Svea and Longyearbyen (Fig. 4) was sufficient for to make a detailed correlation of borehole logs. In addition field observations were used to determine the lateral continuity of different facies. The sequence stratigraphic model was first established for the local area and thereafter propagated to the

larger area of the basin where the data coverage and quality were much poorer (Fig. 4). A few general assumptions were made for the sequence stratigraphic analysis, presented here.

### *Basin Setting and Sediment Supply*

The Central Tertiary Basin is considered to have a flexural origin as a result of compressional folding (Nichols and Lüthje Submitted). Tectonic subsidence would have been an important factor controlling base level within the basin during the early stages of its development. The extensive coal deposits in parts of the basin and abundant glauconite in the shoreface deposits of the Firkanten Formation (Lüthje and Nichols Submitted) indicates low sediment accumulation rates (Amorosi 2003). The combination of low sediment supply and overall subsidence is reflected in the lithostratigraphy which shows development from continental marginal marine setting, through shoreface to offshore transition environments (Fig. 2). This retrogradational pattern through the Firkanten Formation indicates overall transgression towards the north during this stage of the basin development. The area to the north is believed to have been uplifted in late Cretaceous to early Palaeogene times and during this period a fold and thrust belt developed in the west (Nichols and Lüthje Submitted) (Fig. 1). To the east the area of deposition was limited by moderate uplift which has been suggested to be linked to a foreland bulge (Bruhn and Steel 2003) but there are also structural lineaments, the Billefjorden and Lomfjorden-Agardhbukta fault zones (Dallmann 1999) that could have been reactivated during the compression. A simple west-southwest to east-northeast directed coastline back-stepping to the north-northwest is proposed with a provenance of the sediments in the north and west (Nichols and Lüthje Submitted).

### *Correlation*

The unconformity with the Lower Cretaceous is characterised by local topography displaying up to 20 m vertical offset between boreholes located only a few hundred metres apart today. The unconformity could not be used as a reference datum as even relatively low relief would have had a significant impact on the distribution of marginal continental and shallow marine over a large area. Furthermore, the lateral variations indicated by the facies model mean that lithostratigraphic correlation would not provide a satisfactory picture of the relationship between individual sections. However, a sequence stratigraphic correlation was possible due to the excellent quality of the cores and the fact that marginal marine settings are sensitive to even minor relative sea level changes. There are no biostratigraphic or



palynological analyses of the sediments since dissolution of carbonate material and the remarkably intense quartz cementation of the sediment makes it extremely difficult to extract material for dating (Pers. comm.. M. E. Collinson 2006).

#### *Modern Analogues*

In addition to the depositional paleoenvironment model (Fig. 3) modern analogous environments were identified to provide an indication of the scale of the depositional system. Important factors for selecting suitable analogues were that they should show a similar depositional environment, low relief topography, transgressive wave-dominated micro- to mesotidal setting, a comparable sedimentary transportation pattern, a humid temperate climate and siliciclastic deposition with peat production. The two specific areas of interest identified were the Danish Wadden Sea and the French coast in Bay of Biscay. These modern environmental settings were used to provide a sense of scale in the spatial relationships of facies associations. When carrying out the correlation both maximum and minimum ranges of horizontal distances between different depositional elements were considered and related to the modern analogues. Ancient foreland basin deposits that have comparable depositional settings and development (Hart and Plint 1995; Ulicny 1999; Hart and Plint 2003) to the Firkanten Formation were also used as analogues in the interpretation.

#### *Coal as Marker Horizons*

The coal beds provided an additional basis for correlation using differences in maceral content and volatile matter. The maceral composition reflects the coal/peat composition and is therefore related to the depositional environment, tectonic setting, paleoflora, paleoclimate, and paleogeography (Bohacs and Suter 1997; Scott 2002; Moore and Shearer 2003) in addition to degradation, alteration, and diagenesis (Wüst et al. 2001). The inertinite and the volatile content of the coal were found to be influenced by increases in ash and sulphur content, which in turn depends on the depositional environment adjacent to the mire. The seaward side of coastal mires are expected to be marine influenced and therefore the sulphur content naturally may vary across a mire. The values for volatile content were recalculated on the coal fraction of single samples and only samples with low values of ash and sulphur were used in the correlation.

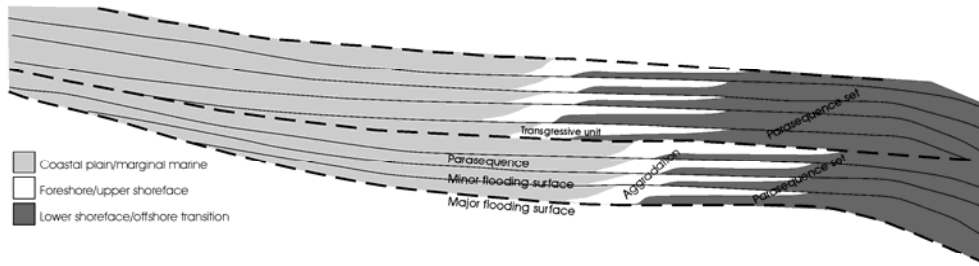
Relatively pure coal samples (< 5 % ash) in the lowest coal seam, the Svea seam, show a high inertinite content (> 10 %, mostly 30-50 %) and a low volatile content (< 30 %). The stratigraphically higher, Longyear seam typically contains a very high proportion of vitrinite (inertinite < 10 %) and a high volatile content (> 30 %, mostly ~40%). The liptinite fraction of the different coals is more or less constant and only the vitrinite/inertinite content varies. Between the Svea and Longyear seams the Todalen seam shows intermediate values of volatiles. The two uppermost coal seams, the Svarteper and Askeladden seams are only found in the area north of Adventdalen, and have high ash and sulphur contents. The older Svea seam and the younger Longyear seam could therefore be readily distinguished and the relationship between these seams is known because they occur vertically distributed in some single cores. Recent study combining the geochemical and maceral data from the Firkanten Formation coals has shown a possible separation of the seams (Orheim et al. 2007). The correlation of coal types was used in building the sequence stratigraphic correlation.

### **SEQUENCE STRATIGRAPHIC CORRELATION**

The Firkanten Formation represents an overall transgressive succession. There are no sequence boundaries within the succession since no relative sea level fall has been detected. The only sequence boundary is the basal unconformity with the Lower Cretaceous Carolinefjellet Formation. A modification of the “type-2” sequences by (Van Wagoner et al. 1990) was used as a sequence stratigraphic model (Fig. 5).

#### *Model*

A model was built for the sequence stratigraphic relationship of the facies (Fig. 5) based on the facies model (Fig. 3) and using both coal seam correlations and length scales from modern analogues, as set out in the previous section. Parasequences representing conformable, genetically related minor progradational successions are separated by minor marine flooding surfaces (Fig. 5). These are combined into larger parasequence sets with mainly aggradational stacking pattern, which are separated by major surfaces of marine flooding. In places a thin lower section in the parasequence set of transgression followed by the general aggradation can be identified. The individual parts of the interpretation are presented below and in the sequence stratigraphic correlations in Figures 6-9.

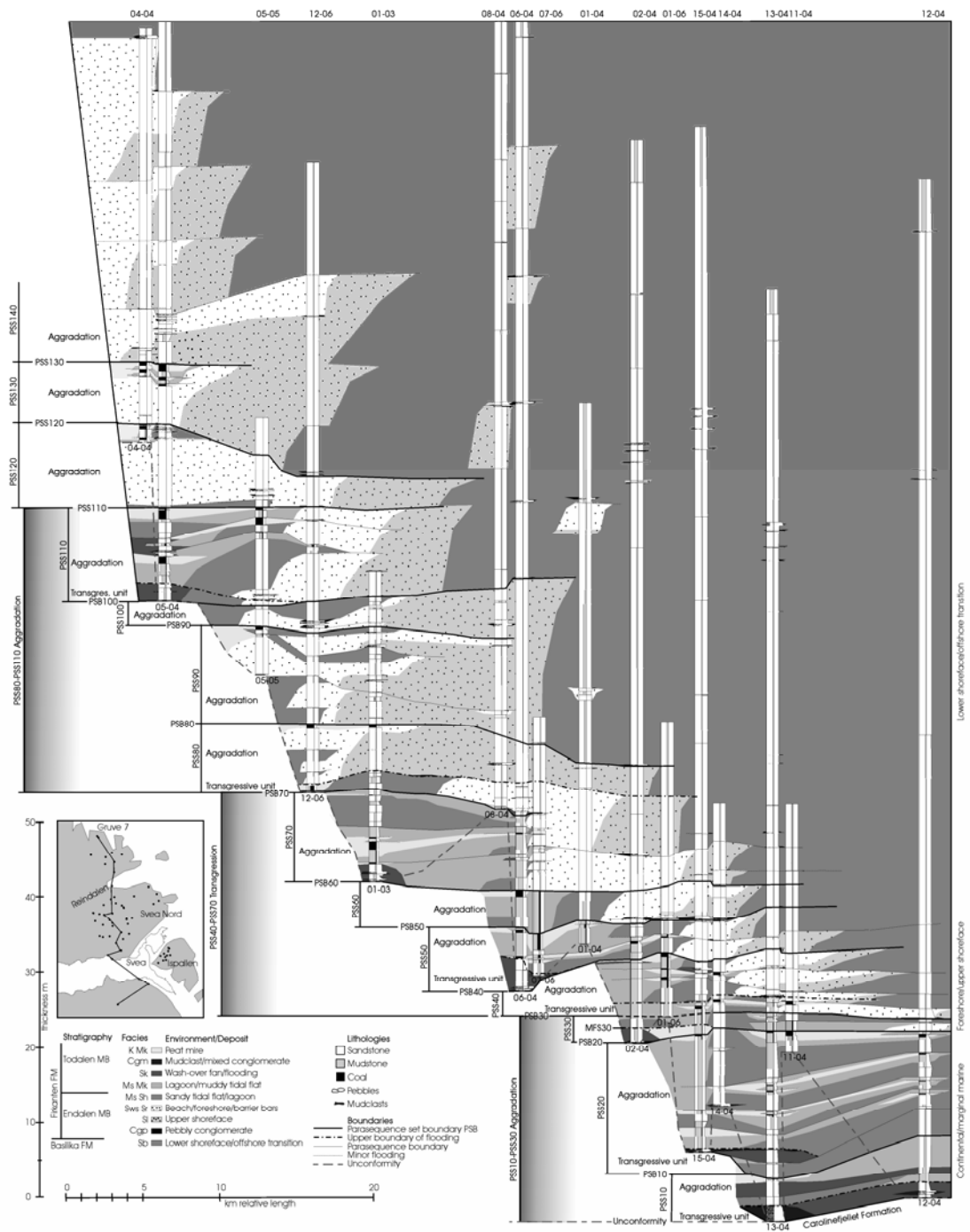


**Fig. 5** Conceptual diagram of the sequence stratigraphic model. The parasequences are minor prograding sections bounded by flooding surfaces. They build up parasequence sets bounded by major flooding surfaces. The parasequence sets sometimes have a transgressive lower unit and a dominant aggrading upper section.

#### *Parasequences – Minor Progradation*

The parasequences are defined as conformable groups of beds bounded by flooding surfaces and are characterised by minor progradation (Van Wagoner et al. 1990; Kamola and Van Wagoner 1995) (Figs 6-7 and 9). Facies of adjacent depositional environment succeed each other in vertical sections when there are no unconformities (Middleton 1973) and therefore the facies model shows the expected successions (Fig. 3). The lower part of the Firkanten Formation, the Todalen Member, comprises continental and marginal marine parasequences deposited in a tidally influenced semi-enclosed lagoon (Fig. 3). The prograding successions in this environment show transition from back barrier shallow marine tidal flat heterolithic muddy sandstone (Facies Sh) through tidal mudflat mudstone and siltstone (Facies Mk and Ms) to marginal marine swamp of carbonaceous mudstone (Facies Mk) overlain by continental peat accumulations (Facies K coal) (Fig. 9A).

The coastal margin (Fig. 3), shows progradation from well sorted sandstone of the barriers and foreshore (Facies Sr vegetated sandstone, Sws well sorted sandstone of the beach and foreshore, and sometimes also Sk wash-over fan organic-rich sandstone) to heterolithic tidal and lagoon deposits (Facies Sh and Ms) and carbonaceous mudstone and coal (Facies K and Mk) (Fig. 9). These parasequences represent the progradation from the seaward side of the barrier bars/foreshore through the wash-over fans, tidal inlets and deltas, to the continental inner side of the lagoon and the marginal marine swamp and mire complexes (Fig. 3). The beach barrier sandstones show root structure and weathering horizons (Facies Sr rooted sandstone) when directly overlain by coal.



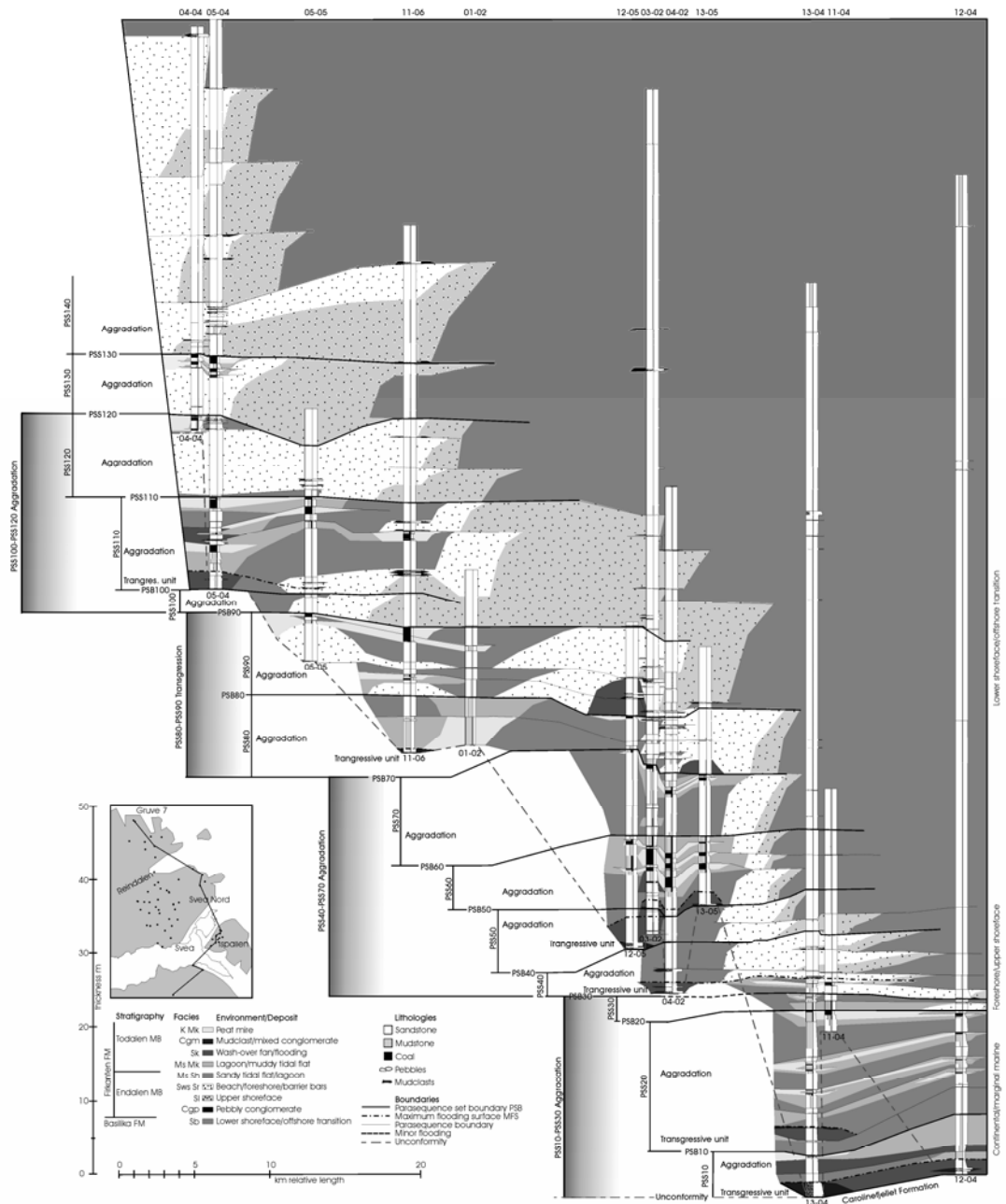
**Fig. 6** Correlation panel of the eastern side of basin from south of Svea to Reindalen to Longyearbyen.

The upper part of the Firkanten Formation, the Endalen Member, represents deeper marine conditions and parasequences show transitions from bioturbated sandstone (Facies Sb), to laminated sandstone (Facies Sl), and well sorted sandstone (Facies Sk organic rich sandstone, Sr rooted sandstone, and Sws well sorted sandstone) representing the transition from the

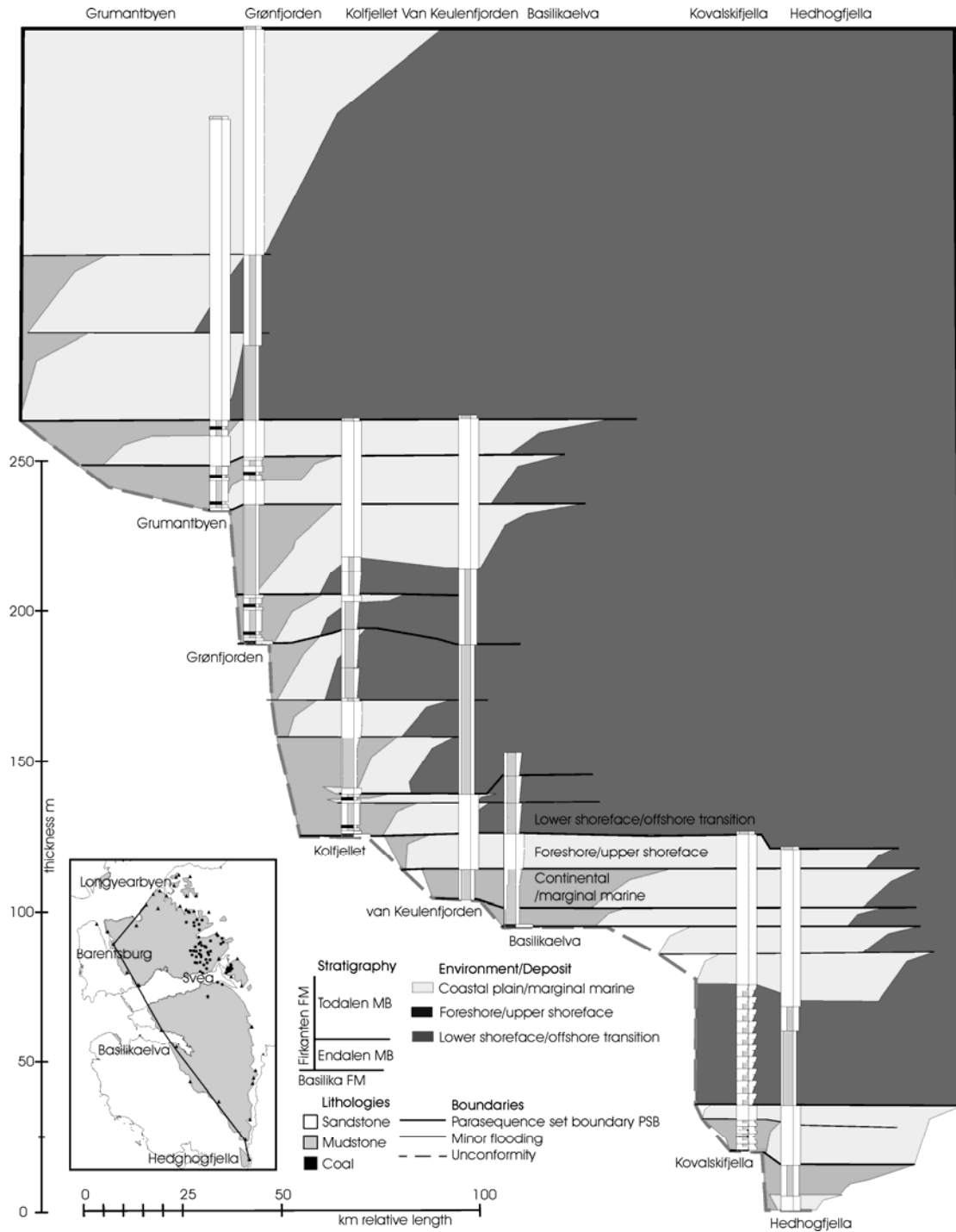
muddy bioturbated lower shoreface, to the storm-dominated hummocky cross stratified shoreface and the wave dominated foreshore respectively (Figs 3, 6-7 and 9B).

*Parasequence Boundaries – Minor Flooding Surfaces*

The parasequences are bounded by minor flooding surfaces characterised by small changes in depositional environment (Fig. 3). It was possible to correlate the flooding surfaces over more



**Fig. 7** Correlation panel of the eastern side of basin from south of Svea to Ispallen to Longyearbyen.



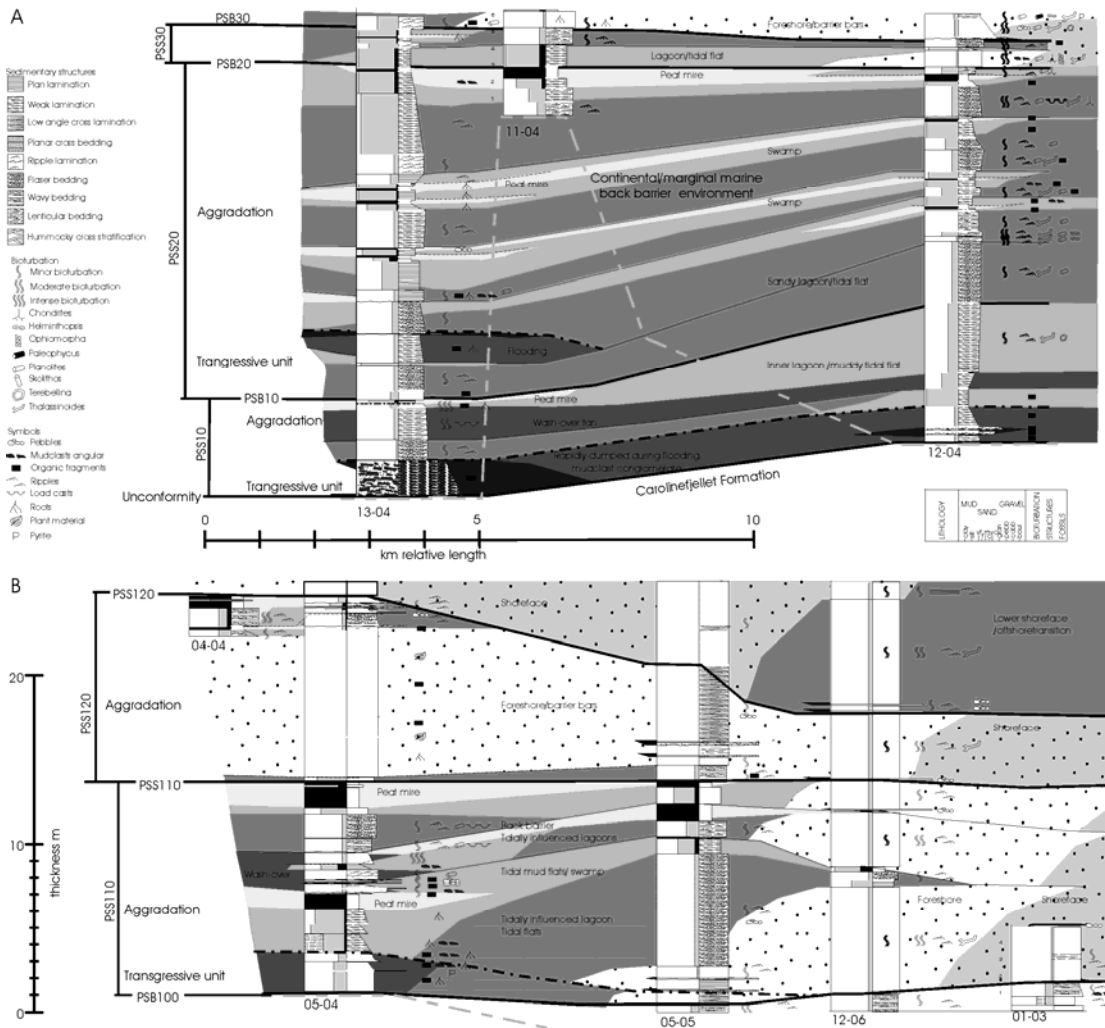
**Fig. 8** Correlation panel of the western side of the basin from Hedghogfjella to Grønfjorden and across the basin to Carolinefjellet. The logs are re-interpreted into the new facies association scheme (Fig. 3). Hedghogfjella, van Keulenfjorden, Grønfjorden, and Grumantbyen after (Kellogg 1975), Kovalskifjella after (Nagy 1966), Basillikaelva after (Nagy 2005), and Kolfjellet after (Kellogg 1975; Nagy 2005).

than 20 km from the continental to the shallow marine environment (Fig. 6). During aggradation the coastline oscillated slightly by repeated progradation and flooding. The minor flooding surfaces do not seem to have been able to propagate very far and only areas already

flooded previously were affected. The most continental parts show facies transitions over the flooding surface from carbonaceous mudstone or coal (Facies association FA1 vegetated subaerial to marginal marine) to heterolithic muddy sandstone or mudstone of tidal flats or lagoons (Facies association FA2 back barrier tidally influenced lagoon) (Figs 6 and 9A). The coal is often interrupted by beds of carbonaceous mudstone or heterolithic mudstone indicating smaller fluctuations that could be due to lateral variations. However, when correlated over larger areas they represent minor relative sea level fluctuations (Figs 6-7).

The marginal marine setting is characterised by parasequence boundaries that show very distinct changes from back-barrier poorly sorted fine grained material with high organic content (Facies association FA2) (Fig. 3) to the well sorted marine sandstone of the foreshore and even upper shoreface (Facies association FA3 barrier bars) (Figs 6 and 9B). The wash-over fan deposits (Facies Sk organic-rich sandstone) with mudclasts (Facies Cgm mudclast conglomerate) are sometimes preserved and represent the flooding events. In the marine sections of the Endalen Member and the Basilika Formation the parasequence boundaries are distinct, displaying changes from the well sorted foreshore (Facies association FA3) to the bioturbated lower shoreface (Facies association FA4 shoreface and offshore transition) (Fig. 6). At the boundaries there are in places thin conglomeratic beds of mostly rounded pebbles deposited during the flooding (Facies Cgp pebbly conglomerate).

As stated above, coastal marginal marine settings such as the Firkanten Formation are especially sensitive to relative sea level changes and will show significant environmental shifts even with small changes. That large areas were affected by even minor changes reflects a gentle low angle relief. The environmental changes over the minor flooding surfaces found in the Firkanten Formation probably only represent small vertical changes of the relative sea level. The facies changes in the marginal marine setting indicate a relative sea level fluctuation of only a couple of metres. Even these small relative sea level fluctuations were detected in the marine setting indicating that the near coastal marine deposits were characterised by a narrow zone of fine grained well sorted sand deposition. Seawards, but still close to the shore, the sediments quickly became muddy. Local variations in bioturbation intensity and grain size occur without reflecting any sea level change.



**Fig. 9** Details of log correlation from the cross section in Figure 6. For legend see Figure 6. (A) Coastal marginal marine setting of a thick aggrading succession with coal typical for the lower part of the Todalen Member in the Svea area. (B) Detailed section showing parasequence progradation and the boundary flooding surfaces in a marginal marine setting of lagoon overlain by peat. The parasequences are stacked in an aggrading pattern. The parasequence set boundary is a major flooding surface with an environmental shift from lagoon to foreshore/shoreface.

*Parasequence Sets – Aggradation and Retrogradation*

Throughout the Firkanten Formation the parasequences are arranged into parasequence sets that show mainly aggradational patterns (Fig. 6). The parasequence sets are bounded by major flooding surfaces and consists of a dominant aggradational succession and occasionally a lower transgressive unit that is thin or mostly absent (Fig. 5). However, it was during the transgression or major flooding event the major changes in the depositional environment took



place (Figs 6-7). The repeated transgressions resulted in a general back-stepping of the coastline moving towards the northwest following the outline of the basin as it deepened and larger areas were flooded (Fig. 6). The thin transgressive units were deposited during the major flooding events when the relative sea level rise was increased. The transgressive record is mainly preserved in the continental part as wash-over fans or deposition of previously weathered material, rip-up clasts, and vegetation (Facies Sk organic-rich muddy sandstone and Cgm mudclasts conglomerate). There are a few more laterally consistent intervals of complete successions from continental to marine, representing a transgressive period when the environment had time to adapt to the changes (Fig. 6; PSS40 and PSS80).

The aggradational system is characterised by parasequences stacked directly on top of each other resulting from sediment packages building up during still-stand of the coastline. Therefore continental (FA1), marginal marine (FA2) (Fig. 6; PSS20), shallow marine (FA3), and marine successions (FA4) (Fig. 6; PSS70) respectively are found in continuous vertical sections (Fig. 9). Due to accommodation space being created in marginal marine and even continental areas during these periods, fine grained backshore deposits are preserved. Extensive, thick coal packages, as found in the mine Svea Nord, represent aggrading successions when organic production kept pace with the base level rise and peat accumulated.

