Faculty of Science

Variations in depositional environments of the Paleogene Firkanten Formation across Adventdalen, from Operafjellet to Breinosa

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Degree of Master of Science (120 credits)
with a major in Earth Sciences
60 hec

Department of Earth Sciences
University of Gothenburg
2021 B1121

UNIVERSITY OF GOTHENBURG

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ISSN 1400-3821

B1121
Master of Science (120 credits) thesis
Göteborg 2021

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Abstract

The lowermost Paleogene clastic infill of the Central Spitsbergen Tertiary Basin, the coal bearing Firkanten Formation, has been the subject of study for researchers in the past but little focus has been on the northeast edge of the basin until now. Due to the economic potential of the coal seams in the formation, the Norwegian mining company, Store Norske Spitsbergen Grubekompani (SNSG), has for several years conducted core drilling in key locations in basin, and for decades, they have given an access to their core material to researchers.

Drill cores and laboratory results from SNSG is used for sedimentological and geochemical investigation for the purpose of comparing the depositional environment in the Operafjellet and Breinosa mountains, to give a better understanding of the depositional setting at the northeast edge of the basin.

Six cores from each mountain were chosen as they characterized the overall lithology of the area, with a complementary field log and observations from Operafjellet mountain. All cores were logged in detail (1:20), and special attention was put on the coal where lithotyping was done on cores with intact coal seams. Furthermore, laboratory results from SNSG, containing ash and sulphur results from the coal seams, were used to support correlation and to investigate the quality of the coal at the basin edge.

In the past, 5 coal seams have been recognised in the Todalen Member, the lowermost member of Firkanten Formation. Two new coal seams, one from the top of Todalen Member and another from the uppermost Endalen Member of the formation are presented with detailed description and names to distinguish them from other seams.

Results show that the Firkanten Formation is deposited in coastal plain to shallow-marine setting and significant lithological differences are observed in the two areas despite their relatively short distance from each other, this is especially noticeable in the Todalen Member where there are coal deposits of higher quality and greater thickness and relatively thicker foreshore to backshore deposits in Operafjellet than in Breinosa. The overall trend of much thicker deposits in Operafjellet suggest a relatively greater accumulation rate and accommodation space at the edge of the basin.

The Todalen Member in Operafjellet is suggested to be deposited on a backshore tidal flat with interfingering upper-shoreface deposit, and in same member further south in Breinosa, there is evidence of deposition on foreshore to proximal lower shoreface. The overlying Endalen Member is suggested to be deposited on lower to uppers shoreface with a small regression at the top of the member allowing for backshore tidal flat deposits with peat accumulation in the top of the formation in Operafjellet.

Facies association distribution and unit thickness along with sulphur and ash conserved within the coal, strongly supports increased marine influence (within the coal) and deeper marine facies in the south of the study area. This indicates a general NW-SE orientation of the coastline and sediment input from the north/north west.

Acknowledgement

Store Norske Spitsbergen Grubekompani (SNSG) is acknowledged for providing me with a job where I could combine my masters project with work. Furthermore, I thank them for the use of geochemical data from coal samples, for core photos and helicopter transport to the field side of Operafjellet. Malte Jochmann, co-supervisor of this project at SNSG/UNIS, is thanked for training me in logging, giving me good criticism so I could develop myself as a logger, helping me to come up with the idea of this project, help with maps of drilling locations and finally hiring me at SNSG and giving me the opportunity to work there for several seasons. Bjarki Friis at Store Norske is thanked for photographs, making sure that we had all the equipment needed for the fieldwork and for help with maps. I also would like to thank all the summer employees and co-workers at Store Norske for logging collaboration, especially the "Endalen family": Chris, Christine, Henriikka and Gauti, which worked with me for few seasons and made my time in Endalen unforgettable. Chris Marshall should get especial thanks for his help in the field, many helpful and interesting discussions throughout the years and for training me in coal lithotyping. I would like to acknowledge my main supervisors, Mark Johnsons (GU) and Maria Jensen (UNIS) for supporting this idea of a project, for their patience and support as the project was put on hold. Maria gets special thanks for taking the time to look at the drill cores with me in Endalen, getting me started, keeping regular meetings with me and giving me great feedbacks and support whenever I needed it, and Mark for getting me through the last part of this project with very useful feedback. My friend Karolina Paquin, I would like to thank for proofreading the thesis. My mother I thank for all the phone calls with the thesis topic and for her support and believe in whatever I do in life. Finally, I would like to thank my amazing husband for his endless support and patience throughout the years and for listening to me go on and on about geology for so, so many years.

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1 Introduction

1.1 Aim of study

The Firkanten Formation consists of the lowermost sediments in the Van Mijenfjorden Group of the Central Tertiary Basin on the island of Spitsbergen in Svalbard. The Van Mijenfjorden Group includes seven Cenozoic sedimentary formations that represent the clastic infill of the basin. The central basin is the largest and most prominent of several individual basins made up by the Cenozoic rocks of Svalbard and indicates the remainder of syn-orogenic foreland basin of a Cenozoic fold-thrust belt. The Central Tertiary Basin forms a NNW-SSE trending syncline with the basin axis being asymmetrical and lying close to the western margin of the basin. The basin dips gently 0-6 degrees in the eastern part of the basin towards its axis, but much steeper dip is present in the western part or 5-30 degrees towards the axis (Dallmann et al. 1999).

The object of this study is to investigate and compare the depositional environment of the Palaeocene Firkanten Formation across the Adventdalen valley, in both the Operafjellet and Breinosa mountains, which are situated on opposite sides of the valley with Operafjellet located on the northeast edge of the basin, and Breinosa to the south of Operafjellet (Fig. 1).

