

**Master Thesis in Geosciences**

**Stratigraphy with biotic responses  
to the Paleocene-Eocene Thermal  
Maximum (PETM) in the Central  
Basin of Spitsbergen**

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**UNIVERSITY OF OSLO**

**FACULTY OF MATHEMATICS AND NATURAL SCIENCES**



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Master Thesis in Geosciences

Discipline: Petroleum Geology and Geophysics

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## Abstract

In this thesis the Paleocene and Eocene transition is the main focus of the analyses of Svalbard cores BH 10/06, BH 07/08 and BH 09/06, from the Central Basin. Special emphasis is laid on biotic responses through the Paleocene-Eocene Thermal Maximum (PETM) and its background environments. The thesis is based on quantitative foraminiferal analysis and data from sediment logs and samples.

The foraminiferal assemblages are agglutinated (benthic) and show low to intermediate diversities. Three assemblages are distinguished and named after the dominant species: FA 1, the *Reticulophragmium arcticum* assemblage; FA 2, the *Trochammina* aff. *inornata* assemblage; FA 3, the *Thurammina* aff. *papillata* assemblage.

The pre-PETM is characterized by the relatively high diversity FA 1 assemblage dominated by shallow digging and deep digging foraminifera suggesting relatively good oxygenation in the upper part of the bottom sediments. The PETM shows major faunal changes including benthic foraminiferal extinctions, and reduced species diversities in FA 2 because the water contains very low amount of oxygen. FA 3 shows a faunal change after the PETM because of delta progradation. The PETM is used as the time horizon in the correlation of the three cores. The Hollendardalen and Marstranderbreen members are present in core BH 09/06 and BH 07/08, and absence in the core BH 10/06. This may show that the Hollendardalen Member was deposited from the west or north-west.

Parts of two depositional sequences and a whole sequence are present in the studied cores: S1 represent the uppermost part of the Grumantbyen Formation. S2 is complete and includes the topmost part of the Grumantbyen Formation and the Marstranderbreen and Hollendardalen members. S3 comprises the lower part of the Gilsonryggen Member.

Keywords: Svalbard, PETM, biofacies, Paleogene, benthic foraminifera.

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## **1. Introduction**

This master thesis is produced at the Department of Geosciences, University of Oslo, as part of a long-term project dealing with the Paleocene-Eocene Thermal Maximum (PETM) in the Arctic. The stratigraphic position and main environmental features of the PETM are already delineated in two sections in Svalbard. The present thesis is an extension of these studies into three new sections.

The PETM is well-documented from low latitudes, but only sparsely recorded from the Arctic (Sluijs et al. 2006, Harding et al. 2011). The resulting environmental changes are mainly recorded from deep oceanic cores, although terrestrial changes are also presented, data from shallow marine environments and arctic areas are rather scarce. As part of a wider field of Svalbard PETM research, the present study also contributes to filling these gaps of information by presenting climatic impact on the marine benthic biota in prodelta shelf environments of the sedimentary succession filling the Central Basin of Spitsbergen.

This thesis deals with changes of depositional conditions and biofacies across the PETM mainly on the basis of foraminiferal faunas, but sedimentary data are also included. The materials forming the basis of the study are drill core logs and core samples. Core logging and sampling took place in August 2010, and this work has been done jointly with master student Ahmad Salman. The drill cores have been provided by Store Norske Spitsbergen Grubekompani (SNKS), and the logging was carried out in the core store of this company in Endalen, outside Longyearbyen.

Micropaleontological laboratory work and taxonomic analyses were carried out in the sediment laboratory of the Department of Geosciences, University of Oslo. Professors Henning Dypvik and Jenő Nagy supervised during the core logging in August 2010, and continued as supervisors during the subsequent work on the thesis. In addition, Dr. Silvia Hess acted as supervisor.

The geological setting, stratigraphic development and climatic background of the Svalbard Paleogene succession are discussed in the next chapter, which is followed by an overview of the methods that are used in the study. The results of the analyses are presented and discussed in separate chapters. The conclusion will outline the expected most important results of the micropaleontological and sedimentological analyses.



## 1.1. Previous research

Detail studies of the Spitsbergen Paleogene focused on the PETM and on the Eocene terrestrial vegetation were conducted by pACE (Paleo Arctic Climates and Environments) and are still in progress with participation of several universities. Preliminary results of the pACE activities in Spitsbergen, including recognition of the PETM are presented in several conference abstracts (e. g. Dypvik et al. 2010, Nagy et al. 2010a and Dypvik et al. 2011).

An important contribution to recognition of the PETM in the Central Basin of Spitsbergen was provided by Manum and Thronsen (1986) who defined the Paleocene-Eocene transition in the Nordenskiöldfjellet section by reporting of a major assemblage of *Apectodinium augustum*. Mass occurrence of this dinocyst has subsequently turned out be a global indicator of the PETM. A paper discussing stratigraphy, water depth and salinity changes during the PETM based on geochemical and dinocyst proxies in the Nordenskiöldfjellet section has been published by Harding et al. (2011). A contemporary paper by Dypvik et al. (2011) dealing with geochemical and clay mineral signals of the PETM based on material from the Nordenskiöldfjellet section and SNSK core BH 09/05.

## 2. Geological background

### 2.1. Geological setting of Svalbard in Paleogene time

The studied drill core sections form parts of the Paleogene succession of the Central Basin of Spitsbergen, which represents the main depositional area of Tertiary sediments in Svalbard. The cores belong to the topmost part of the Grumantbyen Formation and the lower part of the Frysjaodden Formation which contains the PETM.

The Spitsbergen sedimentary basins were marginal to and communicated directly with the paleo-Arctic Ocean. Therefore, we expect that overall environmental conditions of the ocean will be reflected by the Spitsbergen sedimentary successions, but modified to varying degree by local facies changes.

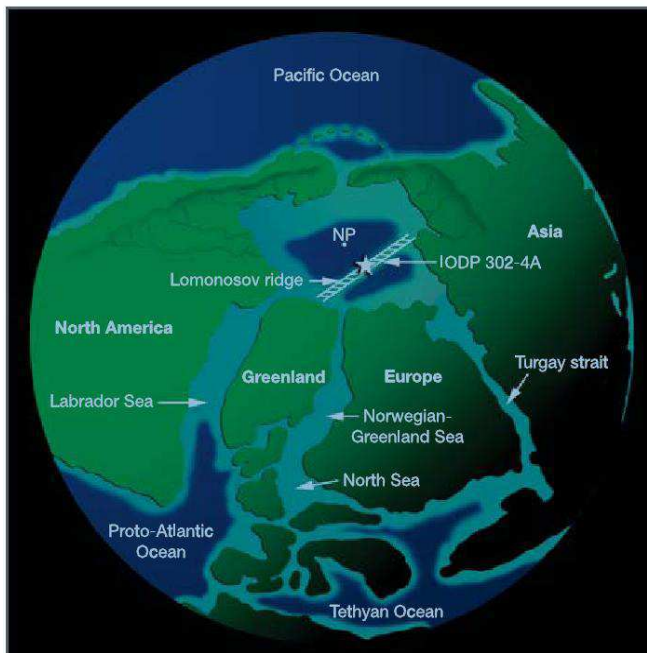


Fig. 2.1. Lomonosov ridge and reconstruction of the Arctic Basin in Late Paleocene–Early Eocene times (From Sluijs et al. 2006).

Important information about environmental conditions of the paleo-Arctic Ocean are provided by recent research conducted by the Integrated Ocean Drilling Program Expedition (IOPD) 302 (or the Arctic Coring Expedition). It recorded a Paleogene marine sedimentary succession from core hole 1 to 4 (Fig. 2.1) located on the Lomonosov Ridge. This deep sea ridge is a portion of continental crust that rifted from the Eurasian shelf margin at high latitude ( $> 85^\circ$ ) during the late Paleocene. It tectonically subsided to its present depths after the Paleocene.

### 2.2. Paleogene succession in the central basin of Svalbard

The sedimentary succession of the Central Basin is 2.3 km thick, and consist of siliciclastic sediments showing repeated facies changes. The dominant lithologies are shales, siltstones and sandstones deposited in mainly in delta-influenced shelf, deltaic and fluvial environments.

The stratigraphy of the Central Basin is treated in several papers including: Livshits (1974), Kellogg (1975), Steel and Worsley (1984), Steel et al. (1985), Dallmann et al. (1999) and Nøttvedt (1985).

Outside of the Central Basin, Tertiary deposits occur in four additional basins, all of which are of small size and contain siliciclastic sediments of Paleogene age. These basins are located at Øyrlandet, Bellsund, Forlandsundet and Kongsfjorden. A revision of the stratigraphy of the Tertiary succession of Svalbard was published by Dallmann et al. (1999). The Central Basin of Spitsbergen contains six Paleogene formations which are described in the following (in ascending order).

- 1) The Firkanten Formation (Fig. 2.2) rests with a regional unconformity on Early Cretaceous sediments. The formation consists of shales, siltstones and sandstones deposited in delta plain, coastal plain, delta front and prodelta environments.
- 2) The Basilika Formation is a succession of dark shales deposited in delta-influenced offshore shelf to prodelta environments.
- 3) The Grumantbyen Formation is composed of highly bioturbated sandstones deposited as sand ridges on a marine shelf.
- 4) The Frysjaodden Formation comprises three members: The Marstranderbreen Member consists of prodelta shales; the Hollendardalen Member is formed of delta front to delta top sandstones with coals; the Gilsonryggen Member is a succession of offshore shelf to prodelta shales and siltstones.
- 5) The Battfjellet Formation is a succession of delta front estuarine, delta plain and coastal sandstones.
- 6) The Aspelintoppen Formation is a thick package of delta plain and fluvial plain deposits mainly sandstones but also shales and coals.

The lower part of the Central Basin sediment infill (the Firkanten, Basilika and Grumantbyen formations) were deposited during the opening up of the basin in a trans-tensional tectonic regime. During this period, sediment transport took place from east to west. The upper three formations were deposited during development of the West Spitsbergen Fold Belt which took

place in a transpressional regime caused by the collision of the Greenland and Barents Sea plates. Previous studies demonstrate that the PETM is located in the lower part of the Gilsonryggen Member of the Frysjaodden Formation (Dypvik et al. 2011, Harding et al. 2011). A typical feature of this member is occurrence of large clinoforms of sandstone deposited from west to east during tectonic rise of the West Spitsbergen Fold Belt.



### 3. Climatic background

#### 3.1. Global Paleogene climate

Extensive scientific research in past two decades supports the opinion that there was warm climate with extreme change in Paleogene time (Zachos et al. 2001). The climate history of the Paleogene is complex, and show that periods of warming and cooling have taken place gradually or suddenly, as shown by stable isotope distributions used as temperature proxies.

The high quality of deep sea sediments cores recovered by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (OPD) form the basis of high-resolution stable isotope stratigraphy in the Tertiary. Zachos et al. (2001) collected the oxygen and carbon isotope data from bottom-dwelling deep-sea foraminifera from various interval of the Tertiary age from the literature, and compiled these into a single global deep-sea isotope record (Fig. 3.1). It shows a change from warm, greenhouse climate in the Paleocene and Early Eocene, followed by cooling with major oscillations through the rest of the Tertiary to develop icehouse conditions.

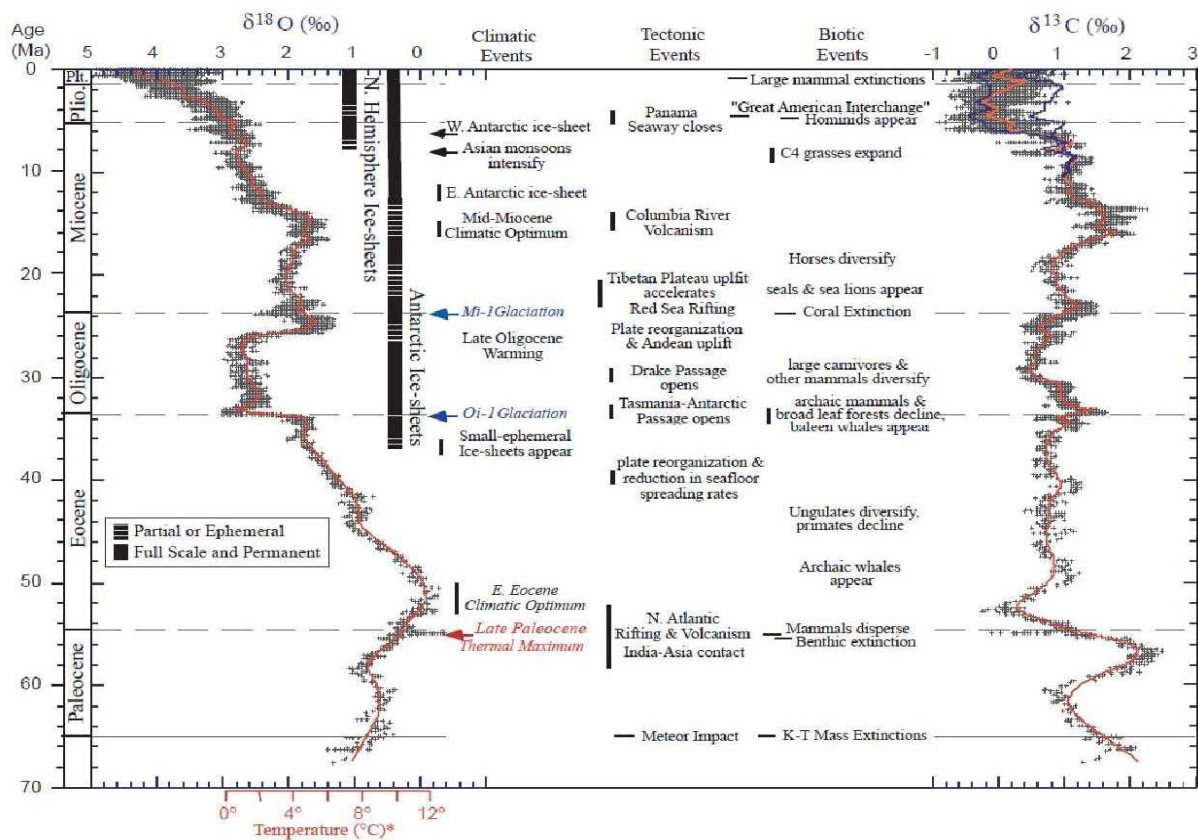


Fig. 3.1. Global deep sea oxygen and carbon isotope chart compiled for the Tertiary, it shows the development with temperature, climatic, tectonic and biotic events (Zachos et al. 2001).



### 3.2 Paleocene – Eocene Thermal Maximum

About 55 Ma ago there was a major climatic excursion of global nature which represents an extreme greenhouse interval known as Palaeocene-Eocene Thermal Maximum (PETM). The warming of the oceans and atmosphere changed the ocean chemistry, and reorganization of the global carbon cycle includes also significant changes (Röhl et al. 2007). The global temperatures increased by ~ 6°C at the beginning of the PETM during a few thousands of years (~20,000 years). Zachos et al. (1993) originally introduced the term “Late Paleocene Thermal Maximum” (LPTM) for this event.

The carbon isotope excursion at the PETM documented rapid global warming, changes in marine and terrestrial ecosystems including mass extinction of benthic foraminifera, a global increase of subtropical dinoflagellates especially of *Apectodinium* (Fig. 3.2) and a turnovers in mammalian life (Crouch et al. 2003, Pagani et al. 2006).