The overall general transgression of the Firkanten Formation indicates a rising relative sea level during this early phase of the basin formation. The thick packages of aggradational deposits indicate that the relative sea level change (related to tectonic subsidence and eustasy) and sedimentation were in pace at most times. Transgression took place in steps (Figs 6-7) represented by periods when subsidence and eustatic sea level rise combined to exceed the sediment flux. This represents the transgressive systems tract of the general sequence stratigraphic concept (Catuneanu 2002). The aggrading successions can be considered to represent periods of still-stand and even minor eustatic sea level fall, which in combination with the tectonic subsidence would give a less pronounced base level rise.

The coastline retrogression followed the tectonically-controlled basin geometry and structural margins of the basin in a north-northwest direction (Fig. 1). This means that the deposits to the north are younger than in the south (Steel et al. 1985) confirmed by the coal seam correlation and the log correlation. Since the Paleogene strata are almost completely eroded north of Isfjorden it is not possible to determine the patterns north of Adventdalen (Fig. 4). However, it would be reasonable to assume that the transgression continued further north, possibly even as far as Ny Ålesund, were there are coal-bearing strata similar to

Firkanten Formation of Paleocene age (Fig. 1) that might be related to the Central Tertiary Basin.

The section between south of Svea and north of Longyearbyen reveals 14 parasequence sets consisting of 2 to 5 parasequences each (Fig. 6). It is not possible to determine the number of parasequence sets making up the entire Firkanten Formation since the data from the southern area are too poor (Fig. 4). However, if it is assumed that both the facies and the stacking pattern did not vary much, the thickness of the Firkanten Formation strata present in the whole Central Tertiary Basin can be estimated to have originally comprised 35 to 40 parasequence sets and about 150 – 200 parasequences (Figs 6-8). The sequence stratigraphic correlation also reveals a larger pattern in which parasequence sets can further be grouped into three larger units (Fig. 6). Parasequence set PSS10 to PSS30 represent a major aggrading section, PSS40 to PSS70 show a general transgressive trend while PSS80 to PSS110 is aggrading. In the upper part (PSS120-140) only the marine deposits are represented and the trend is unclear. The pattern is different in the eastern correlation (Fig. 7) probably due to the raised mire complexes that acted as natural barriers for the marine transgression, and thereby delaying it.

#### *Parasequence Set Boundaries – Major Flooding Surfaces*

The parasequence set boundaries are flooding surfaces showing more distinct facies offset and considerable coastline retrogradation (Figs 5-7). These surfaces often involve marine flooding of previously non-depositional areas and are marked by a facies change from continental or marginal marine setting of mire/swamp and back barrier tidal influenced lagoon (FA1; Facies K coal, Mk carbonaceous mudstone and FA2; Ms muddy siltstone, Sh heterolithic sandstone) to shallow marine barrier island/foreshore and marine shoreface setting (FA3; Sr rooted sandstone Sws well sorted marine sandstone, FA4; Sl laminated sandstone Sb bioturbated sandstone) (Figs 6 and 9B). This indicates a repositioning of the coastline laterally of about 10-15 km or more even if the water depth changed only a few metres.

These boundaries are often associated with pebbly conglomerate (Facies Cgp) made up of rounded, sorted pebbles that most probably represent storm deposits (Lüthje and Nichols Submitted). Since the conglomerate are associated to the marine flooding they could represent transgressive lags deposited by storms on the marine erosion surface (ravinement), which was

created by wave action during transgression (Siggerud and Steel 1999; Catuneanu 2002) (Fig. 6).

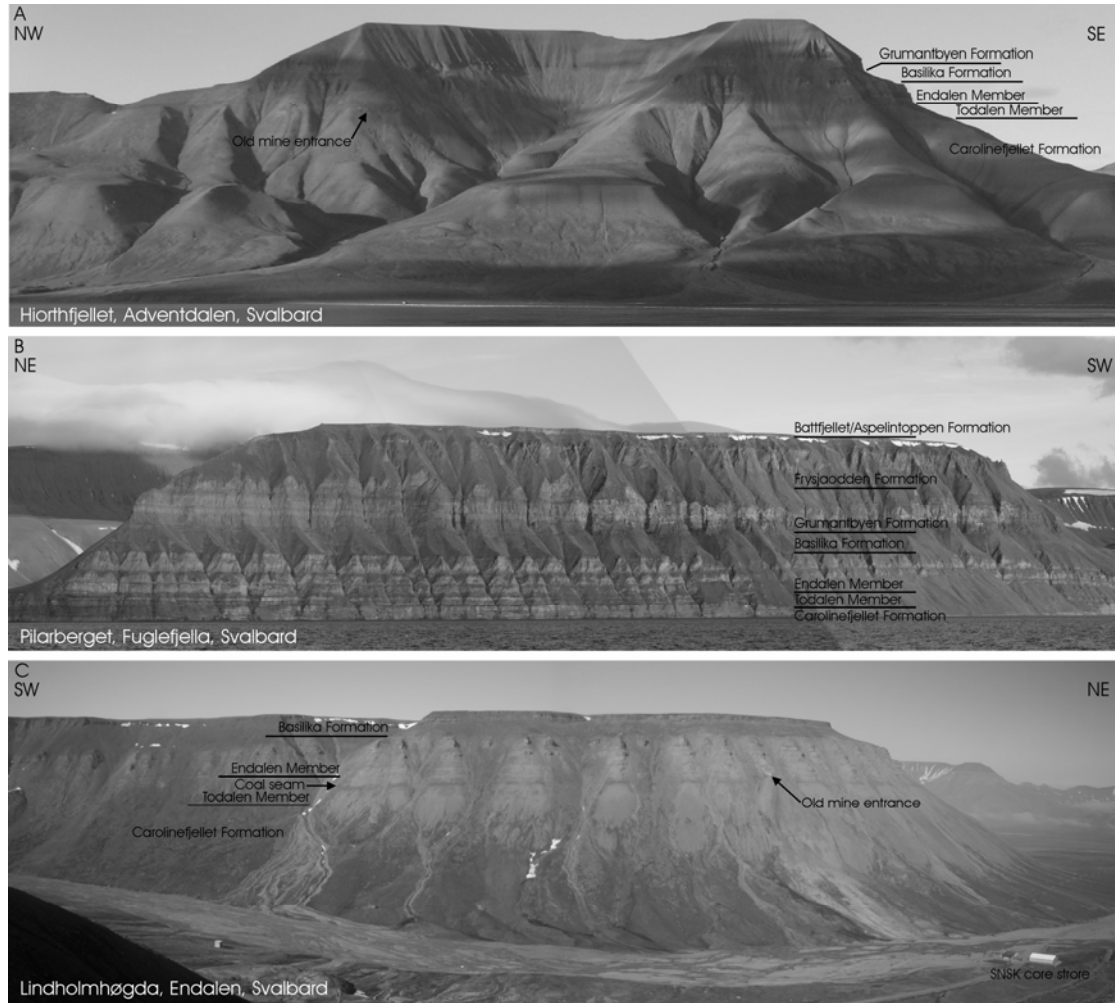
#### *Erosion Surfaces in the Firkanten Formation*

The sequence stratigraphic correlation reveals an overall general transgressive succession throughout the Firkanten and the Basilika Formations, without any clear regressive successions, which is consistent with the depositional model of a transgressive coastline (Figs. 3 and 5-8). There is no evidence for relative sea level fall or related erosion. Outcrops reveal a remarkable flat relief on bed surfaces in all directions with only a few tens of centimetres of undulation (Fig. 10). The few erosive indications present are related to major flooding surfaces and are interpreted as ravinement surfaces.

#### *The Basal Cenozoic Unconformity*

The hiatus at the base of Cenozoic represents a time gap of about 35 Ma. This unconformity with the Carolinefjellet Formation of Albian/Aptian age (Dallmann 1999) is not very prominent and sometimes hard to identify, even though it represents a long time period. The relief of this surface is minor and has been described from outcrop to be only tens of centimetres (Nagy 2005; Nichols and Lüthje Submitted) from the western part of the basin. The sequence stratigraphic correlation of cores reveals a higher relief but still gentle of up to 20 m. However, this relief has been shown to be a localised topography (Jochmann 2004) and lateral correlation was made into a three dimensional grid shown in the correlation panels (Figs 6-7).

During transgression over this relief local highs were left as areas of non-deposition, marked in the correlation panels (Fig. 6) and the topography was subsequently filled in by continental and marginal marine facies. At the basal unconformity there are mudclast conglomerate beds (10 cm – 2 m thick, Facies Cgm) associated with the more pronounced flooding surfaces, which also show poorly sorted sandstone with organic material (Facies Sk), occasionally bioturbated or containing paleosols. The mudclasts are most likely eroded Mesozoic strata but could also contain re-deposited Paleogene beds that were reworked during the flooding. These deposits are the result of erosion and re-deposition of weathered material during flooding of the unconformity (Fig. 9A).



**Fig. 10** Sections showing the general horizontally flat stratigraphy of the Firkanten Formation. (A) Hiorthfjellet north of Adventdalen, the section is 2.5 km wide. (B) Fuglefjella between Bjørndalen and Grumantbyen, 3 km. (C) Lindholmhøgda in Endalen east of Longyearbyen, 2.5 km.

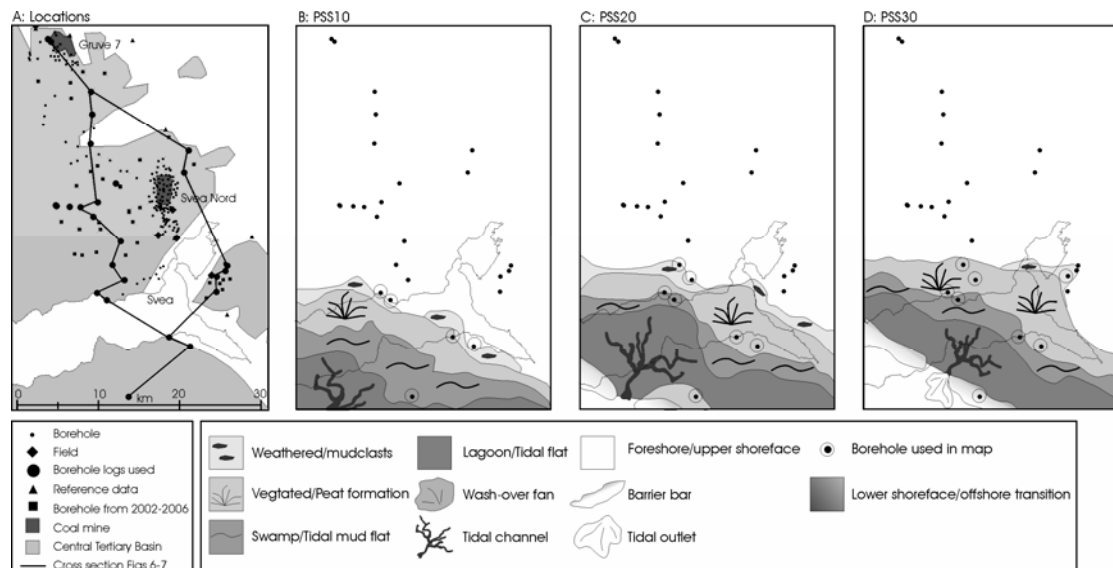
### PALEOGEOGRAPHIC RECONSTRUCTIONS

The paleogeographic maps were constructed from the sequence stratigraphic correlation panels (Fig. 6-8) using information from the depositional model and facies associations (Fig. 3) as well as the modern analogues. The good coverage of cores made it possible to construct detailed maps for the local area between Longyearbyen and Svea presented in Figures 11-13. These relate to the correlation panel in Figures 6 and 7. Figure 14 shows a regional interpretation of the entire basin related to correlations in Figures 6-8. All the cores used in the correlation penetrate the unconformity to Carolinefjellet Formation. In cross section the local topography stands out clearly (Fig. 6-7) and on the paleogeographic reconstruction the highs are represented as areas of non-deposition. These highs shed eroded material to areas nearby, which are often characterised by mudclast conglomerate beds.

*Parasequence Sets PSS10-PSS30 – Aggradation*

Parasequence sets PSS10 to PSS30 represent the initial flooding of the area south of Svea and the succession is in general aggrading. A vegetated coastal plain (FA1) with a tidal influenced lagoon (FA2) was established, protected by sandy barrier bars (FA3). The shoreface (FA3) lay south of the study area.

**PSS10** --- The lower most parasequence (PSS10) represents the initiation of deposition near Svea. The environment was marginal marine with only minor coal deposits, correlated to foreshore and shoreface deposits of the Endalen Member further south as indicated in Figure 11B. The initial flooding left a thick transgressive unit of weathered material (Facies Sk organic-rich sandstone and Cgm mudclasts conglomerate) on top of the unconformity (Fig. 6).



**Fig. 11** Detailed paleogeographic reconstruction from the lower parasequences PSS10 to PSS30 from Figures 6-7 (A) Location of boreholes, settlements, and mines. Outlined are the cross sections in Figures 6-7. (B) PSS10. (C) PSS20. (D) PSS30. For description see text.

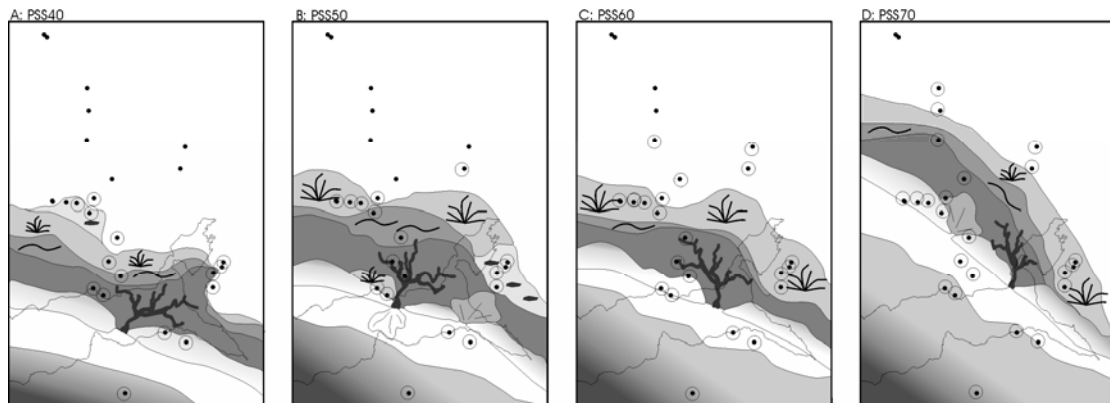
**PSS20** --- The parasequence set PSS20 is thick and consists of mainly aggradational marginal marine or back barrier sediments in the area south of Svea (Fig. 11C). Once again the transgression left a thin layer of mudclast conglomerate and poorly sorted sandstone at the base (Fig. 6). The coastline retrograded somewhat towards the northeast but the main foreshore and shoreface sandstone deposits were still to be found further south.

**PSS30** --- In parasequence set PSS30 the foreshore and beach retrograded 8 km southwest of the area whereas the lagoon and tidal flat area of the back barrier mainly remained in place. The marginal marine area expanded inland (Fig. 11D). The PSS30 is thin with a limited amount of coal deposition.

#### *Parasequence Sets PSS40-PSS70 – Retrograding*

Parasequence sets PSS40 to PSS70 show a general retrogradational trend although there are thick aggradational sections. This period shows the largest lateral environmental changes in this part of the basin.

**PSS40** --- Parasequence set PSS40 is a thick unit with a lower transgressive unit preserved, overlain by an upper aggradational section. The underlying parasequence set PSS30 is thin and indistinct and could be considered as part of a retrograding succession from PSB20 (Fig. 6). However, the position of the coastline in PSS30 was more similar to PSS20 and there is clear major flooding on top the PSB30 (Fig. 12A). PSS40 is characterised by a large environmental shift from the underlying PSS10-PSS30, the coastline moved 9 km and tidally influenced back barrier lagoon started to become established in the Ispallen area. This area also shows distinct local topography with no sedimentation on the highs (Fig. 7) and thick mudclasts conglomerate (Facies Cgm) deposited nearby indicating erosion of the Carlinefjellet Formation from the highs. The area west and northwest of Svea was characterised by muddy lagoon and tidal flat facies with swamps in the proximal part. The flooding extended further north and sedimentation was initiated with deposition of reworked weathered material and vegetation.



**Fig. 12** Detailed paleogeographic reconstruction from the parasequences PSS40 to PSS70 from Figures 6-7. For legend and locations see Figure 11. (A) PSS40. (B) PSS50. (C) PSS60. (D) PSS70. For description see text.

**PSS50** --- During the period of parasequence set PSS50 the coastline moved marginally but the area of sedimentation expanded (> 6 km) including the entire Ispallen area (Fig.12B). As in PSS40 a lot of eroded material was deposited, probably generated from the Carolinefjellet Formation. It is during this parasequence set that the thick coal deposits of Svea Nord mine started to accumulate representing the Svea coal seam. In the Ispallen area the mire complex had not yet been established. The area northwest of Svea was influenced by local topography.

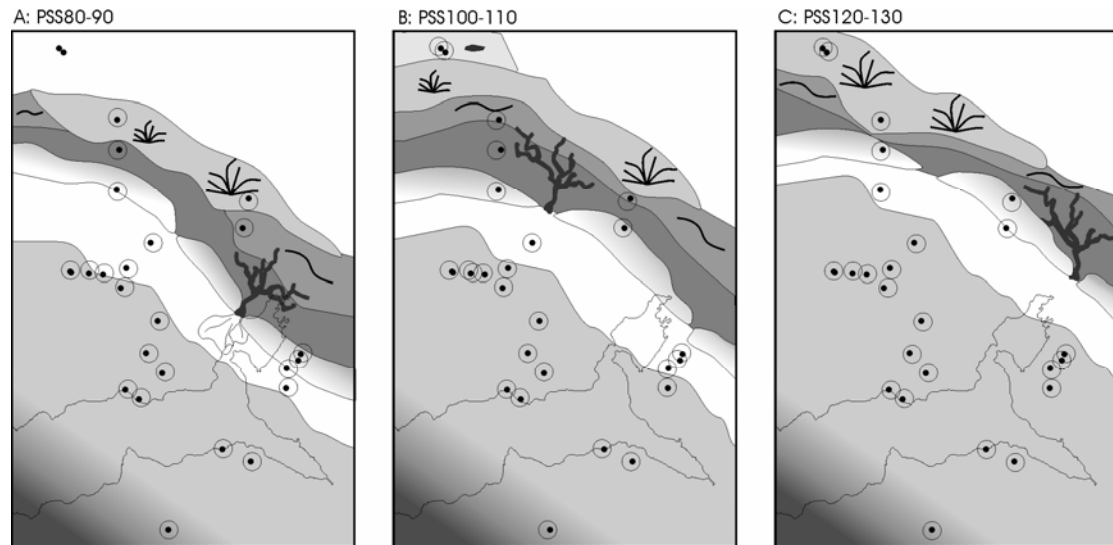
**PSS60** --- In parasequence set PSS60 the Ispallen area became established as a prominent peat mire complex where the thick coal deposits found today accumulated (Fig. 12C). South of Ispallen the foreshore and shoreface only shifted minor distances whereas the area west of Svea was influenced by the marine transgression moving the coastline several kilometres (Figs 6-7). This apparent rotation of the coastline continued through PSS60 and PSS70 and could be speculated to have been caused by increased effect of the structural control on the eastern margin (such as a foreland bulge). However, it could also have been caused by the raised mire complex in Ispallen acting as a natural barrier for flooding, which would have controlled coastline retrogradation. Thick peat sections in raised mires are known to have acted as temporary natural barriers for marine flooding generating stacked facies associations (McCabe and Shanley 1992; Kamola and Van Wagoner 1995). This could partly explain the unusually thick succession of coal and carbonaceous mudstone in the Ispallen area and perhaps also the Svea Nord mine. However, the most important factor for peat accumulation is the balance between organic production and base level rise.

**PSS70** --- The coastline rotated even further in PSS70 with transgression of areas north of Svea in the Reindalen area (Fig 12D). The eastern part in Ispallen was still characterised by raised mires as well as the area of the Svea Nord mine. The thick aggradational section of foreshore and shoreface strata (Fig. 6) is also an indication of the stagnation of the flooding that might have been related to the raised mires.

#### *Parasequence Sets PSS80-PSS110 – Aggrading*

Parasequences PSS80 to PSS110 are characterised in cross section by smaller lateral environmental changes in a general aggrading trend. The shoreface is wider and more prominent than in previous sections. The coastal plain was less developed and the coal deposits are thin.

**PSS80-PSS90** --- Parasequence set PSS80 consist of a transgressive unit followed by aggradation. The coastline moved a distance of around 7 km and a large area was flooded towards Longyearbyen (Fig. 13A). Ispallen show transgression throughout PSS80-PSS90 reflected in the irregular development (Figs 6-7). Both the mire areas the Svea Nord and in Ispallen were flooded, ending the coal accumulation there. The coastline retrograded over the mire and established a foreshore and barrier bar system on top (Fig. 13A). The area with previous foreshore deposits developed into wave dominated shoreface and muddy bioturbated lower shoreface.



**Fig. 13** Detailed paleogeographic reconstruction from the parasequences PSS40 to PSS70 from Figures 6-7. For legend and locations see Figure 11. (A) PSS80-90. (B) PSS100-110. (C) PSS120-130. For description see text.

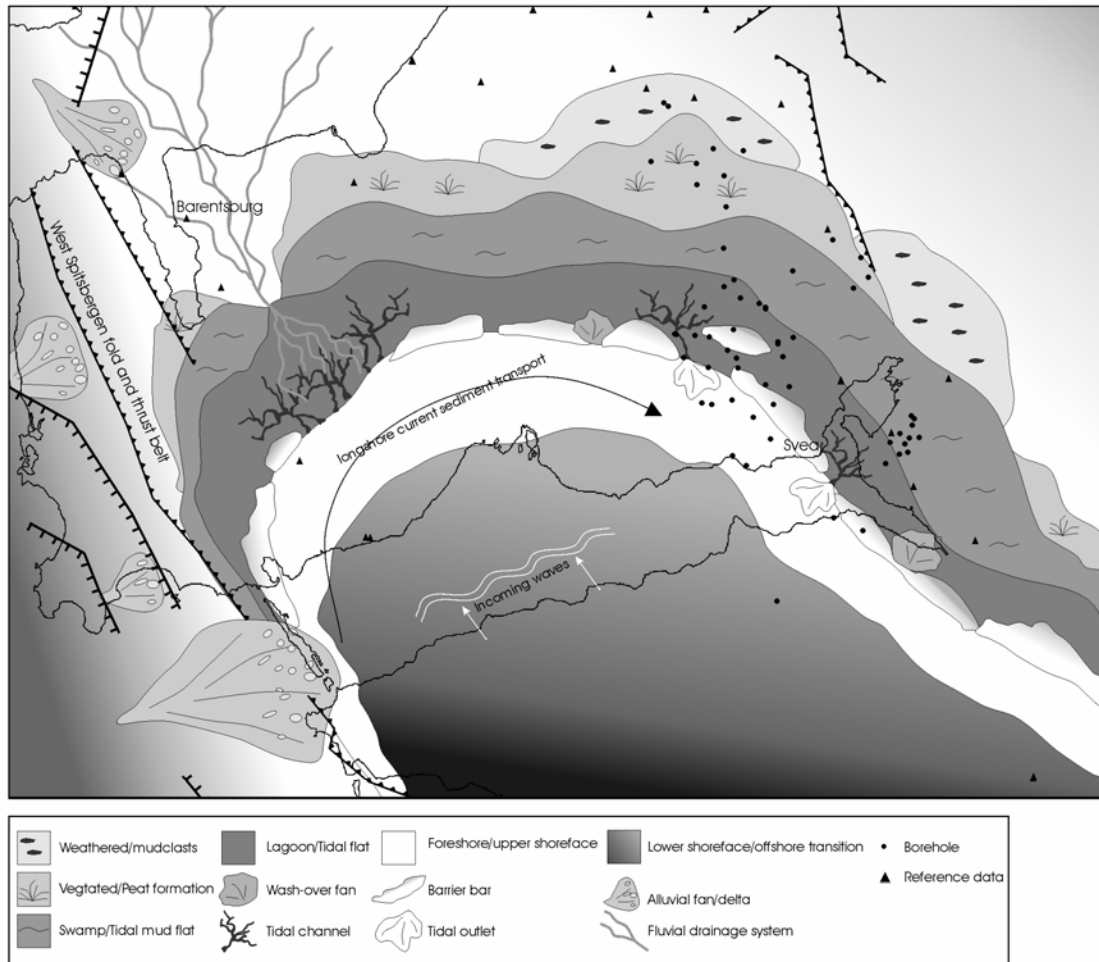
**PSS100-PSS110** --- The following two parasequence sets have similar characteristics. During PSS100 the position of the coastline was unstable and fluctuated considerably up to 5 km but without any significant transgression taking place, similar to PSS90 (Figs 6-7 and 13B-C). The foreshore was marked by deposition of pebbly conglomerate. The Ispallen and Svea Nord areas were characterised by shoreface facies while in the Gruve 7 area in Longyearbyen a back barrier tidally influenced lagoon was established. The main deposition of the Longyear coal seam began in PSS110.

#### *Parasequence Sets PSS120 and above*

Parasequence sets PSS120 and PSS130 are very similar and show a much narrower lagoon and tidal flat section (Fig. 13D). This is different from the lower sections where the tidal lagoon back barrier system was characteristically wide. The mire appears to have developed



close to the barrier bar and this could indicate that the mire once again acted as a barrier for the transgression and causing aggradational stacking of the shoreline (Figs 6-7). Observations from north of Adventdalen (Fig. 4) of tidally influenced lagoonal deposits, indicate a later re-establishment of a wide coastal plain (Wilhelmsson 1999) where the Svarteper and Askeladden coal seams were deposited.

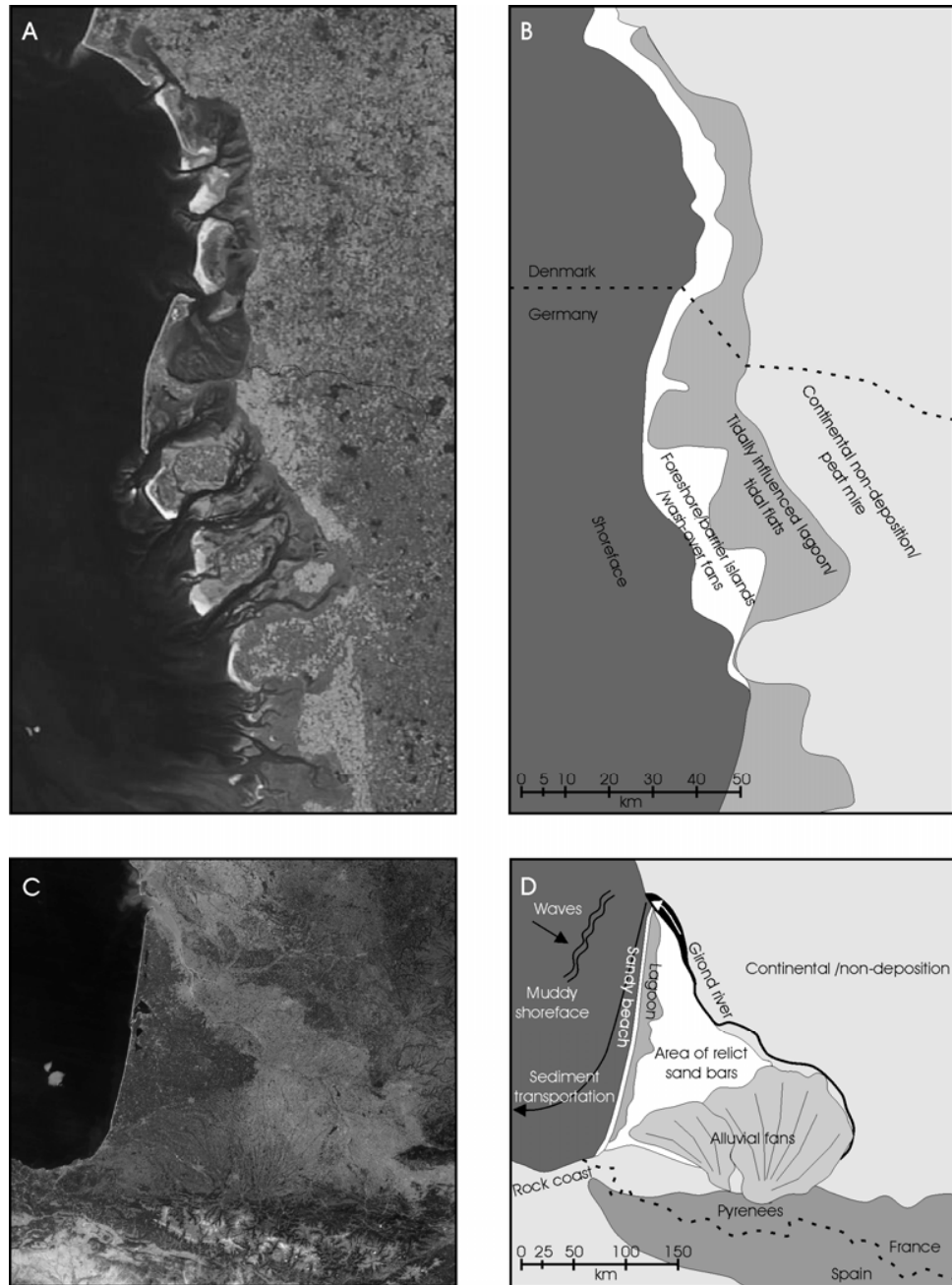


**Fig. 14** Regional paleogeographic reconstruction of the Central Tertiary Basin showing sedimentary transportation pattern, fluvial drainage, and interpretation of the environmental setting.