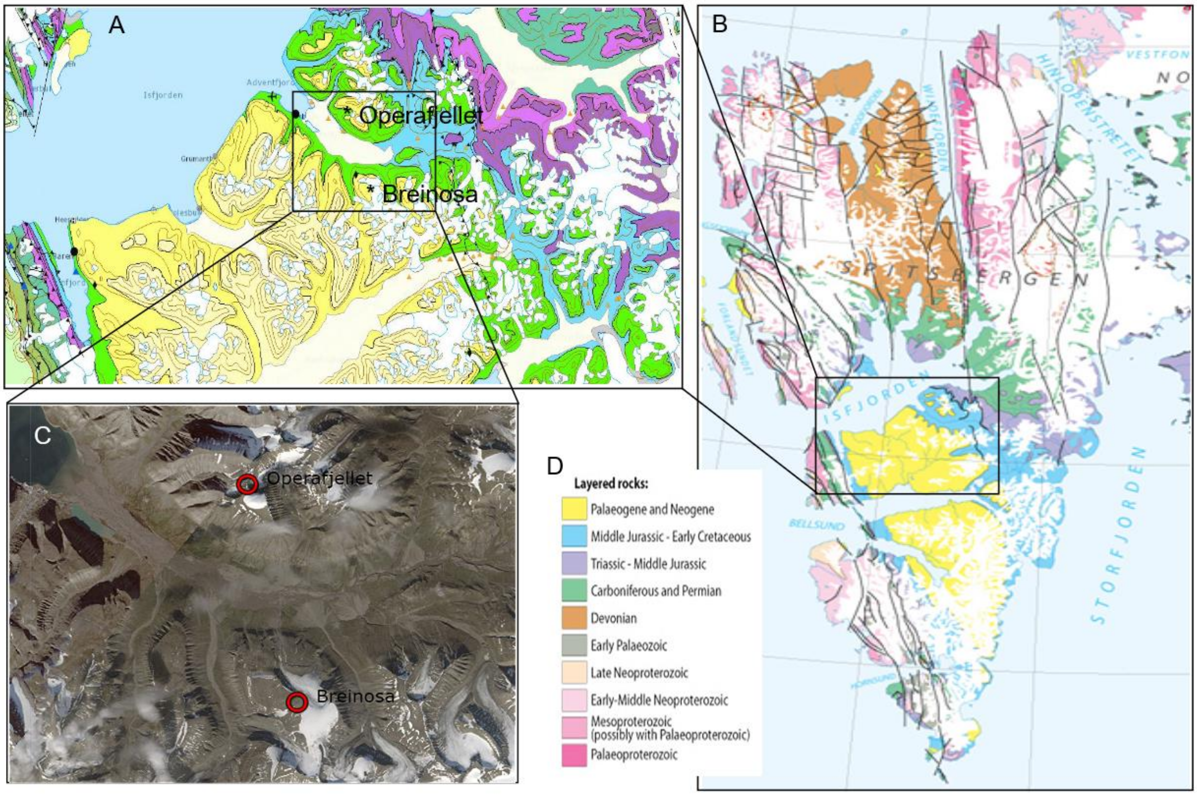


Fig. 1. Geological maps of Spitsbergen and the study area with legend, and an aerial photography of the study objects. Norsk Polarinstsitutt.

Although the Firkanten Formation has been the object of researchers for decades, the focus on the Northeast edge of the basin where Operafjellet is located, has been scarce. Through the exploration history of the coal-mining company Store Norske Spitsbergen Grubekompani (SNSG), considerable amount of drill cores have been extracted throughout the basin, and fieldwork has been conducted both by SNSG geologists and other researchers with the main focus on areas south of Adventdalen. With a detailed focus on the Firkanten Formation in Operafjellet and Breinosa, this research can give new insight into the development of the Firkanten Formation at the basin edge.

Currently, SNSG operates a coal mine in Breinosa, and extensive mapping of the mountain has been done in the past. In 2010 Operafjellet became a relevant part of coal exploration by the company, where the Operafjellet coal field was considered as a possibility to be opened for further exploitation in the future. In the years 2010-2013, several drill cores were taken from Operafjellet that can now be used for further research of the mountain.

Detailed logs from cores from Operafjellet and Breinosa, along with laboratory results from coal samples, comprise the principal data in this study. A great focus will be on the coal in the Firkanten Formation where laboratory results will be used for more thorough correlation of the several coal seams across the valley, because abundance of coal seams in close proximity with partings can often complicate correlation and give false results. The laboratory results are also used for discussion of the depositional area in relation to marine influences and lateral changes within each coal seam. Coal lithotyping, a preliminary petrographic examination of the coal, is conducted on few of the cores for discussion of the formation of the seams.

The logs show a considerable difference in lithology and bed thickness, despite a relatively short distance between the two mountains. I seek to make a detailed description of the sedimentary architecture and environmental interpretation, as well as discuss in detail the coal seams found in both the mountains. I will discuss the variation in the coal seams across the valley to use that for building a foundation for a lateral correlation through the study area in the hopes of giving further insight to the processes at the northeast edge of the basin.

1.2 Previous work

The Firkanten Formation has been the object of investigation for researchers since as early as 1910 when Narthorst described the formation for the first time as the "Lower light sandstone series" (Dallmann 1999). In 1964, Major and Nagy used the name of the Firkanten Formation for the first time (Major and Nagy, 1964, Dallmann, 1999) and the current definition of the formation is published by them in 1972 (Major and Nagy 1972)

In recent decades, the Firkanten Formation has gotten some more attention, and several researchers have published articles and written final projects on it with different focal points. Bruhn and Steel (2003) published a paper suggesting a new interpretation of for the Central Tertiary Sedimentary Basin, in which the entire Paleocene-Eocene basin fill is incorporated into a foreland-basin scenario. Malte Jochmann (2004) wrote his master's thesis about the geology of the Firkanten Formation in the Ispallen area, where the Palaeocene deposits, south of the Van Mijenfjorden Fault Block, are located. Petrographic coal analysis was made to reconstruct the depositional environment and correlate the coal seams, geophysical data was reviewed and the underlying Carolinefjellet Formation was examined resulting in a new model where morphology of the study area plays an important role (Jochmann, 2004). A year later, Jenö Nagy combined diagnostic features of foraminiferal facies with sedimentary data in his paper, to throw light upon the sequent stratigraphic development of the formation (Nagy, 2005). In 2008, Charlotta Jenny Lüthje submitted her PhD thesis, the first comprehensive facies model, sequence stratigraphic analysis and paleogeographic reconstruction of the Firkanten Formation with main concentration on borehole data in the eastern part of the basin, reaching from Adventdalen and southwards (Lüthje, 2008). These are all extensive investigations that gave a good insight into the sedimentology of the Palaeocene Firkanten infill of the Central Tertiary basin.

Furthermore, studies with another focus of the deposition in the Firkanten Formation have been published such as the doctoral thesis of Christopher Marshall (2013), on paleogeographic development and economic potential of the Firkanten Formation. He utilised a large database of drill core logs from Breinosa and south of it to create cross-sections and coal isopach maps to examine spatial relations between seam thickness and paleotopography (Marshall, 2013). Petersen et al (2016), used Detrital zircon U-Pb LA ICP-MS (laser ablation inductively coupled plasma mass spectrometry) age data for Palaeocene and Eocene Sandstone from the Central Tertiary Basin to investigate provenance and to test the filling history of the basin in response to evolving Eurekan orogeny, a mountain building event that generated the West Spitsbergen Fold Belt and peaked at approximately 47-49 MA (Petersen et al. (2016). And finally, Jones et al. (2016) studied prominent and laterally continuous bentonite layers in the lower formations of the Van Mijenfjorden Group for the purpose of using these layers as stratigraphic markers to connect the basin development with regional explosive volcanism and changes to relative plate motions.

More recent studies have also been done on the Firkanten Formation by master's students with the focus on sedimentology of the Firkanten Formation. Re-examination of the Endalen and Todalen Members have been done by Serigstad (2011) and Grasdal (2018). Serigstad made a re-examination of the Todalen Member based on new material available from SNSG with focus on facies analysis and sequent stratigraphy, suggesting in a coastal-plain setting and deposition in an overall stepwise transgressive setting where the coastline retrograded a north-northeasterly direction. The study is focused on a large area of the Central Tertiary Basin from the northeast edge of it to central part of the basin (Serigstad, 2011), Grasdal focused on the upper member of the Firkanten Formation and the large-scale depositional architecture of the Endalen Member and internal architecture of the sedimentary bodies. It is the most recent study done on the Northeast edge of the basin, an investigation of spatial development within the Adventdalen area using field logs and laterally extensive photo-mosaics of outcrops (Grasdal, 2018).