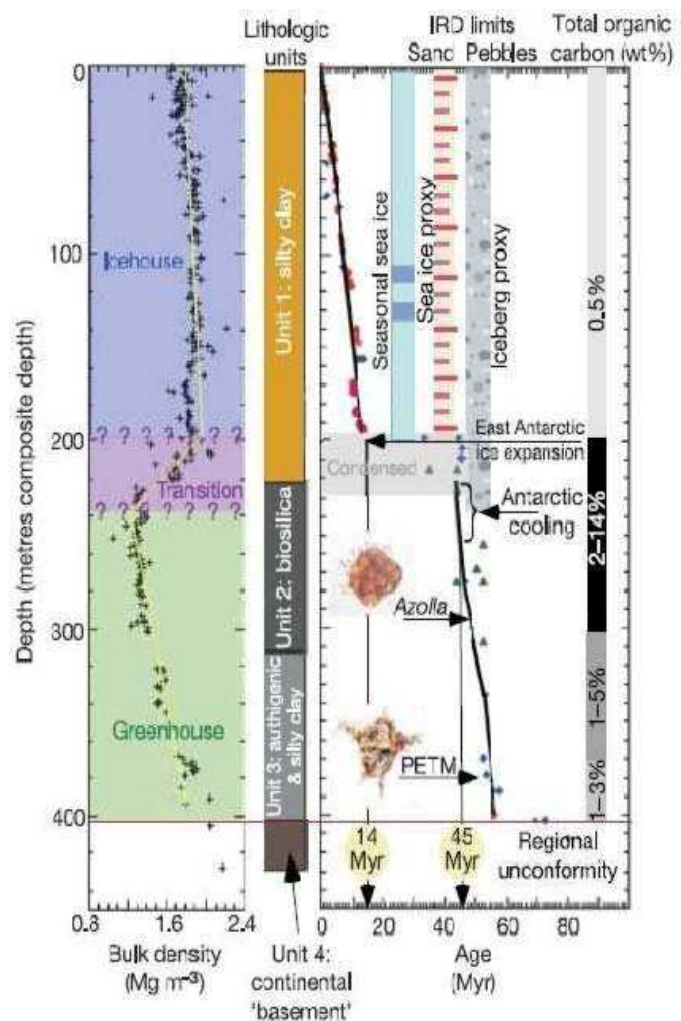


Fig. 3.2. Schematic synthesis of the ACEX coring results on the Lomonosov ridge. Age based on: palaeomagnetic stratigraphy shown as red circles; biostratigraphic data (dinocysts), blue diamonds, silicoflagellates, green triangles; and a few calcareous microfossils, squares (which only occur in the upper 25m). Two microfossils are shown in their stratigraphic position; the upper is *Azolla* and the lower is *Apectodinium* (Modified from Moran et al. 2006).

Cramer & Kent (2005) and Panchuk et al. (2008) outlined the various reasons of causing PETM, and stated that explanation of the huge decrease in  $\delta^{13}\text{C}$  concentrations created the problems in explanation of this event. Dickens et al. (1995) suggested the input of substantial quantities of isotopically light methane from thermal dissociation of seafloor clathrate deposits. The burning of large peat deposits increased the terrestrial accumulation of organic carbon-rich deposits (Kurtz et al. 2003). There is another theory suggesting that a  $^{12}\text{C}$ -rich comet triggered the earth with large energy causing such event. Different authors have argued the causes of PETM differently which include volcanic activity, orbital forcing or intense flood basalt magmatism and generating of metamorphic methane from sill intrusion into possible carbon-rich sedimentary rocks related to the opening of the North Atlantic (Katz et al. 1999, Panchuk et al. 2008, Farley and Eltgroth 2003, Thomas et al. 2002, Storey et al. 2007).



## **4. Material and methods**

Various methods were applied to analyse the depositional conditions across the Paleocene – Eocene thermal maximum (PETM) in the Central Basin of Spitsbergen. The following chapter will include the description of the methods and materials concerning sedimentology and micropaleontology.

### **4.1. Position of studied cores**

In August 2010 the three cores BH 10/06, BH 09/06 and BH 07/08 were obtained from Store Norske Spitsbergen Grubekompani. The positions of cores are shown in Fig. 4.1. They are located in the eastern part of the Central Basin, north of the previously analyzed core BH 09/05 (Riber 2009).

### **4.2. Logging and sampling of drill cores**

The logged and sampled cores were taken from three drill holes located in Central Spitsbergen. The drilling and coring was carried out by SNSK, for mapping of coal reserves in the Paleogene. As mentioned previously, the logging was done in August 2010 in the core storage premises of SNSK in Endalen outside Longyearbyen. The writer and Ahmad Salman logged the three cores BH 10/06 (from 520 m to 475 m core depth), BH 07/08 (from 95 m to 55 m core depth) and BH 09/06 (from 135 m to 100 m core depth) under the supervision of professors Henning Dypvik and Jenő Nagy. The samples were taken from each significant lithology with varying spacing from each core box. A total of 50 samples were collected from BH 07/08, 62 samples from BH 09/06 and 57 samples from BH 10/06. Photographs of the cores were taken by H. Dypvik and J. Nagy. The sampling was assisted by Jonathan Nagy. Millimetric column sheets were used to record the core logging in order to observe grain size lithological composition and sedimentary structures. In addition, bed and lamina thickness, grain size, sorting, color, bioturbation as well as intensity and orientation of fractures were recorded. An example of millimetric column sheet is shown in Appendix 1.

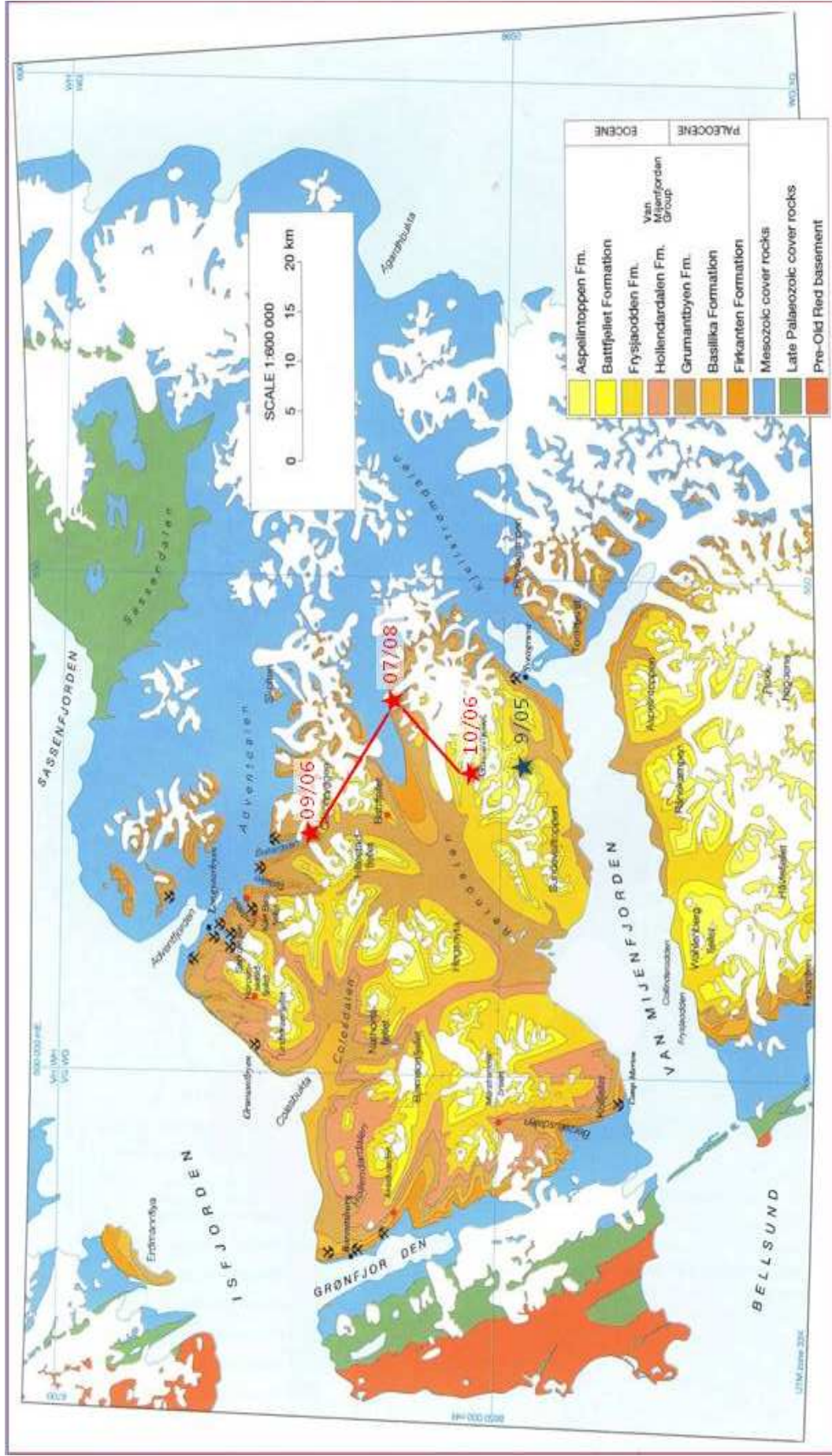


Fig. 4.1. Positions of the studied cores in a geological map of Central Spitsbergen (Map modified from Dallmann et al. 1999).

### **4.3. Sample preparation for foraminiferal analysis**

The sample preparation for the foraminifera was carried at the laboratory at the Department of Geosciences, University of Oslo, Norway. Nearly 35 grams of the each samples has been crushed to sizes of about 0.5cm<sup>2</sup>. The crushed samples were treated with the mixture of tenside and methanol. The samples are occasionally stirred in between 4 to 5 days. After that, the sediment was washed and sieved through the sieves of mesh diameter 63 µm. Then the samples were dried. Because this tenside procedure gave only insufficient disintegration, it was necessary to treat the samples by the sodium hydroxide (NaOH) method. In accordance with this, the dried sediment samples were disintegrated by boiling in a sodium hydroxide solution for a half to two hours. The boiled samples were washed and sieved through sieve set with mesh diameter of 63, 90 and 500 by slight rubbing of the sediments with rubber block on the sieves from the 500 µm mesh downward. The sieved samples were dried. In the PETM and adjacent strata, samples are spaced with shorter distance than in the rest of the core sections.

### **4.4. Picking and counting of foraminifera**

After drying of the sieved samples, the fractions 90 to 500 µm were used for foraminifera analyses. The fractions below or above this interval contained no foraminifera. The foraminifera were hand-picked by using a pen – sized stick with hair at the end. For picking process, a perforated tray was used. The pre-glued microfossil slide with numbered squares was applied under the tray. The pen – sized stick with hair was made electrostatic to pick the foraminifera and dropped down through the holes of the picking tray. Finally the picked foraminifera in the slide were arranged and glued in the proper place using a wet brush. Normally around 150 specimens were picked.

The identification of species was carried out under the supervision of Prof. J. Nagy and by consulting the studies of Boreal foraminiferal assemblages (especially McNeil 1996a, 1996b, 1997, Nagy et al. 2000, 2007). The main criterion for identifying is shape of test, number and shape of chambers, chamber arrangement, location of aperture, shape of aperture and type of wall material.

## **4.5. Micropaleontological indices**

### **4.5.1. Abundance**

The abundance is the number of specimens occurring in a sample. In general the abundance is given as tests per gram sediment. Abundance is mostly determined by the biological productivity of the depositional area but is modified to varying sedimentation rates and also could be affected by diagenetic process (Nagy 2003).

### **4.5.2. Similarity index**

Sanders (1960) defines a similarity index for comparison between two and two samples (assemblages). The similarity between two samples a and b with the total number of n species is calculated by the following formula:

$$A = \sum_{i=1}^n \text{Min}(f_{ia}, f_{ib})$$

Generally the index is matched for pair-wise comparison of adjacent samples through the stratigraphic section. The minimum percentage value is taken and added up over all species in the two samples. Practically sample pairs with similarity above 80% are considered as identical (Murray 1973).

### **4.5.3. Dominance**

The percentage of the most common species in a population is species dominance. It is usually inversely proportional to the diversity. Dominance of a single or few species shows unstable (restricted) environment where as many species represent stable environments (Nagy 2003).

### **4.5.4 Diversities**

The species diversity reflects various features of the depositional environment as different values correlate to different depositional conditions. In general, the values decrease from normal to unstable or extreme environments (restricted facies). The basic expression of diversity is the number of species in the sample. To increase the precision level of

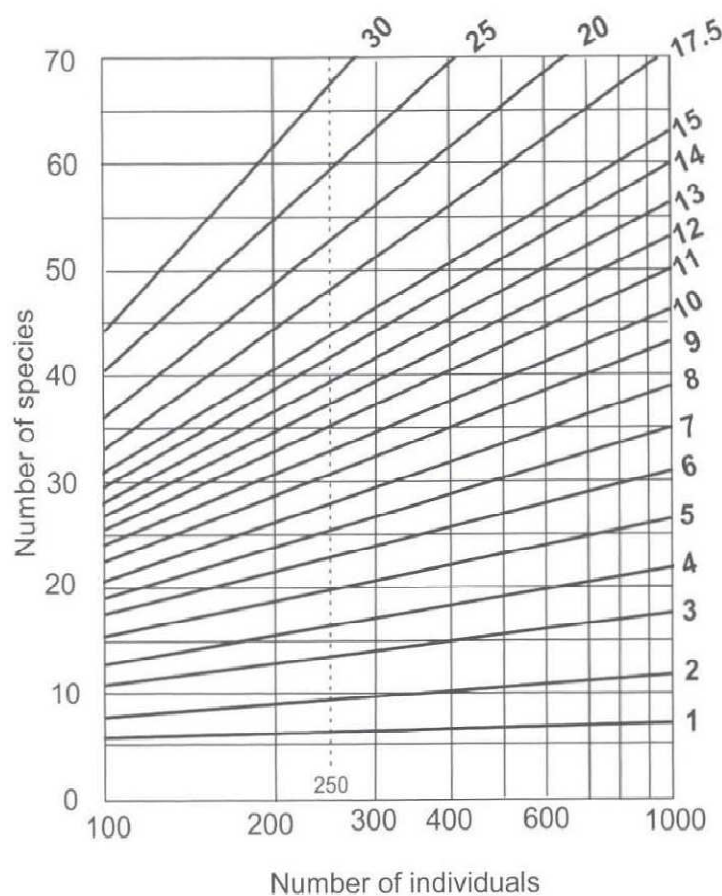
environmental interpretations various diversity indices are developed. In this thesis, the Fisher  $\alpha$ - index and Shannon Weaver – index H(S) is used for diversities calculation. The numerical results of these indices are shown in Appendix 2.

Fisher et al. (1943) introduced the Fisher alpha diversity index which is commonly used to characterise microfossil assemblages. It is determined by the following equation:

$$\alpha = N(1-x)/x$$

where x is a constant <1, based on the number of specimens in the sample (Williams 1964, Fig. 125) and N is the size of sample expressed by the number of specimens. The index assumes a logarithmic series between the number of specimens and number of species.

The alpha values can be found by calculation or plotting of the two parameters in a base graph (Fig. 4.2) which facilitates a visual comparison of samples. This index is particularly useful for comparison of samples of different sizes. Compilation of data from a large number of



modern environments show that normal marine conditions are characterized by alpha above 5, while restricted conditions have lower values.

Fig. 4.2. Base graph for the alpha index to illustrate the relation between the number of specimens and number of species in an assemblage (Murray 2006).

The Shannon-Weaver diversity index was introduced by Shannon and Weaver (1963), and later modified by Buzas and

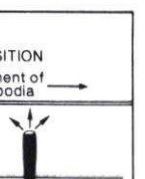
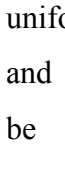
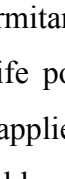
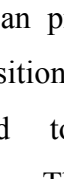
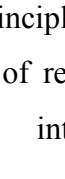
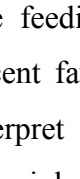
Gibson (1969). Both the number of species and the distribution of specimens between the species (relative frequency) are considered by this index. It is determined by:

$$H(S) = -\sum_{i=1}^S p_i \cdot \ln p_i$$

where S is the number of species and  $p_i$  is the number of specimens within a species divided by the total number of specimens in the sample ( $p$  = percentage divided by 100). When all samples have equal abundance (percentage), the maximum value of H(S) is obtained.