### *Regional Paleogeography*

The regional paleogeographic reconstructions of the Central Tertiary Basin (Fig. 14) are less detailed than the local reconstructions (Figs 11-13) because the coverage and quality of the data are much poorer. The interpretation is therefore more speculative but it is possible to put results and observations into a broader perspective. The south eastern part of the North

Sea coast, the Danish Wadden Sea, and the French coast of the Bay of Biscay were used as modern analogues for the depositional environment (Lüthje and Nichols Submitted) (Fig. 15).



**Fig. 15** Modern analogues (A) Satellite image of the Danish Wadden Sea, a modern analogue for the depositional environment in the Firkanten Formation (MODIS image from NASA Visible Earth, <http://visibleearth.nasa.gov>). (B) The coast is characterised by a wide tidally influenced lagoon and tidal flat areas protected from wave action by barrier bars/islands with well sorted foreshore sand deposition (Lüthje and Nichols Submitted). (C) Satellite image of the Bay of Biscay, a modern analogue for the sediment transportation in the Firkanten Formation (MODIS image from NASA Visible Earth, <http://visibleearth.nasa.gov>). (D) The coast is characterised by longshore current transportation. Fine grained sandstone is deposited in a narrow zone on the foreshore. The shoreface is muddy with glauconite production.

The reconstructions show an overall retrograding coastline with a well developed coastal plain setting of tidally-influenced lagoons and tidal flats. On the coastal plain peat accumulated in mires and swamps. The Wadden Sea (Figs 15A and B) shares many similarities to the Firkanten Formation: the climatic setting is humid temperate and there is extensive peat accumulation on the coastal plain with a microtidal lagoon system protected by barrier islands of well sorted fine grained sand and occasional storm-deposited pebbles. It is to be expected that the sedimentary drainage systems would be controlled by the distribution of subsidence, and in the Central Tertiary Basin subsidence was greatest close to the thrust front on the western side of the basin. The fluvial system would have followed along strike of the fold belt, draining the uplifted northern part. The northern area shows extensive erosion in pre-Paleocene time (Ny Ålesund Subgroup rests on Kap Starostin Formation Permian strata; Dallmann 1999) down to the Permian strata and this would have been a major source of fine-grained sand and mud; coarser sediments would have come from the thrust front in the west (Nichols and Lüthje Submitted). The eastern side of the basin was probably an area of limited sedimentation due to limited availability of accommodation.

The fluvial input to the basin did not build up any identifiable delta but sediment was redistributed along the coast building up barrier bars similar to the patterns seen today in the Bay of Biscay (Figs 15C and D), where sediments derived from the northern side of the Pyrenees enter the basin by the river Gironde (Fig. 15C). In this modern analogue setting the fine grained sand is transported along-shore by wave induced currents and deposited in a narrow belt on the coast as well-sorted foreshore and barrier bar deposits. There is no delta at the river mouth and all sediment is redistributed along shore. Offshore in the Bay of Biscay the sediments are generally muddy with a low sedimentation rate and glauconite production (Pers. comm. T. Jacquin 2007). Glauconite indicates low clastic sedimentation rates (Amorosi 2003) and is abundant in the Firkanten Formation (Lüthje and Nichols Submitted). Transgressive systems typically have a higher tendency to retain sediments on the shore and less is transported offshore creating a relatively sediment starved shoreface. As a consequence of this, the muddy lower shoreface sediments in the Firkanten Formation were probably deposited in shallower water than is indicated by the grain size and bioturbation.

Most of the coarse grained pebbly material in the Firkanten Formation has previously been described as possible valley incision and associated sequence boundary deposits (Bruhn and Steel 2003; Nagy 2005). These pebbly layers are here reinterpreted as storm deposits on the foreshore and shoreface (cf. Hart and Plint 1989; Hart and Plint 1995). The pebbly conglomerates are mostly found related to flooding surfaces and always associated to marine

sediments often showing marine bioturbation like *Ophimorpha*. There are no indications of base level fall and related incision in the Firkanten Formation.

## DISCUSSION

The sequence stratigraphic analysis and the paleogeographic reconstructions of the Firkanten Formation indicate deposition in a marginal marine setting during a period of general base level rise. At times the rate of sediment supply was overall in balance with the tectonic subsidence and eustatic sea level rise creating thick aggradational successions of sediments. During periods when sea level rise and tectonic subsidence exceeded the sedimentation a stepwise retrogradation of the coastline took place. The parasequences typically show evidence of only minor progradation and at no time did any base level fall cause the coastline to regress.

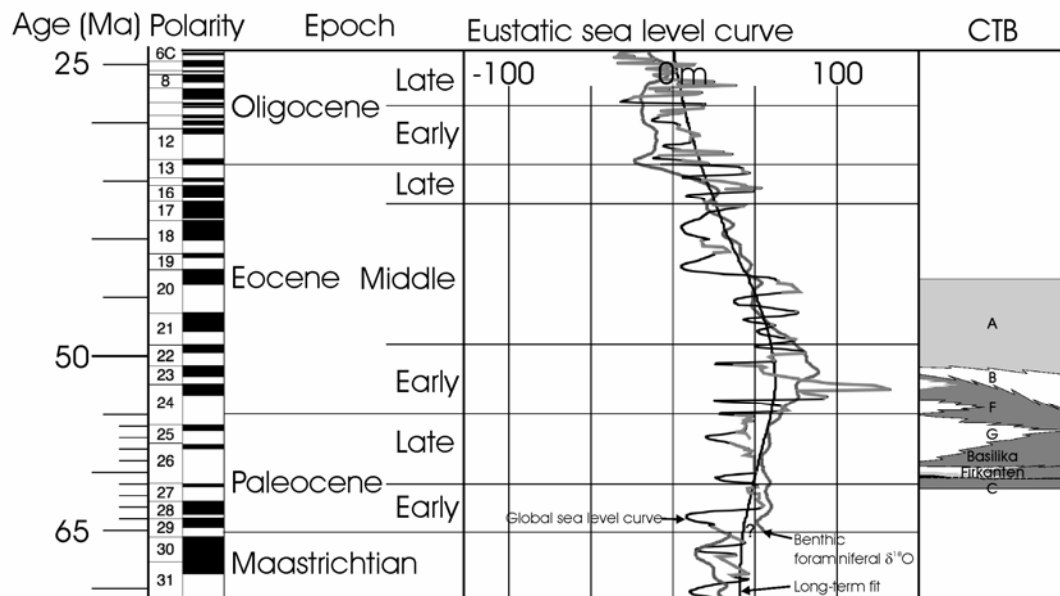
### *Basin Control*

The Central Tertiary Basin developed as a flexural basin adjacent to the West Spitsbergen Fold and Thrust Belt (Fig. 1) on a fully continental crust (Nichols and Lüthje Submitted). Due to the rigidity of the thick crust the subsidence was probably slow and would not have created a deep basin initially. The basin is instead expected to have had gentle relief giving a low gradient basin with a low gradient coast consistent with the depositional environment model (Lüthje and Nichols Submitted). The subsidence was probably controlled by a combination of flexural loading and compressional folding (Nichols and Lüthje Submitted). Superimposed on the background subsidence eustatic sea level variations gave rise to changes in the amount of accommodation created.

The aggradational successions represent periods when tectonically driven subsidence combined with eustatic sea level change were in balance with the sediment supply. The transgression took place during periods of relative sea level rise (Shanley and McCabe 1994) in the Firkanten Formation when eustatic sea level rise combined with the tectonic subsidence outpaced the sediment supply. The transgressive units were preserved because the system had time to adapt to the rising relative sea level and the accommodation created was large enough. There is little evidence of significant variations in sediment supply during deposition of the Firkanten Formation as the facies associations are similar throughout (Lüthje and Nichols Submitted).

*Age Control and Time Span*

The Paleocene/Eocene boundary is in the Frysjaodden Formation just above the Grumantbyen Formation (Fig. 2) (Dallmann 1999). The Firkanten and Basilika Formations are overall transgressive and it is unlikely that they were deposited during any significant eustatic sea level fall due to the lack of evidence of any significant base level fall in the sedimentary record. In late Paleocene time there are two major sea level falls of 25 m respectively and in Early Paleocene one of more than 50 m (Fig. 16) (Miller et al. 2005), all of which are unlikely to have occurred during the Firkanten or Basilika Formations considering that the marginal marine setting is an environment very sensitive to any sea level change.



**Fig. 16** Sea level curve with outline of the correlation to the Firkanten Formation. The global sea level curve after (Miller et al. 2005).

This provides several reference points for comparing the lower part of the Central Tertiary Basin succession to a global sea level curve: the base Paleocene, the Paleocene Eocene boundary and the eustatic sea level falls, even if comparison of sedimentary successions to global sea level curves is only significant when other factors influencing the relative sea level change are eliminated. It is suggested that the Firkanten and Basilika Formations were both deposited between the global sea level falls within the Late Paleocene: this is consistent with the age of the Pantodonts recognised from tracks in the formation (Lüthje et al. Submitted). If this speculation is correct, it indicates that the Firkanten and Basilika Formations were deposited over a time period of about 3.5-5 Ma (Fig. 16). However, if the Firkanten and Basilika Formations represent the period between the later eustatic sea level fall and the base Eocene it would mean that the entire Paleocene succession was

deposited in 1.5 Ma. If the longer time period of about 4 Ma is assumed, this indicates a rate of sedimentation of approximately 100 m in 1 Ma, using the thicknesses of the Firkanten and Basilika Formations from Dallmann (1999). Furthermore, based on the number of parasequences and parasequence sets identified, a 4 Ma time period for the succession would suggest that each parasequence was deposited in about 30k years and the parasequence sets in about 100k years. This is approximately the time period of 5th order for parasequences and 4th order for parasequence sets (Miall 1995): the same magnitude is found in the Alberta foreland basin (Plint 1991).

### *Basin Geometry*

The Central Tertiary Basin was structurally bound to the north, east, and west but opened up towards the south. The geometry of the basin was asymmetrical with the highest subsidence closest to the thrust front in the west but also getting shallower towards the uplifted northern area (Nichols and Lüthje Submitted). Flexural basins are typically asymmetrical and expected to have the greatest subsidence near the thrust front (Zhang and Bott 2000). The asymmetrical geometry is also described from the upper part of the Central Tertiary Basin (Helland-Hansen 1990) and is indicated by the interpretation of isopachs in the Paleogene strata (Manum and Throndsen 1978). However, the isopach distribution does not necessarily indicate the coastal outline, which is the interpretation that some previous authors have made (Kellogg 1975).

The asymmetry would have resulted in differences in sedimentation patterns from east to west. The environment on the eastern side was probably more stable since both sediment supply and subsidence were lower where the environment could develop an equilibrium state: this is reflected in the thick coal deposits in this area. The western side of the basin was characterised by high sediment input but also a high subsidence rate, which would lead to an environment characterised by more regular shifts as a reaction to imbalance between sediment supply and subsidence. This can be seen in the thinner coal sections split by mudstone intervals found in Barentsburg on the western side of the basin (Fig. 1). However, the type of coastal environment is not expected to change significantly since it is the same factors dominating the coast formation on both sides; wave and tidal energy. The climate was probably also the same over the whole area as it was a small basin.

Fluvial drainage naturally follows pathways to the lowest region with the highest subsidence rate and would therefore have been concentrated near the thrust front. The

sediments were redistributed in the basin by wave and/or tide induced long-shore currents (Fig. 14). The pebbly material was also sorted along-shore by the currents and therefore occurs only as granule and pebble size in the eastern part (Lüthje and Nichols Submitted). Alluvial fans deposits would have formed close to the thrust front since they are deposited in the area of largest creation of accommodation. However, in the Firkanten Formation strong currents, probably storm-induced, were able to transport and redeposit some of the material.

The topography of the underlying unconformity (Steel and Dalland 1978; Jochmann 2004) influenced the lower part of the Todalen Member and the development of coastal plain and marginal marine deposits. The sequence stratigraphic analysis confirms that the sedimentary differences are caused by this local relief and not, as has been suggested, to reflect different sub-basins in Todalen Member (cf. Steel et al. 1985). The range of the topography is less than 20 m, which was filled up by the coastal plain succession.

#### *Coal formation*

Correlation of coal seams from the sequence stratigraphic analysis and understanding of the conditions required for coal formation in the basin provide important information about the distribution of the seams. Formation of thick coal deposits, like in the mine Svea Nord, require a long-term balance between organic production and subsidence in a setting of limited sedimentary input (Shanley and McCabe 1994). If the organic production is too high or the base level rise too low the organic material is exposed and thereby oxidised or eroded. If the subsidence or base level rise is too high the area is flooded (Bohacs and Suter 1997; Davies et al. 2005). Even small sea level changes would have influenced large areas due to the low relief in the Firkanten Formation.

During the deposition of the Firkanten Formation thick packages of peat could be deposited on the coastal plain due to the low clastic sediment input. The fluvial deposition was constrained to the western side of the basin (Nichols and Lüthje Submitted) and the coast was protected by barrier bars from wave influence and by a broad lagoon/tidal flat from tidal influence (Lüthje and Nichols Submitted). The climate was humid temperate, favourable for organic plant production (Golovneva 2000). The apparent low subsidence rate in the Central Tertiary Basin, due to that the flexural basin was created on full continental rigid crust, seems to have been favourable for peat accumulation. In the Firkanten Formation, the raised mire systems acted as natural dykes resulting in thick aggradational sections of peat. Previous models that indicated coal formation on a delta plain (e.g. Steel and Dalland 1978) are not

consistent with either the facies model or the transgressive setting indicated by the sequence stratigraphic analysis.

The asymmetrical basin resulted in more sediment input in the western area. This would have led to shorter periods of balance between organic production and base level rise, and raised mire systems did not have time to develop properly resulting in thinner coal seams. Therefore the most optional place for coal deposition was on the eastern side of the basin.

## CONCLUSIONS

The new sequence stratigraphic analysis and paleogeographic reconstruction provide a model for the development of the Firkanten Formation through time.

- An overall transgressive succession for the Firkanten and Basilika Formations is consistent with the depositional environment model.
- The lower unconformity with the Lower Cretaceous is the sequence boundary and the initial flooding surface, followed by transgression that took place in a step-wise retrograding pattern with intervening aggradational sections.
- There are no indications of relative sea level fall identified within the succession.
- The succession can be divided into parasequences bounded by minor flooding surfaces and parasequence sets separated by major flooding surfaces.
- The parasequence sets contain retrogradational and aggradational patterns, with the latter dominant in the successions.
- The paleogeographic reconstruction indicates a low relief coastal environment with protecting barrier bars and tidally-influenced lagoons.
- The basin was bound to the west by the thrust front, to the north by uplift and to the east by a structurally controlled area with restricted sedimentation.
- The asymmetry of the flexural basin is reflected in the depositional environment: the western area is influenced by higher subsidence rate and sediment supply resulting in thinner coal deposits whilst the eastern area was the most favourable area for peat accumulation due to low subsidence and sediment supply, where raised mire complexes had time to develop.
- The raised mires acted as natural dykes for transgressions resulting in thick sections of peat accumulations.



## ACKNOWLEDGMENTS

SNSK (Store Norske Spitsbergen Kulkompani) are thanked for providing access to their data records, core store facilities and the mines in Longyearbyen and Svea Nord. Charlotta Lühje would also like to thank SNSK for providing funding for a PhD project carried out at UNIS, Royal Holloway University of London and at the University of Bergen. M. Lühje is acknowledged for careful reading of the manuscript

## REFERENCES

- AMOROSI, A., 2003, Glaucony and Verdine, in Middleton, G.V., ed., *Encyclopedia of Sediments and sedimentary rocks*, p. 331-333.
- BERGH, S.G., BRAATHEN, A., and ANDRESEN, A., 1997, Interaction of basement-involved and thin-skinned tectonism in the tertiary fold-thrust belt of central Spitsbergen, Svalbard: *AAPG Bulletin*, v. 81, p. 637-661.
- BOHACS, K., and SUTER, J., 1997, Sequence stratigraphic distribution of coaly rocks: Fundamental controls and paralic examples: *AAPG Bulletin*, v. 81, p. 1612-1639.
- BRAATHEN, A., BERGH, S.G., and MAHER, H.D., 1999, Application of a critical wedge taper model to the Tertiary transpressional fold-thrust belt on Spitsbergen, Svalbard: *Geological Society of America Bulletin*, v. 111, p. 1468-1485.
- BRUHN, R., and STEEL, R., 2003, High-resolution sequence stratigraphy of a clastic foredeep succession (Paleocene, Spitsbergen): An example of peripheral-bulge-controlled depositional architecture: *Journal of Sedimentary Research*, v. 73, p. 745-755.
- CATUNEANU, O., 2002, Geological Society of Africa Presidential Review No. 1 Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls: *Journal of African Earth Sciences*, v. 35, p. 1-43.
- CEPEK, P., and KRUTTZSCH, W., 2001, Conflicting Interpretations of Tertiary biostratigraphy of Spitsbergen and new palynological results, in Tessensohn, F., ed., *Intra-continental fold belts; Case 1: West Spitsbergen*, *Geologisches Jahrbuch; Polar Issue No. 7: Hannover, Bundesanstalt für Geowissenschaften und Rohstoffe*, p. 551-599.
- DALLMANN, W., HJELLE, A., OHTA, Y., SALVIGSEN, O., BJORNRUD, M.G., HAUSER, E.C., MAHER, H., and CRADDOCK, C., 1990, *Geological map of Svalbard B11G Van Keulenfjorden*: Norwegian Polar Institute.

- DALLMANN, W.K., 1999, Lithostratigraphic lexicon of Svalbard, Norsk Polarinstitut, 318 p.
- DAVIES, R.C., DIESSEL, C., HOWELL, J., FLINT, S.S., and BOYD, R., 2005, Vertical and lateral variation in the petrography of the Upper Cretaceous Sunnyside coal of eastern Utah, USA: implications for the recognition of high-resolution accommodation changes in paralic coal seams: *International Journal of Coal Geology*, v. 61, p. 13-33.
- GOLOVNEVA, L.B., 2000, Palaeogene climates of Spitsbergen: *GFF The Geological Society of Sweden*, v. 122, p. 62-63.
- HART, B.S., and PLINT, A.G., 1989, Gravelly shoreface deposits: a comparison of modern and ancient facies sequences: *Sedimentology*, v. 36, p. 551-557.
- HART, B.S., and PLINT, A.G., 1995, Gravelly shoreface and beachface deposits, in Plint, A.G., ed., *Clastic Facies Analysis - a Tribute to the Research and Teaching of Harold G. Reading*, International Association of Sedimentologists, Special Publication 22, p. 75-99.
- HART, B.S., and PLINT, A.G., 2003, Stratigraphy and sedimentology of shoreface and fluvial conglomerates: insights from the Cardium Formation in NW Alberta and adjacent British Columbia: *Bulletin of Canadian Petroleum Geology*, v. 51, p. 437-464.
- HELLAND-HANSEN, W., 1990, Sedimentation in Paleogene Foreland Basin, Spitsbergen: *AAPG Bulletin*, v. 74, p. 260-272.
- JOCHMANN, M., 2004, The geology of the Ispallen area, Svalbard, with emphasis on the coal bearing Firkanten Formation: Diploma. Ludwig Maximilians Universität, München, 88 p.
- KALGRAFF, K.L., 1978, Aspects of Sedimentation in Firkanten Formation, Tertiary, Svalbard: *Cand. Scient. Universitetet i Bergen, Bergen*, 178 p.
- KAMOLA, D.L., and VAN WAGONER, J.C., 1995, Stratigraphy and facies architecture of parasequences with examples from the Spring Canyon Member, Blackhawk Formation, Utah, in Van Wagoner, J.C., and Bertram, G.T., eds., *Sequence Stratigraphy of Foreland Basin Deposits*, AAPG Memoir, 64, p. 27-54.
- KELLOGG, H.E., 1975, Tertiary Stratigraphy and tectonism in Svalbard and continental drift: *The AAPG Bulletin*, v. 59, p. 465-485.
- LÜTHJE, C., MILÀN, J., and HURUM, J., Submitted, Paleocene Tracks of the Pantodont genus *Titanoides* in Coal-Bearing Strata, Svalbard, Arctic Norway. *Proc. R. Soc. B*
- LÜTHJE, C., and NICHOLS, G., Submitted, Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. *Sedimentology*

- MANUM, S.B., and THRONDSSEN, T., 1978, Rank of coal and dispersed organic matter and its geological bearing in the Spitsbergen Tertiary: Norsk Polar institutt årsbok 1977, p. 159-177.
- MANUM, S.B., and THRONDSSEN, T., 1986, Age of Tertiary formations on Spitsbergen: Polar Research, v. 4, p. 103-131.
- MCCABE, P.J., and SHANLEY, K.W., 1992, Organic Control On Shoreface Stacking Patterns - Bogged Down In The Mire: Geology, v. 20, p. 741-744.
- MIALL, A.D., 1995, Whither stratigraphy? Sedimentary Geology, v. 100, p. 5-20.
- MIDDLETON, G.V., 1973, Johannes Walther's Law of Correlation of Facies: Geological Society of America Bulletin, v. 84, p. 979-987.
- MILLER, K.G., KOMINZ, M.A., BROWNING, J.V., WRIGHT, J.D., MOUNTAIN, G.S., KATZ, M.E., SUGARMAN, P.J., CRAMER, B.S., CHRISTIE-BLICK, N., and PEKAR, S.F., 2005, The phanerozoic record of global sea-level change: Science, v. 310, p. 1293-1298.
- MOORE, T.A., and SHEARER, J.C., 2003, Peat/coal type and depositional environment - are they related? International Journal of Coal Geology, v. 56, p. 233-252.
- NAGY, J., 1966, Preliminary report on the geology of Eastern Torell Land, Vestspitsbergen: Norsk Polar institutt årsbok, v. 1964, p. 69-72.
- NAGY, J., 2005, Delta-influenced foraminiferal facies and sequence stratigraphy of Paleocene deposits in Spitsbergen: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 222, p. 161-179.
- NICHOLS, G., and LÜTHJE, C., Submitted, Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. Basin Research.
- ORHEIM, A., BIEG, G., BREKKE, T., HORSEIDE, V., and STENVOLD, J., 2007, Petrography and geochemical affinities of Spitsbergen Paleocene coals, Norway: International Journal of Coal Geology, v. 70, p. 116-136.
- PLINT, A.G., 1991, High-frequency relative sea-level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence for a glacio-eustatic control? in Macdonald, D.I.M., ed., Sedimentation, Tectonics and Eustasy, International Association of Sedimentologists, Special Publication 12, p. 409-428.
- SCOTT, A.C., 2002, Coal petrology and the origin of coal macerals: a way ahead? International Journal of Coal Geology, v. 50, p. 119-134.
- SHANLEY, K.W., and MCCABE, P.J., 1994, Perspectives on the sequence stratigraphy of continental strata: AAPG Bulletin, v. 78, p. 544-568.
- SIGGERUD, E.I.H., and STEEL, R.J., 1999, Architecture and trace-fossil characteristics of a 10,000-20,000 year, fluvial-to-marine sequence, SE Ebro basin, Spain: Journal of Sedimentary Research, v. 69, p. 365-383.

- STEEL, R., and DALLAND, A., 1978, Undersøkelser av den kullførende del av Firkanten Formasjonen (Tertiær) i østlige del av Nordenskiöld land Svalbard, Geologisk Institutt Universitetet i Bergen, p. 62.
- STEEL, R., DALLAND, A., KALGRAFF, K.L., and LARSEN, V., 1981, The central Tertiary basin of Spitsbergen - sedimentary development in a sheared margin basin, in Kerr, J.W., and Fergusson, A.J., eds., *Geology of the North Atlantic Borderlands*, Canadian Society of Petroleum Geologists, Memoir 7., p. 647-664.
- STEEL, R., GJELBERG, J., HELLAND-HANSEN, W., KLEINSPEHN, K., NØTTVEDT, A., and RYE-LARSEN, M., 1985, The tertiary strike-slip basin and orogenic belt of Spitsbergen: SEPM Special Publication No. 39, p. 339-359.
- ULICNY, D., 1999, Sequence stratigraphy of the Dakota Formation (Cenomanian), southern Utah: interplay of eustasy and tectonics in a foreland basin: *Sedimentology*, v. 46, p. 807-836.
- VAN WAGONER, J.C., MITCHUM, R.M.J., CAMPION, K.M., and RAHMANIAN, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies, v. *Methods in Exploration Series*, No. 7: Tulsa, Oklahoma, AAPG, 55 p.
- WILHELMSSON, J.C., 1999, Depositional Environment and Sequence Stratigraphy of the Coal-bearing Todalen Member, Firkanten Formation (Paleocene) at Adventdalen, Svalbard: Cand. Scient. University of Oslo, Oslo/Longyearbyen.
- WÜST, R.A.J., HAWKE, M.I., and BUSTIN, R.M., 2001, Comparing maceral ratios from tropical peatlands with assumptions from coal studies: do classic coal petrographic interpretation methods have to be discarded? *International Journal of Coal Geology*, v. 48, p. 115-132.
- YTRELAND, G.K., 1980, Sedimentation along the Western margin of the Central Tertiary Basin, (Firkanten Formation), Spitsbergen: Cand. Scient. University of Bergen, Bergen, 183 p.
- ZHANG, G.-B., and BOTT, M.H.P., 2000, Modelling the evolution of asymmetrical basins bounded by high-angle reverse faults with application to foreland basins: *Tectonophysics*, v. 322, p. 203-218.

**6. ARTICLE 3 - FLEXURAL BASIN, PALEOCENE SPITSBERGEN**

**Article 3**

**Provenance and Flexural Basin Development: the Paleocene  
of the Central Tertiary Basin, Spitsbergen**

**Gary Nichols**

Department of Earth Sciences, Royal Holloway University of London, Egham,  
Surrey, TW20 0EX, UK

**Charlotta Lüthje**

University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway.

Submitted to Basin Research

Citation: Nichols, G. and Lüthje, C. *Submitted*. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. Basin Research.

# Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen

GARY NICHOLS<sup>1</sup> and CHARLOTTA LÜTHJE<sup>2</sup>

<sup>1</sup> Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey, TW20 0EX, UK

<sup>2</sup> University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway.

## ABSTRACT

The provenance of sediments in Late Paleocene strata in the Central Tertiary Basin of Spitsbergen in the Arctic north of Norway indicate that the adjacent West Spitsbergen Fold and Thrust Belt was uplifted between the Late Cretaceous and the Early Palaeocene. The distribution of facies in the basin also indicates a flexural origin to the basin. The Central Tertiary Basin fill is 1900 m thick and consists of mudstones, sandstones and rare conglomerates deposited in continental to shallow marine environments. The sandstones are mainly mature quartz arenites that are considered to have been reworked from a thick Mesozoic succession of terrigenous clastic shallow marine strata to the north and northwest of the basin. Some of the conglomerate pebbles are lithic clasts of Cretaceous beds, but others are well-cemented, grey quartz sandstones and black cherts derived from Carboniferous and Permian strata respectively. The provenance of these Late Paleozoic clasts in the Late Paleocene conglomerate beds in the west provide evidence that there was uplift and erosion in Late Cretaceous to Early Palaeocene time of at least 2000 m of rock in an area of folding and thrusting in the West Spitsbergen Fold and Thrust Belt, directly adjacent to the western margin of the basin. Deformation of the Paleogene strata is limited to within a few kilometres from the fold belt and most of the basin fill is undeformed, tapering in thickness towards the east. The succession of mainly fine-grained facies, including coal, in the eastern part of the basin and coarser units in the west are consistent with a flexural origin for the basin, formed as a result of early Paleogene crustal shortening. At that time Spitsbergen was part of a continental landmass which was continuous from East Greenland across to the Barents Shelf. The basin is considered to have formed by compressional folding of this crust rather than flexural loading following collision.

*Keywords: flexural basin, Cenozoic, Spitsbergen, conglomerate and sandstone provenance*

## INTRODUCTION

The Svalbard archipelago lies at the edge of the Barents Shelf and is the most north westerly part of the Eurasian continental area (Fig. 1). Extensive exposures provide a geological record from the Precambrian to the Holocene (Fig. 2), including a succession of Paleogene strata in the central and southern part of the main island, Spitsbergen, the Central Tertiary Basin (Fig. 3). Seams of bituminous coal have been mined from the lower part of the Cenozoic succession for over 100 years and coal exploration provides information from cores as well as outcrop in coastal and valley sections.