Two studies using petrographical and sedimentological investigations have been done in the last decade where Svinth (2011) investigated the boundary of the Todalen and Endalen Members to interpret the deltaic environment in which they were deposited in, to establish a provenance area for the sandstone, and to point out the prevalent diagenetic processes taking place during the subsequent burial (Svinth, 2011). Furthermore, a petrographical, sedimentological and geochemical research was done by Osaland in 2018, where she focused on the sandstones from the Central Tertiary Basin, looking into factors controlling the types and distribution of authigenic minerals, identifying geochemical trends in sediment cores, and discussing the consistency between authigenic signatures and vitrinite reflectance measurements of coal/organic matter (Osaland, 2018)

Other studies worth mentioning are the sedimentological development study of the Askeladden sequence of the Todalen Member in Lunckefjellet with the aim of making a sedimentological description and a paleogeographic model of the Askeladden sequence based on interpretation and correlation of facies and facies associations (Aspøy, 2011). And lastly, a study was done to improve the general understanding of the Grønfjorden Bed at the base of Firkanten Formation, which was previously poorly studied. This investigation focused on the sedimentology of the Grønfjorden Bed and associated deposits from Grønfjorden. Evidence of a northwest towards the southeast paleocurrent direction for fluvial conglomerates and sandstones is presented which suggests the presence of a wide fluvial valley in the Grønfjorden area at the time of deposition. The initial fluvial environment is suggested to have contributed as a tributary valley to a much larger fluvial valley system (Berg, 2018)

All the studies mentioned above covered significantly large parts of the basin focusing on various topics. What they have in common though, is to focus on the Firkanten Formation. They show that the Firkanten Formation in Breinosa is characteristic for the formation, but some non-representative features are now found in Operafjellet, thus investigation covering the whole Firkanten Formation in detail at the Northeast edge of the basin was needed. Little is known about the area, and the opportunity to investigate further occurred when, after a long break, new drill-core material became available after drilling and exploration started in the Operafjellet mountain again in 2010 by SNSG.

1.3 Introduction to coal

Coal is the altered remains of prehistoric vegetation (World Coal Association, worldcoal.org) that originally accumulated in swamps, peat bogs, marshes and freshwater swamps as the product of initial decomposition of vegetal matter. Of these, the freshwater swamps are the most important for the accumulation of the extensive, thick peat deposits of the past that produced the coal that is mined today (Stefanko, 1983). The climatic condition of which most of the peat deposits of the past was formed was probably not that far from today's climate. Although, it was most likely relatively warmer, with more abundant and regular rainfall than today and more plentiful vegetation, suitable and properly located for peat deposition. During coal-forming geological periods, these conditions probably resulted in peat deposition rate twice as great as present day (Stefanko, 1983). Furthermore, according to Stefanko (1983) the values given for comparison of estimated time required for the deposition of peat to provide 30 cm thick coal seams of various ranks of coal are: Lignite = 160 years, bituminous coals = 260 years and anthracite = 490 year.

Large and Marshall (2014) have however discovered that the balance between productivity and decay determines the rate at which carbon accumulates in peat, and this is quite well studied for Holocene peat (Clymo, 1984, 1992; Yu et al., 2011; Belyea and Malmer, 2004; Yu et al., 2010b; Large and Marshall 2014) although volumetric growth rates of these peat deposits do not provide a proper method of understanding thick coal and lignite without considerable assumptions of hiatuses (Shearer et al. 1994, Large and Marshall 2014). Large and Marshall (2014) suggest that combining global carbon accumulation patterns in peat with estimated loss during coalification should make it possible to project the amount of time needed for carbon accumulation within a coal seams.

In their paper, Large and Marshall (2014) state that volumetric growth rates and density of the Holocene peat deposits are not as well understood, but for any coal, given knowledge of its carbon concentration and paleoclimate or palaeolatitude at the time of deposition, they can provide a method for estimating the time required for the carbon accumulation. Having studied the Svalbard Palaeocene coals to a considerable extent where the coal is approximately 82% organic carbon with density around 1.3 g/m^3, Marshall (pers.comm.) calculates approximate time of 40 cm is 20,000 years roughly if given the carbon accumulation rate 20g/m2 and thickness of a coal seam 2.15 m. The difference between former methods and the new from Large and Marshall 2014 is quite great as in the past; time contained within coal has mostly been estimated by using a volumetric approach without including processes of carbon accumulation and loss during peat formation and coalification which would be more appropriate method to yield more accurate results.

It is clear that considerable time was needed for accumulation and coalification of the many coal seams that are present in the Central Spitsbergen Tertiary Basin. A special focus will be on all the coal seams and they will be discussed in detail here.

1.3.1 Classification and characteristics of coal

Degree of metamorphism, or rank, characterizes varieties of coal and is a quite common method of coal classification. The word rank is used to nominate coal differences due to progressive change from lignite to anthracite (Stefanko, 1983); it is based on the degree of increase in organic carbon content, coalification and carbonification of coal due to burial and metamorphism (Boggs, 2011) (see table 1).

The rank of coal is as following:

- Lignite: The lowest rank of coal is lignite which is brown or brownish black coals that contain high moisture and often keeps much of the structure from the original woody plant fragment. Lignite is commonly from Cretaceous or Tertiary.

- Sub-bituminous coal: The coal ranked between lignite and bituminous coals and has properties intermediate between them are sub-bituminous coal (Boggs, 2011). It can vary a bit in physical properties and can be similar to bituminous coal and be banded or have same properties as cannel coal, non-banded, dull and black.
- Bituminous: Bituminous coals are hard black coals with higher carbon content than lignite and keeps less moisture and fewer volatiles.
- Anthracite: Anthracite is the highest ranked coal and commonly has over 90 percent carbon content. It is hard, black, shiny and dense and breaks with conchoidal fracture.

For distinguishing one coal from another on the base of its sulphur or ash content (ash content being the non-combustable residue after coal is burned, often expressed as a percentage of the original weight) the word grade can be used. High grade coal is therefore a relatively pure and high rank coal is one that has undergone de-volatilization and contains less volatile matter, oxygen and moisture than it did before, it is then considered high on the scale of coals (Stefanko, 1983).

Table 1.

Classification of coal put together from Boggs (2011), Tucker (2011) and Stefanko (1983).

Class (rank)	Anthracite	Bituminous	Subbituminous	Lignite
Characteristics and structures	Black, hard, shiny, dense, conchoidal fractures, bright and lustrous	Black, hard, bright layers, break in cuboidal fragments along the cleat	Black. Can vary in physical properties. Can be banded or non-banded and dull	Brown-brownish black, original woody plant fragments
Calorific value limits (Btu/lb) moist, mineral	----	10,500-14,000	8,300-10,500	6,300-8,300
Volatile matter (wt.%), dry-mineral and matter-free basis	2-14	22- >30	>31	>31
Fixed Carbon limits (wt.%) dry, mineral-and matter-free basis	86-98	69-86	<69	<69

Cannel coal and boghead coal have the bituminous rank and much higher content of volatiles than anthracite (see table 1) they are non-banded, dull, black coals that also break with conchoidal fracture. The cannel coal is dominantly composed of spores while boghead coals are mostly composed of non-spore algal remains. Bone coal is very impure coal that contains high ash content (Boggs, 2011). The term impure coal can be accompanied by adjectives such as silty, shaly or sandy, to refer to the type of impurities in the coal (www.usgs.cov).

Stopes (1935) (as cited in Boggs, 2011) suggested the name macerals for coal which under microscope can be seen having several kinds of organic units which are single fragments of plant debris or, sometimes, fragments consisting of more than one type of plant tissue. Macerals are the building blocks of coal, just as minerals are to rocks (Kentucky Geological Survey 10.09.2020). Macerals are divided into three main groups: Vitrinite, Inertinite and liptinite and the starting material for them are woody tissue, bark, fungi, spores etc. but they are however not always recognizable in coals. The coal macerals are identified by their various characteristics such as: Reflectivity, degree of anisotropy or isotopy, presence or absence of fluorescence, morphology, relief and size (Boggs, 2011). The specifics of each macerals group will not be discussed further in this research; however, a further focus will be put on the lithotypes and classes.