#### 4.5.5. Morphogroup analysis

Morphology analysis uses the principle that foraminiferal morphology reflects the environment where the organism lives, i.e. the organisms possess a good correlation between their morphology and their life habitat. Morphological divisions are based on life positions and feeding habits (Jones and Charnok 1985). Nagy (1992) constructed morphologic units, morphogroups subgroups and morphotypes in fossil assemblages (Fig. 4.3). According to the

MORPHO-GROUP AND SUBGROUP	MORPHOTYPE	CHAMBERS	SUPPOSED FEEDING HABIT	SIMULATED LIFE POSITION Deployment of pseudopodia →
1	1-a Tubular	Unilocular	Primary suspension-feeder	Epifaunal elevated 
2	2-a Globular	Unilocular	Passive deposit-feeder	Surficial 
	2-b Planoconvex-trochospiral, Planoconvex-streptospiral	Multilocular	Active herbivore, detritivore, omnivore	Surficial 
3	3-a Rounded-planispiral	Multilocular	Active detritivore, bacterivore, herbivore	Infaunal to surficial 
	3-b Subcylindrical, Tapered	Multilocular	Detritivore, bacterial scavenger	Infaunal 
4	4-a Flattened-planispiral, Irregular	Bilocular	Active to passive herbivore, detritivore	Epifaunal to phytal 
	4-b Irregular-attached	Unilocular		

uniformitarian principle feeding habit and life position of recent faunas can be applied to interpret ancient assemblages. The principle is not simple to apply to environmental interpretations owing to the large evolutionary changes that have taken place during geological time, and because the analysis requires complex comparisons.

Fig. 4.3. Morphological units of foraminifera defined by their inferred feeding habits and life positions (Nagy 1992).



## 4.6. Geochemical analysis

The geochemical analyses of total organic carbon carried out in order to assist the environmental interpretations. In the present thesis these proxies are employed to supplement data from biotic analyses.

### 4.6.1. Total organic carbon and calcium carbonate analysis

The selected samples are analyzed for total organic carbon (TOC) at the department of Geosciences, University of Oslo. About 0.35 gram of pulverized sample is treated with CR-412 Carbon Analyser which is a non-dispersive infrared instrument for the determination of carbon content in different samples.

Initially the samples are combusted at 1350° C so that carbon is released from the carbon bearing materials and is oxidized to CO<sub>2</sub>. Then the content of total carbon (TC) in the sediment is determined by the instrument in this gas.

Secondly the pulverized sample is treated with diluted hydrochloric acid (1:9). Then the treated sediment is washed and dried to remove carbonates from the sample. The content of total organic carbon (TOC) is yield from the treated samples of the CR-412 measurements.

The subtraction of total carbon (TC) and TOC gives total inorganic carbon (TIC):

$$\text{TIC} = \text{TC} - \text{TOC}$$

The calcium carbonate which in terms of percentage is calculated by following equation:

$$\text{CaCO}_3 (\%) = \text{TIC} * \text{M}_w (\text{CaCO}_3) / \text{M}_w (\text{C}) = \text{TIC} * 8.333$$

where M<sub>w</sub> (CaCO<sub>3</sub>) and M<sub>w</sub> (C) are molar weights of calcium carbonate and carbon respectively.

## 4.7. Photo and graphics

Photographs of the cores were taken by professors H. Dypvik and J. Nagy. The figures are edited by the software Photoshop, Illustrator and Paint.

#### 4.8. Sequence stratigraphic framework

In this thesis the depositional sequence stratigraphic model is used in accordance with Emery and Myers (1996). These authors defined sequence stratigraphy as the subdivision of sedimentary basin fills into genetic packages bounded by unconformities and their correlative conformities. The stratigraphic signatures are a result of the interaction of tectonics, eustasy and climate. The sediment supply to the basin is controlled by tectonics, eustasy and climate (Emery and Myers 1996). The depositional architecture is the function of accommodation space and sediment supply (after Galloway 1989). Progradational geometries result when the sediment supply exceeds accommodation space whereas retrogradational geometries result as the sediment supply is less than the creation of accommodation space. Aggradational geometries occur when accommodation space and sediment supply are roughly balanced (Emery and Myers 1996).

The term systems tract was initially defined by Brown and Fisher (1977) as a combination of contemporaneous depositional systems. The depositional system is a three-dimensional assemblage of lithofacies, genetically linked by active or inferred processes and environments (Fisher and McGowen 1967).

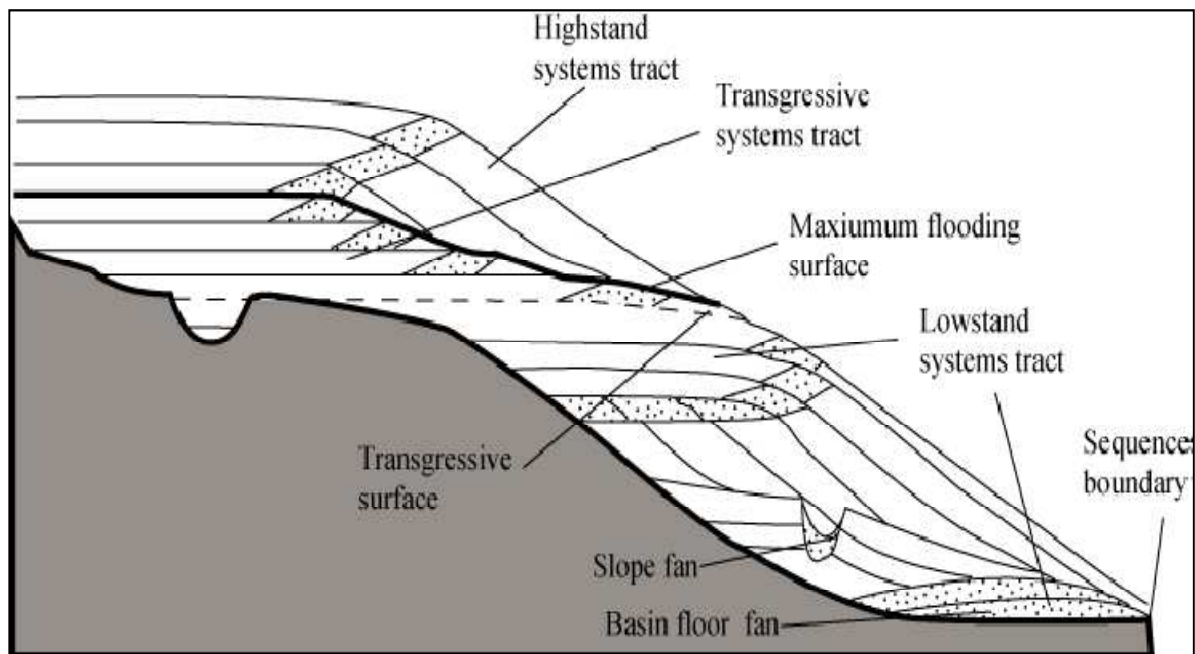


Fig. 4.4. Type 1 sequence showing five separate sedimentary packages (Emery and Myers 1996).

The basal (stratigraphically oldest) system tract is the lowstand system tract (LST) (Fig. 4.4) which is deposited during an interval of relative sea-level fall with a subsequent slow relative



sea-level rise (Emery and Myers, 1996). LST is generally progradational to retrogradational in geometric style. The transgressive system tract (TST) is the middle system tract which is deposited in a period where sediment supply is less than the creation of accommodation space. The transgressive systems tract is bounded by the transgressive surface and the maximum flooding surface (Emery and Myers 1996) (Fig. 4.4). TST successions are retrogradational, generally thin and can be absent in the stratigraphic record. The highstand systems tract (HST) is the youngest which is deposited in the period when the rate of accommodation space is less than the rate of sediment supply. HST successions generally form prograding parasequence sets that downlaps on the maximum flooding surface (MFS) characterized by sediment starvation and condensed interval.

The direction of shoreline displacement is characterised by transgression and regression. In terms of shoreline trajectory, the shoreline displacement is the shoreline path viewed along a cross-sectional depositional-dip section (Helland-Hansen and Martinsen 1996).

The concept of shoreline movements can be introduced through distinct classes of development. A normal regression is the basinward movement of shoreline when rate of sedimentation is greater than rate of accommodation, whereas a forced regression is the basinward movement of shoreline due to fall in sea level. Transgression is the landward movement of shoreline. The relative movement of shoreline is of great importance in sequence stratigraphy.

## **5. Lithostratigraphy of core sections**

### **5.1. Core BH 10/06**

This core BH 10/06 section comprises the upper part of the Grumantbyen Formation and the Gilsonryggen Member of the Frysjaodden Formation (Fig. 5.1). The Grumantbyen Formation consists of highly bioturbated greenish grey sandstone and siltstone. The uppermost part at about 513 m has ripple lamination, trough cross bedding and clasts of chert. It forms an upward fining succession which is overlain by an about 10 cm thick conglomerate bed marking the base of the Gilsonryggen Member of the Frysjaodden Formation.

The base of the Gilsonryggen Member from ca. 513 m to 511.4 m has a mixed lithology containing upto 50% sandstone, nearly equal portion of siltstone and shale and a thin conglomeratic bed at 511.8 m. The interval from 511.4 m to 484.8 m consists of homogeneous dark-grey shales with a very thin bed of conglomerate (Fig. 5.1) and low admixture of silt from 492.6 m to 489.5 m. The typical features of the shales are parallel lamination, low amount of bioturbation at the base, presence of scattered chert clasts and pyrite concretions. Plants debris and slickensides are also observed. From 484.8 m to 477.6 m the dark-grey shales have low silt content which reflects slight coarsening-upward developments. Few pyrite concretions and slickensides are observed. Then follows a homogeneous interval of shales which contains pyrite concretions and slickensides at some levels. In this section the TOC content of the Gilsonryggen shales ranges from 0.24 to 3.28%, the calcium carbonate from 2.64 to 41.80% and the hydrogen index from 1.0 to 1.36 (Salman, Pers. com. 2011).

### **5.2. Core BH 07/08**

The lowermost 3.3 m of section includes the uppermost 1.2 m of the Grumantbyen Formation (Fig. 5.2). This interval consists of grey to greenish, heavily bioturbated sandstone containing two thin interbeds of conglomerate. This is overlain by a 2.2 m thick nearly homogeneous conglomerate bed marking the boundary towards the Frysjaodden Formation. The next unit is a 0.6 m thick shale bed interpreted to represent the Marstranderbreen Member. Then follows the Hollendardalen Member which is a 4.0 m interval of sandstone with thin shale interbeds, planar and ripple lamination, and local bioturbation. The interval 88.2 to 85.1 m belongs to

the Gilsonryggen Member, and is dominated by shale but contains heavily bioturbated sandy beds. Thus, the lower part of this member reveals an upward-fining development.

The rest of the section is dominated by shales typical of the Gilsonryggen Member. The interval from 85.1 to 72.5 m is a succession of homogeneous dark-grey shales with a sandy horizon (Fig. 5.2). Typical features of the shales are parallel lamination, absence of bioturbation and presence of scattered pyrite concretions. Two occurrences of ripple lamination are observed. From 72.5 to 57.0 m the dark-grey shales have a low sand content which in five instances is reflected by faint coarsening-upwards developments. Also here, the shales are laminated, non-bioturbated and locally contain concretions of pyrite. In this section the TOC content of the Gilsonryggen shales ranges from 0.27 to 2.70%, the calcium carbonate from 0.00 to 20.28%, and the hydrogen index from 0.86 to 1.95 (Salman, Pers. com. 2011).

### **5.3. Core BH 09/06**

This section covers the uppermost part of the Grumantbyen Formation and the lower part of the Frysjaodden Formation. The later includes the Marstranderbreen, Hollendardalen and lower part of the Gilsonryggen Member (Fig. 5.3). The Grumantbyen Formation consist of fine-grained highly bioturbated greenish-grey sandstone. It forms an upward-fining succession together with the sandy beds composing the lowermost part of the Marstranderbreen Member.

The interval from 128.5 to 123.0 m represents the Marstranderbreen Member composed of shales with small amounts of bioturbation in the lower part and rich bioturbation in the upper part (Fig. 5.3). At 128.3 m a thin conglomerate bed occurs. The upper beds show an upward-increasing silt content. The overlying Hollendardalen Member is composed of sandstones showing parallel and ripple lamination, and locally contains much bioturbation. Three of the sandstone beds show upward-coarsening, and the lower part of the member shows a generally upward-coarsening development. The base of the Gilsonryggen Member is sharp and located at 116.3 m. This member consist of shales strongly bioturbated at base and very sparsely bioturbated higher up. Very small amounts of silt or fine sand are present at two or three levels. In this section the TOC content of the Gilsonryggen shales ranges from 1.42 to 3.03%,

the calcium carbonate from 0.10 to 4.77%, and the hydrogen index from 1.1 to 1.5 (Salman, Pers. com. 2011).

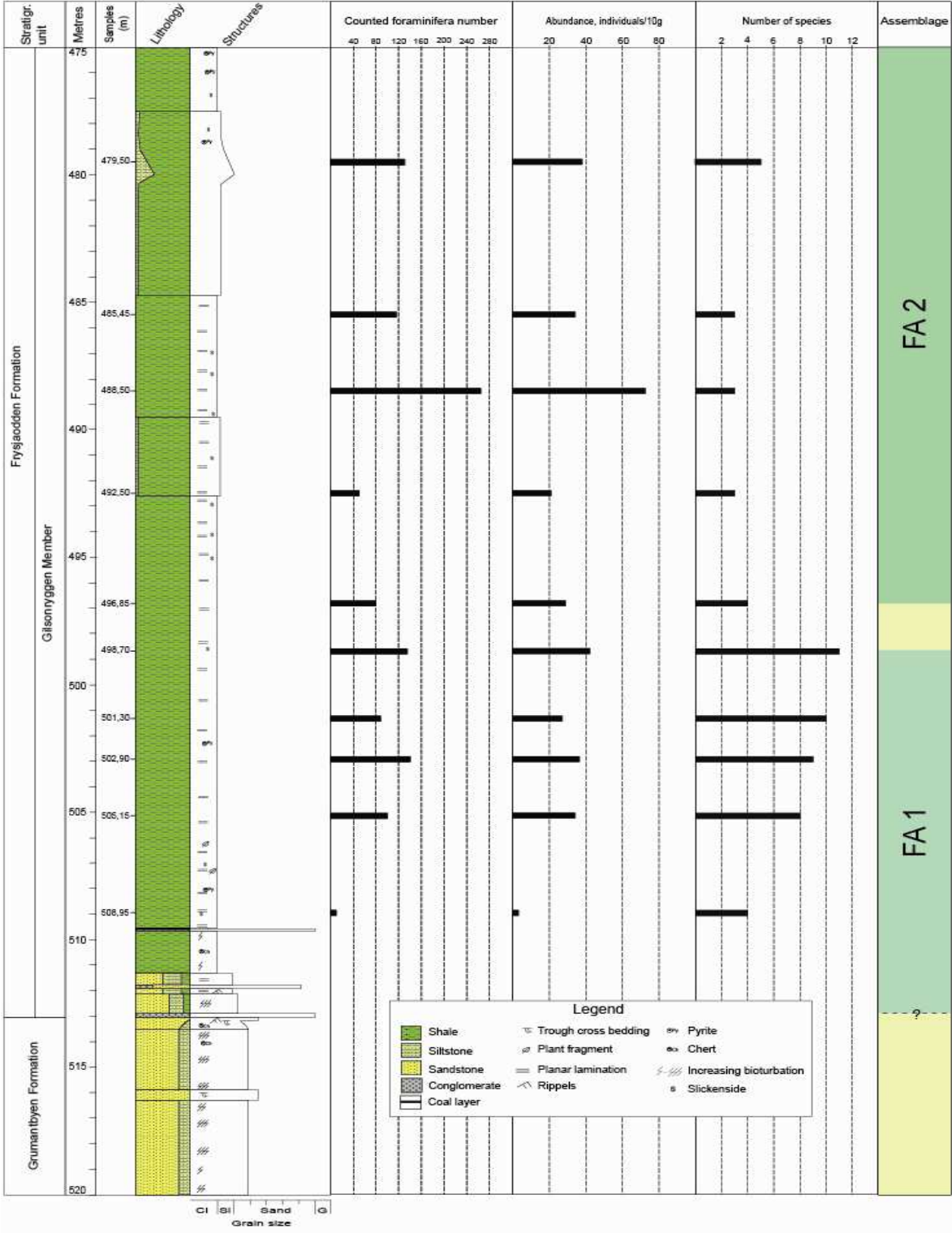


Fig. 5.1. Lithological column of the core BH 10/06 with number of counted foraminifera, individuals per 10g of sediments and number of species. (Light yellow intervals in assemblage column: no fossil data). See Appendix 2 for numerical values. 21