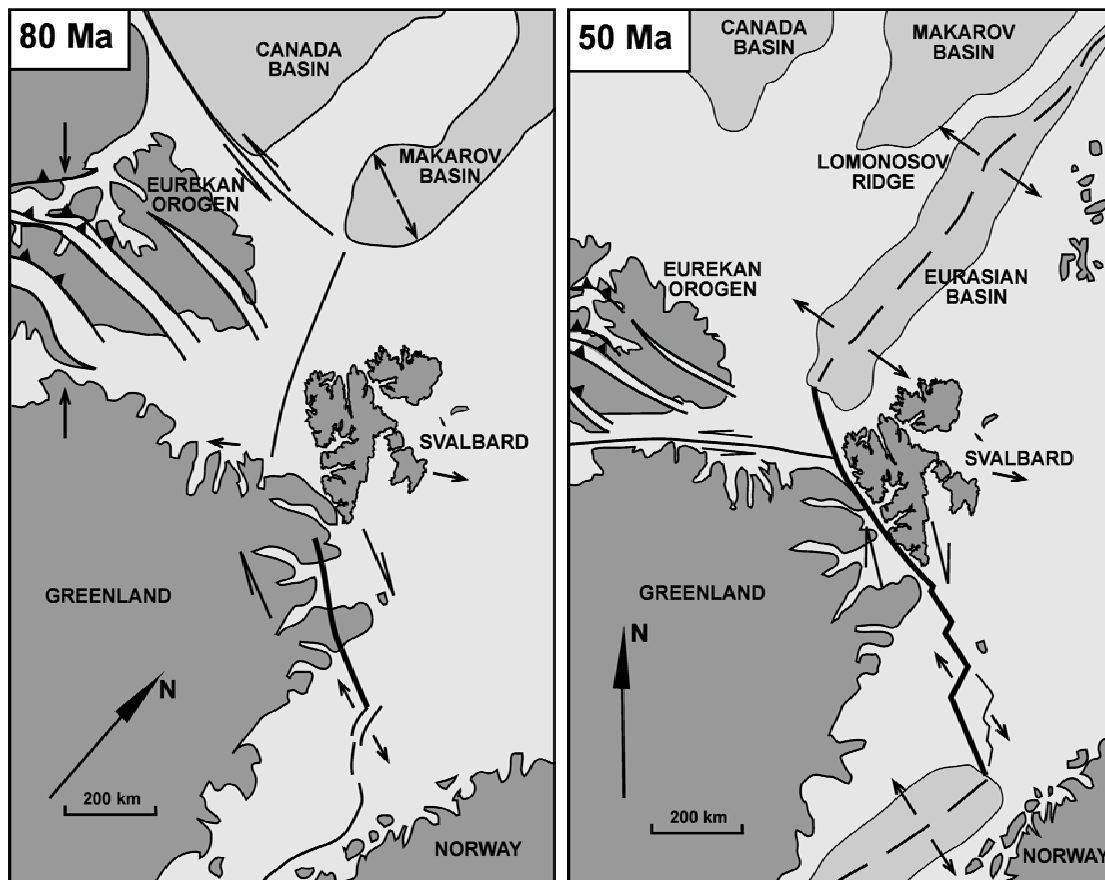


Fig. 1 Plate tectonic reconstruction model of Svalbard and Greenland from Cretaceous and Paleogene, after (Blythe and Kleinspehn, 1998).

The origin of the Central Basin of Spitsbergen has been described previously as formed in an extensional or transtensional setting (Kellogg, 1975; Steel et al., 1981; Steel and Worsley, 1984; Steel et al., 1985) with more recent work focussing on a flexural origin (Bruhn and Steel, 2003) in a compressional or transpressional setting (Muller and Spielhagen, 1990; Braathen and Bergh, 1995; Braathen et al., 1999a; Paech, 2001). To the west of the basin lies the West Spitsbergen Fold and Thrust Belt (Fig. 3), a zone of Cenozoic shortening and the structural patterns in the basin indicate a compressional or transpressional phase in the basin





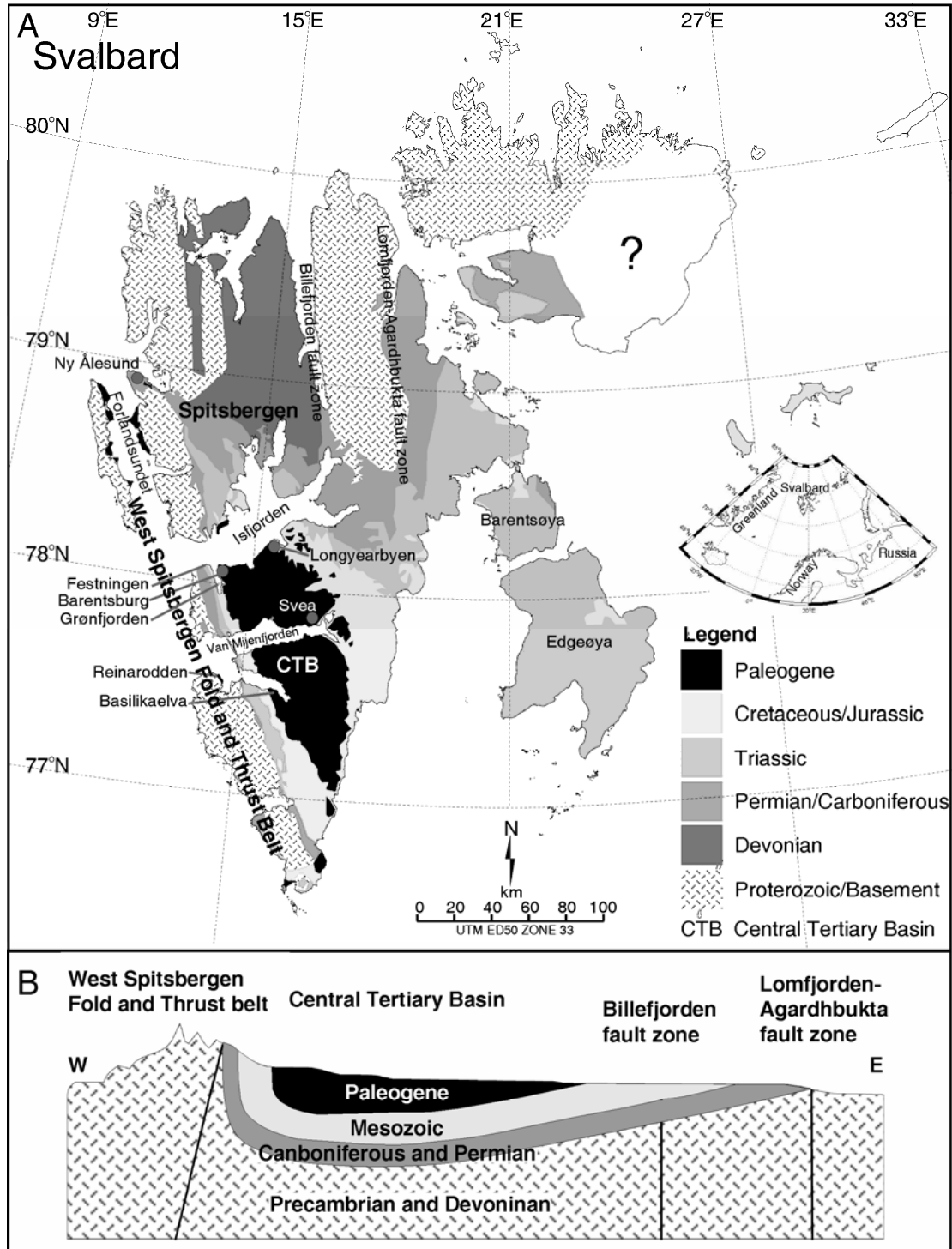


Fig. 3 (A) A simplified geological map of Svalbard, after (Dallmann 1999). The main Paleogene strata are found in the Central Tertiary basin that occupies the centre of the southern part of the main island, Spitsbergen. (B) A simplified cross section over the Central Tertiary Basin from west to east.

history (Maher et al., 1995; Bergh et al., 2000). The source of the mud, sand and rare gravelly material has been attributed to sources both from the fold belt to the west and also from the north-eastern side of the basin (Steel et al., 1981; Steel et al., 1985; Harland, 1997; Dallmann, 1999; Bruhn and Steel, 2003).

In this paper, data from outcrops and cores are used to determine the provenance of the sandy and gravelly deposits and the implications these provenance data have for the origins of the basin. The uplift and subsidence history of this area of the crust is considered from late Cretaceous to Paleogene times. This is related to the new depositional model for the oldest part of the basin fill (Lüthje and Nichols, Submitted a) and a sequence stratigraphic analysis of the succession (Lüthje and Nichols, Submitted b).

## **GEOLOGICAL BACKGROUND**

### *Tectono-stratigraphic history*

The sedimentary record of Svalbard includes an almost continuous section from post-Caledonian Devonian strata until Oligocene with one major hiatus between the Albian-Aptian and the Paleocene (Steel and Worsley, 1984; Dallmann, 1999) (Fig. 2). The Precambrian Hekla Hoek, which is the deformed pre-Devonian Basement, occurs in the northern part of the archipelago and in the Western Spitsbergen Fold and Thrust Belt. Following the Caledonian orogeny, Devonian continental clastic deposits form thick successions in extensional and strike-slip basins. These are commonly red-beds and have a stratigraphic thickness of up to 6000 m in northern Spitsbergen (Harland, 1997). A further period of extension in the Early Carboniferous created small rift basins in which quartz-rich fluvial sandstones, conglomerates, mudstones and coal beds were deposited, making up the Billefjorden Group, which is up to 2500 m thick (Dallmann, 1999).

The Late Carboniferous saw the start of a long period of deposition in a shallow marine setting, uninterrupted by any significant deformation until the Late Cretaceous. During this period Svalbard was an area of continental crust that was continuous from the Barents Shelf of northwest Europe through to Greenland and North America (Harland, 1997) (Fig. 1). The Gipsdalen Group is up to 1800 m thick and consists of Late Carboniferous evaporites and platform carbonates with chert-rich beds in places. Shallow marine carbonate deposition continued through the Permian with the Templefjorden Group, which is extensively silicified and contains chert nodules and beds. These resistant strata form impressive cliffs in central Spitsbergen and prominent ridges in the western part of the island. The Templefjorden Group is approximately 460 m thick. From Early Triassic to mid-Cretaceous times Svalbard was mainly an area of shallow marine clastic sedimentation with the deposits of the Sassendalen, Kapp Toscana, and Adventdalen Groups that are dominated by mudstone and sandstone deposited in an epicontinental sea. There are some coarser sandstones associated with deltaic and coastal environments, in addition to volumetrically insignificant, pebbly condensed units.

The overwhelming majority of the 2500 m or more of the Mesozoic succession (Dallmann, 1999) is made up of interbedded mudstone and very fine to fine sandstone (Fig 2).

A major hiatus separates Aptian-Albian strata from the Cenozoic succession that is found mainly in the central and southern part of Spitsbergen, the Central Tertiary Basin. The Paleogene strata in the Central Tertiary Basin are up to 1900 m thick and are predominantly fine-grained sandstones and mudstones with significant coal seams and minor conglomeratic units (Dallmann, 1999). The deposits in the Van Mijenfjorden Group of Paleocene to Oligocene age are interpreted as marginal marine coastal to shallow marine and offshore environments (Steel and Dalland, 1978, Dallmann, 1999; Bruhn and Steel, 2003; Lüthje and Nichols, Submitted a). Two separate, small areas of Late Eocene or Early Oligocene beds (Dallmann, 1999; Cepek and Kruttzsch, 2001) occur in Forlandsundet and at Reinardodden, both on the western side of the island (Fig. 3).

#### *Early Cenozoic succession*

The coal-bearing strata of the Firkanten Formation, the oldest unit in the Central Tertiary Basin basin-fill succession (Fig. 4), were formerly described as being the deposits of a delta system prograding from the east and northeast (e.g. Steel et al., 1981; Steel et al., 1985; Bruhn and Steel, 2003). The Firkanten Formation strata have recently been reinterpreted as the deposits of a wave-dominated coastal plain environment (Lüthje and Nichols, Submitted a) (Fig. 5). This new paleogeographic model is based on a detailed facies analysis using outcrop data and cores, provided by the local coal mining company SNSK (Store Norske Spitsbergen Kulkompani). The facies model has revealed that the coal-forming peat swamps formed along a coastal plain, bordered by lagoons, microtidal mudflats and beach barrier systems. Fluvial channel-fill units have not been recognised in the succession on the eastern side of the basin (where the thickest coal units are found) and furthermore the sands within the succession are rich in glauconite (Lüthje and Nichols, Submitted a) indicating marine origin. Thin conglomeratic beds within the succession, formerly interpreted as the basal parts of fluvial channel-fill successions, have been reinterpreted as transgressive lags and foreshore deposits, based on the occurrence of sandstone containing glauconite and abundant Ophiomorpha burrows directly overlying the conglomerate. An exceptional conglomerate unit, the Grønfjorden Bed, occurs on the western side of the basin and the provenance of clasts in this unit is an important factor in the analysis of the basin formation, discussed further below.

Analysis of the spatial and temporal relationships between coastal plain, shoreline and shallow marine facies in the Firkanten Formation indicates that the strata are arranged in an

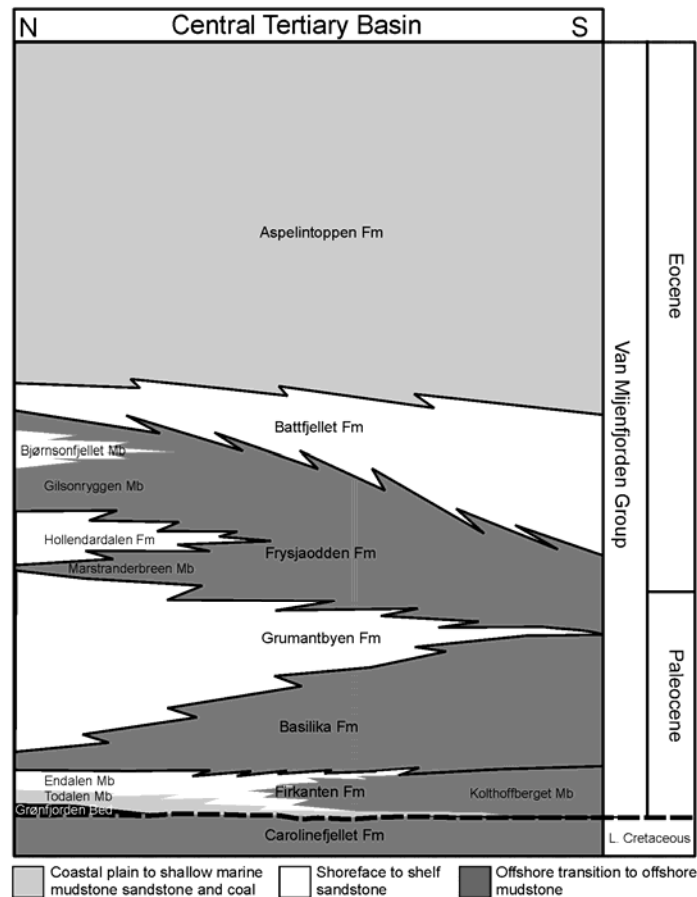


Fig. 4 The stratigraphy of the Paleogene Van Mijenfjorden Group in the Central Tertiary Basin of Spitsbergen. The focus of this study is on the lower part of the succession, the Todalen and Endalen Members of the Firkanten Formation, from (Lüthje and Nichols, Submitted a), partly based on (Steel et al., 1985; Bruhn and Steel, 2003). Geometries are based on relative thickness variations (Dallmann, 1999) over the basin.

overall retrogradational pattern and that the formation was deposited as part of a general transgressive succession (Lüthje and Nichols, Submitted b). Paleogeographic reconstructions based on facies distributions and a sequence stratigraphic analysis of the Firkanten Formation show that the shoreline moved in a northward direction through time, but the transgression was asymmetric, with greater shoreline displacement in the west than in the eastern side of the basin (Lüthje and Nichols, Submitted b). This pattern reflects differential subsidence and suggests lower rates in the east and greater subsidence in the west. The strata in the Central Tertiary Basin form an overall wedge shape, thinning toward the east from the west where the thickest succession is preserved (Kellogg, 1975; Manum and Throndsen, 1978, Winsnes, 1988) (Fig. 3b).

The transgressive succession continues into the Basilika Formation, which is composed of fine-grained, offshore facies and is then overlain by a progradational pattern in the

Grumantbyen Formation. A return to retrogradation in the latest Paleocene culminated in the regional maximum flooding of the basin in the marine shale of the Frysjaodden Formation, at a level which is approximately coincident with the Paleocene and Eocene boundary (Steel et al., 1985; Manum and Throndsen, 1986; Dallmann, 1999). The Eocene succession is dominantly progradational as the marine offshore facies of the Frysjaodden Formation pass into shoreface and marginal marine in the Battfjellet Formation, and then to continental deposits of the Aspelintoppen Formation (Dallmann, 1999).

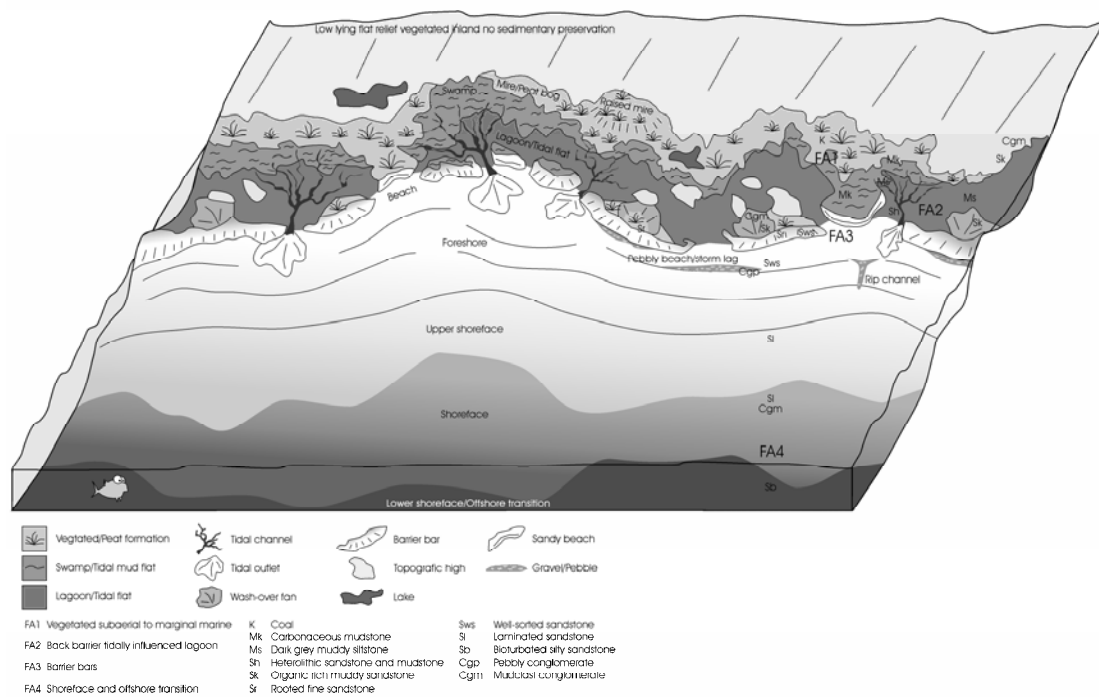


Fig. 5 Conceptual diagram for the depositional environment and the distribution of facies and facies associations in the Firkanten Formation, from (Lüthje and Nichols Submitted a).

### *Late Cenozoic uplift*

Late Cenozoic uplift and Quaternary glaciation have resulted in the exposure of Precambrian through to Cenozoic rocks. On the western side of Spitsbergen units of all ages are deformed in the West Spitsbergen Fold Belt (Fig. 3), which runs approximately north-south. In the core of this small mountain belt, metamorphic rocks of the Hekla Hoek form peaks over 750 m above sea level. On the eastern side of the West Spitsbergen Fold Belt Carboniferous through to Cenozoic strata are deformed to vertical or steeply dipping towards the east (Fig. 3b). In the central and eastern parts of Spitsbergen and further east to the islands of Edgeøya and Barentsøya strata ranging from the Devonian to the Cenozoic generally show little

deformation, except in relation to major fault zones, as the Billefjorden Fault Zone and the Lomfjorden-Agardhbukta Fault Zone in eastern Spitsbergen (Fig. 3). There is, however, a general trend from north to south in the ages of the rocks exposed. In the northern part of Spitsbergen, north of Isfjord, outcrop is dominated by Precambrian, Devonian and Carboniferous units. In southern Spitsbergen, apart from the areas around the West Spitsbergen Fold Belt, the strata outcropping are younger, with the Mesozoic and the Cenozoic widely exposed. Uplift has resulted in Eocene strata being exposed at 1270 m above sea level and vitrinite reflectance data indicate that over 1500 m of Late Eocene and younger strata have been eroded (Manum and Throndsen, 1978).

### **ORIGIN OF THE CENTRAL TERTIARY BASIN**

The tectonic control on the Central Tertiary Basin has been considered by a number of authors over the last four decades (e.g. Livsic, 1974; Kellogg, 1975; Steel et al., 1985; Muller and Spielhagen, 1990; Lyberis and Manby, 1993a; Lyberis and Manby, 1993b; Braathen and Bergh, 1995; Maher et al., 1995; Manby and Lyberis, 1996; Bergh et al., 1997; Braathen et al., 1999a; Braathen et al., 1999b; Manby and Lyberis, 2000; Paech, 2001; Saalman and Thiedig, 2001; Saalman and Thiedig, 2002; Bruhn and Steel, 2003). The models developed have been based on the recognition of the patterns of faulting observable in the field today, the distribution of facies in the basin and the timing of both tectonic and depositional events.

#### *Transtension-transpression models*

Large-scale strike-slip faults are prominent features of the geology of Spitsbergen and the Central Tertiary Basin has in the past been considered to have been a consequence of extensional movement between pairs of faults (Kellogg, 1975; Steel et al., 1981; Steel and Worsley, 1984; Steel et al., 1985). The Paleocene succession (Firkanten, Basilika and Grumantbyen Formations) was regarded as sourced from the east, with deltaic units building out westwards from the eastern and northeastern margins of the basin (Fig. 6). A change to progradation from the west, in the Eocene succession (Battfjellet and Aspelintoppen Formations) was interpreted as a drainage reversal connected to the onset of compression and the development of the West Spitsbergen Fold Belt (Helland-Hansen, 1990). These models therefore considered the Central Tertiary Basin to have a history of transtension in the Paleocene followed by transpression in the Eocene (e.g. Steel et al., 1985; Harland, 1997; Maher, 2001).

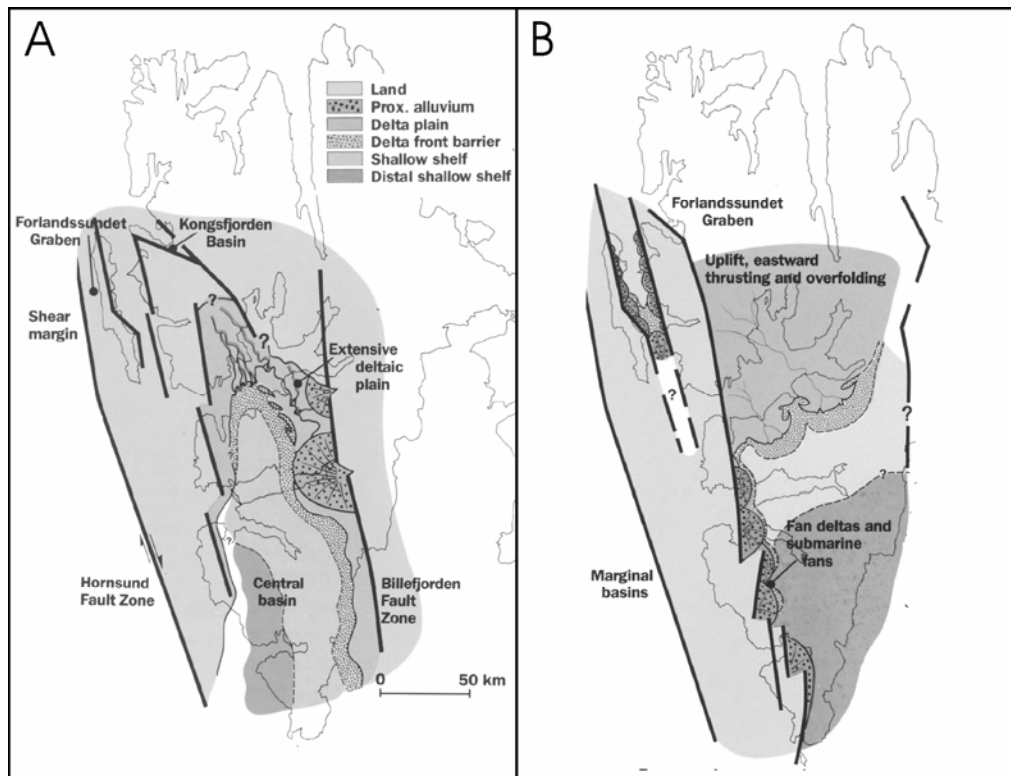


Fig. 6 Paleogeographic reconstructions of the Firkanten Formation from (A) Paleocene and (B) Eocene, from (Worsley et al., 1986).

#### *Foreland Basin model*

The structures in the pre-Cenozoic rocks of the West Spitsbergen Fold Belt clearly indicate that there has been an episode of compressional tectonic in western Spitsbergen, and structures in the Central Tertiary Basin succession show that this continued into the Paleocene and Eocene (Braathen et al., 1995; Bergh et al., 1997; Braathen et al., 1999a). In an analysis of the Central Tertiary Basin succession by Bruhn and Steel (2003) the basin was interpreted as being a flexural basin, formed by loading in the west due to the thickening of the crust in the West Spitsbergen Fold Belt. It was suggested that the sediment source during the deposition of the Firkanten, Basilika and Grumantbyen Formations lay to the east. A forebulge resulting from the crustal flexure was responsible for generating the uplift and hence the relief from which the detritus was shed. The shallow marine facies of the Grumantbyen Formation extend across the basin, indicating that the basin was filled almost to sea level during the Paleocene and earliest Eocene, and erosion of the forebulge alone cannot account for the volume of sediment required to fill the basin. Uplift of a forebulge is approximately 10% of the subsidence in the basin at a thrust front (Allen and Allen, 2005) and therefore a major sediment source other than the forebulge is required. The wholly flexural origin of the Central Tertiary Basin proposed by Bruhn and Steel (2003) is consistent

with the decrease in thickness of basin fill from west to east, but the forebulge alone cannot be considered responsible for the relief to provide the source area for the sediments in the lower part of the basin fill.

*Timing of compression in the West Spitsbergen Fold Belt*

A key factor in determining the origin of the Central Tertiary Basin is establishing the timing of the formation of the West Spitsbergen Fold Belt. The foreland flexure origin for the basin favoured by Bruhn and Steel (2003) requires the onset shortening in the West Spitsbergen Fold Belt, and loading of the crust to the east of it, to have occurred prior to the Late Paleocene. On the basis of evidence from Northern Greenland, Manby and Lyberis (2000) argue that deformation in the West Spitsbergen Fold Belt occurred in the Late Cretaceous to Paleocene, which would be consistent with the Late Paleocene flexural subsidence forming the Central Tertiary Basin suggested by Bruhn and Steel (2003). However, this timing is disputed by other authors who contend that the main episode of compression and uplift occurred in late Paleocene and Eocene times (Maher et al., 1995; Braathen et al., 1999a). Thermochronological studies using  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  age spectra and apatite fission track length models (Blythe and Kleinspehn, 1998) indicate that uplift may have commenced in the Late Cretaceous (Manby and Lyberis, 2000), but the data also show that there was significant uplift in the Eocene (Maher, 2001). Deformation of Eocene strata in the Central Tertiary Basin confirm that shortening in the West Spitsbergen Fold Belt continued into the Eocene (Braathen et al., 1999b) but the onset is not clearly indicated by any growth geometries in the Paleocene strata.

*Provenance constraints on the origin of the Central Tertiary Basin*

Analysis of the provenance of detritus in the Central Tertiary Basin provides means to resolve some of the uncertainties related to the timing and mechanism of formation of the basin. The occurrence of clasts from a recognisable bedrock lithology in a sedimentary unit provides evidence that the bedrock was exposed and undergoing erosion at the time of deposition of the unit ('Law of Included Fragments'). This provides unambiguous evidence of the timing of uplift, provided that the pathway of the clasts from origin to deposition can be established. In the Central Tertiary Basin, conglomerate beds within the succession can be put in the context of the facies distributions within the basin and used to provide evidence of the timing of uplift in the West Spitsbergen Fold Belt.



## **THE GRØNFJORDEN BED**

The Grønfjorden Bed is a defined stratigraphic unit within the Firkanten Formation (Dallmann, 1999) and is found in the western part of the basin (Kellogg, 1975; Ohta 1992). The type locality of this conglomeratic unit is in Grønfjorden, and outcrops are well exposed on the western side of the fjord opposite the Russian coal mining settlement of Barentsburg on the southern side of Isfjorden (Fig. 3). The most complete exposure lies about 1 km from the distinctive headland of Festningen, a readily accessible coastal outcrop. A sharp unconformity surface marks the contact between the Grønfjorden Bed and the underlying unit, the Carolinefjellet Formation, which is Aptian-Albian in age (Figs 2 and 4). Viewed from the east, this contact appears to be almost horizontal. However, the apparent structural simplicity of this exposure is deceptive because the exposed section is in fact in the core of a tight syncline, and beds a few metres to the west are vertical, younger to the east. The rigidity of the conglomerate has resulted in an exposure which is much less deformed than the surrounding strata, but it is cut by a number of reverse faults which displace the unconformity surface. Faults apart, this unconformity shows less than a metre of relief in stretches of exposure over a hundred metres in length.

The beds overlying the unconformity are conglomerate throughout the exposure in Grønfjorden. The conglomerate is clast-supported and the pebble to cobble size clasts are generally well-rounded (Fig. 7) and spherical, showing little sign of imbrication. Cross-stratification in the bed is picked out by inclined lenses of coarse sandstone (Fig. 7). Overlying the beds (Figs 7 and 8) is a succession of trough-cross-bedded and cross-laminated sandstones with carbonaceous laminae. At 5.5m above the unconformity the top of a fining-up succession is marked by a shaly coal bed. The characteristics of the beds here indicate that the Grønfjorden Bed was most probably deposited by a gravelly braided river, an interpretation also reached by previous authors (Kellogg, 1975; Dallmann, 1999).