Four main coal lithotypes were recognized by Stopes (1919) (Boggs, 2011): Vitrain, clarin, durain and fusain (see table in Fig. 46). Types of coal such as Humic (banded) coal or Sapropelic (non-banded) coal are a geological classification based on visible appearance of coal and lithotypes are subclassification of the types, based on internal layering or banding of the coal (uky.edu-01.10.2020). These lithotypes which are comprised of thin bands or layers of humic coal (banded coal), can be recognized based on macroscopic textural appearance and petrographical or microscopic constituents (See Table 2). Lithotyping is based on the gelification index (Diesel, 1992; Siavalas et al., 2004) which is used to determine the moisture of the peatland and is defined as the ratio of the gelified macerals to the non-gelified macerals. This can tell us how wet the environment was during the peat/coal formation and even suggest forest fires or lightning strikes in the case of fusain.

Lithotyping was originally designed for macroscopic identification (Stach et al., 2013, Flores, 2014) which was designed to be preliminary to petrographic examination. Coal bands can be visually studied/logged, with the naked eye, especially in mines (Flores, 2014), and now also in cores.

Table 2.

Principal Coal Lithotypes for humic (banded) coal. Modified from Boggs (2011) with pers. Comm. Christopher Marshall.

Principal coal Lithotypes	
Vitrain	Brilliant, glossy, vitreous, black coal, 3-5 mm thick bands; breaks with conchoidal fracture; clean to the couch. Mainly vitrinite.
Clarin	Smooth fracture with pronounced gloss; dull intercalations or striations; small-scale sub lamination within layers give surface a silky luster; the most common macroscopic constituent of humic coals. Clarain mixture or layers of both vitrain and durain.
Durain	Occurs in bands a few cm thick; firm, somewhat granular texture; broken surface has a fine lumpy or matte texture; characterized by lack of luster, grey to brownish black colour, and earthy appearance. Mainly inertinite.
Fusain	Soft, black; resembles common charcoal; occurs chiefly as irregular wedges; friable and porous if not mineralized. Signifies fires.

2 Study area

2.1 Svalbard

Svalbard is an archipelago comprising several islands, located from 74-81° North and 10-35° East. The climate in Svalbard is mild relative to its high latitude but vegetation is scarce and high trees are absent in the present-day environment. The total land area of the archipelago is 62 000km^2, and approximately 60% of that is covered with glacier and inland ice. Although such a big part of the archipelago is covered with ice, mountains and coasts display excellent outcrops for geological research. These successions expose rocks ranging from Precambrian to Paleogene that have been studied actively by international researchers in Svalbard for approximately 170 years (Steel and Worsley, 1984). Furthermore, several drilling projects have given even better coverage of the strata from areas that are completely ice covered and therefore contributed significantly to even more thorough and detailed research.

2.2 Operafjellet and Breinosa

Operafjellet and Breinosa are two mountains situated on opposite sides of Adventdalen valley (see Fig. 2), a 30 km long and approximately 6 km wide valley in which Adventdalselva river runs westwards through and ends up in Advendfjorden fjord. Many smaller valleys branch into Adventdalen valley and Breinosa is situated in between two of them, Bolterdalen and Foxdalen valleys on the southern side of Adventdalen. The highest top of Breinosa is Foxfonna glacier which is 818 meters high (Norsk Polarinstitutt, maps). In Breinosa, Store Norske is currently operating the only coal mine that is located close to the Longyearbyen settlement, Gruve 7.

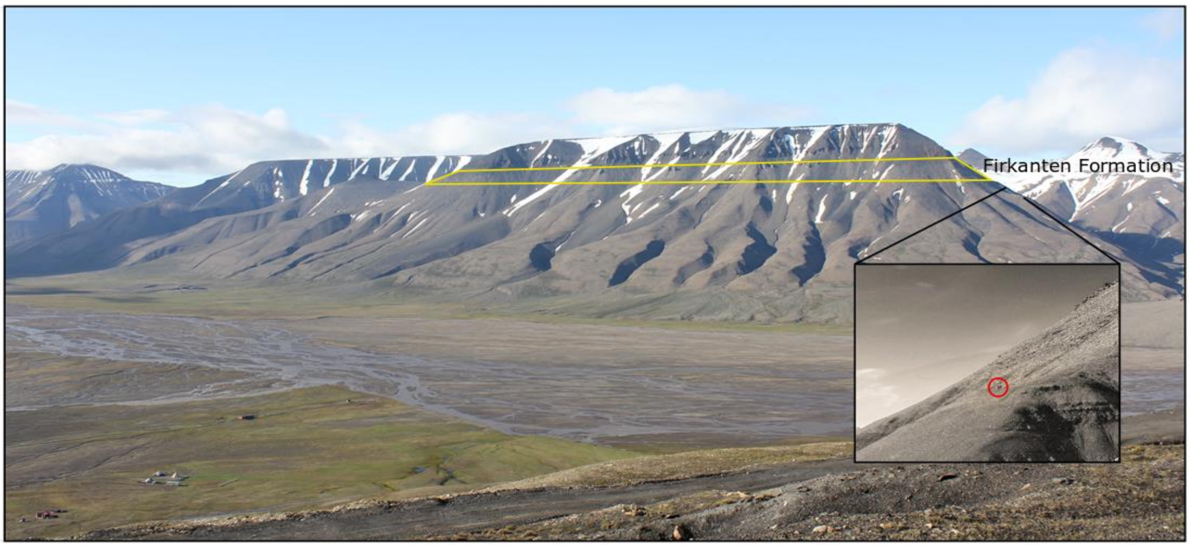


Fig. 2. A view over Adventdalen, from Breinosa towards Operafjellet. Firkanten is marked within the yellow box. Small picture (by Bjarki Friis) shows the field work location taken from Northeast of the mountain towards Breinosa, fieldworkers for scale inside the red circle.

Operafjellet is a considerably larger and higher mountain than Breinosa where the mountain tops have been given the themed names Tenoren, Dirigenten, Alten and Bassen (see Fig. 3). Operafjellet lies between the valleys Mälardalen and Helvetiadalen, two tributary valleys of the northern side of the Adventdalen valley (Norsk Polarinstitutt, maps).

Both mountains consist of Cretaceous to Palaeocene sediments, with Firkanten Formation most likely the best studied formation due to its economic potential of its coal bearing Todalen Member. In the comparison of the two mountains, Breinosa is investigated better than Operafjellet due to the excessive drilling and in mine logging, despite difficulties with finding outcrops in the mountain due to scree.

Operafjellet mountain on the other hand provides good relatively good outcrops, and fieldwork was carried out there to support observations made during core logging. The field side was located in the south-westernmost point of the mountain close to core 15-2010 (see Fig. 4). Further fieldwork was not done due to difficulty in accessing the mountain.