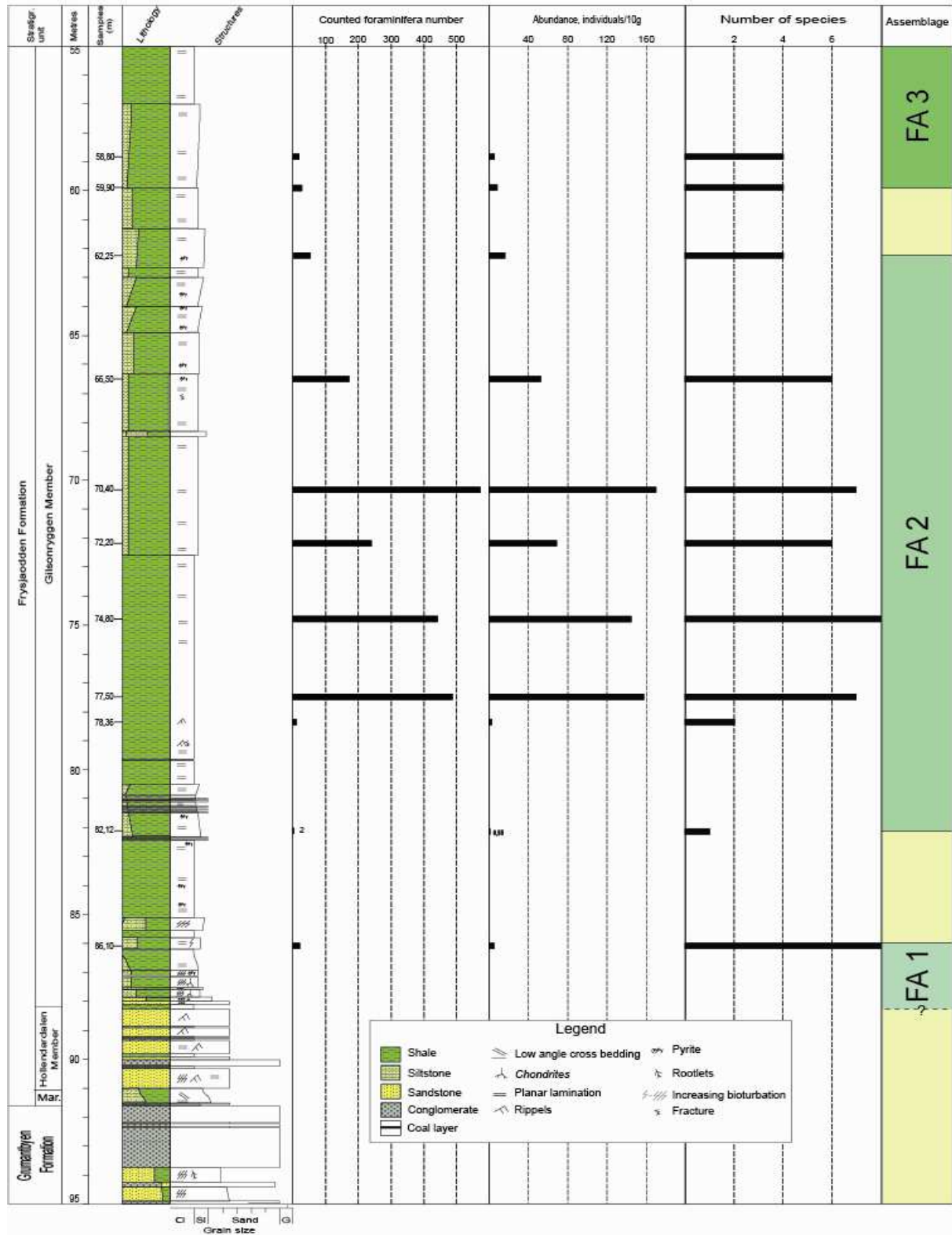


Fig. 5.2. Lithological column of the core BH 07/08 with number of counted foraminifera, individuals per 10 g of sediments and number of species (In assemblage column light yellow intervals: no fossil data). See Appendix 2 for numerical values.

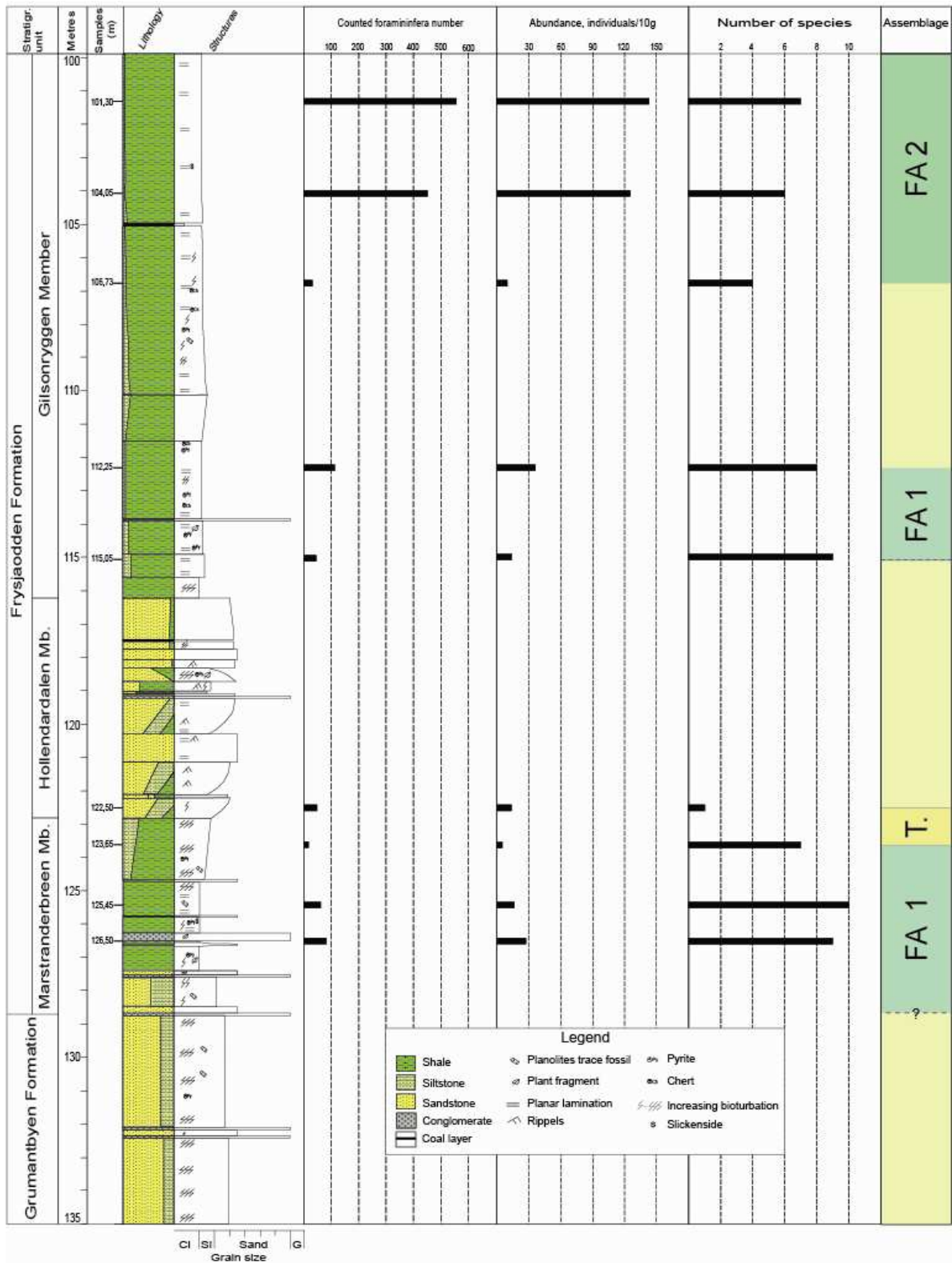


Fig. 5.3. Lithological column of the core BH 09/06 with number of counted foraminifera, individuals per 10 g of sediments and number of species (In the assemblage column the light yellow intervals: no fossil data, T. is anomalous *Trochammina* fauna). See Appendix 2 for numerical values.

## 6. Foraminiferal stratigraphy of core sections

Based on the stratigraphic distribution of the identified species, the faunal succession is subdivided into three foraminiferal assemblages (FA) named after a dominant species. The assemblages are (in ascending order): FA 1 *Reticulophragmium arcticum*, FA 2 *Trochammina* aff. *inornata*, FA 3 *Thurammina* aff. *papillata* (Table 6.1, 6.2, 6.3 and Appendix 4). All three assemblages consist of agglutinated species and have low to intermediate diversities.

### 6.1. Core BH 10/06

From this core 10 samples were processed for foraminifera (Table 6.1). The lowermost sample was very poor in species, by containing only 10 tests. Five samples, from 508.95 to 498.70 m contained FA 1 dominated by *Reticulophragmium arcticum*, *R. borealis*, *Thurammina* aff. *papillata*, *Labrospira turbida* and *Trochammina* aff. *inornata*. The top of the assemblage shows a marked faunal turnover by disappearance of 5 species.

The upper part of the core, from 496.85 to 479.5 m is composed of the FA 2 assemblage is typified by extremely low species numbers. The dominant species is composing 74% *Thurammina* aff. *papillata*. This is followed by *Trochammina* aff. *inornata* and *Birsteniolla* sp. 1. The other five species occurring in the assemblage are seldom, and are found each in one sample forming less than 7%.

### 6.2. Core BH 07/08

Eleven samples were processed for the foraminifera (Table 6.2). The lowermost sample belongs to FA 1 and contained 8 species the most dominant of which are *Trochammina* aff. *inornata*. Other species include *Reticulophragmium arcticum*, *Thurammina* aff. *papillata*, *Reticulophragmium borealis*, *Labrospira turbida*, *Reticulophragmium* aff. *ministicooense*, *Haplophragium multicubiculus* and *Trochammina* sp. 1.

From 82.12 m to 62.25 m the core contains FA 2 dominated by *Thurammina* aff. *papillata* followed by *Trochammina* aff. *inornata* and *Verneuilionides* aff. *durus*. Other species are *Trochammina* sp. 1, *Glaphyrammina* sp.1, *Verneuilina* sp., *Rheophax* aff. *metensis*, *Psammosphaera* aff. *fusca*, *Verneuilinoides* aff. *exadum*, *Birsteniolla* sp. 1, *Spiroplectommina* aff. *biformis* and *Ammodiscus* aff. *macilentus*. In sample 82.12 m *Thurammina* aff. *papillata* form monospecific fauna.

The upper part of the core, from 59.90 to 58.80 m contains only six species. They compose an FA 3 assemblage dominated by *Thurammia* aff. *papillata*, and *Trochammia* aff. *inornata*. The other four species were found each in one sample.

### 6.3. Core BH 09/06

This core includes 9 samples from 126.50 to 101.30 m (Table 6.3). From 126.50 to 112.25 m the samples belong to the FA 1 assemblage which is relatively rich in species except at 122.50 m containing only a single species *Trochammia* aff. *inornata*. The FA 1 is characterized by high percentage of *Recticulophragmium arcticum*, *Labrospira turbida* and *Convallina* aff. *elongata*, and common occurrence of *Recticulophragmium* aff. *ministicoogense*, *Convallina* aff. *logani* and *Trochammia* aff. *inornata*. *Textularina* genus indet. is also observed at 112.25 m. The other significant species are *Haplophragmoides* aff. *perexilis*, *Trochammia* aff. *parlevis* and *Verneulinoides* aff. *durus*.

The uppermost 3 samples form an FA 2 assemblage. *Trochammia* aff. *inornata* is highly dominant with maximum of 89.8%. *Thurammia* aff. *papillata* and *Verneulinoides* aff. *exadum* are common species in these samples. The occurrence of *Birsteiniolla* sp. 1 and *Ammodiscus* aff. *macilentus* are typical of the upper two samples.



Table 6.1. Range chart of the core BH 10/06 showing the percentage distribution of foraminiferal species. Two foraminiferal assemblages are distinguished in the core.

Depth in meters	Gram of sediments	ASSEMBLAGE										Number of species								
479.50	34,24	<i>Haplophragmoides reindeeresis</i>	<i>Trochammina</i> sp. 1	<i>Reticulophragmium borealis</i>	<i>Reticulophragmium arcticum</i>	<i>Haplophragmoides aff. richardsensis</i>	<i>Verneuilionides</i> sp. 1	<i>Labrospira turbida</i>	<i>Thurammina</i> aff. <i>papillata</i>	<i>Convallina</i> aff. <i>logani</i>	<i>Haplophragmoides multicusculus</i>	<i>Trochommina</i> aff. <i>inornata</i>	<i>Reticulophragmium</i> aff. <i>ministicogense</i>	<i>Convallina</i> aff. <i>elongata</i>	<i>Ammotium</i> sp.	<i>Birsteinilla</i> sp. 1	<i>Rheophax</i> aff. <i>metensis</i>	<i>Psammosphoera</i> sp.	<i>Thuramminopsis</i> sp. 1	5
485.45	34,13								47,41		51,72	16,92					0,86	1,54		3
488.50	36,58								33,96		61,51	61,51				4,53				3
492.50	24,50								29,41		68,63	68,63				1,96				3
496.85	27,75								51,25		41,25	41,25				6,25	1,25			4
498.70	32,00		4,44	3,70	12,59		1,48	15,56	5,19	9,63	0,74	37,04	5,19	4,44						11
501.30	32,71		5,68	4,55	21,59		5,68	14,77	10,23	7,95	10,23	13,64	5,68							10
502.90	38,60		3,57	6,43	30,00		7,86	5,00	10,71		5,71	6,43	24,29							9
505.15	29,40		2,00	17,00	57,00	4,00	2,00	5,00	10,00	3,00										8
508.95	33,34	10,00	10,00	20,00	60,00															4





## 7. Morphogroups analysis

Morphogroup analyses of foraminifera are applied for ecological and paleoecological interpretations. Murray (1973) defined morphological units on the basis wall composition and structure of modern faunas and applied these to interpret fossil assemblages (Wright and Murray 1972). Later the morphological units are defined on the basis of test shape and chamber arrangement by Nagy (1992) who applied these on Jurassic assemblages.