The clast composition of the conglomerate comprises a variety of very resistant lithologies: granules and small pebbles are of black chert and white vein quartz whilst the larger clasts are pale grey quartz-rich sandstones (also noted by Steel and Dalland, 1978; Bruhn and Steel, 2003) and metamorphic quartzites (also recognised by Nagy, 2005). In addition to the clasts themselves being well-lithified and the conglomerate as a whole is extremely well indurated: fractures in the beds cut through the bed cleanly, indicating that there is no difference in strength between the clasts and the cemented matrix that they are embedded in.

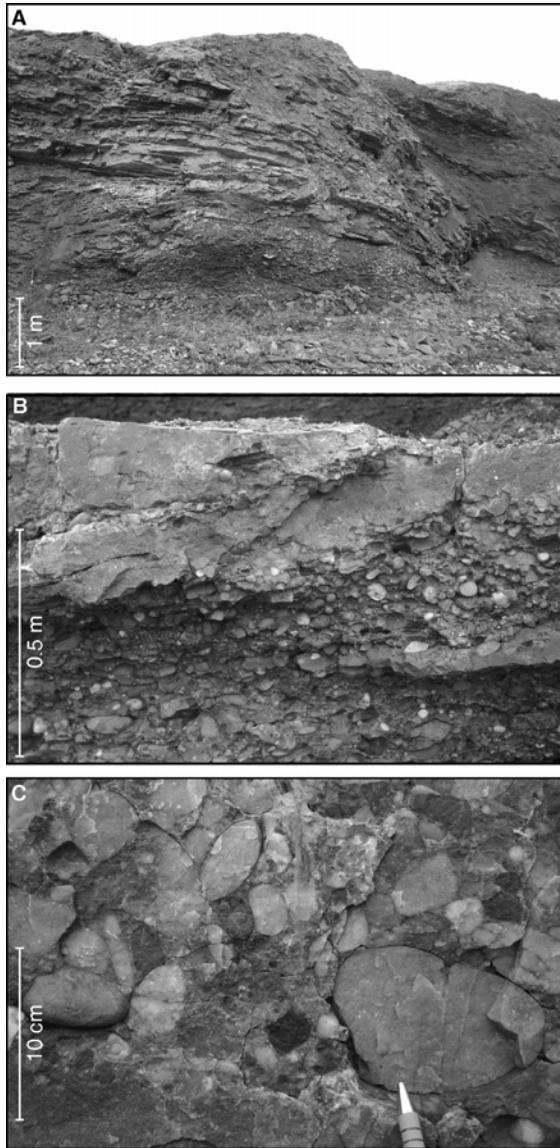


Fig. 7 Pictures of the Grøn fjorden Bed in Grøn fjorden, Spitsbergen.

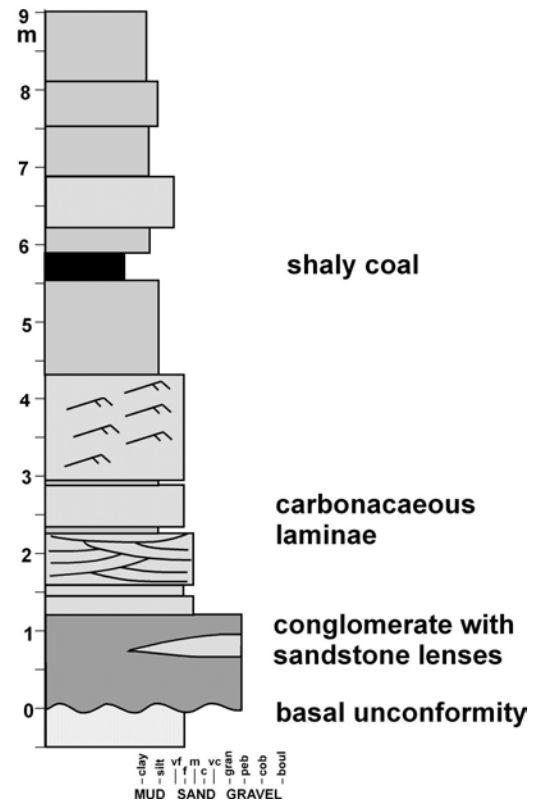


Fig. 8 Sedimentary log of the Grøn fjorden Bed from Grøn fjorden, Spitsbergen.

A further outcrop of the Grøn fjorden Bed occurs at Basilikaelva, on the south western side of Van Keulen fjord, about 80 km south of its type locality (Fig 3). The conglomerate here is 50cm thick and lies on the Carolinefjellet Formation with a sharp, low-relief unconformity. The overlying beds are mainly carbonaceous mudrocks with grey-purple mottling suggesting weakly-developed paleosols. A fluvial origin for the beds here is less clear than at Grøn fjorden, and above 12 m from the unconformity the succession is dominated by wave-rippled sandstone and bioturbated mudstones deposited in a shallow marine setting.

*Relationship with other units of the Firkanten Formation*

The Firkanten Formation is divided into a lower Todalen Member and an upper Endalen Member. The former is the coal-bearing unit and is made up predominantly of beds of fine sandstone and mudstone deposited in coastal, near shore and shallow marine environments (Lüthje and Nichols, Submitted a). Thin conglomerate beds occurring in the central and eastern parts of the basin are interpreted as transgressive lag of foreshore deposits occurring associated with major flooding surfaces at a number of levels within the succession (Lüthje and Nichols, Submitted b). Many of these conglomerates are compositionally identical to the Grønfjorden Bed, but others are made up of less spherical and less well rounded clasts of brown mudrock, interpreted as having been eroded from the Carolinefjellet Formation occurring on local highs on the unconformity (Lüthje and Nichols, Submitted a; Lüthje and Nichols, Submitted b). The quartz, quartzite and chert clasts in the Firkanten Formation are considered to have the same provenance as the Grønfjorden Bed, but their distribution in the basin is interpreted to have been by wave-driven longshore currents and storms (Lüthje and Nichols, Submitted a). They were concentrated on flooding surfaces during transgression as pebbly lags (Hart and Plint, 1989; Hart and Plint, 1995) in contrast to the fluvial origin of the Grønfjorden Bed.

*Provenance of the Grønfjorden Bed clasts*

The clast assemblage of vein quartz, grey quartzite, metamorphic quartzite and black chert found in the Grønfjorden Bed can be compared with potential sources in bedrock lithologies in the pre-Cenozoic succession on Svalbard. Considering first the Mesozoic succession, the Triassic, Jurassic and Early Cretaceous strata exposed today are dominantly mudrocks and fine sandstone beds (Dallmann, 1999) (Fig. 9). The only widespread conglomerate bed exposed in the Isfjord area is the Brentskardhaugen Bed, a very distinctive, thin (c. 1 m) orange unit of highly phosphatized small pebble conglomerate of Jurassic age. The Triassic Slottet Bed is similar to the Brentskardhaugen Bed but is only found in the southwest of Spitsbergen. Within the Early Cretaceous strata the Festningen Sandstone Member contains some well rounded and sub-spherical granules and pebbles of crystalline quartz and quartzite but metamorphic quartz clasts have not been recognised. The Mesozoic succession does not appear to be a potential source area for the clasts in the Grønfjorden Bed; moreover, clasts of brown, fine sandstone/mudstone derived from the Mesozoic which occur in the Firkanten Formation in the east of the basin, are not found in the Grønfjorden Bed.

The Palaeozoic succession exposed on Spitsbergen contains rock units that are potential source areas. Carboniferous and Permian limestones of the Gipsdalen and Templefjorden Groups are locally highly silicified and in particular the Permian Kapp Starostin Formation contains grey to black chert (Dallmann, 1999). Early Carboniferous beds of the Billefjorden Group exposed 2-3 km west of Festningen are well-indurated pale grey quartz arenites that include granules of vein quartz and elsewhere this group includes coarse, quartzitic sandstones and conglomerates (Dallmann, 1999). Devonian strata are not considered to be a likely source of the clasts in the Grønfjorden Bed because the sandstones in these strata are commonly strongly reddened. Pre-Devonian strata of the Hekla Hoek Group exposed in the West Spitsbergen Fold Belt contain a wide variety of lithologies, including metamorphic quartzites, many of which could have provided sources of the clasts seen in the Grønfjorden Bed.



Fig. 9 Fine-grained Mesozoic strata at Janusfjellet south of Isfjorden, Spitsbergen, looking south. Janusfjellet is 800m high.

The most likely provenance of the clasts in the Grønfjorden Bed is therefore from Precambrian quartzites, metaquartzites and vein quartz, some of which could have been reworked into Early Carboniferous rocks of the Billefjorden Group, and black chert from the Late Carboniferous and Permian strata. This implies that these rock units were undergoing erosion at the time of deposition of the Grønfjorden Bed in the Late Paleocene.

*Paleogeographic reconstruction*

The distribution of the fine-grained facies in the Firkanten Formation during the Late Paleocene has been established on the basis of outcrop and core data and, with the exception of the Grønfjorden Bed in the west, conglomerates only occur as thin transgressive lags and foreshore deposits or as local marine reworking of the underlying Carolinefjellet Formation (Lüthje and Nichols, Submitted a). The absence of other fluvial, conglomeratic facies in the Firkanten Formation on the eastern side of the basin indicate that the source of the detritus for the fluvial Grønfjorden Bed is most likely to have been the west or north western side of the basin. Furthermore, outcrops of Precambrian metamorphic rocks as well as Permian and Carboniferous strata occur all along the western side of the basin in the West Spitsbergen Fold Belt and are a nearby source for the pebble clasts. Outcrops of the upper Paleozoic strata also occur in the east and northeast of Spitsbergen (Fig. 3), but they would have been covered with a thick succession of Mesozoic rocks prior to late Cenozoic uplift and erosion (Dallmann, 1999).

The Grønfjorden Bed is therefore interpreted as the deposits of a river system draining into the Central Tertiary Basin from the west or northwest. The river supplied pebbly material into the shallow marine environment on the western side of the basin from where it was reworked by shallow marine wave and storm processes, then redeposited in shoreface and foreshore environments, especially during transgressive events (Lüthje and Nichols, Submitted b) (Fig. 10). The high degree of rounding of the clasts of resistant lithologies indicates that they were not directly eroded from bedrock and deposited in the Grønfjorden Bed. Vein quartz and quartzite clasts may have been components of conglomerate beds in the Billefjorden Group and had been well-rounded prior to erosion from the Carboniferous strata. It is also possible that there were several cycles of erosion and deposition during the early Cenozoic, although there is no direct evidence for this.

*Implications of the Grønfjorden Bed provenance*

The presence in the Grønfjorden Bed of pebbles that were transported from the west and are derived from Carboniferous and Permian lithologies is evidence that the West Spitsbergen Fold Belt was undergoing uplift and erosion by the Late Paleocene. Palaeogeographic reconstructions of the Mesozoic strata indicate that they extended to the west of the current outcrop area and would have overlain the Paleozoic rocks currently in the West Spitsbergen Fold Belt (Worsley et al., 1986). Palaeozoic and Mesozoic strata involved in the deformation on the eastern flank of the West Spitsbergen Fold Belt are well-exposed near Festningen (Fig.

3), and there are over 2000 m of strata between the Carboniferous quartzite units and the unconformity with the Paleocene (Ohta et al., 1992). The distribution of the shelf facies in the stratigraphic units suggests that this thickness extended west over the West Spitsbergen Fold Belt area. Therefore at least 2000 m of uplift and erosion had taken place in the West Spitsbergen Fold Belt prior to the Late Paleocene.

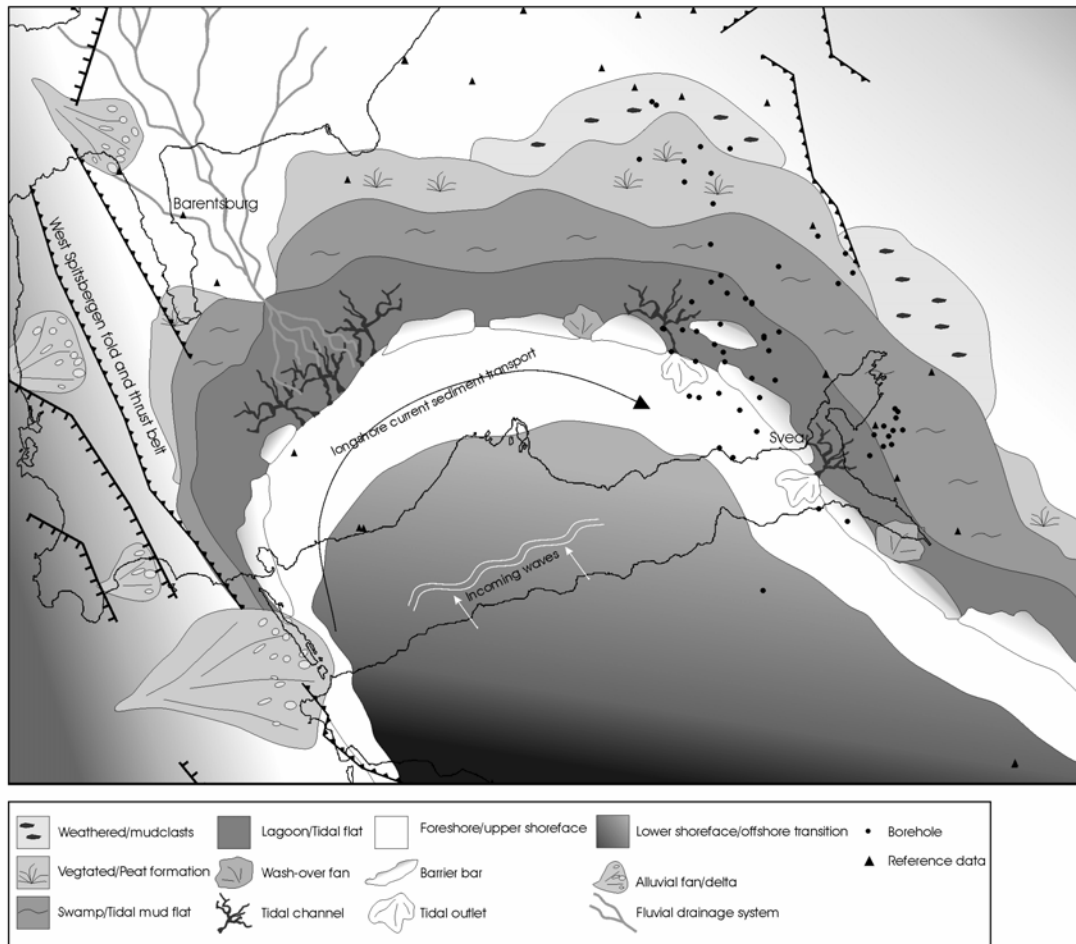


Fig. 10 Regional paleogeographic reconstruction of the Central Tertiary Basin showing sedimentary transportation pattern, fluvial drainage, and interpretation of the environmental setting, from (Lüthje and Nichols Submitted b).

### PROVENANCE OF SEDIMENT IN THE FIRKANTEN FORMATION

A striking feature of the sandstone beds in the Firkanten Formation is that the grain size is almost uniformly very fine to fine-grained (Lüthje and Nichols, Submitted a). Sands from younger units within the Central Tertiary Basin, such as the Grumantbyen and Battfjellet Formations are similarly fine-grained. In the Firkanten Formation the only significant exceptions are some coarser beds associated with the conglomerates of the Grønfjorden Bed and the pebbly transgressive lags that occur elsewhere in the succession. Petrographic

analysis of the Firkanten Formation sandstones reveals that they are dominantly well-sorted quartz arenites, and sub-lithic arenites. Lithic clasts of chert and authigenic glauconite are the most common other grain types present. These sandstones were transported and deposited mainly by wave action in the Late Paleocene, but their textural and compositional maturity indicates that they were most probably reworked from older sandstones as second or more cycle deposits.

The obvious source of fine-grained sand is the Triassic to early Cretaceous strata of Spitsbergen. The Sassendalen, Kapp Toscana, and Adventdalen Groups are dominated by mudstone and sandstone deposited in an epicontinental sea and most of the sandstone beds are very fine to fine-grained. The general trend of older rocks being exposed in the northern part of Spitsbergen is related to differences in the amount of uplift across the area. This has been related to a pulse of activity in the High Arctic Large Igneous Province in the Albian (Maher, 2001). Late Cretaceous uplift and erosion of at least 1000 m has been estimated for northern Spitsbergen (Maher, 2001) and this would have led to the removal of a considerable volume of fine-grained material being transported away from the area of uplift in the north and towards the south. The source of most of the sandy and muddy sediment for the Firkanten Formation (and probably much of the younger units of the Central Tertiary Basin) was therefore the erosion of Mesozoic strata in northern Spitsbergen.

Lüthje and Nichols (Submitted b) present a paleogeographic reconstruction based on the distribution of facies in the Late Paleocene of the Central Tertiary Basin (Figs 5 and 10). Supply of sediments into the basin is considered to be from the northwest because the shoreline facies in the central and eastern part of the basin show no evidence of fluvial or delta channels feeding into the basin from the northeast (Lüthje and Nichols, Submitted a). Wave-driven longshore currents and storm events would have transported the fine sand and mud from the northwestern corner of the basin and redistributed the material into offshore, shoreface and foreshore areas of deposition to the east and south. The sparse conglomerate beds were supplied by rivers entering the basin from the West Spitsbergen Fold Belt. Fluvial facies were deposited close to the western margin of the basin and reworked by storms and marine flooding events to form deposits further east.

## **FORMATION OF THE CENTRAL TERTIARY BASIN**

The clasts of Carboniferous and Permian lithologies in the Grønfjorden Bed provide evidence that the West Spitsbergen Fold Belt was uplifted and undergoing erosion by the Late Paleocene. The West Spitsbergen Fold Belt is known to be a fold and thrust belt (Braathen et

al., 1995; Bergh et al., 1997; Braathen et al., 1999a; Braathen et al., 1999b) and therefore the uplift can be attributed to compressional tectonics. Furthermore, the amount of erosion into the Late Palaeozoic and Mesozoic strata (c. 2000 m) indicate that the compression-related uplift had been underway for some time before the onset of sedimentation in this part of the basin. The simplest explanation for the origin of the Central Tertiary Basin is therefore that it is related to Paleocene compressional tectonics and is a flexural basin, as suggested by Bruhn and Steel (2003). The flexural basin model presented here is more consistent with provenance and facies distribution data than the extensional origin suggested by other authors (Steel et al., 1981; Steel et al., 1985).

#### *Foreland Basins formed by loading*

Basins formed by flexure of continental crust occur adjacent to mountain belts where loading by thrust sheets and nappes results in the formation of a foreland basin (Beaumont, 1981; Allen and Allen, 2005). Retroarc foreland basins form in relation to subduction-related arc magmatism at an active continental margin (Dickinson, 1974; Catuneanu, 2004), a setting which cannot be considered to apply in the case of the Central Tertiary Basin because there is no evidence of subduction or a magmatic arc in the region at that time.

Peripheral foreland basins typically form where plate collision creates an orogenic belt. The load occurs on foreland crust which may be somewhat thinned and hence flexes readily (Watts, 1992; Allen and Allen, 2005). Flexural basins in these tectonic settings show a pattern of basin fill which commences with relatively deep water facies that shallows up to shallow water and continental deposits as the sediment supply from the orogenic belt exceeds flexural subsidence (Einsele, 2000). The basin-fill succession in the Central Tertiary Basin does not follow this pattern: there are no deep marine facies in the Firkanten Formation at the base of the succession, and overall sedimentation in the basin occurred in shelf environments in two major transgressive-regressive cycles (Steel et al., 1981; Steel et al., 1985). Furthermore, the West Spitsbergen Fold Belt did not form as a result of collision of continental plates following ocean closure. During the Late Cretaceous and Early Cenozoic Spitsbergen and adjacent areas of Greenland were a zone of intraplate deformation, which went through phases of compression, transpression, transtension and extension although there is not a consensus amongst these authors on the timing and relative importance of the events ( Steel et al., 1985; Muller and Spielhagen, 1990; Lyberis and Manby, 1993b; Maher et al., 1995; Manby and Lyberis, 1996; Bergh et al., 1997; Braathen et al., 1999a; Braathen et al., 1999b; Manby and Lyberis, 2000; Bruhn and Steel, 2003).



Therefore the Central Tertiary Basin does not conform to either the peripheral or retroarc models for foreland basin development. The tectonic setting is one of intraplate deformation, not collision of two plates in either an Alpine-Himalayan orogenic belt type of setting or an Andean-type subduction-related setting.

*The mechanism of flexure to form the Central Tertiary Basin*

In the Festningen area the Carboniferous to Cretaceous strata along the boundary between the West Spitsbergen Fold Belt and the Central Tertiary Basin strike parallel to the fold belt and are steeply dipping, approximately vertical. A similar general pattern is seen at the mouth of Van Mijenfjord where vertical beds of resistant Carboniferous and Permian limestones form a long island, which projects into steep ridges to the north and south. At its type locality the Grønfjorden Bed is deformed, but the general trend of the Firkanten Formation here is vertical, parallel to the underlying Mesozoic strata. Cross-sections across the Central Tertiary Basin (Kellogg, 1975; Winsnes, 1988) show that the structure is a broad asymmetric syncline affecting all the strata from the Cenozoic down to the Carboniferous (Fig. 3b). This regional pattern and the steep beds at the boundary with the West Spitsbergen Fold Belt are consistent with the formation of the basin by compressional folding of the crust (Zhang and Bott, 2000). Numerical modelling by Zhang and Bott (2000) (Fig. 11) shows that strongly asymmetric folding of the crust related to compression across steep faults could create foreland basins which could accumulate several thousand metres of sediment. The scale of the Central Tertiary Basin compressional flexure is consistent with the models showing that the basin could be over 150 km wide, approximately the width of the Central Tertiary Basin in central Spitsbergen (100 km). The western margin of the West Spitsbergen Fold Belt is thought to be related to a major crustal lineament, the Hornsund fault zone (Harland, 1997), a structure that could have acted as the steep fault that controls the location of the western side of the asymmetric flexure in the crust (Zhang and Bott, 2000). There is no sign of significant advance of the deformation front during deposition in the Central Tertiary Basin, and deformation in the Late Paleocene to Eocene is limited to rotation through to vertical close to the West Spitsbergen Fold Belt and minor reverse faults further east. To the east the Billefjorden and/or Lomfjorden-Agardhbukta fault zones may have limited the folding, although evidence for post-Mesozoic movement is limited to a small change in regional dip on either side of the Billefjorden fault zone.

The compressional folding model of basin formation does not require a thick pile of thrust sheets to be stacked up to create the load for flexural deformation of the crust. This is consistent with the fact that the West Spitsbergen Fold Belt is a relatively small mountain

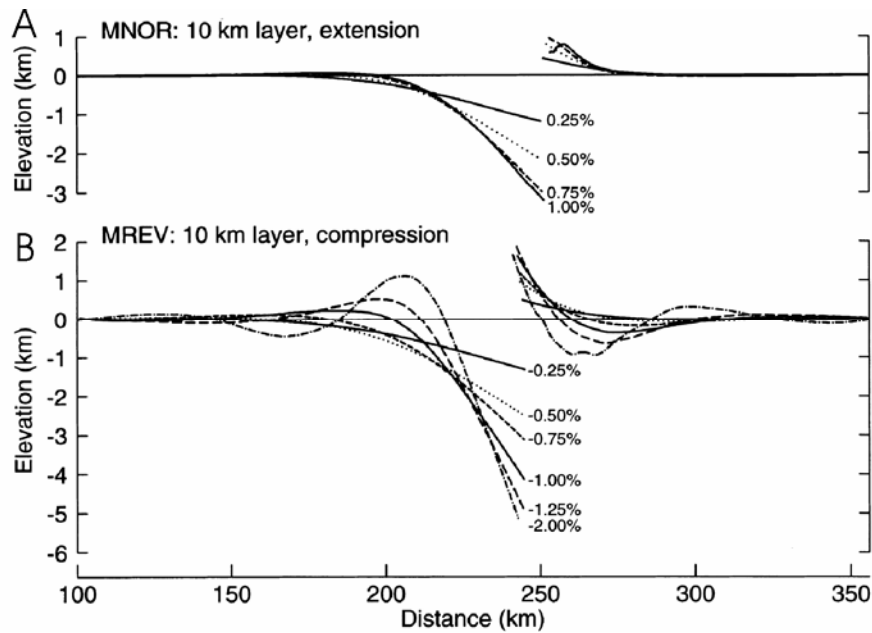


Fig. 11 Modelled basin profiles of (A) extensional normal faulted model versus (B) compressional 10-km-thick reverse faulted model development. The stacked flexure profiles compare the evolution to increased stretching (0.25% to 1.00% strain) respectively shortening ( $-0.25\%$  to  $-2.00\%$  strain), after (Zhang and Bott, 2000).

belt, only 35 km wide perpendicular to strike in central Spitsbergen, although the width may have been greater in the Paleocene. There is some indirect palaeontological evidence that the West Spitsbergen Fold Belt did not form a major mountain belt in the Palaeocene. The recent discovery of tracks made by Late Paleocene Pantodonts in the Firkanten Formation (Lüthje et al., Submitted) is the first evidence of these mammals migrating from North America to Eurasia. This migration would have been impeded by either a seaway or a mountain barrier between Spitsbergen and Greenland. Uplift in the West Spitsbergen Fold Belt related to intraplate compression must therefore have been sufficient to promote erosion of around 2000 m of rock, but by the Late Paleocene the relief created was not enough to impede the passage of Pantodonts.

## CONCLUSIONS

The provenance of pebbles deposited at the western margin of the Central Tertiary Basin in the Late Paleocene provides an important indicator of the mechanism of basin formation. The most probable source of these clasts is from Carboniferous and Permian strata in the adjacent West Spitsbergen Fold Belt and this requires that about 2000 m of strata were eroded at some point during the Late Cretaceous and Early Paleocene. Uplift must therefore have commenced prior to the Late Paleocene and this means that the compression to create the West Spitsbergen Fold Belt had started by this time. The formation of the Central Tertiary Basin is

considered to be related to this compression, not by thrust sheet loading but by long wavelength asymmetric folding associated with a steep fault between the Central Tertiary Basin and the West Spitsbergen Fold Belt.

As the Central Tertiary Basin developed it was supplied mainly by mud and fine sand eroded from Mesozoic rocks in northern Spitsbergen, an area that had undergone uplift in the Late Cretaceous. Small amounts of coarser detritus were supplied directly from the West Spitsbergen Fold Belt in the west. The eastern side of the basin underwent less subsidence as the magnitude of the flexure decreased eastwards. This combined with the absence of significant sediment input from the east, provided the most favourable conditions for peat accumulation leading to the thickest coal seams of the Firkanten Formation occurring here. Sedimentation in the basin occurred in shallow marine environments, and through the Paleocene progressive transgression forced the coastline further north as the accommodation created by flexural subsidence during this period exceeded the sediment supply.

#### **ACKNOWLEDGEMENTS**

SNSK (Store Norske Spitsbergen Kulkompani) are thanked for providing access to their data records and core store facilities. G. Nichols acknowledges the support of the University Centre on Svalbard (UNIS) and C. Lüthje would also like to thank SNSK for providing funding for a PhD project carried out at UNIS and at the University of Bergen, Norway. M. Lüthje is acknowledged for careful reading of the manuscript.

#### **REFERENCES**

- ALLEN, P.A. & ALLEN, J.R. (2005) *Basin Analysis, Principles and Applications*. Blackwell Publishing, Oxford.
- BEAUMONT, C. (1981) Foreland basins. *Geophys. J. R. Astr. Soc.*, **65**, 291-329.
- BERGH, S.G., BRAATHEN, A. & ANDRESEN, A. (1997) Interaction of Basement-Involved and Thin-Skinned Tectonism in the Tertiary Fold-Thrust Belt of Central Spitsbergen, Svalbard. *AAPG Bulletin*, **81**, 637-661.
- BERGH, S.G., MAHER, H.D. & BRAATHEN, A. (2000) Tertiary Divergent Thrust Directions from Partitioned Transpression, Broggerhalvoya, Spitsbergen. *Norsk Geologisk Tidsskrift*, **80**, 63-81.
- BLYTHE, A.E. & KLEINSPEHN, K.L. (1998) Tectonically Versus Climatically Driven Cenozoic Exhumation of the Eurasian Plate Margin, Svalbard: Fission Track Analyses. *Tectonics*, **17**, 621-639.