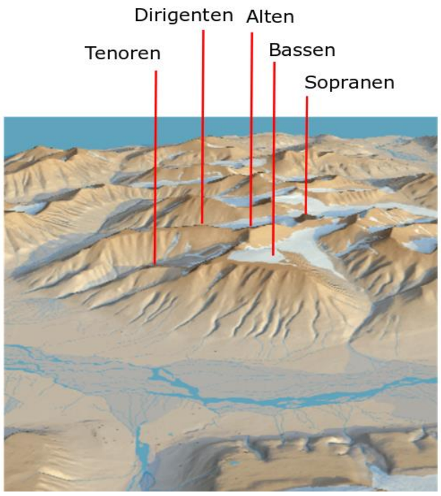


Fig. 3. The mountain tops of Operafjellet. Map: Topo-Svalbard

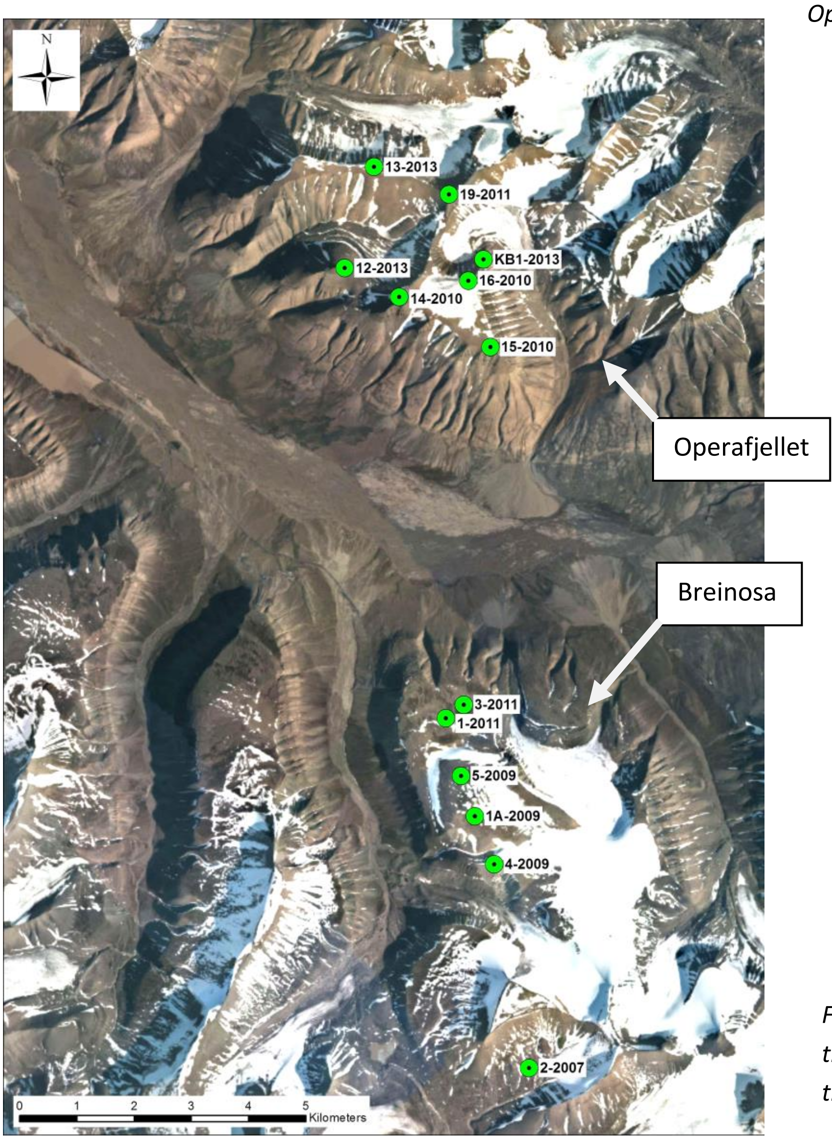


Fig. 4. Map of the study area with the locations off drill cores used in the study.

2.3 Central Spitsbergen Tertiary basin

The Central Tertiary Basin (see geological map in Fig. 5) in Spitsbergen forms a broad, NNW-SSE trending syncline bounded by the West Spitsbergen Orogeny deformation belt in the West (Harland, 1965, 1969; Müller and Spielhagen, 1990) and the Lomfjorden fault zone in the East (Müller and Spielhagen, 1990). The basin is infilled with clastic rocks (Dallmann et al., 1999), that are approximately 1.5 km thick in the northeast and thickens up to 2.5 km in the southwest (Steel and Worsley, 1984).

Fig. 5. Geological map of Svalbard, The Norwegian Polar institute. Red circle has been placed on the study area.

The Palaeocene sediments in Svalbard rest on a regional unconformity corresponding to a northward-increasing hiatus that spans most of the Late Cretaceous (Bruhn and Steel, 2003) Sediments from the late Cretaceous are therefore absent due to uplift, subaerial erosion and slight tilting of the Barents shelf (Birkenmajer, 1981; Müller and Spielhagen, 1990). This uplift could be the result of doming related to onset of trans-tensional tectonics between Greenland and Svalbard (Steel and Worsley, 1984; Müller and Spielhagen, 1990). Furthermore, Bruhn and Steel (2003) suggest that the unconformity was, in addition to the regional uplift, a product of initial peripheral bulge formation (cf. Stockmal et al., 1986; Crampton and Allen 1995). In the lowermost Palaeocene basin fill, sediment transport from the north is observed and in the rest, sediments transport from east to west is observed (Kalgaff 1978; Tønseth, 1981; Nøttvedt, 1985; unpublished data of J Gjelberg and the authors; Bruhn and Steel, 2003; Lüthje, 2008; Svinth, 2011). This suggests that in late Cretaceous, the northern part of Spitsbergen may have been an elevated area but did not have higher topographical significance in the Palaeocene when the sediment transport into the basin was dominated by N-S trending topography (Bruhn and Steel, 2003).

Based on paleo stress analysis of the Todalen and Endalen Members of the Firkanten Formation, a short sinistral strike-slip phase has been suggested by Kleinspehn et al. (1989) for the motion between Svalbard and Greenland in the earliest Palaeocene. Due to this erosion, the Paleogene sediments of the basin overlie the Albian/Aptian aged strata of the Carolinefjellet formation, an alternation of sandstones and shales (Müller and Spielhagen, 1990).

2.4 Van Mijenfjorden Group

The Paleogene and Neogene sediments overlying the Cretaceous Carolinefjellet Formation are divided up into seven formations, consisting of clastic sediments that are mostly shale and sandstones with coal bearing units in the lowermost and uppermost parts, representing delta-related shelf sedimentation of Palaeocene age. These Paleogene formations are collected within one group, the Van Mijenfjorden Group (Harland, 1969; Dallmann et al., 1999) with Firkanten, Basilika and Grumantbyen formations covering the Palaeocene part of the succession (see Fig. 6)

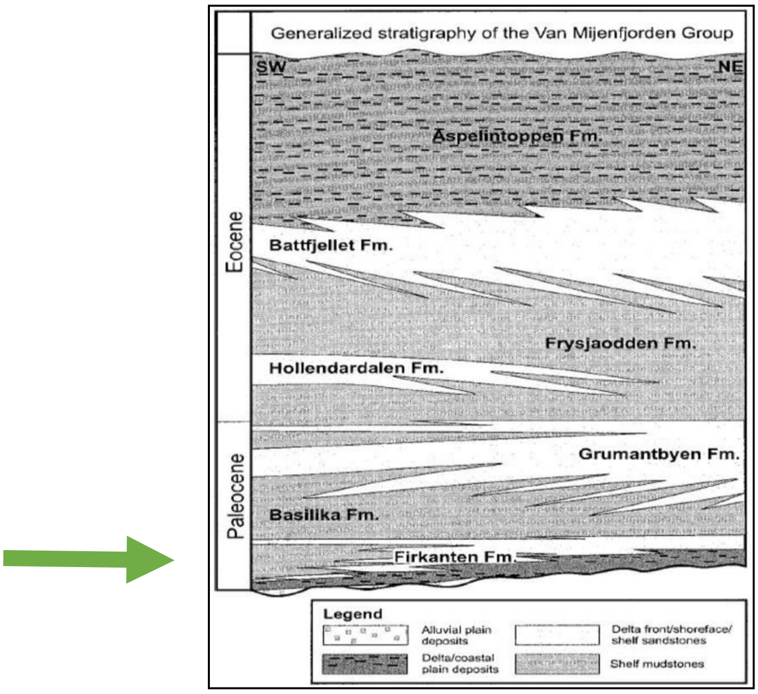


Fig. 6. An overview of the Palaeocene and Eocene stratigraphy of the Van Mijenfjorden Group. (Bruhn and Steel 2003). Arrow pointing at the Firkanten Formation.