The application of morphogroup analysis is an important tool in low oxygen environments as it is assumed for the Gilsonryggen Member of the Frysjaodden Formation. It is assumed that the shape of foraminifera reflects the life habitat of the organism particularly when it is differentiated between epifaunal and infaunal components. In environments with normal marine oxygen content the different morphogroups show a well-balanced distribution. In such environments the presence of the infaunal groups 3-a and particularly the deep-digging group 3-b are important, because occurrence of these show that the bottom sediment contains oxygen. Absence of the infaunal groups and presence of the epifaunal groups 2-a and 2-b show that the sediment is anoxic except at the seabed surface where oxygen is present. Total absence of foraminifera indicates anoxic bottom water conditions.

In this thesis, morphogroup analysis is carried out on the samples in the core BH 10/06. Based on the stratigraphic distribution of the species we can assume that the morphogroup distribution in the other two cores has similar trends to this (Table 6.2, 6.3). The foraminiferal species in core BH 10/06 are arranged in four groups and six subgroups showing marked variations. All the usually distinguish morphogroups are present except morphogroup 1-a. The distinguished morphogroups comprise the species listed in Table 7.1.

The percentage composition of morphogroups per sample have been calculated (Appendix 3) and is shown stratigraphically in Fig. 7.1 with corresponding lithology of core BH 10/06. The foraminiferal assemblages (FA) are indicated as previously.

The lower part of the assemblage FA 1 is highly dominated by morphogroup 3-a composed of shallow digging to surfacial species of which *Recticulophragmium borealis*, *Recticulophragmium arcticum* and *Labrospira turbida* are the most common species in these samples. The upper part of the FA 1 is highly dominated by the deep digging morphogroup 3-

b which is most common in the uppermost sample of the core. This distribution shows that the seabed was oxygenated and also the upper part of the bottom sediments contain so much oxygen that the deep form could exist there.

Table 7.1. Morphogroups comprising the species occurring in the core BH 10/06.

<b>Morphogroups</b>	<b>Species in the Gilsonryggen Mb. of Frysjaodden Fm.</b>
1-a:	No species
2-a:	<i>Psammosphoera</i> sp. <i>Thurammina</i> aff. <i>papillata</i> <i>Thuramminopsis</i> sp. 1
2-b:	<i>Trochammina</i> aff. <i>inornata</i> <i>Trochammina</i> sp. 1
3-a:	<i>Haplophragmoides multicubculus</i> <i>Haplophragmoides reindeerensis</i> <i>Haplophragmoides</i> aff. <i>richardsensis</i> <i>Labrospira turbida</i> <i>Recticulophragmium arcticum</i> <i>Recticulophragmium borealis</i> <i>Recticulophragmium</i> aff. <i>ministicooense</i>
3-b:	<i>Ammotium</i> sp. <i>Convallina</i> aff. <i>elongata</i> <i>Convallina</i> aff. <i>logani</i> <i>Rheophax</i> aff. <i>metensis</i> <i>Verneuilionides</i> sp. 1
4-a:	<i>Birsteiniolla</i> sp. 1

The lower part FA 2 is highly dominated by surfacial morphogroup consisting mainly *Trochammina* aff. *inornata* while higher up the partly immersed group 2-a is dominating. *Thurammina* aff. *papillata* is the most common species in this part. The dominance of 3-b and almost total absence of the infaunal digging forms indicate almost no oxygen in the sediments and low oxygen content in the water above the bottom surface. This morphogroup distribution suggests generally low oxygen content which is in agreement with the PETM where low oxygen to anoxic conditions in deeper water are assumed to be a typical feature (Moran et. al. 2006).

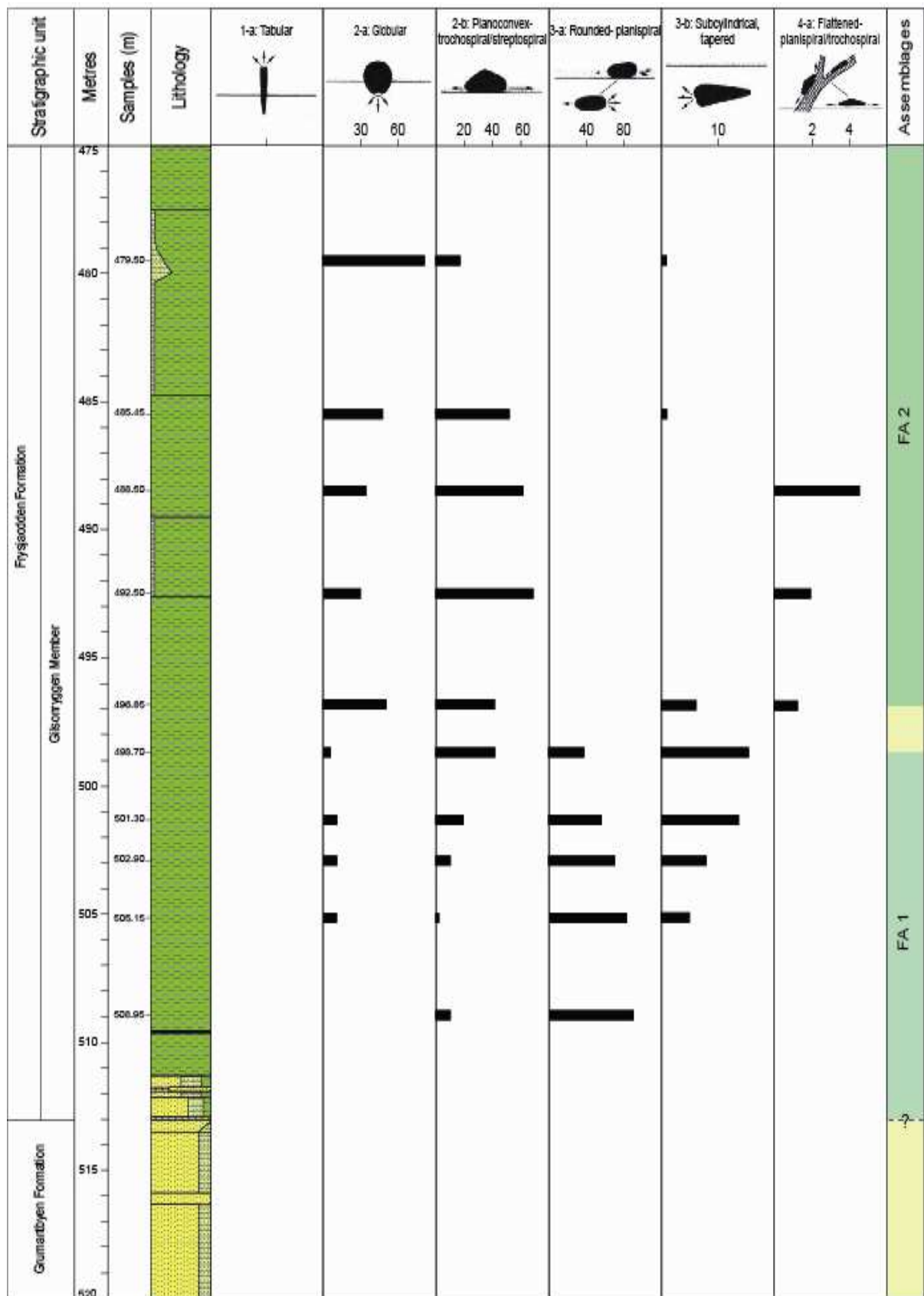


Fig. 7.1. Morphogroups distribution through the core BH 10/06 together with foraminiferal assemblages.

## 8. Stratigraphy of biofacies parameters

This chapter gives an overview of the stratigraphic distribution of proxies, which are used for biofacies interpretation in the three cores. These are number of individuals per sample, number of species per sample, alpha diversity index, H(S) diversity index, dominance, similarity index and morphogroup distribution. The number of individuals per sample is strongly variable (Table 6.1, 6.2 and 6.3, Appendix 4). From samples containing less than 150 specimens all foraminifera were picked and counted. In spite of this, these poor samples are also included in the calculation of indexes. Several samples have given less than 50 specimens but also these give useful indications because the diversities are generally low. Consequently, precision level of the calculated diversity and similarity proxies are reduced according to the number of specimens counted. In general, the number of specimens in a sample is influenced by several factors as biological productivity, sedimentation rates and preservation.

### 8.1. Core BH 10/06

Ten samples were analyzed from this core where the number of specimens per gram sediment is little variable (Fig. 5.1 and Fig. 8.1) except a few samples, particularly the lowest one which contains only 2.9 specimens per 10 g sediment. The highest number 72.44 specimens per 10 g sediment (sp/10 g s) occur at 488.5 m.

In assemblage FA 1, an upward increasing number of species ranging from 4 to 11 is found associate with intermediate amount of specimens per 10 g sediment. The diversity reaches maximum values with the alpha 2.9, H(S) 2.18 and the number of species 10. In accordance with this, the dominance is low, only 22% in these samples. In the lowermost part of FA 1 with low number of species, the dominance is high 60%. Similarly low alpha 2.47 and H(S) 1.09 occur in two samples. The shallow to deep digging morphogroups 3-a and 3-b are strongly dominant while the epifaunal group is seldom to subordinate (Fig. 7.1).

An equal number of species 3 are observed in two samples in the middle part of assemblage FA 2 (Fig 5.1). The number of species range from 3 to 5, the alpha varies from 0.47 to 1.03, the H(S) changes from 0.69 to 0.93. The dominance is the highest 74% at the upper part. The number of species is 3 and alpha 0.47 and the H(S) 0.81 at 488.5 m. This assemblage is

dominated by the surface dwelling morphogroups 2-a and 2-b. The epifaunal group 4-a is somewhat increased in one sample (Fig. 7.1).

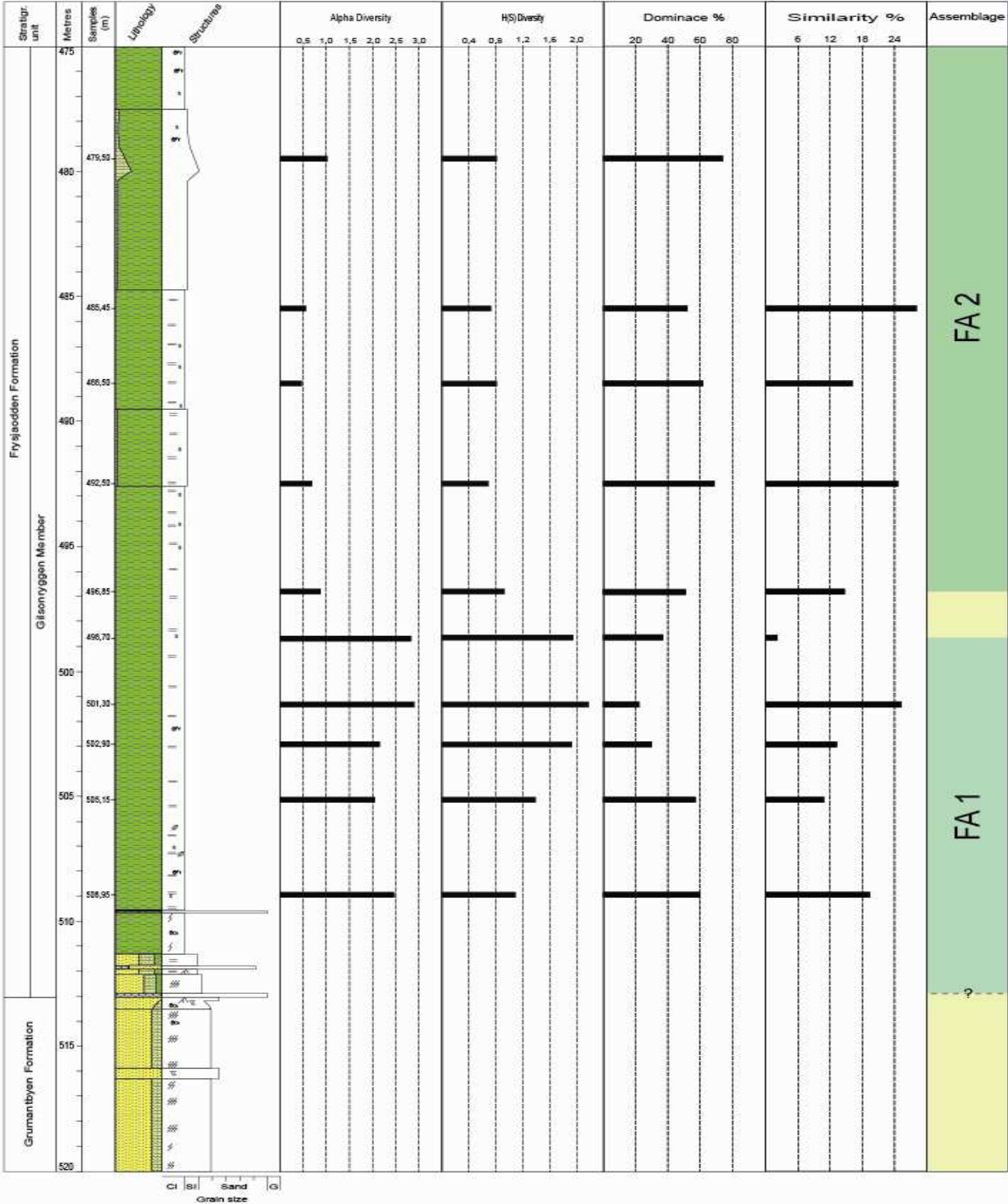


Fig. 8.1. Lithological column of the core BH 10/06 with alpha and H(S) diversity indices, dominance and similarity index. See Appendix 2 for numerical values.



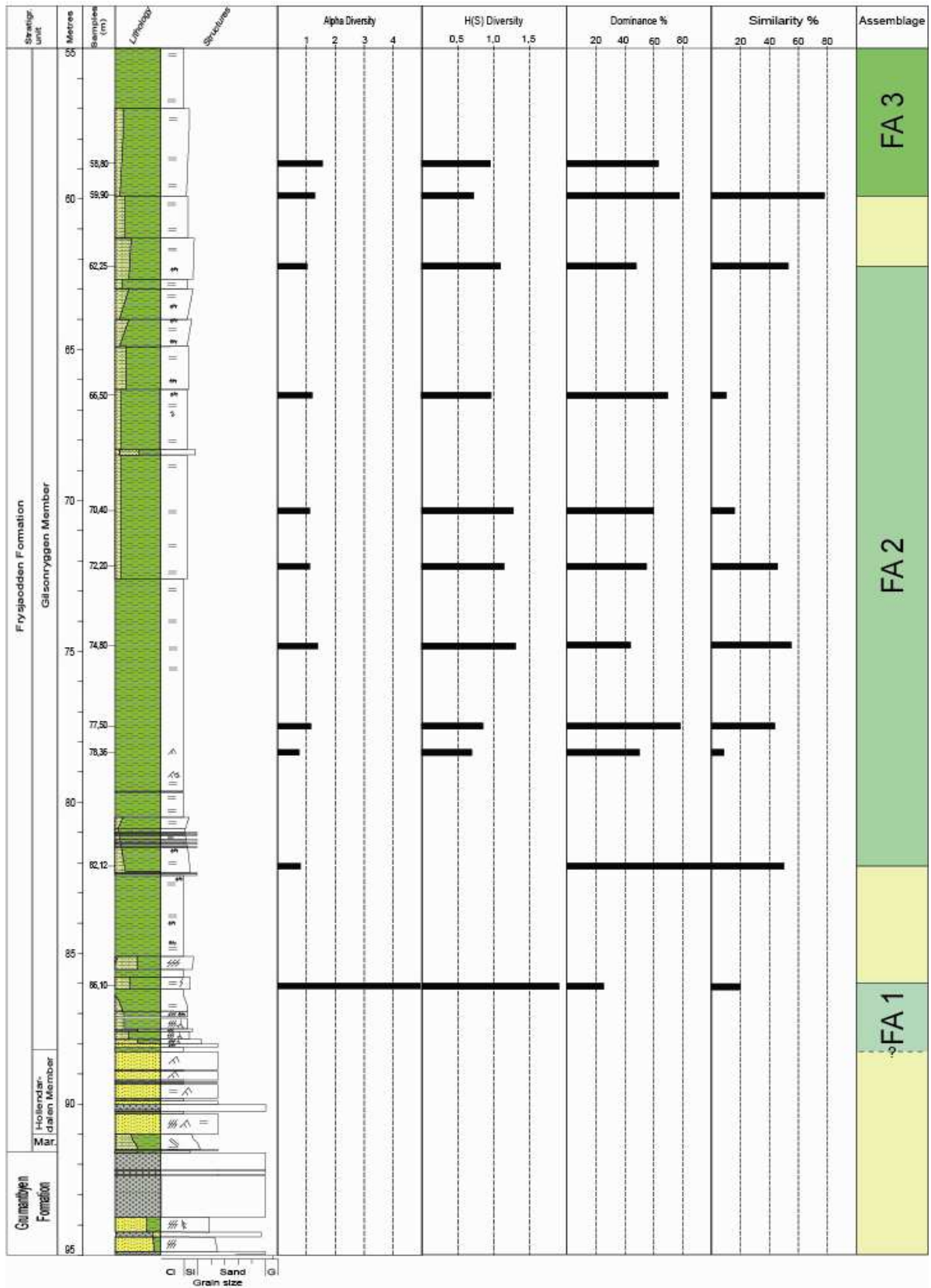


Fig. 8.2. Lithological column of the core BH 07/08 with alpha and H(S) diversity indices, dominance and similarity index. See Appendix 2 for numerical values.