- BRAATHEN, A. & BERGH, S.G. (1995) Kinematics of Tertiary Deformation in the Basement-Involved Fold-Thrust Complex, Western Nordenskiöld-Land, Svalbard - Tectonic Implications Based on Fault-Slip Data-Analysis. *Tectonophysics*, **249**, 1-29.
- BRAATHEN, A., BERGH, S.G. & MAHER, H.D. (1995) Structural Outline of a Tertiary Basement-Cored Uplift Inversion Structure in Western Spitsbergen, Svalbard - Kinematics and Controlling Factors. *Tectonics*, **14**, 95-119.
- BRAATHEN, A., BERGH, S.G. & MAHER, H.D. (1999a) Application of a Critical Wedge Taper Model to the Tertiary Transpressional Fold-Thrust Belt on Spitsbergen, Svalbard. *Geological Society Of America Bulletin*, **111**, 1468-1485.
- BRAATHEN, A., BERGH, S., KARLSEN, F., MAHER, H., ANDRESEN, A., HANSEN, A.I. & BERGVIK, A. (1999b) Kinematics of the Isfjorden-Ymerbukta Fault Zone: A Dextral Oblique-Thrust Ramp in the Tertiary Fold-Thrust Belt of Spitsbergen. *Norsk Geologisk Tidsskrift*, **79**, 227-239.
- BRUHN, R. & STEEL, R. (2003) High-Resolution Sequence Stratigraphy of a Clastic Foredeep Succession (Paleocene, Spitsbergen): An Example of Peripheral-Bulge-Controlled Depositional Architecture. *Journal of Sedimentary Research*, **73**, 745-755.
- CATUNEANU, O. (2004) Retroarc Foreland Systems-Evolution through Time; Geological Society of Africa Presidential Review, No. 7. *Journal of African Earth Sciences*, **38**, 225-242.
- CEPEK, P. & KRUTZSCH, W. (2001) Conflicting Interpretations of Tertiary Biostratigraphy of Spitsbergen and New Palynological Results. In: *Intra-Continental Fold Belts; Case 1: West Spitsbergen, Geologisches Jahrbuch; Polar Issue No. 7* (Ed. by F. Tessensohn), 551-599. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
- DALLMANN, W.K. (1999) *Lithostratigraphic Lexicon of Svalbard*. Norsk Polarinstitut.
- DICKINSON, W.R. (1974) Plate Tectonics and Sedimentation. *SEPM Special Publication No. 22*, 1-27.
- EINSELE, G. (2000) *Sedimentary Basins; Evolution, Facies, and Sediment Budget*, Second edn. Springer-Verlag, Berlin.
- HARLAND, W.B. (1997) *The Geology of Svalbard*. Memoirs of the Geological Society London.
- HART, B.S. & PLINT, A.G. (1989) Gravelly Shoreface Deposits: A Comparison of Modern and Ancient Facies Sequences. *Sedimentology*, **36**, 551-557.
- HART, B.S. & PLINT, A.G. (1995) Gravelly Shoreface and Beachface Deposits. In: *Clastic Facies Analysis - a Tribute to the Research and Teaching of Harold G. Reading* (Ed. by A. G. Plint), 75-99. International Association of Sedimentologists, Special Publication 22.

- HELLAND-HANSEN, W. (1990) Sedimentation in Paleogene Foreland Basin, Spitsbergen. *The American Association of Petroleum Geologists Bulletin*, **74**, 260-272.
- KELLOGG, H.E. (1975) Tertiary Stratigraphy and Tectonism in Svalbard and Continental Drift. *The American Association of Petroleum Geologists Bulletin*, **59**, 465-485.
- LIVSIC, J.J. (1974) Palaeogene Deposits and the Platform Structure of Svalbard. *Norsk Polarinstitutt Skrifter*, 51.
- LÜTHJE, C. & NICHOLS, G. (Submitted a) Coal Formation in a Coastal Plain Setting, Paleocene, Spitsbergen, Arctic Norway. *Sedimentology*.
- LÜTHJE, C. & NICHOLS, G. (Submitted b) Transgressive Coastal Plain to Shallow Marine Development of the Paleocene Strata of Spitsbergen, Arctic Norway. *Journal of Sedimentary Research*.
- LÜTHJE, C., MILÀN, J. & HURUM, J. (Submitted) Paleocene Tracks of the Pantodont Genus Titanoides in Coal-Bearing Strata, Svalbard, Arctic Norway. *Proceedings of the Royal Society B*.
- LYBERIS, N. & MANBY, G. (1993a) The Origin of the West Spitsbergen Fold Belt from Geological Constraints and Plate Kinematics - Implications for the Arctic. *Tectonophysics*, **224**, 371-391.
- LYBERIS, N. & MANBY, G. (1993b) The West Spitsbergen Fold Belt - the Result of Late Cretaceous-Paleocene Greenland-Svalbard Convergence. *Geological Journal*, **28**, 125-136.
- MAHER, H. (2001) Manifestations of the Cretaceous High Arctic Large Igneous Province in Svalbard. *The Journal of Geology*, **109**, 91-104.
- MAHER, H.D., BRAATHEN, A., BERGH, S., DALLMANN, W. & HARLAND, W.B. (1995) Tertiary or Cretaceous Age for Spitsbergen's Fold-Thrust Belt on the Barents Shelf. *Tectonics*, **14**, 1321-1326.
- MANBY, G. & LYBERIS, N. (1996) State of Stress and Tectonic Evolution of the West Spitsbergen Fold Belt. *Tectonophysics*, **267**, 1-29.
- MANBY, G. & LYBERIS, N. (2000) Pre-Ocean Opening Compression of the Northwestern Atlantic Margin: Evidence from Eastern North Greenland. *Journal Of The Geological Society*, **157**, 707-710.
- MANUM, S.B. & THRONSEN, T. (1978) Rank of Coal and Dispersed Organic Matter and Its Geological Bearing in the Spitsbergen Tertiary. *Norsk Polar institutt årsbok 1977*, 159-177.
- MANUM, S.B. & THRONSEN, T. (1986) Age of Tertiary Formations on Spitsbergen. *Polar Research*, **4**, 103-131.

- MULLER, R.D. & SPIELHAGEN, R.F. (1990) Evolution of the Central Tertiary Basin of Spitsbergen - Towards a Synthesis of Sediment and Plate Tectonic History. *Palaeogeography Palaeoclimatology Palaeoecology*, **80**, 153-172.
- NAGY, J. (2005) Delta-Influenced Foraminiferal Facies and Sequence Stratigraphy of Paleocene Deposits in Spitsbergen. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **222**, 161-179.
- OHTA, Y., HJELLE, A., ANDRESEN, A., DALLMANN, W. & SALVIGSEN, O. (1992) Geological Map of Svalbard B9g Isfjorden. *Norsk Polarinstitutt Temakart*, Norwegian Polar Institute. Oslo.
- PAECH, H.-J. (2001) Compressive Structures in the Central Basin, Spitsbergen. In: *Intra-Continental Fold Belts; Case 1: West Spitsbergen, Geologisches Jahrbuch; Polar Issue No. 7* (Ed. by F. Tessensohn), 413-442. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
- SAALMANN, K. & THIEDIG, F. (2001) Tertiary West Spitsbergen Fold and Thrust Belt on Broggerhalvoya, Svalbard: Structural Evolution and Kinematics. *Tectonics*, **20**, 976-998.
- SAALMANN, K. & THIEDIG, F. (2002) Thrust Tectonics on Broggerhalvoya and Their Relationship to the Tertiary West Spitsbergen Fold-and-Thrust Belt. *Geological Magazine*, **139**, 47-72.
- STEEL, R. & DALLAND, A. (1978) Undersøkelser Av Den Kullførende Del Av Firkanten Formasjonen (Tertiær) I Østlige Del Av Nordenskiöld Land Svalbard, Geologisk Institutt Universitetet i Bergen, 62.
- STEEL, R., DALLAND, A., KALGRAFF, K.L. & LARSEN, V. (1981) The Central Tertiary Basin of Spitsbergen - Sedimentary Development in a Sheared Margin Basin. In: *Geology of the North Atlantic Borderlands* (Ed. by J. W. Kerr & A. J. Fergusson), 647-664. Canadian Society of Petroleum Geologists, Memoir 7.
- STEEL, R. & WORSLEY, D. (1984) Svalbard's Post-Caledonian Strata - an Atlas of Sedimentological Patterns and Palaeogeographic Evolution. In: *Petroleum Geology of the North European Margin* (Ed. by A. M. e. a. Spencer), 109-135. Graham & Trotman, London.
- STEEL, R., GJELBERG, J., HELLAND-HANSEN, W., KLEINSPEHN, K., NØTTVEDT, A. & RYE-LARSEN, M. (1985) The Tertiary Strike-Slip Basin and Orogenic Belt of Spitsbergen. *Society of Economic Paleontologists and Mineralogists Special Publication No. 39*, 339-359.
- WATTS, A.B. (1992) The Effective Elastic Thickness of the Lithosphere and the Evolution of Foreland Basins. *Basin Research*, **4**, 169-178.

- WINSNES, T.S. (1988) Bedrock Map of Svalbard and Jan Mayen. *Norsk Polarinstitutt Temakart*, Norwegian Polar Institute. Oslo.
- WORSLEY, D., AGA, O.J., DALLAND, A., ELVERHØI, A. & THON, A. (1986) *The Geological History of Svalbard, Evolution of an Actic Archipelago*. Statoil, Asker Trykkeri, Stavanger.
- ZHANG, G.-B. & BOTT, M.H.P. (2000) Modelling the Evolution of Asymmetrical Basins Bounded by High-Angle Reverse Faults with Application to Foreland Basins. *Tectonophysics*, **322**, 203-218.

**7. ARTICLE 4 - PANTODONT TITANOIDES, PALEOCENE SVALBARD**

**Article 4**

**Paleocene tracks of the Pantodont genus *Titanoides* in coal-bearing strata, Svalbard**

**C. Lüthje**

University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway.

**Jesper Milàn**

Geological Institute, University of Copenhagen, Øster Voldgade 10, 1350  
Copenhagen K, Denmark

**Jørn Hurum**

Natural History Museum (Geology), University of Oslo, P.O. box 1172 Blindern,  
0318 Oslo, Norway

Submitted to Proceedings of the Royal Society B

Citation: Lüthje, C., Milàn, J. and Hurum, J. Submitted. Paleocene tracks of the Pantodont genus *Titanoides* in coal-bearing strata, Svalbard, Arctic Norway. Proc. R. Soc. B.



# Paleocene Tracks of the Mammal Pantodont genus *Titanoides* in Coal-Bearing Strata, Svalbard, Arctic Norway

Charlotta Lüthje<sup>1</sup>, Jesper Milàn<sup>2</sup>, and Jørn Hurum<sup>3</sup>

<sup>1</sup> University Centre on Svalbard, P.O. Box 156, Longyearbyen, N-9171, Norway

E-mail: lott@lythje.com

<sup>2</sup> University of Copenhagen, Øster Voldgade 10, 1210 København K, Denmark

<sup>3</sup> University of Oslo, Postboks 1172 Blindern, 0318 Oslo, Norway

## Abstract

Large footprints in Paleocene coal deposits from Svalbard were recently discovered. The age, large size, and excellent preservation of the tracks enabled genus-level identification of the track maker to the Pantodont *Titanoides*. These are the earliest evidence of a large mammal on the Arctic islands and are the northernmost discovery from the Paleocene. The traces are described in detail and are named *Thulitheripus svalbardii* Ign nov. isp. nov. Large Paleocene Pantodonts are previously only known from North America. The presence of Pantodonts in the Paleocene strata of Svalbard, confirms the postulated DeGeer route for migration of mammals in the Paleocene/Eocene.

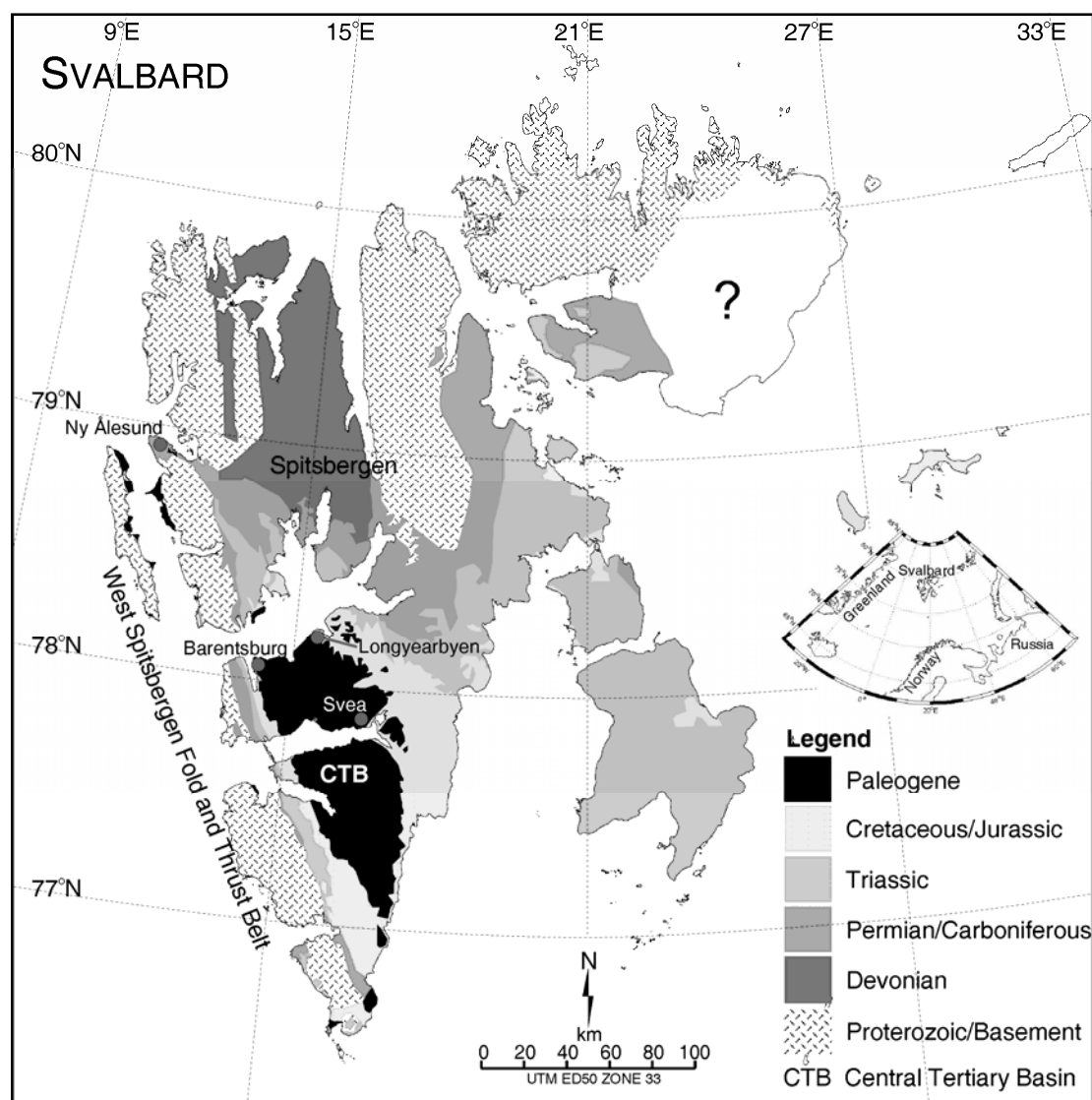
**Keywords:** Pantodont, *Titanoides*, *Thulitheripus svalbardii* Ign nov. isp. nov., Paleocene, coastal plain, Svalbard

## 1. Introduction

This is the first discovery of fossil mammal footprints on Spitsbergen in the Svalbard archipelago, Arctic Norway. Size and excellent quality of the footprints make them unique and provide a possibility to identify the track maker and its implication for understanding the regional geology. The tracks were discovered on the 20<sup>th</sup> December 2006 by the miners Håvard Dyrkollbotn and Kent Solberg, in the roof of the coal mine (Gruve 7) in Longyearbyen (Fig. 1). This coal is in the Todalen Member of the Firkanten Formation (Fig. 2), of Paleocene age (Manum and Throndsen, 1986).

The track record of Paleocene mammals are scarce and so far only a handful of tracks and trackways are described worldwide e.g. (McCrea *et al.*, 2004; Lucas 2007). There are no known skeletal remains of mammals from the Paleocene of Svalbard and the adjacent

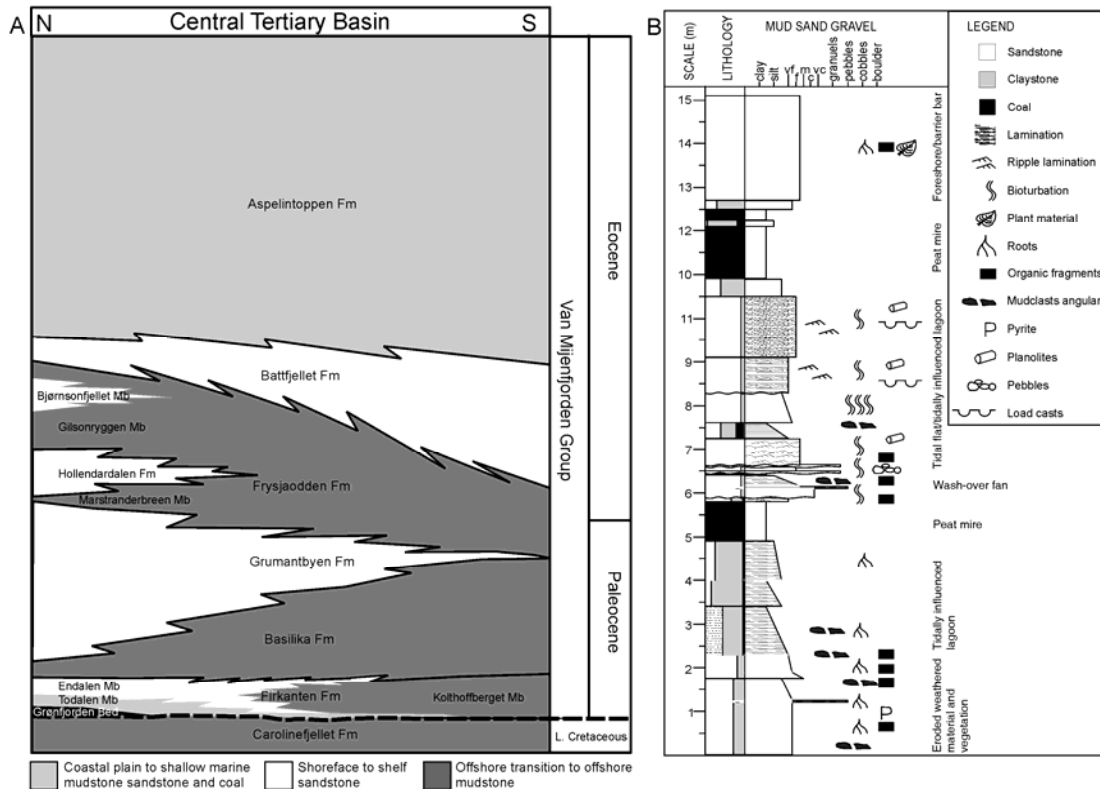
Paleocene deposits of Greenland have so far not yielded any vertebrate fossils either. The only vertebrate fossil ever recorded from this unit on Svalbard is an amiid fish (Lehman, 1951). The size of the footprints implies they were made by a large mammal.



**Fig. 1** A simplified geological map of Svalbard. The main Paleogene strata are found in the Central Tertiary basin that occupies the centre of the southern part of the main island, Spitsbergen, after (Dallmann, 1999).

## 2. Geological background

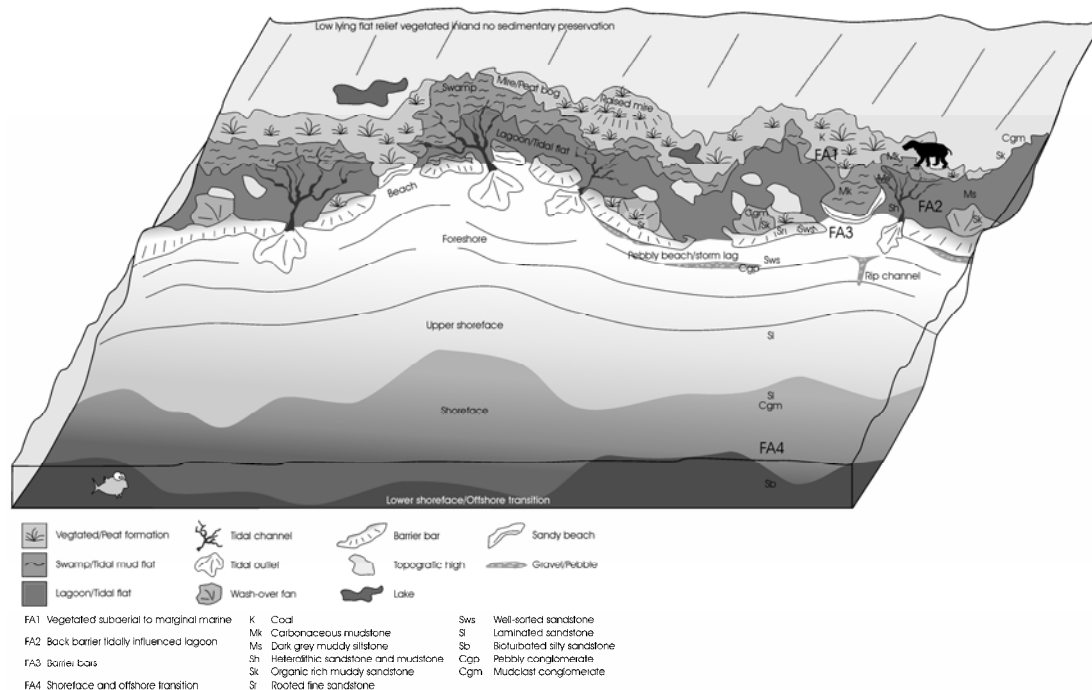
The main Paleogene succession on Spitsbergen is found in the Central Tertiary Basin (Fig. 1) consisting of 1.9 km clastic strata (Dallmann, 1999) deposited in a flexural basin (Nichols and Lüthje, Submitted). The Todalen Member of the Firkanten Formation is the lowest stratigraphic unit and is separated from the underlying Carolinefjellet Formation (Albian/Aptian) by an unconformity representing about 35 million years (Fig. 2). The



**Fig. 2** (A) The stratigraphy of the Paleogene Van Mijenfjorden Group in the Central Tertiary Basin of Spitsbergen, from (Lüthje and Nichols, Submitted b), based partly on (Bruhn and Steel, 2003; Steel *et al.*, 1985), geometries are based on relative thickness variations (Dallmann, 1999) over the basin. (B) Sedimentary log of core BH05-2004, from a location near Gruve 7.

Firkanten and Basilika Formations (Fig. 2A) form a general transgressive succession (Lüthje and Nichols, Submitted a) from continental and marginal marine coastal plain to shoreface and offshore transition (Steel *et al.*, 1981; Dallmann, 1999; Lüthje and Nichols, Submitted b). The Todalen Member was deposited in a marginal marine to coastal plain setting, characterised by tidally influenced lagoons protected by sandy barrier bars (Fig. 3) (Lüthje and Nichols, Submitted b). On the coastal plain large peat mire complexes built up the thick coal seams being mined today. The tracks were found at the boundary between the coal and overlying sandy deposits.

In Paleogene time Svalbard was situated closely to the northern part of Greenland and Ellesmere Island, Canada (Fig. 4) (Blythe and Kleinspehn, 1998). The convergence with Greenland due to plate movement in connection with the opening of the Northern Atlantic created the western fold and thrust belt and the related flexural basin (Blythe and Kleinspehn, 1998; Nichols and Lüthje, Submitted).



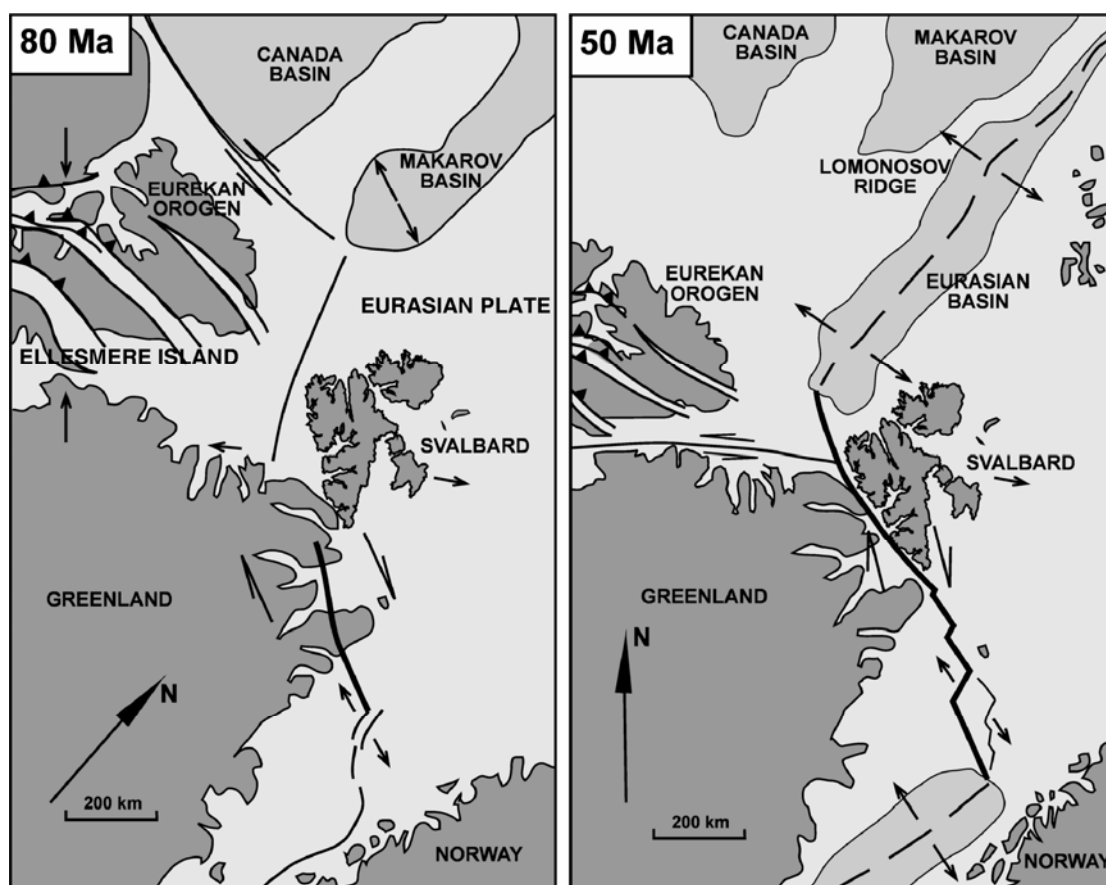
**Fig. 3** Conceptual diagram of the depositional environment and the distribution of facies and facies associations in the Firkanten Formation, from (Lüthje and Nichols, Submitted b). The pantodonts tracks were found at the boundary between coal and wash-over fan deposits represented by the swamp environment. The animals are likely to have lived in the vegetated near coastal zone where the large peat mires were situated.

### 2.1 Locality Gruve 7, Longyearbyen

The tracks were found at the boundary between the coal and overlying muddy, organic-rich fine grained sandstone (Fig. 2B). The coal, which is high bituminous, was accumulated as peat in extensive mire complexes on the coastal plain (Fig. 3) and has been mined several places on Svalbard the last 100 years.

Normally tracks would not be expected to be preserved in coal since it originates from peat, which is not expected to keep an imprint. However, tracks and trackways are commonly encountered in the top surface of coal seams as the lithological differences between the coal and the overlying sediments are optimal for track preservation e.g. (Peterson, 1924; Parker and Balsby, 1989; Parker and Rowley, 1989; Hurum *et al.*, 2006). Furthermore, the worldwide commercial coal quarrying helps to expose large, potentially track-bearing surfaces.

The tracks in Gruve 7 also are situated in a 2-5 cm thick layer of sapropelic coal on top of the ombrotrophic coal. Sapropelic coal is normally produced by algal, bacterial, or fungal organic production in stagnant swamps under anaerobic conditions (McCabe, 1984) and greatly improved the possibilities for preservation of the tracks. The tracks show that the animals sunk deep into the sticky substrate leaving a good imprint since an algal mat does not have the

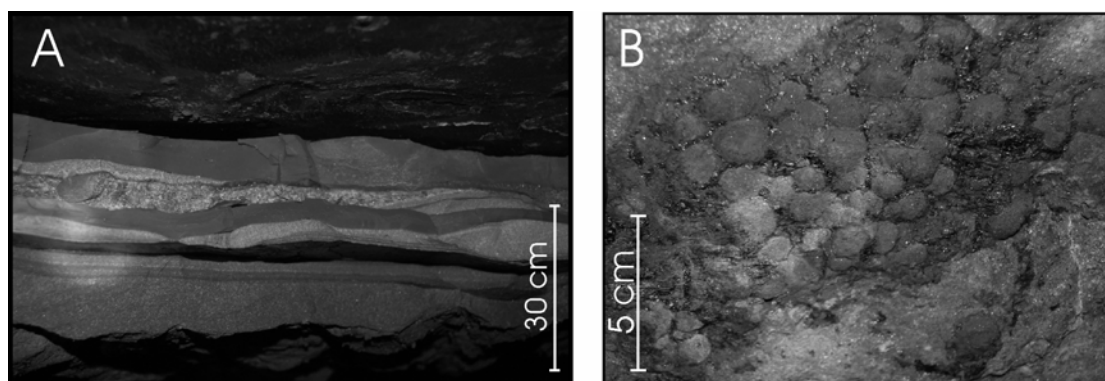


**Fig. 4** Plate reconstruction of Svalbard and Greenland in the Late Cretaceous and Eocene, after (Blythe and Kleinspehn, 1998).

same elastic properties as peat. Some of the tracks were found to have been imprinted in the sandstone on top of the coal. This suggests that they are either of slightly later in time (hours) and/or the surface area was mud covered in places and sandy in others.

The preservation of the tracks was also improved by being covered shortly after by fine grained sandstone from the marine transgression that were already ongoing. The sapropelic coal indicates a base level rise where the environment became too waterlogged for peat production and therefore became a swamp. The mire was flooded by raised ground water level, which is characteristic for swamps. Swamps can be influenced by both fresh and marine salt water. In this case the following marine transgression on top of the coal indicates that the swamp was created by marine flooding from a rising relative sea level.