2.5 Firkanten Formation

Reaching from the Cretaceous hiatus and resting on lower Cretaceous sediment, the lower Palaeocene Firkanten Formation is 170 m thick at the type section at Karl Bayfjellet and thins out towards the northeast where it can be less than 100 m thick (Dallmann et al., 1999). The base of the formation is often marked by a conglomerate referred to as the Grønfjorden Bed . But where that and paleo-weathering is absent, the lower boundary can be difficult to recognise. The basal sandstone is softer or more massive than the sandstones of the underlying Carolinefjellet Formation, which consists of well laminated, platy sandstones alternating with silt (Dallmann et all., 1999). At times one can find the trace fossil zoophycus in the upper part of Carolinefjellet which has yet to be found/described for Firkanten Formation (Observations by SNSG geologists, Personal comm. Malte Jochmann, and verification during logging by author of this study). The formation consists of three different members of which some are discontinuous over the basin, and a basal conglomerate bed. The lower most member is the coal bearing Todalen Member. In the northeast part of the basin, the uppermost member is the sand prone Endalen Member and in the western and southern part of the basin the same interval contains south-westerly thickening wedges of shale and siltstone, this member that is called Kolhoffbergen Member, wedges out and disappears north-eastwards and is therefore absent in the study area.

Two new coal seams are now recognised in Firkanten Formation in Operafjellet by the present author, one of the seams is from the top of the Endalen Member, here named Bassen seam, and the other from the top of the Todalen Member, here named Dirigenten seam. These seams have not been described in detail before although the coal seam at the Endalen Member has been mentioned briefly in the master thesis of Grasdal (2018).

2.5.1 Grønfjorden Bed

The Grønfjorden Bed defines the base of the Firkanten Formation where it is present as the bed is irregularly developed across the basin. It reaches its maximum of over 4.5 m thickness in the type area, north-western corner of Grønfjorden, and has been reported to reach up to 2 meter thickness in the northeast, at Bassen in Operafjellet and in the western part of the basin in Kolfjellet in Van Mijenfjorden (Dallmann et al., 1999).

Grønfjorden Bed consists of both clast and matrix supported conglomerates, conglomeratic sandstones and associated sandstones (Dallman et al., 1999). It is considered to be an incised valley deposit that formed during maximum regression by alluvial processes that cut into the underlying Cretaceous strata (Nagy, 2005; Berg, 2018).

2.5.2. Todalen Member

The lowermost part of the formation, the Todalen Member, is coal bearing with marine and non-marine sandstones, siltstone and shale interbeds (Dallman et al., 1999). Three to five rhythmic succession of alternating shale-siltstone-sandstone-coal are described from the northeast part of the Central Basin with coal and shale dominating the north of Adventdalen and bioturbated marine sandstones and shale are more pronounced in the member south of Van Mijenfjorden. Thickening of the unit shows a slight deepening of depositional environment to the west and the rhythmic successions represent repeated progradation and retrogradation of deltaic systems. These systems mainly build out from east and northeast of the basin (Dallmann et al., 1999).

The Todalen Member contains the most important productive coal deposits of Svalbard. In recent years, it has been exploited by Store Norske in the Gruve 7 mine in Breinosa, which is still operating and providing coal to the local coal plant. Five main coal seams are recognized within the Member. Major and Nagy (1972) have named those seams from the lower most seam to the upper: Svea, Todalen, Longyear, Svarteper and Askeladden (Major and Nagy, 1972, Harland et al., 1976, Harland et al., 1997, Orheim et al., 2007, Marshall, 2013). In addition to these seams, the newly recognized Dirigenten seams lies on the top as the highest seam in the member and second highest in the whole formation (see Fig. 7).

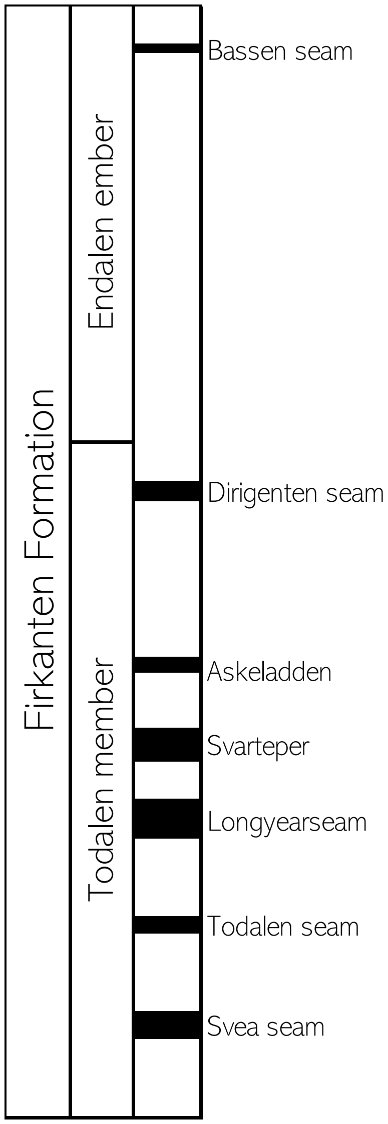


Fig. 7. Stratigraphic illustration with relative position off the coal seams in the Firkanten Formation built on core 19-2011 where all coal seams are present. See full log in appendix I.

2.5.3. Endalen Member

The uppermost part of the formation, Endalen Member, consists of light, highly bioturbated or laminated/cross-stratified marine sandstones with thin conglomerates, siltstones and clay ironstone interbeds (Dallman et al., 1999). It usually consists of stacked series of some 4-5 coarsening upwards parasequences (Steel et al., 1981, Dallmann et al., 1999, Nagy, 1995) that form very prominent cliffs and represent transgression and regression of deltaic or barrier shoreline which repeatedly built out from the northeast (Dallmann et al., 1999).

The Endalen Member varies in thickness from 40 m in the northeast to 100 m in south and southwest where it shows a deepening of facies. In the west of the basin and south of Van Mijenfjorden, Endalen Member interfingers with the shaly Todalen Member (Dallmann et al., 1999; Grasdal, 2018) (see Fig. 8).