## 8.2. Core BH 07/08

In the 11 samples analyzed from this core the number of specimens is strongly variable (Figs. 5.2 and 8.2). Lowest amounts, varying from 0.6 to 16.0 sp/10 g s are found in the lower and upper part of the section. The middle part shows intermediate to high values ranging from 52.4 to 169.7 sp/10 g s.

In the single sample forming assemblage FA 1 the diversity values are high as shown by the number of species 8, alpha 4.9, and H(S) 1.9. In accordance with this, the dominance is low 25%. The lower part of FA 2 reveals minimum diversities expressed by low species numbers 1 to 2, alpha 0.8, and H(S) (0.7 not given for this extremely poor sample). The dominance attains 100%.

The middle and upper parts of FA 2 is typified by an increase in diversities, although the values are strongly variable ( Figs. 5.2, 8.2): the species numbers range from 4 to 7, the alpha varies from 1.2 to 1.4, the H(S) changes from 0.9 to 1.3. As usual the dominance also here reveals a general trend inversely related to the diversities. The two samples representing FA 3 are typified by reduced species numbers 4, and H(S) 0.7 and 1.0, while the dominance increased to a maximum of 77.8%. In this assemblage, the alpha values have increased to 1.3 and 1.6 opposing the other two diversity proxies. This is probably caused by the low number of counted specimens, biasing the results of calculation.

## 8.3. Core BH 09/06

In this core 9 samples are analyzed where the number of species per gram is strongly variable (Fig. 5.3 and Fig. 8.3). The lowest amounts of sp/10 g s are found in the upper part of assemblage FA 1 at 123.65 m and the lower part of FA 1 at 115.05 m. Also the lower part of the assemblage FA 2 has strongly reduced low amount of specimens.

Anomalous *Trochammina* fauna at 122.5 m is observed between assemblages FA 1 and FA 2, and is marked by T. in figures and tables. The single sample from this fauna has very low diversity which is shown by the number of species 1, alpha 0.18, H(S) 0. In accordance with this the dominance is high 100%.

The assemblage FA 1 from 126.5 to 123.65 m has the highest number of species of 10 in the middle part with alpha 3.4, H(S) 1.98 and low dominance 20%. The highest alpha 4.74 at 123.65 m is observed with the lowest specimens sp/10 g s. The two samples representing the upper FA 1 interval are identified by reduced species number 9 to 8, alpha 3.38 to 1.97 and H(S) 1.9 to 1.68, whereas the dominance increases slightly.

The increasing specimens values of sp/10 g s occur in assemblage FA 2. The values range from 9.46 to 143.86 sp/10 g s. The middle sample at 104.05 m shows low diversity by the number of species is 6, alpha 0.98, H(S) 0.26. Corresponding to this the dominance is high 90%.

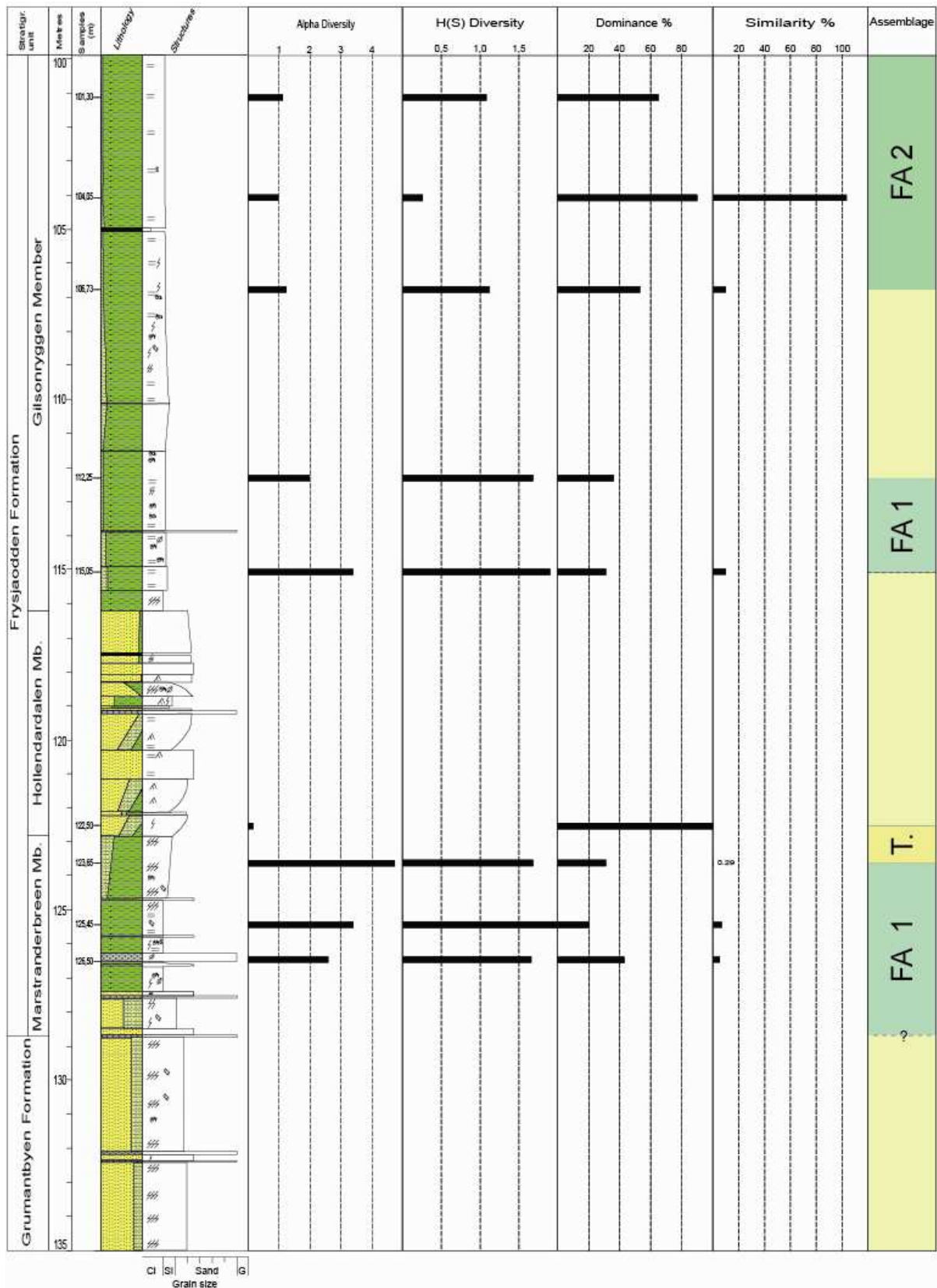


Fig. 8.3. Lithological column of the core BH 09/06 with alpha and H(S) diversity indices, dominance and similarity index. (T. is anomalous *Trochammina* fauna). See Appendix 2 for numerical values.

## **9. Biofacies interpretation and correlation**

### **9.1. The Marstranderbreen Member prodelta**

The Hollendardalen Member succession in the core BH 07/08 and BH 09/06 are regarded as delta front to delta plain deposits. The deltaic nature of this sand dominated unit is reflected by occurrence of coal seams and rootlet horizons in the uppermost part of the member in Nordenskiöldfjellet section (Dypvik et al. 2011, Harding et al. 2011).

The Marstranderbreen Member succession is interpreted as a prodelta shale deposit owing to its coarsening upward relation to the sandstones of the overlying deltaic Hollendardalen Member (Fig. 9.2, 9.3). The foraminifera occurring in the Marstranderbreen Member belong to the FA 1 assemblage showing low species diversities with average alpha values 3.57, suggesting restricted environmental conditions. The main restricting factor was probably low salinity suggested by the prodeltaic depositional setting. One of the dominant genera of this member, *Reticulophragmium*, is also dominant in the prodelta shales of the Kolthoffberget Member of the Firkanten Formation, reported by Nagy (2005). Rich occurrence of bioturbation in the upper part of the member suggests well-oxygenated waters (Fig. 9.3). In the lower part of the member reduced amount of bioturbation and presence of some lamination indicate some oxygen depletion.

### **9.2. The pre-PETM transgression**

The lowermost beds of the Gilsonryggen Member show an upward-coarsening trend in core BH 10/06 and BH 07/08 by replacement of sandy-silty beds by shales (Figs. 9.1, 9.2). In core BH 09/06, there is an abrupt change from the Grumantbyen sandstones to the Gilsonryggen shales (Fig. 9.3). The upward coarsening trend suggests upward-increasing water depth during a transgressive sea level rise. A transgressive development leading to the PETM is also recorded by Harding et al. (2011) from the Nordenskiöldfjellet section.

The foraminifera occurring in the transgressive interval before PETM belong to the FA 1, which is represented by five samples in core BH 10/06, one sample in core BH 07/08 and two samples in core BH 09/06. The alpha diversity of these samples is in average 2.83, indicating restricted environmental conditions. Low salinity in relatively shallow water seems to be an active restricting factor. In addition, somewhat reduced oxygenation is assumed, because the

shales are laminated and non-bioturbated, except the lowermost part of the interval where some bioturbation occurs. The interpretation that the oxygen content at the sea bed was not much reduced is also based on the observation that the surficial to shallow infaunal morphogroup 3-a and the deep – digging infaunal morphogroup 3-b are strongly dominant (Fig. 7.1). In core BH 10/06, the diversity increases from alpha 0.47 to 2.9 through five samples (Fig. 9.1), suggesting improving conditions. On the contrary, the upper sample in core BH 09/06 has lower alpha than the lower ones (Fig. 9.3).

### **9.3. The PETM anomaly**

As shown previously in this thesis, the onset of the PETM is marked by a faunal turnover. The PETM interval contains foraminiferal facies FA 2, which is represented by four samples in core BH 10/06 with average alpha 0.68, seven samples in core BH 07/08 with average alpha 1.22 and three samples in BH 09/06 with average alpha 1.11 (Figs. 9.1, 9.2, 9.3 and Appendix 2). The lowest alpha values, ranging from 0.47 to 0.98, are found in the lowermost part of this interval in the three cores. Occurrence of a faunal turnover with disappearance of species is in accordance with the general development of the PETM as shown by Zachos et al. (1993) and Harding et al. (2011).

The low diversity agglutinates nature of the foraminiferal assemblages is explained by a combined effect of low salinity and low oxygen conditions. It is mentioned previously that the background salinity of the Svalbard PETM was reduced owing to the prodelta nature of the Gilsonryggen Member. This was additionally lowered during the PETM by increased freshwater influx to the paleo-Arctic Ocean owing intensified hydrologic cycles (Brinkhuis et al. 2006). High influx of freshwater to the Central Basin at this event is demonstrated by Dypvik et al. (2011) by showing increased amount of kaolinite in SNSK core BH 09/05. Increased amount of kaolinite is explained by intensive weathering of rocks in humid climate (Salman, Pers. com. 2011).

It is assumed that high influx of freshwater produced a salinity-stratified water column in the depositional basin (Dypvik et al. 2011, Harding et al. 2011). This stratification together with increased marine productivity leads to low oxygen conditions. In the studied cores, reduced oxygen was an important restricting factor as shown by the extremely low diversities,

particularly in the lower part of the PETM anomaly. This is supported by the laminated nature of the shales, almost total absence of bioturbation and the high dominance of the small-sized *Trochammina* aff. *inornata*. It is demonstrated that small sized species of *Trochammina* are typical of low salinity hypoxic waters (Nagy et al. 2010b). Additional indication of strongly reduced oxygen at the PETM level is given by the morphogroup analysis of core BH 10/06 (Fig. 7.1). It shows that the surface – dwelling groups are very strongly dominant, while infaunal groups were almost totally absent. It means that the bottom sediment was almost anoxic.

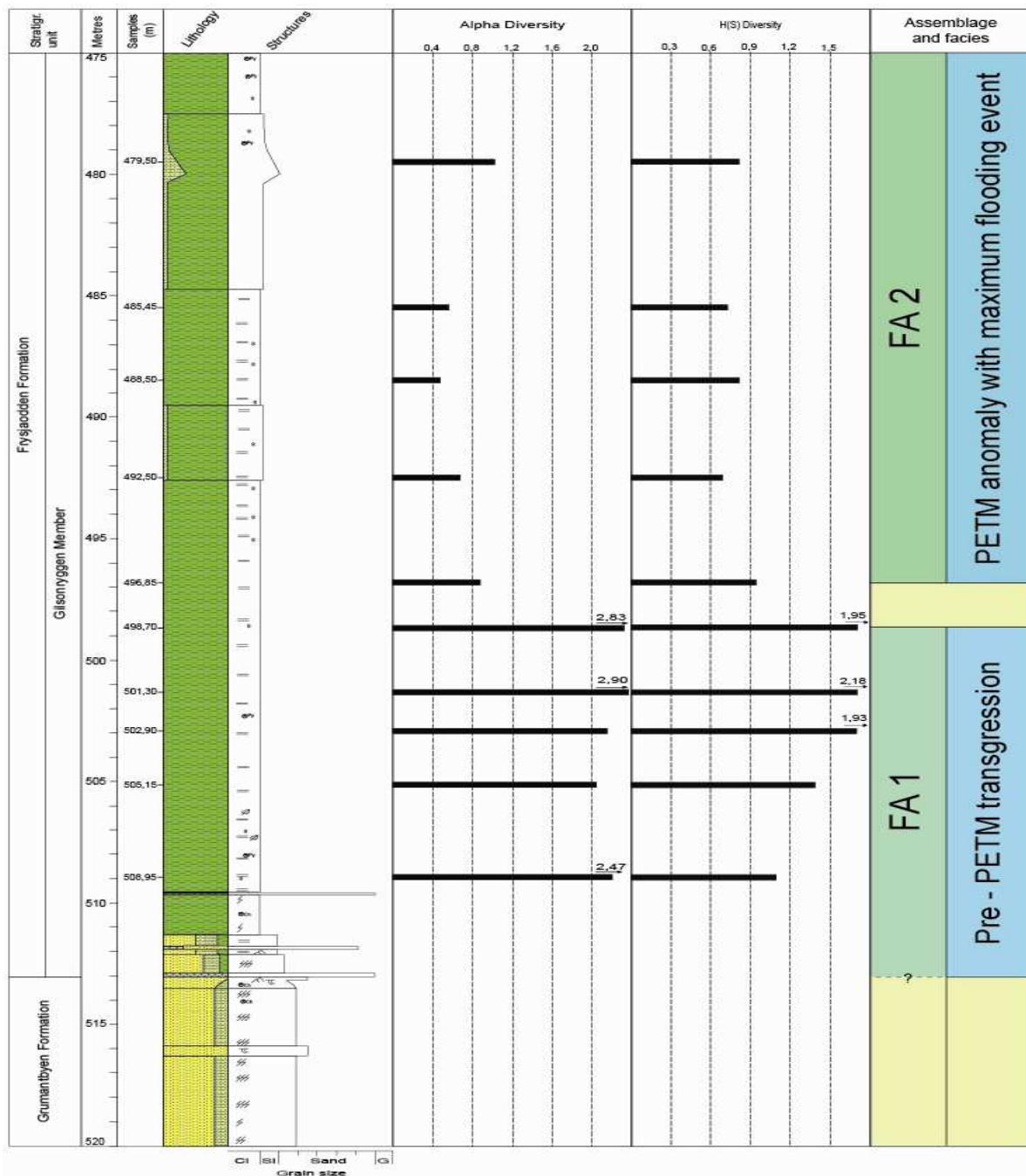


Fig. 9.1. Foraminiferal assemblages and facies distribution in the core BH 10/06.