The sandstone on top of the tracks is organic-rich with poor structural development and pebbly layers (Figs 2B and 5A). The section is interpreted to represent part of a wash-over fan deposited on top of the swamp and the mire by the marine transgression. *Teredolites* trace fossils (Fig. 5B) found in the overlying sandstone were created by marine burrowing and dwelling bivalves that typically bore into organic deposits that are flooded (Pemberton *et al.*, 1992).



**Fig. 5** (A) Wash-over fan deposits on top of sapropelic coal. (B) *Teredolites* trace fossils.

### 3. The track assemblage

The track assemblage consists of 17 individual imprints exposed on a 5 metres stretch along the roof of the coal mine. All tracks are preserved as natural casts of silty sandstone (Fig. 6).

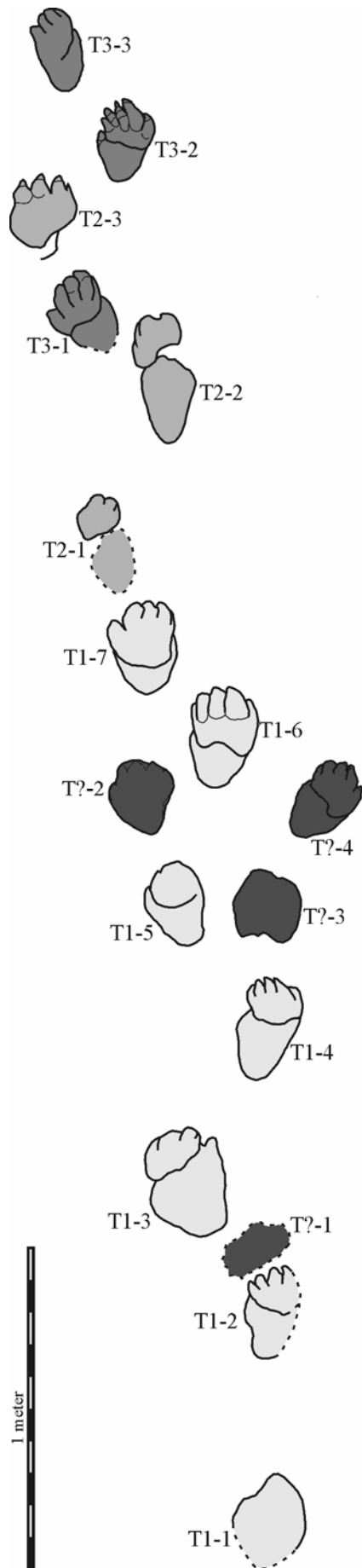
#### 3.1 Trackways

The tracks can be divided into three individual trackways, based on differences in size and pace length. Four individual tracks can not readily be assigned to any specific trackway (Fig. 7). The three trackways are numbered T1–T3, with each individual track within the trackway numbered in running order. The four unassigned tracks are designated T?.

The trackways are set in a narrow gauge pattern, with the tracks from left and right side of the animal set close to the midline of the trackway. Manus (fore limb) and pes (back limb) imprints are pentadactyl, with short, broad digits. The pes impressions are in most cases partly overstepping the manus impression, obscuring the details of the pedal digits, and hindering



**Fig. 6** Photo of the tracks as they were discovered in the roof of the coal mine, 1 metre ruler for scale.



exact measurements of the dimensions of the pes. The size of the manus imprint is on average half the size of pes imprints, ranging from one third to two thirds the size of the pes. The manus are more deeply impressed than the pes, typically several centimetres deeper than the pes. However, a few pes tracks are found impressed behind the manus imprint showing the complete pedal imprint.

### 3.2 Manus

The manus imprints are pentadactyl. The impression of digits III and IV are the longest with digits II – I of decreasing length and digit V is of equal length to digit I. Each digit impression terminates in the impression of short laterally compressed sharp claws. In the best preserved specimens, a weak division of the digits into digital pads are present (Fig. 8).

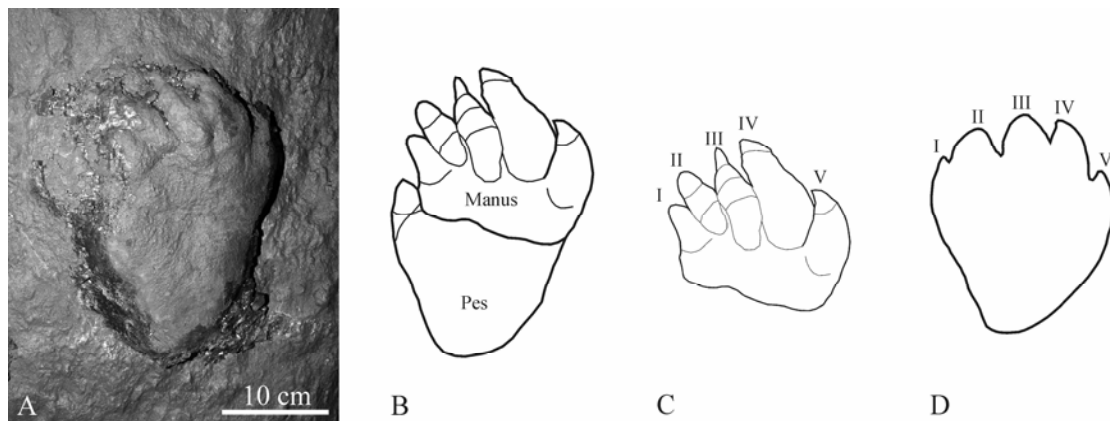
### 3.3 Pes

The pes are partly overstepping the manus imprints in most of the observed specimens in the trackways, so only the rear end of the pes imprint is preserved, hindering descriptions of the digits. In two cases the pes is not overstepping the manus (Fig. 7, T2-1 and T2-2), but unfortunately the tracks are too indistinctly preserved to reveal any anatomical details.

**Fig. 7** Sketch of the complete track assemblage from the mine. The sketch is redrawn from a photograph mosaic of the mine roof. The tracks belonging to the three different trackways are indicated by different shades of grey and each trackway is numbered T1 – T3, with each consecutive track numbered. The four tracks designated T? Indicates tracks that can not be assigned to the three trackways. Tracks indicated by broken lines are very badly preserved or damaged during mining.

One specimen however has preserved the complete pes imprint (Fig. 7, T?-2). The specimen was found detached from the sand layer on top of the coal seam. From below it appeared as a smooth subcircular rounded depression filled with sandstone. When carefully excavated the upper side of the cast revealed the perfect impression of a pes.

The pes imprint is pear shaped and measures 24 cm in length and 22 cm in width. There are impressions of five short, triangular, forward facing, hoof-like digits, with the middle digit being the longest being with a length of 4 cm, and the adjacent digits, subsequently shorter (Fig 8).



**Fig. 8** (A) Well-preserved partly overlapping manus and pes impression. Notice the sharp terminations of the digits. (B) Interpretative sketch of the track, with anatomical features of the feet. (C) Manus reconstructed without the partly overprinting pes. (D) Pes reconstructed from several partly well-preserved specimens.

### 3.4 Interpretations of tracks and trackways

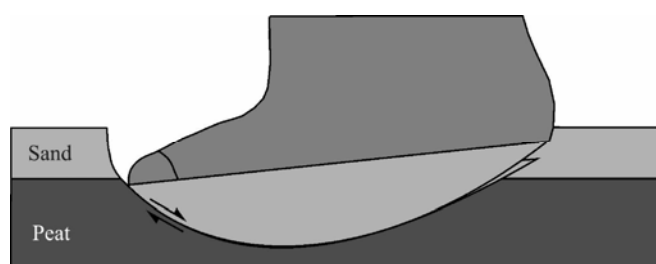
All the tracks are deeply impressed into the substrate but the manus prints are more deeply impressed than the pes prints. The impressions of the manual digits are preserved as elongated impressions representing the movement of the digits first sinking deeply into the substrate and subsequently being lifted out of the substrate, which hinders the reconstruction of the exact manus shape. The pes impressions are in all but three specimens partly overprinting the manus impressions. However, they have been lesser impressed into the substrate, and thereby in most cases not leaving any impressions of the pedal digits. In two examples the pes impression is located behind the manus impressions, but in these cases the pes impressions are too poorly preserved to reveal anything but the gross shape of the pes. The only complete pes impression is the one preserved as part of the rounded depression.

The peculiar morphology of the sandstone depressions with the pes imprint is the result of the foot being emplaced on a relatively firm substrate, creating a rotated disc of material below the foot during the kick-off when the weight of the animal are transferred to the distal parts of the digits (Thulborn and Wade, 1998). This exercises a downward and backward force on



the sediment subjacent to the foot, creating the rotated disc below the foot. Faint striations from the rotation are preserved on the underside of the disc. A condition similar to the formation of rotated discs is described from Middle Jurassic theropod tracks from the Entrada Sandstone in Utah (Graversen *et al.*, 2007).

The majority of the tracks are preserved as natural casts of true tracks, and sapropelic coal is preserved squeezed between the casts of the digit impressions, demonstrating that the animals were walking directly on top of the mire/swamp deposit before it was covered. The two tracks preserved as rotated discs, are emplaced later than the trackways, as the rotated disc itself is composed of the same sandstone that overlies the coal seam. The tracks have thereby been emplaced after deposition of the sandlayer (Fig. 9).



**Fig. 9** The tracks preserved as rotated discs of sandstone, are formed when the animal walks on a few cm thin layer of sand deposited on top of the peat. When the weight of the animal is transferred forward during the stride, the sandlayer below the foot breaks and forms a rotated disc below the foot.

#### 4. Systematic ichnology

This is the first worldwide record of such large-sized, well-preserved tracks and trackways from the Paleocene, and we erect the following new ichnogenus and species to accommodate them, *Thulitheripus svalbardii* Ign nov. isp. nov.

*Thulitheripus* Ign. nov.

Diagnosis: Late Paleocene, quadrupedal narrow-gauge trackway, manus and pes pentadactyl with impressions of short forward facing digits. Digits III and IV are the longest with digits II – I of decreasing length and digit V is of equal length to digit I. The pes is trapezoid in outline and almost symmetrical along the midline. The digits are triangular in shape, digit III being the longest with the adjacent digits being subsequently shorter. Manus impression is on average half the size of the pes impression.

*Thulitheripus svalbardii* Isp. nov.

Diagnosis: *Thulitheripus* having impressions of sharp laterally compressed claws on the manual digits. Pedal digits terminate in impressions of blunt hoof-shaped claws.

Holotype: a double track showing manus and pes in the collection of Svalbard Museum (SVB 2058), Longyearbyen, Norway.

Additional material: a double track showing manus and pes (SVB 2059) a double track showing manus and pes (SVB 2060) and a track showing pes (SVB 2061).

Etymology: *Thulitheripus*, Thulitheri, meaning great beast from the north and Pus, a foot. *Svalbardii* after the Arctic island Svalbard where the tracks are found.

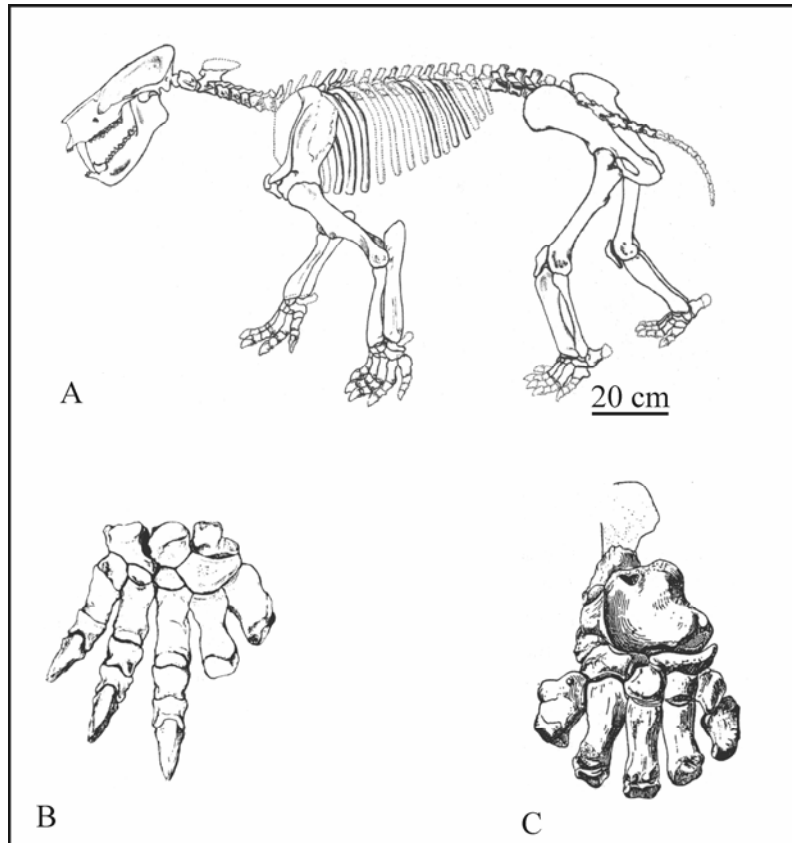
Type locality: Ceiling of the coal mine Gruve 7, 12 km southeast of Longyearbyen in the mountain Breinosa, on Svalbard, Arctic Norway, in Paleocene strata of the Todalen Member, Firkanten Formation, Van Mijenfjorden Group.

### **5. Taxonomic identification: Pantodont Titanoideidae**

The detailed preservation of the tracks enables a unique identification of the track maker on a high taxonomic level. The late Palaeocene age, the size, and the morphology of the tracks strongly suggests that the tracks have been made by pantodonts which were the only known mammals with a sufficient body-size during the Palaeocene (Rose, 2006). The configuration of blunt claws on the hind feet and sharp laterally compressed claws on the forefeet suggests that the tracks are made by a Titanoideid pantodont like *Titanoides* (Coombs, 1983; Lucas, 1998). Titanoideids are the only large pantodonts in the Paleocene which possessed laterally compressed claws on the manus (Fig. 10). The claws of the pes are unknown in *Titanoides*, but based on the track evidence, it is suggested that Titanoideidae possessed blunt hoofs on the pes. All other known pantodont genera with preserved manus and pes had blunt hoofs on both (Rose, 2006).

Purported pantodont tracks have previously been reported from the Eocene Checkanut Formation, Northeastern Washington, but these tracks are only preserved as indistinct rounded depressions, without any anatomical details about the foot morphology of the track maker, and were only suggested to be of pantodont origin due to their size (Mustoe, 2002).

Pantodonts were omnivorous and herbivorous large mammals that lived in the Northern hemisphere (except one pantodont-type from South America) in the Paleocene and Eocene. Primitive forms were small and some of them with a body weight of about 10kg. More derived forms were large and some exceeded 500kg. The only known Titanoideid genera in the late Paleocene: *Titanoides* is known from western North America (Rose, 2006). The pantodonts on Svalbard have presumably migrated from Northern America. This is the northernmost identified evidence of pantodonts from this period.



**Fig. 10** (A) Skeleton of the Pantodont *Titanoides*, after (Simons, 1960). (B) The manus of *Titanoides* bears sharp laterally compressed claws. (C) The unguals of the pes are unknown in this genus

## 6. Regional paleogeography

### 6.1 Paleoenvironment

The Firkanten Formation represents a low gradient costal plain setting with a wave dominated shore with tidal influence (Lüthje and Nichols, Submitted b). The lower Todalen Member is characterised by muddy fine grained sandstone, carbonaceous mudstone and coal deposits (Fig. 2) representing tidally influenced lagoons, swamp, and mire depositional environment respectively (Lüthje and Nichols, Submitted b). The extensive mires with rich vegetation must have been attractive for herbivores (Fig. 3). The terrestrial vegetation has been characterized as the “Paleocene and Eocene polar, broad leaved, deciduous forests” by Collinson and Hooker (2003). These forests were present in the Greenland Region (Greenland, Svalbard, Ellesmere Island and Scotland) and typified by *Trochodendroides*, *Corylites* and *Metasequoia* (Collinson and Hooker, 2003).

The coastal plain was protected from waves and storms by barrier bars and islands. The upper Endalen Member consists of well sorted fine grained sandstone with characteristic marine

bioturbation like *Ophimorpha*, deposited in a wave and storm dominated foreshore and shoreface setting (Lüthje and Nichols, Submitted b).

### 6.2 Climate

The climate on Spitsbergen in Paleocene and Early Eocene has been interpreted to be warm-temperate with a high humidity equally distributed over the year based on fossil plant material (Golovneva, 2000; Cepek and Krutzsch, 2001). It was a very favourable climate for plant production even though plate reconstruction places Spitsbergen at 65-68° N at this time (Cepek and Krutzsch, 2001). In Late Eocene the climate changed to almost cool-temperate. The mean annual temperature has been estimated to around +12°C in the Paleocene and only +8°C in the Late Eocene (Golovneva, 2000).

### 6.3 Age of sediments

The control on the dating of the Firkanten Formation is a poor due to poor fossil record but a Paleocene age can be concluded. The Paleocene to Eocene boundary is in the Frysjaodden Formation (Fig. 2) (Manum and Throndsen, 1986; Dallmann, 1999; Nagy *et al.*, 2000). Sequence stratigraphic analysis indicates a general stepwise but overall transgressive succession with no relative sea level fall detected in the Firkanten Formation (Lüthje and Nichols, Submitted a) indicating it was deposited in a period with no major eustatic sea level falls. Compared to global sea level curve a Late Paleocene age for the Firkanten Formation is suggested (Lüthje and Nichols, Submitted a).

### 6.4 Tectonic setting

The Central Tertiary Basin was formed as a flexural basin to the West Spitsbergen fold and thrust belt (Steel *et al.*, 1985; Bruhn and Steel, 2003; Nichols and Lüthje, Submitted) due to convergence between the Eurasian plate and Greenland (Fig. 4). In Paleocene there was a land contact from Svalbard to Northern Greenland and Ellesmere Island, Canada (Blythe and Kleinspehn, 1998). Even a narrow sound would probably have prevented the pantodonts from migrating from the American continent, implying that the opening of the Greenland Svalbard strait seaway must have taken place after the deposition of Firkanten Formation.

The postulated DeGeer route for migration of mammals from North America to an isolated Fennoscandia in the Paleocene/Eocene via Northeastern Canadian Arctic, Greenland, Svalbard and the Barents shelf (Janis, 1993) is supported by the pantodont tracks. The late Paleocene Cernaysian mammal age of Europe lack evidence of large herbivores like pantodonts,. However, pantodonts are preserved in deposits of the same age in North America (Lofgren *et al.*, 2004). The younger Eureka Sound formation (early Eocene) at Ellesmere Island in the Canadian Arctic with its vertebrate assemblage is the only other high Arctic finding of this

age (Dawson *et al.*, 1976; Rose *et al.*, 2004). Unfortunately no pantodonts has yet been described from the locality (Dawson, 1990).

The sedimentary record in the thrust belt indicates substantial erosion (Nichols and Lüthje, Submitted). The most important factor creating the Central Tertiary Basin was compressional folding (Nichols and Lüthje, Submitted). When the basin was established flexural loading and isostasy would have had some effect on further basin development. The compressional folding model suggests that the orogeny did not necessarily create a mountain belt with high elevation (Zhang and Bott, 2000). The uplift and erosion of thick sediments could still have taken place without the formation of great mountain belt (Nichols and Lüthje, Submitted) if the uplift and erosion were in balance. Any great orogenic belt would have been a natural obstruction for the pantodonts to cross. Therefore the presence of pantodont tracks is consistent with a low relief topography.

## 7. Conclusion

The footprints in Gruve 7 are a unique discovery. There are no previous records of Paleogene terrestrial mammals from Svalbard and they are they are the first evidence of Pantodonts this far north. The excellent quality and preservation of the tracks gave rise to further identification.

- The tracks are identified to be from a Titanoideid pantodont.
- The ichnology classification suggested for the tracks are *Thulitheripus svalbardii* Ign nov. isp. nov.
- The identification of the tracks as belonging to Titanoideid pantodont suggests Late Paleocene age for the Firkanten Formation.
- The Paleocene age of the strata makes this the earliest discovery this far north and east of pantodonts.
- The tracks are found in sapropelic coal deposited in a swamp later covered by marine fine grained sandstone by a marine transgression.
- The presence of pantodont tracks in the Firkanten Formation suggests that there was no seaway between Svalbard and Greenland/Ellesmere Island in Paleocene time.
- The topography of the thrust belt was probably limited since this would otherwise have implied an obstruction for the migrating pantodonts.

### **Acknowledgement**

SNSK (Store Norske Spitsbergen Kulkompani) are thanked for providing access to the mine in Longyearbyen. Charlotta Lühje would also like to thank SNSK for providing funding for a PhD project carried out at UNIS, Royal Holloway University of London and at the University of Bergen. Jesper Milàn was supported by the Danish Natural Science Research Council. An early version of the manuscript was thoroughly reviewed by Gary Nichols and M. Lühje is acknowledged for careful reading of the manuscript.

### **References**

- Blythe, A.E., Kleinspehn, K.L., 1998. Tectonically versus climatically driven Cenozoic exhumation of the Eurasian plate margin, Svalbard: Fission track analyses. *Tectonics*, 17, 621-639.
- Bruhn, R., Steel, R., 2003. High-resolution sequence stratigraphy of a clastic foredeep succession (Paleocene, Spitsbergen): An example of peripheral-bulge-controlled depositional architecture. *Journal of Sedimentary Research*, 73, 745-755.
- Cepek, P., Krutzsch, W., 2001. Conflicting Interpretations of Tertiary biostratigraphy of Spitsbergen, new palynological results. In: Tessensohn F. (Eds), *Intra-continental fold belts; Case 1: West Spitsbergen*, *Geologisches Jahrbuch; Polar Issue No. 7*, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, 551-599.
- Collinson, M.E., Hooker, J.J., 2003. Paleogene vegetation of Eurasia: framework for mammalian faunas. *Deinsea*, 10, 41-83.
- Coombs, M. C., 1983. Large mammalian clawed herbivores: A comparative study. *Transaction of the American Philosophical Society* 73, 1-96.
- Dallmann, W.K., 1999. *Lithostratigraphic lexicon of Svalbard*. Norsk Polarinstitutt, 318 pp.
- Dawson, M.R., 1990. Terrestrial vertebrates from the Tertiary of Canada's Arctic Islands. In: C.R. Harington (Ed.), *Canada's missing dimension: science and history in the Canadian Arctic islands*, *Canadian Museum of Nature* 1, 91-104.
- Dawson, M.R., West, R.M., Hutchison, J.H., 1976. Paleogene terrestrial vertebrates: northernmost occurrence, Ellesmere Island, Canada, *Sciences* 192, 781-782.
- Graversen, O., Milàn, J. Loope, D.B., 2007. Dinosaur Tectonics – a structural analysis of theropod undertracks with a reconstruction of theropod walking dynamics. *The Journal of Geology* 115, 375-386.
- Golovneva, L.B., 2000. Palaeogene climates of Spitsbergen. *GFF The Geological Society of Sweden*, 122, 62-63.

- Hurum, J.H., Milàn, J., Hammer, Ø., Midtkandal, I., Amundsen, H., Sæther, B., 2006. Tracking polar dinosaurs - new finds from the Lower Cretaceous of Svalbard. *Norwegian Journal of Geology* 83, 397–402.
- Janis, C.M., 1993. Tertiary mammal evolution in the context of changing climates, vegetation, and tectonic events. *Annual Review of Ecology and Systematics*, 24, 467-500.
- Lehman J.P., 1951. Un nouvel Amiidé de l'Eocène du Spitzberg, *Pseudamia heintzi*. *Tromsø Museums Årshefte* 70, 1-11.
- Lofgren, D. L., Lillegraven, J. A., Clemens, W. A., Gingerich, P. D., Williamson, T. E., 2004. Paleocene biochronology: The Puercan through Clarkforkian Land Mammal Ages. In: Woodburne, M.O. (Ed.), *Late Cretaceous and Cenozoic Mammals of North America. Biostratigraphy and Geochronology*, Columbia University Press, New York, 43–104.
- Lucas, S. 1998. Pantodonta. In: Janis, C.M., Scott, K.M., Jacobs, L.L., (Eds), *Evolution of Tertiary Mammals in North America. Volume 1: Terrestrial Carnivores, Ungulates, and Ungulate-like Mammals*, 274-283.
- Lucas, S.G., 2007. Cenozoic mammal footprint biostratigraphy and biochronology. In: Lucas, S.G., Spielmann, J.A., Lockley, M.G. (Eds), *Cenozoic Vertebrate Tracks and Trackways*, *New Mexico Museum of Natural History and Science Bulletin*, 42, 103-111.
- Lüthje, C., Nichols, G., Submitted a. Transgressive Coastal Plain to Shallow Marine Development of the Paleocene Strata of Svalbard. *Journal of Sedimentary Research*.
- Lüthje, C., Nichols, G., Submitted b. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. *Sedimentology*.
- Manum, S.B., Throndsen, T., 1986. Age of Tertiary formations on Spitsbergen. *Polar Research*, 4, 103-131.
- McCabe, P.J., 1984. Depositional environments of coal and coal-bearing strata. In: Rahmani, R.A., Flores, R.M. (Eds), *Sedimentology of coal and coal-bearing sequences. Special Publication No. 7, International Association of Sedimentologists*, Blackwell Scientific Publications, Oxford. pp. 13-42.
- McCrea, R.T., Pemberton, S.G., Currie, P.J., 2004. New ichnotaxa of mammal and reptile tracks from the Upper Paleocene of Alberta. *Ichnos*, 11, 323-339.
- Mustoe, G. E., 2002. Eocene bird, reptile and mammal tracks from the Chuckanut Formation, Northwest Washington. *Palaios* 17, 403-413.
- Nagy, J., Kaminski, M.A., Kuhnt, W., 2000. Agglutinated Foraminifera from Neritic to Bathyal Facies in the Palaeogene of Spitsbergen and the Barents Sea. In: Hart, M.B., Kaminski, M.A., Smart, C.W. (Eds), *Proceedings of the Fifth International Workshop on Agglutinated Foraminifera*, Grzybowski Foundation Special Publication, 7. pp. 333-361.
- Nichols, G., Lüthje, C., Submitted. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. *Basin Research*.

- Parker, L.R., Balsby, J.K., 1989. Coal mines as localities for studying dinosaur trace fossils, In: Gillette, D.G., Lockley, M.G. (Eds). *Dinosaur tracks and traces*. Cambridge University Press. pp 353–359.
- Parker, L.R., Rowley, R.L., 1989. Dinosaur footprints from a coal mine in east-central Utah. In: Gillette, D.G., Lockley, M.G. (Eds). *Dinosaur tracks and traces*. Cambridge University Press. pp. 361–366.
- Pemberton, S.G., MacEachern, J.A., Frey, R.W., 1992. Trace fossil facies models: Environmental and allostratigraphic significance. In: Walker, R.G., James, N.P. (Eds), *Facies Models Response to sea level change*, Geological Association of Canada. pp. 47-72.
- Peterson, W., 1924. Dinosaur tracks in the roofs of coal mines. *Natural History* 24, 388–397.
- Rose, K. D., 2006. *The beginning of the age of mammals*. The Johns Hopkins University Press, Baltimore, 431 pp.
- Rose, K.D., Eberle, J.J., McKenna, M.C., 2004. *Arcticanodon dawsonae*, a primitive new palaeodont from the Lower Eocene of Ellesmere Island, Canadian High Arctic. *Canadian J. Earth Sci.* 41 (6), 757-763.
- Simons, E.L., 1960. The Paleocene pantodonta. *Transactions of the American Philosophical Society*, 50, 1-98.
- Steel, R., Dalland, A., Kalgraff, K.L., Larsen, V., 1981. The central Tertiary basin of Spitsbergen - sedimentary development in a sheared margin basin. In: Kerr, J.W., Fergusson, A.J. (Eds), *Geology of the North Atlantic Borderlands*, Canadian Society of Petroleum Geologists, Memoir 7. 647-664.
- Steel, R., Gjelberg, J., Helland-Hansen, W., Kleinspehn, K., Nøttvedt, A., Rye-Larsen, M., 1985. The tertiary strike-slip basin and orogenic belt of Spitsbergen. *SEPM Special Publication No. 39*, 339-359.
- Thulborn, R. A., M. Wade, 1989. A footprint as history of movement. In: Gillette, D. D., M. G. Lockley (Eds.), *Dinosaur tracks and traces*. Cambridge University Press, 51-56.
- Zhang, G.-B., Bott, M.H.P., 2000. Modelling the evolution of asymmetrical basins bounded by high-angle reverse faults with application to foreland basins. *Tectonophysics*, 322, 203-218.



## 8. CONCLUSIONS

*This chapter summarises the conclusions from the research. The answers to the questions raised to the old interpretation are addressed and the new understanding of the Firkanten Formation and the Central Tertiary Basin is emphasised. Limitations and suggested work for the future are also discussed.*

The PhD research project was initiated to investigate the depositional environment of the Firkanten Formation and its implications to coal exploration. The new interpretation and understanding that came out of this project has given a more comprehensive picture of the formation of the Central Tertiary Basin.

A new depositional environment model was proposed for the entire Firkanten Formation together with a paleogeographic reconstruction. A sequence stratigraphic model for the first phase of sediment infill of the Central Tertiary Basin was formed in line with the depositional environment. The tectonic control on the basin was discussed from a basin formation perspective and a new compressional model for basin formation was put forward.