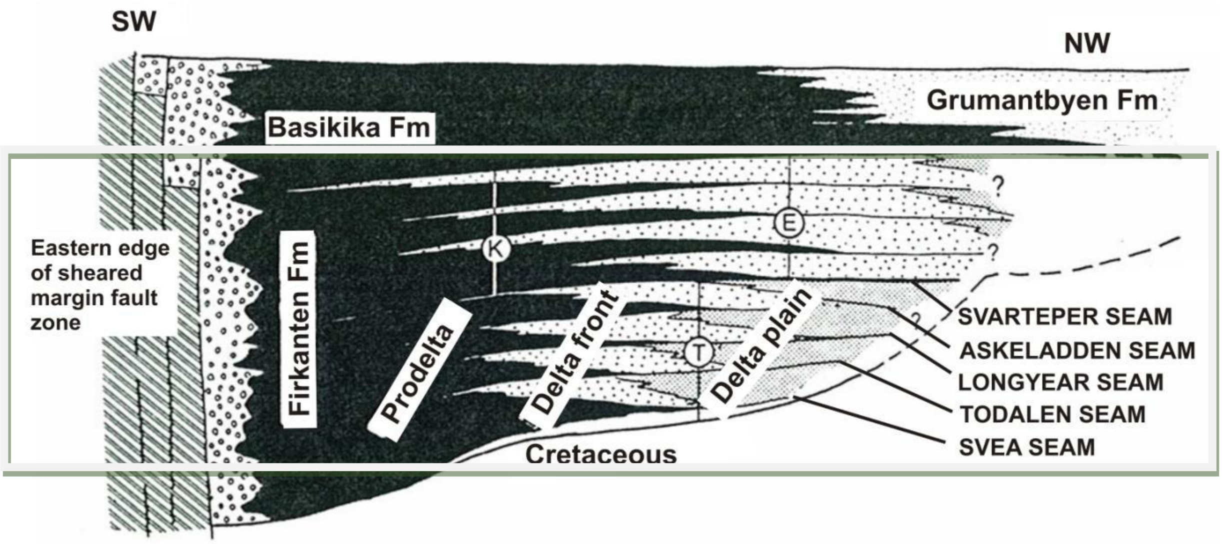


Fig. 8. South-West to North-West stratigraphic succession of the Tertiary deposits in the Central Spitsbergen sedimentary basin, modified from Steel et al. 1981. K = Kolthoffberget Member, E = Endalen Member and T = Todalen Member. Firkanten Formation is within the box. Note the 5 previously recognised coal seams of Todalen Member.

2.5.4. Todalen Member

The third member of the formation is called the Todalen Member and is only observed in the southern and western part of the basin where it overlies the Todalen Member and underlies the youngest sandstone bodies of the Endalen Member. Todalen Member is the finer-grained lateral equivalent to the Endalen Member consisting of repeated rhythmic successions of shales with minor organic rich, highly bioturbated, and very fine sand present in the type area, Kolthoffberget. The member represents repeated shoaling-upward conditions on the pro-deltaic or shelf areas within the basin (Dallmann et al., 1999). This member is not present in the study area and will not be discussed further.

3 Methods and material

The study is mainly based on core logging from several drill cores from SNSG, which were mostly logged by myself at 1:20 scale during my time as summer staff for the SNSG. The detailed logging was done over several summers, and some of the older cores were relogged using photographs of the cores and old SNSG logs from former staff. Furthermore, revisits to the core facility to look at unclear structures was also done. Fieldwork was carried out to complement the core logging, to see lateral extent in the section and to confirm that the structures in the cores were indeed what they seem to be.

Coal samples from the cores were sent to the SNSG geochemical lab for analysis. Data from this was provided by SNSG. After all the logging was completed, the logs were simplified and rescaled to 1:100 (see appendix) and facies analysis done on all the logs. Some of the most complete logs were chosen to represent a succession across the valley from Operafjellet to Breinosa. They were made into a correlation diagram where the coal seams were used as the marker horizons between the cores. Furthermore, the facies associations were used to double check that everything was correctly correlated and that facies associations were not overlapping between cores.

The rest of the cores were used to achieve better coverage of the study area, and to make sure those cores chosen represented the overall trend of each mountain. All of the logs were used when looking into coal data. Thickness, sulphur and ash correlation was done using all the cores in the study and lithostratigraphic logging was done on cores from 2013 where coal was still intact before being sent to the lab.

3.1 Core analysis

Core logging for the study was done in the Store Norske logging facility in Endalen, (see Fig. 9). The logs start from the boundary of Cretaceous and Tertiary, beginning with the Grønfjorden Bed where present, and ending on the boundary of Firkanten Formation and Basilika Formation on the top. A few of the older Breinosa cores had only the Todalen Member present and Endalen Member was therefore absent in those cores. The cores were all logged in the scale 1:20 by hand, using an A3 logging sheet, magnifying lens, measuring stick, grain size chart and a hammer for more accurate grain-size estimation on a fresh fracture inside the core instead of the drill-polished side off the core. Coal samples were taken from all the cores and sent to lab analysis (further description in 3.2. Coal analysis below). The legend used was based on the legend in the book lithostratigraphic Lexicon of Svalbard by W.K. Dallmann (1999).

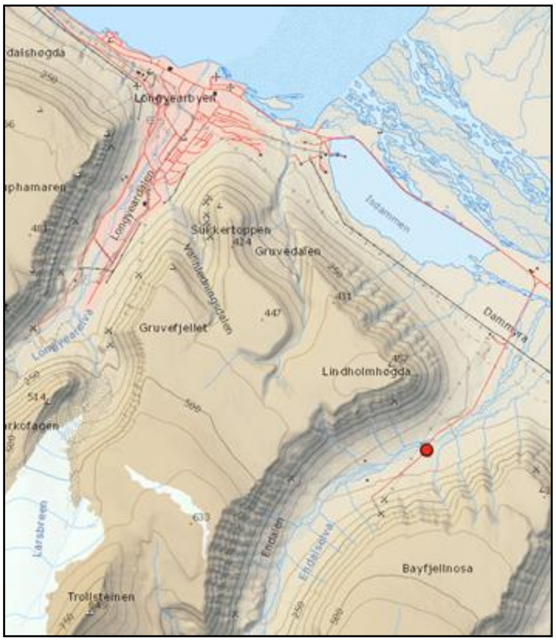


Fig. 9. Map showing Longyearbyen and the SNSG`s core logging facility in Endalen which is marked with a red dot. Topo Svalbard.

The angle of the drill holes were strictly measured and controlled by the Store Norske geologists and drilling crew and this was not an issue in the cores chosen for this thesis as they were drilled vertically, avoiding giving the structures extra tilt. The quality of the cores was quite good and not too fractured. The diameter of the cores were either 41,6 or 42 mm. In some cores there was a core loss during drilling, which was measured as accurately as possible by drilling staff and noted in the logs. The biggest focus during logging was on the grain size and the structures seen in the cores and logging it in 1:20 gave the possibility to focus on and note details in the core. Complete lists of the cores that were chosen for this thesis can be seen in table 3.

All cores from when drilling started in Operafjellet in 2010 to present day were chosen to be used for this study. Breinosa, as mentioned above, has a large number of cores taken from the mountain in the last decades, so coverage, condition, existing original photographs and drilling location of the cores were important when choosing which cores to use. Furthermore, Core 2-2007 was included for representing the area south of the study area and the lithological and stratigraphic development that comes with a small southward increase of the study area.

Table. 3.

List of drill cores used in this project.

	Operafjellet	Breinosa
Core identity	14-2010	2-2007
	15-2010	1A-2009
	16-2010	4-2009
	19-2011	5-2009
	12-2013	1-2011
	13-2013	3-2011
	kb1-2013	

3.2 Coal analysis

SNSG takes coal samples from all Todalen Member coal seams, from all cores drilled by the company, and I was a part of the sampling for the cores sampled during my time logging there. The coal seams in Todalen Member are always sampled and occasionally the floor, roof and the parting of coal seams relevant for the mining operation.