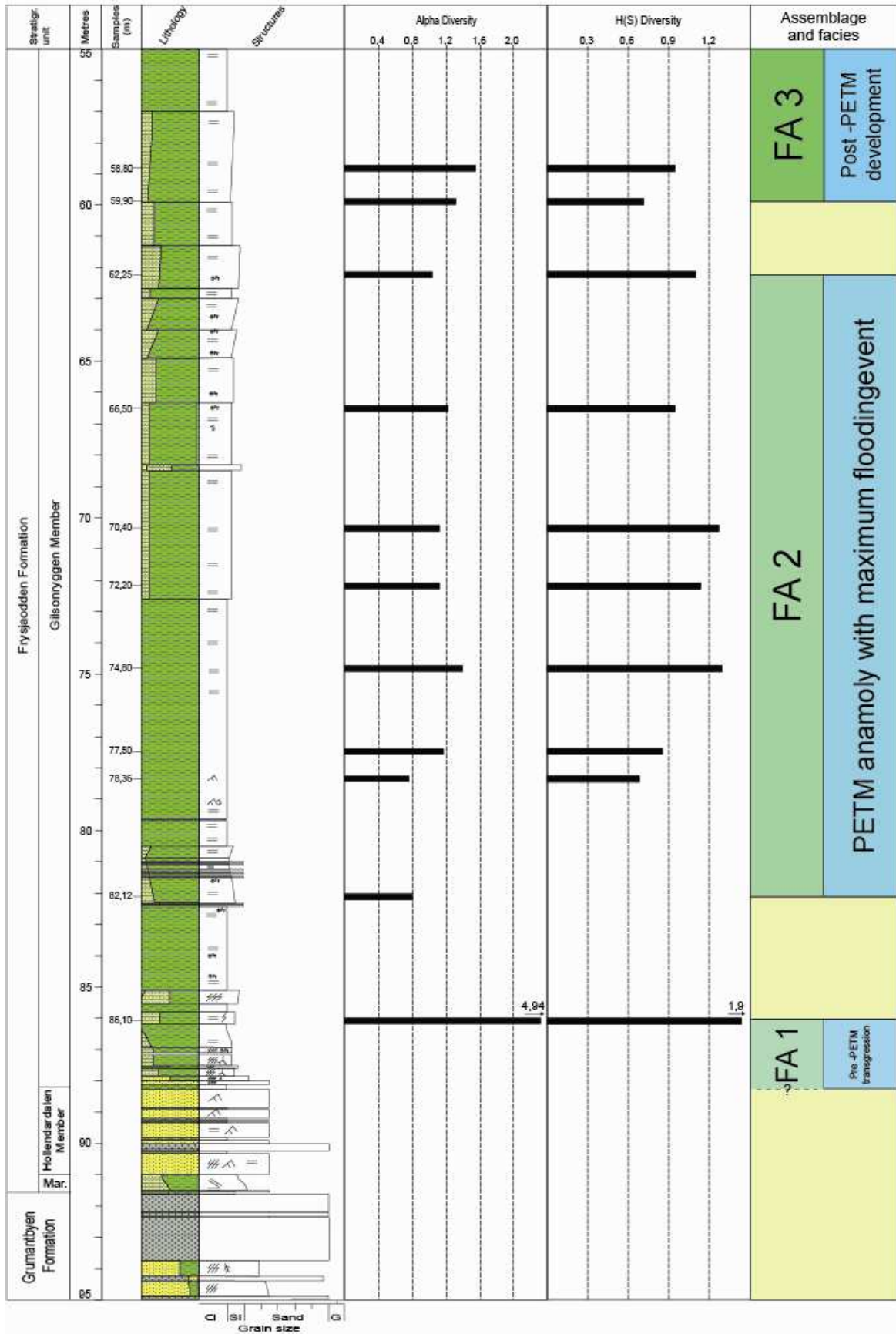


Fig. 9.2. Foraminifera assemblages and facies distribution in the core BH 07/08.



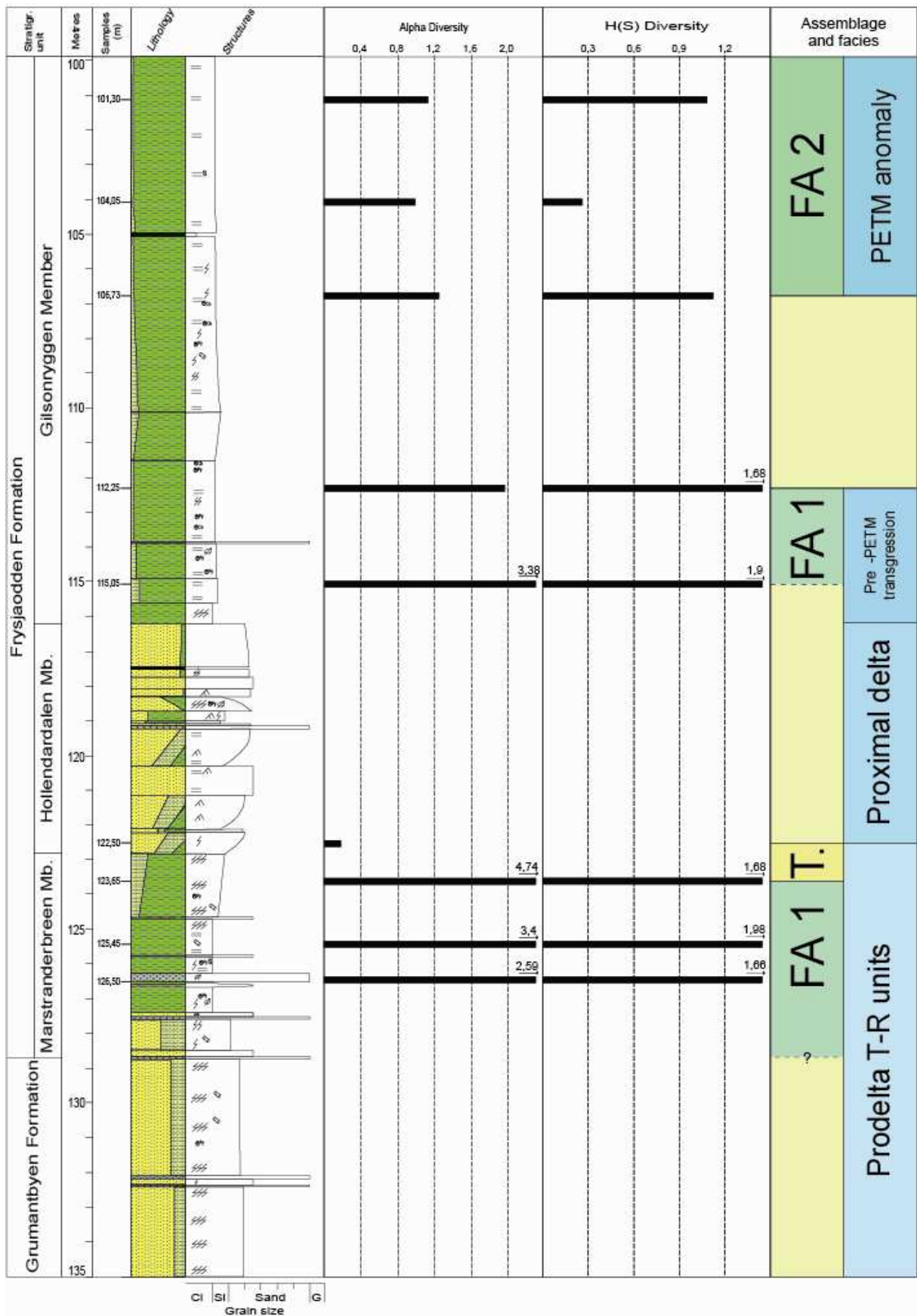


Fig. 9.3. Foraminifera assemblages and facies distribution in the core BH 09/06.

#### 9.4. The post-PETM development

In the uppermost part of core BH 07/08, two samples contain low diversity faunas belonging to FA 3. The alpha values 1.29 and 1.55 respectively. This interval represents a marked faunal change from dominance of *Trochammina* aff. *inornata* to high dominance of *Thurammina* aff. *papillata*. This change is probably caused by starting progradation of the Battfjellet-Aspelintoppen deltaic system. The diversities are low with maximum alpha 1.55 and H(S) 0.95. These low values indicate restricted environmental conditions.

#### 9.5. Correlation of core sections

The culmination of the PETM represents a time line (red line in Fig. 9.4) which is of the same age at basinal and global scale because of the global occurrence of the warming in the PETM. In the analyzed cores the position of this peak could not be defined exactly, because of the large stratigraphic distance between the samples. The critical intervals not covered by samples are from 509 to 520 m in core BH 10/06, 8.90 m in core BH 07/08 and 8.50 m in core BH 09/06. For correlation of the cores the base of these intervals are used (Fig. 9.4). This is defined by the highest observed occurrence of FA 1 assemblage, which is used as an approximate timeline. The last occurrence of *Reticulophragmium arcticum* is a good marker of this level.

To correlate the top of the Grumantbyen Formation in core BH 10/06 and BH 07/08, the conglomerate bed at the top of this formation is used (Fig. 9.4). This correlation is continued to core BH 09/06 by using the well-marked drop in grain-size at the boundary between Grumantbyen Formation and the Marstranderbreen Member. The high degree of bioturbation typical of the sandstones of the Grumantbyen Formation helps in the correlation.

In core BH 09/06, the Marstranderbreen Member is 5.85 m thick. It is assumed that the 0.1 m thick shale above the conglomerate at the top of the Grumantbyen Formation is a very thin equivalent of this member. The Hollendardalen Member is 6.80 m thick in core BH 09/06 and is reduced to 2.75 m in core BH 07/08. In the Nordenskiöldfjellet section the thickness of the Marstranderbreen Member is 3.90 m and Hollendardalen Member is 8.70 m thick (Rüther 2007). The Marstranderbreen and Hollendardalen members are absent from core BH 10/06 and the same is the case in core BH 09/05 (Dypvik et al. 2011) and in the Liljevalchfjellet section (Nagy, Pers. com. 2011). These observations show that the Marstranderbreen and

Hollendardalen members disappear towards south or south-east, and are probably replaced by the shales below the PETM. These shales contain the FA 1 assemblage and are 12.50 m thick in the BH 10/06 core and much thinner in cores BH 07/08 and BH 09/06 where they are about 2 m and 2.75 m respectively.

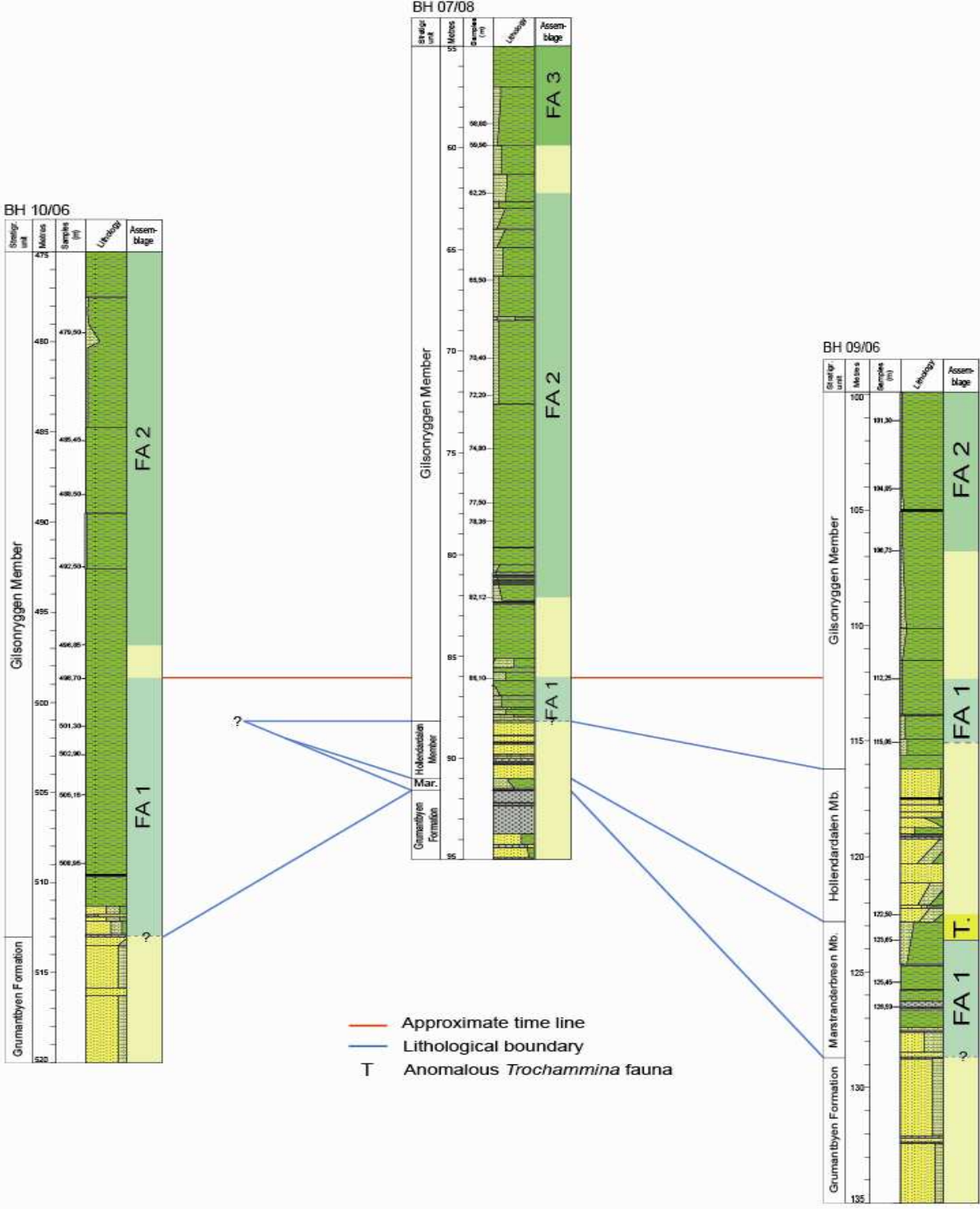


Fig. 9.4. Biofacies distribution and correlation of the three analyzed cores using the top of assemblage FA 1 as an approximate time line.