### 8.1 Summary of conclusions

These general conclusions were made from this work:

- The Firkanten and Basilika Formations were deposited in an overall transgressive wave and storm dominated shallow marine setting.
- The subsidence of the basin was controlled by flexural tectonic of the crust from compressional folding creating a depression in front of the thrust front.
- The stepwise retrogradation of the basin, with intervening aggradational successions, took place in periods of increased relative sea level rise, probably eustatically driven.
- The tectonic subsidence was at any time larger than the eustatic sea level fall and no relative sea level falls were detected.
- The basin was bound to the west by the thrust front, to the north by uplift and to the east by a structurally controlled area with restricted sedimentation.
- The pebbly sediments were generated from the fold and thrust belt in the west while the sand provenance was from the eroded Mesozoic strata in the north; no indications of an easterly sediment source was found.

- The Late Paleocene Firkanten Formation sediments rest on the Lower Cretaceous Carolinefjellet Formation and a minor but important local relief found in the unconformity influenced the initial deposition.
- The coal and carbonaceous mudstone of the Todalen Member were deposited on the sheltered low relief coastal plain in mires and swamps which gradually extended into lagoons and tidal flats in a microtidal energy regime.
- The coastal plain was inhabited by the Late Paleocene mammal Pantodont *Titanoides*, previously known from Northern America indicating an open migration path without major seaways or elevated mountain belts.
- The asymmetry of the flexural basin is reflected in the deposits where the western area is influenced by higher subsidence rate and sediment supply resulting in thinner coal deposits.
- The fluvial input is suggested to have been minor and only influencing the sedimentation in the western part of the basin, shown by the pebbly fluvial/alluvial fan delta of the Grønfjorden Bed.
- The eastern part of the basin was favourable for peat accumulation due to low subsidence and clastic sediment supply, where raised mire complexes had time to develop.
- The raised mires acted as natural dykes for transgressions resulting in thick sections of peat accumulations.
- The protecting barrier bars were built up by fine grained sandstone from longshore currents transporting sediments from the west towards the east and the glauconite content indicate a low sedimentation rate.
- The lower shoreface was mud prone and partly heavily bioturbated.

## 8.2 Answers to questions to old interpretation

Some questions were raised regarding the earlier interpretation of the Firkanten Formation. These have been discussed both in Chapter 3 *Synopsis of articles* and in the different articles. A short conclusion of the answers is presented here:

1. Does the Todalen Member represent a fluvial delta system?

No, the Todalen member was deposited on a low relief coastal plain in a microtidal regime with tidally influenced lagoons and peat mires protected from the wave and storm dominated shore by barrier bars.
2. Why are the coal-layers thick and broad and why are there no extensive fluvial channel deposits in the sections?

The peat mires developed on a coastal plain without any significant fluvial input on the eastern side of the basin and raised mires acted as natural dykes for marine transgressions resulting in extensive thick aggradational coal deposits.

3. Were there estuaries in the Todalen Member?

No, since there are not found any indications of relative sea level fall or fluvial systems it is unlikely that there was any valley incision and hence no estuaries, therefore the tidally influenced deposits represent tidal flats and lagoons.

4. How were the conglomeratic beds deposited and where were the pebbles generated?

The pebbles were generated from the thrust belt and shed into the basin as alluvial fan deltas, from where they were transported by longshore currents especially during storms and deposited on the foreshore and shoreface but also as wash-over fans in the lagoons.

5. If the Todalen Member does not represent a delta plain setting, then what do the Endalen Member and the Basilika Formation represent?

The Todalen Member is better described as a coastal plain deposit and this implies that the Endalen Member is the sandy foreshore and upper shoreface and the Basilika Formation is the lower shoreface and offshore transition of a wave and storm dominated transgressive coast.

6. Where did the sediments in the Firkanten Formation come from?

The sandstone is shown to be generated from eroded Mesozoic strata in the north of the Central Tertiary Basin, which shows extensive erosion, the pebbles were generated from the thrust belt.

7. How was the basin formation related to the thrust belt?

The basin formed as a depression in front of the thrust front from compressional tectonic movements, probably as compressional folding rather than a classical foreland basin formed by flexural loading.

8. Could the peripheral bulge have been a source of sediments for the Firkanten Formation?

No, since there is no evidence of significant uplift or erosion to the east and due to the limited size of the suggested foreland bulge, it is better described as an area with limited sedimentation/accommodation space that possibly was structurally controlled.

9. What type of depositional coastline is represented in the Firkanten Formation?

The Firkanten Formation was a retrograding depositional coastline with a wave and storm dominated shore with barrier bars and an inland area of tidally influenced lagoons and tidal flats gradually extending into swamps and peat mires.

10. How did the Central Tertiary Basin form?

The Central Tertiary Basin formed from tectonic compression in a strike slip regime from convergence between Svalbard and Greenland in connection with the opening of the Northern Atlantic.

**8.3 Future research and limitations to this work**

The aim of the PhD project was to create a comprehensive model of the formation of the Firkanten Formation. The work resulted in a new depositional environmental model and a better understanding of the formation of the basin and the sequence development. However, during this work additional questions were raised that could not be answered within the scope of this PhD. To follow up on these questions, the results of this project have been linked to other research projects.

(i) The Pantodont tracks in the coal on Svalbard prove a close contact to the North American continent. To get a better understanding of the regional concept of how Svalbard, Northern Greenland, and Ellesmere Island were connected during the rifting and opening of the Arctic Ocean and the Northern Atlantic more work is needed to implement the results from the PhD project with data from the other regions. This has been initiated as project with CASP (Cambridge Arctic Shelf Programme, [www.casp.cam.ac.uk](http://www.casp.cam.ac.uk)). The aim is to implement the regional understanding of Northern Greenland and Ellesmere Island with the results from Svalbard. In addition CASP possesses raw data in form of sedimentary logs and samples that previously have not been processed or interpreted, from the western side of the Central Tertiary Basin. These new data will be processed and interpreted using the methods, the facies model, and the sequence stratigraphic model developed during this PhD work. One of the limitations to the PhD work was inadequate data from the southern and western part of the basin. This is partly due to limited field exposures of the Firkanten Formation in these areas. Therefore the data from CASP, which also contains cores from the western side, will be important.

(ii) As part of this work it would be interesting to look further into the provenance, including petrography of the sediments but also the burial and uplift of the basin, which would involve establishing the thermal history by the use of for example, a detailed vitrinite reflectance study.

(iii) The Paleocene Ny Ålesund Subgroup, from the Ny Ålesund area in the northern part of Spitsbergen (Fig. 1.1) has been suggested to be linked to the Central Tertiary Basin on the

basis of similarity of the sediments. It is not possible to establish a direct link since the strata from north of Barentsburg all the way to Ny Ålesund was eroded during Cenozoic glaciations. To try to establish whether the two basins were the same, a project has been initiated to look at the sedimentary signature of the Ny Ålesund subgroup. This work started in 2005 with a short field season in Ny Ålesund and will be finished after the field season 2008. The preliminary results of this project suggest that the two basins might have been connected.

(iv) The coal samples gathered from the 3 mines; Gruve 3, Gruve 7, and Svea Nord have not been analysed for maceral content due to lack of access to the necessary equipment. However, it has been shown possible to use a detailed maceral study of complete vertical sections of coal seams to establish the relative sea level variations that took place during the accumulation of the peat (Davies, 2004; Davies et al., 2005). This will give further vital information to the sequence stratigraphy and perhaps better pinpoint the correlation of seams. A project has been initiated in connection with Liverpool University to look at the maceral distribution of the coal seams from the Central Tertiary Basin. The maceral content of the coal could also give more information about the climate and possible changes since the maceral reflects the environment in which it was accumulated. It is also possible that a detailed study of the coal might reveal more information on the age of the sediments, especially if the maceral trends can get linked to sequence stratigraphic changes or perhaps global sea level changes.

(v) Defining the age of the Firkanten Formation is problematic since the biostratigraphy has proved to be hard to evaluate due to the absence of calcareous microfossils and intense quartz cementation of the sediment. It could be interesting to look at the possibility to extract palynomorphs from the coal for dating. A possibility could be to look further into a combination of data from separate sources such as coal macerals, plant material, sediment, fossils, trace fossils, paleoecological reconstructions, and tectonic plate reconstructions to make a comprehensive model that could further define the age. Each of the analysis would give a time range and combined together it might result in a more specific definition of the age.

## 9. REFERENCES

*In this section the references from Chapters 1-3 and 8 are presented. The references in the articles (Chapter 4-7) are presented respectively in the articles.*

- Allen, P.A. & Allen, J.R.** 2005. Basin Analysis, Principles and Applications. Blackwell Publishing, Oxford.
- Allen, P.A., Homewood, P. and Williams, G.D.** 1986. Foreland basins: an introduction. In: *Foreland Basins Spec. Publs int. Ass. Sediment. 8* (Eds P.A. Allen and P. Homewood), pp. 3-12. Blackwell Scientific Publications.
- Bergh, S.G., Braathen, A. and Andresen, A.** 1997. Interaction of basement-involved and thin-skinned tectonism in the tertiary fold-thrust belt of central Spitsbergen, Svalbard. *AAPG Bulletin*, **81**: 637-661.
- Blythe, A.E. and Kleinspehn, K.L.** 1998. Tectonically versus climatically driven Cenozoic exhumation of the Eurasian plate margin, Svalbard: Fission track analyses. *Tectonics*, **17**: 621-639.
- Bohacs, K. and Suter, J.** 1997. Sequence stratigraphic distribution of coaly rocks: Fundamental controls and paralic examples. *AAPG Bulletin*, **81**: 1612-1639.
- Boyd, R., Dalrymple, R. and Zaitlin, B.A.** 1992. Classification of Clastic Coastal Depositional-Environments. *Sedimentary Geology*, **80**: 139-150.
- Braathen, A. and Bergh, S.G.** 1995. Kinematics of Tertiary Deformation In The Basement-Involved Fold-Thrust Complex, Western Nordenskiold-Land, Svalbard - Tectonic Implications Based On Fault-Slip Data-Analysis. *Tectonophysics*, **249**: 1-29.
- Braathen, A., Bergh, S.G. and Maher, H.D.** 1995. Structural Outline of A Tertiary Basement-Cored Uplift Inversion Structure In Western Spitsbergen, Svalbard - Kinematics And Controlling Factors. *Tectonics*, **14**: 95-119.
- Braathen, A., Bergh, S.G. and Maher, H.D.** 1999. Application of a critical wedge taper model to the Tertiary transpressional fold-thrust belt on Spitsbergen, Svalbard. *Geological Society of America Bulletin*, **111**: 1468-1485.
- Bruhn, R.** 1999. *The Firkanten Formation: Sequential architecture and controls on coastal plain-to-nearshore deposition in the Paleogene foreland basin on Spitsbergen*, Cand.Scient. Københavns Universitet, Longeyearbyen/ København.
- Bruhn, R. and Steel, R.** 2003. High-resolution sequence stratigraphy of a clastic foredeep succession (Paleocene, Spitsbergen): An example of peripheral-bulge-controlled depositional architecture. *Journal of Sedimentary Research*, **73**: 745-755.
- Catuneanu, O.** 2004. Retroarc foreland systems-evolution through time; Geological Society of Africa Presidential Review, No. 7. *Journal of African Earth Sciences*, **38**: 225-242.

- Catuneanu, O. and Sweet, A.R.** 1999. Maastrichtian-Paleocene foreland-basin stratigraphies, western Canada: a reciprocal sequence architecture. *Canadian Journal of Earth Sciences*, **36**: 685-703.
- Cepek, P.** 2001. Paleogene calcareous nannofossils from the Firkanten and Sarsbukta Formations on Spitsbergen. In: *Intra-continental fold belts; Case 1: West Spitsbergen, Geologisches Jahrbuch; Polar Issue No. 7* (Eds F. Tessensohn), pp. 535-547. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
- Cepek, P. and Krutzsch, W.** 2001. Conflicting Interpretations of Tertiary biostratigraphy of Spitsbergen and new palynological results. In: *Intra-continental fold belts; Case 1: West Spitsbergen, Geologisches Jahrbuch; Polar Issue No. 7* (Eds F. Tessensohn), pp. 551-599. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.
- Cmiel, S.R. and Fabianska, M.J.** 2004. Geochemical and petrographic properties of some Spitsbergen coals and dispersed organic matter. *International Journal of Coal Geology*, **57**: 77-97.
- Covey, M.** 1986. The evolution of foreland basins to steady state: evidence from the western Taiwan foreland basin. In: *Foreland Basins Spec. Publs int. Ass. Sediment. 8* (Eds P.A. Allen and P. Homewood), pp. 77-90. Blackwell Scientific Publications.
- Dalland, A.** 1979. Structural geology and petroleum potential of Nordenskiöld land, Svalbard. In: *Norwegian Sea Symposium* (Eds O. Torvanger et. al), Norsk Petroleumsforening, Tromsø.
- Dallmann, W., Hjelle, A., Ohta, Y., Salvigsen, O., Bjornrud, M.G., Hauser, E.C., Maher, H. and Craddock, C.** 1990. Geological map of Svalbard B11G Van Keulenfjorden. In: *Norsk Polarinstitutt Temakart*. Norwegian Polar Institute, Oslo.
- Dallmann, W., Winsnes, T.S., Birkenmajer, K., Nagy, J. and Salvigsen, O.** 1994. Geological map of Svalbard C11G Kvalvågen C12G Markhambreen. In: *Norsk Polarinstitutt Temakart*. Norwegian Polar Institute, Oslo.
- Dallmann, W.K.** 1999. *Lithostratigraphic lexicon of Svalbard*. Norsk Polarinstitutt, 318 pp.
- Davies, R.C.** 2004. *High resolution sequence stratigraphy analysis of paralic coal seams from the Book Cliffs, eastern Utah, USA*. Ph.D., University of Liverpool, Liverpool.
- Davies, R.C., Diessel, C., Howell, J., Flint, S.S. and Boyd, R.** 2005. Vertical and lateral variation in the petrography of the Upper Cretaceous Sunnyside coal of eastern Utah, USA: implications for the recognition of high-resolution accommodation changes in paralic coal seams. *International Journal of Coal Geology*, **61**: 13-33.
- DeCelles, P.G. and Giles, K.A.** 1996. Foreland basin systems. *Basin Research*, **8**: 105-123.
- Dickinson, W.R.** 1974. Plate tectonics and sedimentation. *SEPM Special Publication No. 22*, 1-27.

- Golovneva, L.B.** 2000. Palaeogene climates of Spitsbergen. *GFF The Geological Society of Sweden*, **122**: 62-63.
- Hansen, J.-A.** 2004. *Paleogeographic reconstruction of the Firkanten Formation (Paleocene) in Reindalen area, Spitsbergen*. M.Sc., Norgen teknisk-naturvitenskaplige universitet, Trondheim.
- Hansen, O.K.** 1982. *Den sedimentologiske utvikling og dens innvirkning på kuldannelse i nedre Firkanten formasjonen (paleocen) på nordsiden av Adventdalen, Spitsbergen*, Cand.Scient. Universitetet i Bergen, Bergen.
- Harland, W.B.** 1995. The West Spitsbergen Fold Belt - The Result of Late Cretaceous-Paleocene Greenland-Svalbard Convergence - Discussion. *Geological Journal*, **30**: 189-195.
- Harland, W.B.** 1997. *The geology of Svalbard*, **17**. Memoirs of the Geological Society London.
- Heller, P.L., Angevine, C.L., Winslow, N.S. and Paola, C.** 1988. 2-Phase Stratigraphic Model of Foreland-Basin Sequences. *Geology*, **16**: 501-504.
- Hirst, J.P.P. and Nichols, G.J.** 1986. Thrust tectonic control on Miocene alluvial distribution patterns, southern Pyrenees. In: *Foreland Basins Spec. Publs int. Ass. Sediment. 8* (Eds P.A. Allen and P. Homewood), pp. 247-258.
- Hjelle, A., Lauritzen, Ø., Salvigsen, O. and Winsnes, T.S.** 1986. Geological map of Svalbard B10G Van Mijenfjorden. In: *Norsk Polarinstitutt Temakart*. Norwegian Polar Institute, Tromsø.
- Jochmann, M.** 2004. *The geology of the Ispallen area, Svalbard, with emphasis on the coal bearing Firkanten Formation*, Diplom, Ludwig Maximilians Universität, München.
- Jones, T.P. and Chaloner, W.G.** 1991. Fossil Charcoal, Its Recognition and Palaeoatmospheric Significance. *Global and Planetary Change*, **97**: 39-50.
- Kalgraff, K.L.** 1978. *Aspects of Sedimentation in Firkanten Formation, Tertiary, Svalbard*, Cand.Scient. Universitetet i Bergen, Bergen.
- Kellogg, H.E.** 1975. Tertiary Stratigraphy and tectonism in Svalbard and continental drift. *The American Association of Petroleum Geologists Bulletin*, **59**: 465-485.
- Kostro, F.** 2005. *Character of the basal unconformity of the Paleocene successions in the Central Basin, Svalbard*. Diplom, University of Freiberg, Freiberg.
- Livsic, J.J.** 1974. Palaeogene deposits and the platform structure of Svalbard. *Norsk Polarinstitutt Skrifter* 51.
- Lüthje, C., Milàn, J. and Hurum, J.** Submitted. Paleocene tracks of the Pantodont genus Titanoides in coal-bearing strata, Svalbard, Arctic Norway. *Proceedings of the Royal Society B*.



- Lüthje, C. and Nichols, G.** Submitted a. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. *Sedimentology*.
- Lüthje, C. and Nichols, G.** Submitted b. Transgressive coastal plain to shallow marine development of the Paleocene strata of Spitsbergen, Arctic Norway. *Journal of Sedimentary Research*.
- Lyberis, N. and Manby, G.** 1993. The West Spitsbergen Fold Belt - The Result of Late Cretaceous-Paleocene Greenland-Svalbard Convergence. *Geological Journal*, **28**: 125-136.
- Major, H., Haremo, P., Dallmann, W., Andresen, A., Kjærnet, T. and Nøttvedt, A.** 2001. Geological map of Svalbard C9G Adventdalen. In: *Norsk Polarinstitutt Temakart*. Norwegian Polar Institute, Tromsø.
- Manby, G. and Lyberis, N.** 2000. Pre-ocean opening compression of the Northwestern Atlantic margin: evidence from eastern North Greenland. *Journal of The Geological Society*, **157**: 707-710.
- Manum, S.B. and Throndsen, T.** 1978. Rank of coal and dispersed organic matter and its geological bearing in the Spitsbergen Tertiary. *Norsk Polar institutt årsbok 1977*, 159-177.
- Manum, S.B. and Throndsen, T.** 1986. Age of Tertiary formations on Spitsbergen. *Polar Research*, **4**: 103-131.
- McCabe, P.J.** 1984. Depositional environments of coal and coal-bearing strata. In: *Sedimentology of coal and coal-bearing sequences. Special Publication No. 7* (Eds R.A. Rahmani and R.M. Flores), pp. 13-42. International Association of Sedimentologists, Blackwell Scientific Publications, Oxford.
- Michelsen, J.K. and Khorasani, G.K.** 1991. A regional study on coals from Svalbard: organic facies, maturity and thermal history. *Bull. Soc. Geol. Fr.*, **162**: 385-297.
- Midbøe, P.S.** 1985. *Kongsfjordfeltet (Paleocene) Spitsbergen, sedimentologisk og tektonisk utvikling*, Cand.Scient. University of Bergen, Bergen.
- Moore, T.A. and Shearer, J.C.** 2003. Peat/coal type and depositional environment - are they related? *International Journal of Coal Geology*, **56**: 233-252.
- Müller, R.D. and Spielhagen, R.F.** 1990. Evolution of The Central Tertiary Basin of Spitsbergen - Towards A Synthesis of Sediment And Plate Tectonic History. *Palaeogeography Palaeoclimatology Palaeoecology*, **80**: 153-172.
- Nagy, J.** 1966. Preliminary report on the geology of Eastern Torell Land, Vestspitsbergen. *Norsk Polar institutt årsbok 1964*, 69-72.
- Nagy, J.** 2005. Delta-influenced foraminiferal facies and sequence stratigraphy of Paleocene deposits in Spitsbergen. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **222**: 161-179.

- Nagy, J., Kaminski, M.A. and Kuhnt, W.** 2000. Agglutinated Foraminifera from Neritic to Bathyal Facies in the Palaeogene of Spitsbergen and the Barents Sea. In: *Proceedings of the Fifth International Workshop on Agglutinated Foraminifera* (Eds M.B. Hart, M.A. Kaminski and C.W. Smart), pp. 333-361. Grzybowski Foundation Special Publication, 7.
- Nichols, D.J.** 1995. The role of palynology in paleoecological analyses of Tertiary coals. *International Journal of Coal Geology*, **28**: 139-159.
- Nichols, G. and Lüthje, C.** Submitted. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. *Basin Research*.
- Nøttvedt, A.** 1982. *Characteristics and evolution of the Askeladden deltaic sequence (Paleocene) on Spitsbergen - with comparison to the Ravenscar Group deltaic sequence (Bajocian) of Northeast England*. Dr.Scient, University of Bergen, Bergen.
- Nøttvedt, A., Livbjerg, F., Midbøe, P.S. and Rasmussen, E.** 1992. Hydrocarbon potential of the Central Spitsbergen Basin. In: *Arctic geology and petroleum potential, NPF spec. publ. 2* (Eds T.O. Vorren et al.), pp. 333-361. Norwegian Petroleum Society.
- Ohta, Y., Hjelle, A., Andresen, A., Dallmann, W. and Salvigsen, O.** 1992. ISFJORDEN, Svalbard 1:100 000. Temakart nr. 16. Norwegian Polar Institute.
- Orheim, A., Bieg, G., Brekke, T., Horseide, V. and Stenvold, J.** 2007. Petrography and geochemical affinities of Spitsbergen Paleocene coals, Norway. *International Journal of Coal Geology*, **70**: 116-136.
- Reading, H.G. and Collinson, J.D.** 1996. Clastic coasts. In: *Sedimentary Environments: Processes, Facies and Stratigraph* (Eds H.G. Reading) 3rd ed, pp. 154-231. Blackwell Science Ltd, Oxford.
- Salvigsen, O., Winsnes, T.S. and Steel, R.** 1989. Geological map of Svalbard C10G Braganzavågen. In: *Norsk Polarinstitutt Temakart*. Norwegian Polar Institute, Tromsø.
- Schweitzer, H.-J.** 1980. Environment and climate in the Early Tertiary of Spitsbergen. *Palaeogeography Palaeoclimatology Palaeoecology*, **30**: 297-311.
- Scott, A.C.** 1987. Coal and coal-bearing strata: recent advances and future prospects. In: *Coal and coal-bearing strata: Recent advances* (Eds A.C. Scott). The Geological Society, Blackwell Scientific Publications.
- Scott, A.C.** 1989. Observations On The Nature And Origin of Fusain. *International Journal of Coal Geology*, **12**: 443-475.
- Scott, A.C.** 2002. Coal petrology and the origin of coal macerals: a way ahead? *International Journal of Coal Geology*, **50**: 119-134.

- Shearer, J.C., Moore, T.A. and Demchuk, T.D.** 1995. Delineation of the distinctive nature of Tertiary coal beds. *International Journal of Coal Geology*, **28**: 71-98.
- Sinclair, H.D.** 1997. Flysch to molasse transition in peripheral foreland basins; the role of the passive margin versus slab breakoff. *Geology*, **25**: 1123-1126.
- Steel, R. and Dalland, A.** 1978. Undersøkelser av den kullførende del av Firkanten Formasjonen (Tertiær) i østlige del av Nordenskiöld land Svalbard, Geologisk Institutt Universitetet i Bergen.
- Steel, R., Dalland, A., Kalgraff, K.L. and Larsen, V.** 1981. The central Tertiary basin of Spitsbergen - sedimentary development in a sheared margin basin. In: *Geology of the North Atlantic Borderlands* (Eds J.W. Kerr and A.J. Fergusson), pp. 647-664. Canadian Society of Petroleum Geologists, Memoir 7.
- Steel, R., Gjelberg, J., Helland-Hansen, W., Kleinspehn, K., Nøttvedt, A. and Rye-Larsen, M.** 1985. The tertiary strike-slip basin and orogenic belt of Spitsbergen. *SEPM Special Publication No. 39*, 339-359.
- Steel, R. and Worsley, D.** 1984. Svalbard's post-Caledonian strata - an atlas of sedimentological patterns and palaeogeographic evolution. In: *Petroleum Geology of the North European margin* (Eds A.M.e.a. Spencer), pp. 109-135. Graham & Trotman, London.
- Stemmerik, L. and Worsley, D.** 2005. 30 years on - Arctic Upper Palaeozoic stratigraphy, depositional evolution and hydrocarbon prospectivity. *Norwegian Journal of Geology*, **85**: 151-168.
- Sweet, A.R. and Cameron, A.R.** 1991. Palynofacies, Coal Petrographic Facies And Depositional-Environments - Amphitheater Formation (Eocene To Oligocene) And Ravenscrag Formation (Maastrichtian To Paleocene), Canada. *International Journal of Coal Geology*, **19**: 121-144.
- Teichmuller, M.** 1958. Rekonstruktionen verschiedener Moortypen des Hauptflötzes der niederrheinischen Braunkohle. *Fortschr. Geol. Rheinl. Westfalen*, **2**: 599-612.
- Teichmuller, M.** 1987. Recent advances in coalification studies and their application to geology. In: *Coal and coal-bearing strata: Recent advances* (Eds A.C. Scott), pp. 127-169. The Geological Society, Blackwell Scientific Publications.
- Teichmuller, M.** 1989. The Genesis of Coal From The Viewpoint of Coal Petrology. *International Journal of Coal Geology*, **12**: 1-87.
- Tønseth, D.** 1981. *The Sedimentary History of Firkanten Formation (Palaeocene) in the Adventdalen Area (Spitsbergen)*, Cand. Scient. Universitetet i Bergen, Bergen.
- Vonderbank, K.** 1970. Geology and Fauna der Tertiären Ablagerungen Zentral-Spitsbergens. *Norsk Polarinstitut Skrifter* 156.

- Ward, C.R.** (Ed) 1984. *Coal geology and coal technology*. Blackwell Scientific Publications.
- Wilhelmsson, J.C.** 1999. *Depositional Environment and Sequence Stratigraphy of the Coal-bearing Todalen Member, Firkanten Formation (Paleocene) at Adventdalen, Svalbard*, Cand. Scient. University of Oslo, Oslo/ Longyearbyen.
- Winsnes, T.S.** 1988. Bedrock map of Svalbard and Jan Mayen. In: *Norsk Polarinstitutt Temakart*. Norwegian Polar Institute, Oslo.
- Wolfe, J.A.** 1980. Tertiary climates and floristic relationships at high latitudes in the northern hemisphere. *Palaeogeography Palaeoclimatology Palaeoecology*, **30**: 313-323.
- Worsley, D., Aga, O.J., Dalland, A., Elverhøi, A. and Thon, A.** 1986. *The geological history of Svalbard, evolution of an arctic archipelago*. Statoil, Aske Trykkeri, Stavanger.
- Wüst, R.A.J., Hawke, M.I. and Bustin, R.M.** 2001. Comparing maceral ratios from tropical peatlands with assumptions from coal studies: do classic coal petrographic interpretation methods have to be discarded? *International Journal of Coal Geology*, **48**: 115-132.
- Ytreland, G.K.** 1980. *Sedimentation along the Western margin of the Central Tertiary Basin, (Firkanten Formation), Spitsbergen*. Cand.Scient., University of Bergen, Bergen.
- Zhang, G.-B. and Bott, M.H.P.** 2000. Modelling the evolution of asymmetrical basins bounded by high-angle reverse faults with application to foreland basins. *Tectonophysics*, **322**: 203-218.

## 10. APPENDIX

*The appendix found on the attached CD contains full scale images of some of the figures in the thesis and the articles in addition to some extra material such as pictures of cores and from field. There are also pdf versions of the article manuscripts in a larger layout format.*

1. Facies
  - 1.1. Core pictures of the facies
  - 1.2. Field pictures of facies
  - 1.3. Facies tables (A3 word document and excel file)
2. Logs
  - 2.1. Borehole logs (1:50/1:200)
  - 2.2. Reference logs (redrawn 1:50)
  - 2.3. Legend
3. Picture gallery
  - 3.1. Photomicrograph
  - 3.2. Pictures from the mines and the core store
4. Figures in large scale
  - 4.1. Facies pictures from cores and field (Figs 4A and B in Article 1)
  - 4.2. Depositional environment model (Fig. 3 in Article 2)
  - 4.3. Correlation log panels (3; black and white/colour; Figs 6-8 in Article 2)
  - 4.4. Paleogeographic reconstructions (Figs 11-14 in Article 2)
5. Articles as pdf with double line spacing and figures at the end of the text
  - 5.1. Article 1: Lüthje, C. and Nichols, G. Submitted. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. *Sedimentology*.
  - 5.2. Article 2: Lüthje, C. and Nichols, G. Submitted. Transgressive coastal plain to shallow marine development of the Paleocene strata of Spitsbergen, Arctic Norway. *Journal of Sedimentary Research*.
  - 5.3. Article 3: Nichols, G. and Lüthje, C. Submitted. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. *Basin Research*.
  - 5.4. Article 4: Lüthje, C., Milàn, J. and Hurum, J. Submitted. Paleocene tracks of the Pantodont genus *Titanoides* in coal-bearing strata, Svalbard, Arctic Norway. *Proceedings of the Royal Society B*.
6. Thesis as pdf