## 10. Sequence stratigraphy and correlation

The three core sections are here interpreted by means of a depositional sequence stratigraphic model. This model is used for example by Emery and Myers (1996). The nomenclature is here modified by replacing “High stand systems tract” by “Regressive systems tract”. In the cores, three depositional sequences are recognized and marked by S1, S2, and S3 (Fig. 10.1).

In the studied cores S1 includes the uppermost part of the Grumantbyen Formation. Its base is at the transition between the Firkanten Formation (Nagy, Pers. com. 2011), and the sequence contains the Basilika Formation and most of the Grumantbyen Formation. S2 is only found in core BH 07/08 and BH 09/06. It starts with a conglomeratic bed in the Grumantbyen Formation or in a thick conglomeratic unit at the top of this formation. The samples from this interval were hard to disintegrate therefore could not be analyzed for foraminifera.

The lower part of the transgressive systems tract of S2 is formed by the topmost part of the Grumantbyen Formation which shows fining up development into the Marstranderbreen Member which is also visible in core BH 09/06 and in the Nordenskiöldfjellet section (Dypvik et. al. 2011). The maximum flooding surface of S2 is in the shales of the Marstranderbreen Member containing a relatively high diversity foraminiferal assemblage belonging to FA 1. The regressive system tract comprises the upper part of the Marstranderbreen Member and the whole Hollendardalen Member. The coarsening up development can be seen in regressive system tract.

The transgressive trend in the lower part of the Marstranderbreen Member in BH 09/06 is characterized by the coarsening upwards siltstone and sandstone continuing in the sandstones of the Hollendardalen Member. The upper part of the Grumantbyen Formation in BH 07/08 is characterized by conglomerate deposit of about 2.5 m and this can probably be correlated with the transgressive systems tract of S2 in core BH 09/06 (Fig. 10.1).

S3 starts at the top of the Hollendardalen Member in the section BH 09/06, BH 07/08 and top of the Grumantbyen Formation in the section BH 10/06. In the Nordenskiöldfjellet section, S3 starts on the top of the Hollendardalen Member sowing root horizon. Each of the cores, the maximum flooding occurs at PETM in the lower part of the Gilsonryggen Member. The HST

comprises the middle and upper part of the Gilsonryggen Member, the whole Battfjellet Formation and the whole Aspelintoppen Formation (Nagy, Pers. com. 2011).

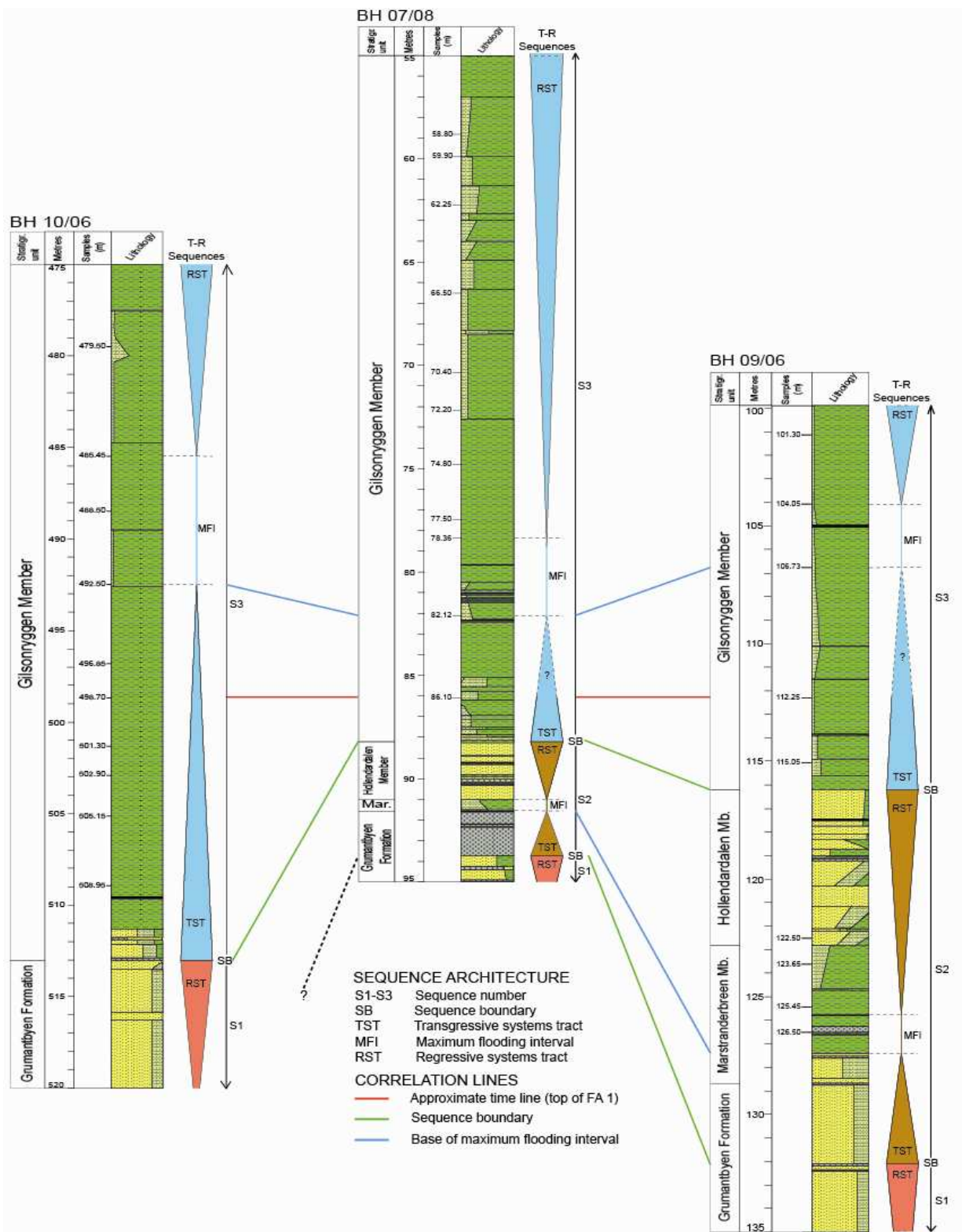


Fig. 10.1. Sequence stratigraphy and correlation of the three analyzed cores, using the top of the FA 1 as an approximate time line.

## 11. Conclusions

The thesis deals with changes of biofacies and depositional conditions across the PETM, mainly on the basis of combined data from sedimentary field logging and foraminiferal assemblages. The data originate from three analyzed core sections located in the Central Paleogene Basin of Spitsbergen. The main results of the analysis are:

1) The foraminiferal assemblages consist of agglutinated (benthic) species and show intermediate to low diversities. Three types of foraminiferal assemblages are distinguished in the analysed cores:

- FA 1: The *Recticulophragmium arcticum* assemblages were observed before the PETM and disappear at the beginning of this event.
- FA 2: The *Trochammina* aff. *inornata* assemblages was formed during PETM.
- FA 3: The *Thurammina* aff. *papillata* assemblages occur after PETM.

2) The pre-PETM deposits are characterized by relatively high foraminiferal diversities. The assemblages occurring here are dominated by shallow digging and deep digging foraminifera suggesting relatively good oxygenation in the upper part of the bottom sediments. The PETM is characterized by an extremely low diversity assemblages consisting of species living on the sediment surface because the water contained very low amount of oxygen and the sediment was almost anoxic. FA 3 shows a faunal change to be dominated by *Thurammina* aff. *papillata*, and we assume that it is caused by start of delta progradation.

3) The PETM is used as the time horizon helping correlation of lithological boundaries in the three cores. The correlation shows that the Hollendardalen and Marstranderbreen members are present in the BH 09/06 and BH 07/08 and absent in the core BH 10/06. This is in agreement with that deposition of the Hollendardalen Member was deposited from west or north-west.

4) Sequence stratigraphic analysis shows that parts of two sequences and a complete sequence are present in the studied cores:

- S1: Is represented by the uppermost part of the Grumantbyen Formation, and is present in all three cores.

- S2: Is complete and consists of the topmost part of the Grumantbyen Formation, the Marstranderbreen Member and the Hollendardalen Member, and is present in two of the cores.
- S3: Is represented by the lower part of the Gilsonryggen Member, and is present in all three cores.

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**Appendices 1-4**

**Appendix 1. Logging sheet used during the core logging.**

SHEET NO:		SCALE: SECTION: FORMATION		REMARKS, DESCRIPTION AND INTERPRETATION	
METRES A.B.		ORB scale 1 2 3 4 5 6			
LITHOLOGY	GRAIN SIZE AND SEDIMENTARY STRUCTURES	COLOURS			
CLAY SILT	VT F M G I VC F L M 0.0025 0.125 0.25 0.5 1 2 4 8 16 PBEL F L M	CLAY SILT F M G I VC F L M			
DATE:			BY:		



**Appendix 2. Counted foraminiferal number, abundance, and number of species, diversity indices, dominance and similarity with foraminiferal assemblages of the three cores:**

**BH 10/06**

Depth in meter	Counted foraminifera number	Abundance, individuals/10g	Number of species	Alpha diversity	H(S) diversity	Dominance (%)	Similarity (%)	Foraminiferal assemblage
479,5	130	37,97	5	1,03	0,81	74		FA 2
485,45	116	33,99	3	0,56	0,73	52	28,0	
488,5	265	72,44	3	0,47	0,81	62	16,1	
492,5	51	20,82	3	0,69	0,69	69	24,6	
496,85	80	28,83	4	0,88	0,93	51	14,8	
498,7	135	42,19	11	2,83	1,95	37	2,2	FA 1
501,3	88	26,9	10	2,9	2,18	22	25,3	
502,9	140	36,27	9	2,15	1,93	30	13,2	
505,15	100	34,01	8	2,05	1,39	57	10,9	
508,95	10	2,999	4	2,47	1,09	60	19,4	

**BH 07/08**

Depth in meter	Counted foraminifera number	Abundance, individuals/10g	Number of species	Alpha diversity	H (S) diversity	Dominance (%)	Similarity (%)	Foraminiferal assemblage
58,80	19	5,16	4	1,55	0,95	63,2		FA 3
59,90	27	7,92	4	1,29	0,72	77,8	78,0	
62,25	50	16,03	4	1,02	1,09	48,0	52,8	FA 2
66,50	172	52,44	6	1,21	0,96	69,7	10,1	
70,40	572	169,73	7	1,12	1,27	60,0	15,8	
72,20	239	68,88	6	1,12	1,14	54,8	45,5	
74,80	442	144,54	8	1,39	1,3	43,7	54,9	
77,50	487	157,45	7	1,16	0,85	78,4	43,5	
78,36	10	2,63	2	0,75	0,69	50,0	8,4	
82,12	2	0,55	1	0,8	0	100	50,0	FA 1
86,10	20	4,97	8	4,94	1,9	25,0	20,0	

**BH 09/06**

Depth in meter	Counted foraminifera number	Abundance, individuals/10g	Number of species	Alpha diversity	H(S) diversity	Dominance (%)	Similarity (%)	Foraminiferal assemblage
101,3	555	143,86	7	1,13	1,08	65		FA 2
104,05	451	125,17	6	0,98	0,26	90	104	
106,73	30	9,46	4	1,24	1,12	53	9,76	
112,25	112	36,13	8	1,97	1,68	36	0	FA 1
115,05	45	13,79	9	3,38	1,9	31	10,2	
122,5	47	13,32	1	0,18	0	100	0	T.
123,65	16	4,58	7	4,74	1,68	31	0,29	FA 1
125,45	61	15,84	10	3,4	1,98	20	6,57	
126,5	81	27,16	9	2,59	1,66	43	5,5	

**Appendix 3. Percentages of morphogroups through the core BH 10/06 with foraminiferal assemblages.**

Depth in meters	Morphogroup 1a	Morphogroup 2a	Morphogroup 2b	Morphogroup 3a	Morphogroup 3b	Morphogroup 4a	Foraminiferal assemblage
497.50		82,31	16,92		0,77		FA 2
485.45		47,41	51,72		0,86		
488.50		33,96	61,51			4,53	
492.50		29,41	68,63			1,96	
496.85		51,25	41,25		6,25	1,25	
498.70		5,19	41,48	37,78	15,55		FA 1
501.30		10,23	19,32	56,82	13,63		
502.90		10,71	10	71,43	7,86		
505.15		10	2	83	5		
508.95			10	90			

Appendix 4. Range chart showing number of foraminiferal specimens with foraminiferal assemblages defined in the three cores:

BH 10/06

Depth in meters	Gram of sediment	<i>Haplophragmoides reindeerensis</i>	<i>Trochammina</i> sp. 1	<i>Reticulophragmium borealis</i>	<i>Reticulophragmium arcticum</i>	<i>Haplophragmoides aff. richardsonensis</i>	<i>Verneuilionides</i> sp. 1	<i>Labrospira turbida</i>	<i>Thurammina</i> aff. <i>papillata</i>	<i>Convallina</i> aff. <i>logani</i>	<i>Haplophragmoides multicutubiculus</i>	<i>Trochommina</i> aff. <i>inornata</i>	<i>Reticulophragmium</i> aff. <i>ministicooense</i>	<i>Convallina</i> aff. <i>elongata</i>	<i>Ammotium</i> sp.	<i>Birsteinioilla</i> sp. 1	<i>Rheophax</i> aff. <i>metensis</i>	<i>Psammospira</i> sp.	<i>Thuramminopsis</i> sp. 1	Number of species	Counted foram number	ASSEMBLAGE
479.50	34,24						1		96			22						2	9	5	130	
485.45	34,13								55			60					1			3	116	
488.50	36,58								90			163				12				3	265	FA 2
492.50	24,50								15			35				1				3	51	
496.85	27,75								41			33			5	1				4	80	
498.70	32,00		6	5	17		2	21	7	13	1	50	7	6						11	135	
501.30	32,71		5	4	19		5	13	9	7	9	12	5							10	88	
502.90	38,60		5	9	42		11	7	15		8	9	34							9	140	FA 1
505.15	29,40		2	17	57	4	2	5	10	3										8	100	
508.95	33,34	1	1	2	6															4	10	

58,80	36,80	<i>Haplophragmoides multicubiculus</i>									
59,90	34,10	<i>Reticulophragmium</i> aff. <i>ministicoogense</i>									
		<i>Labrospira turbida</i>									
		<i>Reticulophragmium borealis</i>									
		<i>Reticulophragmium arcticum</i>									
62,25	31,20	<i>Thurammina</i> aff. <i>papilata</i>	12	1	5	4	4	1	5		
66,50	32,80	<i>Trochammina</i> sp. 1	21	4	4	24					
70,40	33,70	<i>Trochommina</i> aff. <i>Inornata</i>	19	3	343	8	7				
72,20	34,70	<i>Birsteiniolla</i> sp. 1	4	6	76	7					
74,80	30,58	<i>Spiroplectommina</i> aff. <i>biformis</i>	56	11	161	14					
77,50	30,93	<i>Rheophax</i> aff. <i>metensis</i>	131	6	382	4	7	12	41		
78,36	38,05	<i>Verneuilinoides</i> aff. <i>exudum</i>	52	11	4	6	2	6	193		
82,12	36,60	<i>Verneuilina</i> sp.	15	26	56	33	8	1	64		
		<i>Psammosphaera</i> aff. <i>fusca</i>	5	5	4	33	8	1	120		
		<i>Verneuilionides</i> aff. <i>durus</i>	2		3	8			3		
		<i>Ammodiscus</i> aff. <i>macilentus</i>			1	1			1		
		<i>Glaphyrammina</i> sp. 1							1		
		<i>Thurammina</i> sp. 1							1		
86,10	40,23	Number of species	1	1	2	4	4	4	4	8	
		Counted foram number	40,23	40,23	40,23	40,23	40,23	40,23	40,23	20	
		ASSEMBLAGE								FA 1	