All the coal from the cores was sampled with the help of SNSG staff members. Each sample was approximately 20 cm. These samples were taken to the SNSG´s chemistry lab where more geochemical tests were done on the samples including checking for ash (inorganic material) and measuring its sulphur contents, calorific content, free swelling index, etc. The results from the lab are used in this study with the focus primarily on ash and sulphur. The mean average values for both sulphur and ash was calculated for each seam (see appendix ii). The Bassen seam at the top of Endalen Member, formerly ill-recognized and relatively thin seam, has not been sampled for chemical analysis due to its insignificance for exploration and mining operations.

Furthermore, in the newest cores, a thorough coal logging or lithotyping was done in collaboration with Dr. Christopher Marshall of SNSG. This was not possible to do on the older cores as the coal from them had been destroyed during sampling and chemical analysis. The coal was logged by looking at its structure and reflectance at approximately 10 cm intervals with prominent changes noted within each interval. This was done to be able to register if the coal fitted in the categories of clarin, fusain, durain or vitrain, detailed later in this study.

This method of analysing the coal started in 2013, so coal in the cores that were drilled during 2013 and onwards have been lithotyped before the coal was removed from the core boxes and sent to the laboratory. Unfortunately, the cores from Breinosa were all drilled before 2012 so the lithotyping is limited to Operafjellet coals.

The coal is often of significant stratigraphic importance, and it played a vital role in making the correlation across the study area. As it can often be easy to follow a coal seam through a study area, it can complicate correlation when the coal seams are as numerous as they are in the Central Tertiary Basin, especially due to many partings of the seams and their proximity to each other as in the case of Todalen Member. Lab results showing ash and sulphur concentrations and seam thickness were used to confirm that each seam is followed correctly through the study area and they are not mixed with one another. It was also used for discussion for each seam and its development through the study area. The laboratory results from SNSG is an extensive data set from which I focused on the ash and sulphur average from each seam. I looked at the laboratory results from each core separately, compared it with the logs I had made to establish which sample was from which seam. From there I took the mean average from each seam, excluding the partings, roof and floor which often were included in the results from the lab and could give an abnormally high values for inorganic material.

3.3 Fieldwork

Fieldwork was conducted over two days on the south-east side of Operafjellet. Transportation was provided by SNSG, which flew us with a helicopter to the exact location of the planned logging (see Fig. 10), on the steep hillside of the mountain, just east-northeast of drill hole 15-2010 (Approximate location is at 7820813˚N 16.11506˚E, see Fig. 4). The lower boundary of the Firkanten Formation was prominent with a thick Grønfjorden Bed representing the base of the formation from which the logging started, and we worked our way upwards to the cliffs of Endalen Member. The same methods were used with field logging as with the core logging, although the lateral extent of the section gave us a proper view of bigger sedimentary structures. This was taken in consideration while redrawing the core logs.

Fig. 10. The study area in Operafjellet, note the people for scale sitting at the boundary of Firkanten Formation and underlying Carolinefjellet Formation. Photo: Bjarki Friis.

3.4 Facies

Sedimentary facies are the main building blocks of sedimentary succession with specific visually distinguishable characteristics such as texture, structure, mineral composition, colour, bioturbation etc. (Nemec 1996), that reflect the depositional process or conditions under which it was formed. It is a convenient means of describing rocks seen in the field and it forms the basis of facies analysis which makes it possible to reconstruct paleoenvironment by interpreting the sediments in terms of physical, chemical and ecological conditions at the time of deposition (Nichols, 2009).

Facies analysis for this study was first done at the core logging facility in Endalen, and then further developed and confirmed when looking at the logs and photographs afterwards. For the facies determination, each facies was identified, 11 in total, written down and given a name, description and an interpretation of the environment it formed in. During the facies analysis, I focused on separating sedimentary processes at various depositional areas in coastal environments such as continental, marine and the positions on shoreface during formation of said facies.

3.5 Facies Association

According to Collinson, (1969), a facies association is a combination of closely related facies or groups of facies that are genetically related to one another and have some environmental significance. Allen (1983) called these large-scale facies associations architectural elements, raising the significance of the building blocks of various depositional systems (Walker, 2006).

After the facies were established, they were colour coded and logs were coloured accordingly. This was done to get a better overview of the detailed and complex data from the logs, and to help visualize and establish facies associations. This made it clearer as to which facies were commonly found associated with each other and were representing a particular environment. A total of 5 facies associations were established and a table of associations was then made. The table identifies the costal sub-environment for each association, which facies are included in the association, a description of the association and finally an interpretation.

3.6 Limitations and advantage of drill core analysis.

Logging drill cores provides a better opportunity of studying fine structures that might often get lost in the field due to irregular sections of hard sedimentary rocks and their weathering. The observations from the cores were used to describe detailed sedimentary structures, whereas the lateral variation and the scale of cross bedding was added from the outcrop observations. The outcrop study was not without limitation either as much of the study area is covered by scree and is therefore obstructed big parts of the section.

The biggest limitation of core logging is that some structures also get lost within the limited distribution. There is also a lack of lateral control of the cores. One cannot count on the directions of bedding planes because cores may be rotated. Larger scale features can also be incorrectly interpreted due to the core´s lack of lateral extension. For example, a simple large-scale cross bed can be interpreted as two different sedimentary environments. It could be described as plane parallel lamination with a bed of dipping plane parallel lamination on top, or it can be interpreted as a large-scale cross bedding (See figure 11 for further explanation). This might be very easy to see in the field but in a core, this can cause problems for interpretation of the structures and therefore a field work was conducted in the study area to complement the core logs already made.

Furthermore, a problem that is not only contained within core logging is, intensively bioturbated sandstone mixed with structurally massive homogenous sandstone, where the bioturbated sandstone might be wrongfully interpreted due to lack of clear evidence of visual burrows. As well, a massive, homogenous sandstone, might also be incorrectly described, as it is common for such sandstones to actually contain some structures within the sand. But, they are not observed with the naked eye due to lack of grainsize variations and homogenous colour of the grains. This can often be looked at using a microscope where structures can be determined on microscopic scale. The large-scale cross bedding, massive sandstones and intensively bioturbated sandstones of the Endalen Member can therefore be studied in further detail.

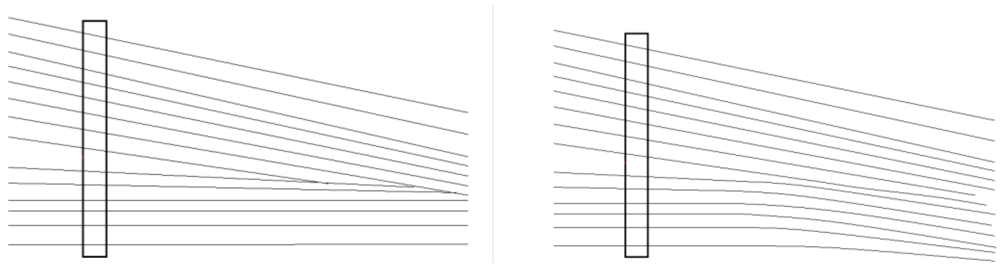


Fig. 11: The figure to the left shows a core`s placement within a big scale bedding. If the whole section would be visible and not just the core, the section would be interpreted as Shoreface sandstone with very large cross beds. However, as the core only shows a part off the section then it is here interpreted as thinly laminated sandstone, but it is kept in mind that this might actually be Shoreface sandstone or even dunes.

The figure to the right shows a core`s placement within a large-scale bedding. If the whole section is analysed, it would be interpreted as Foreshore sandstone with plane parallel or slightly seawards dipping laminae such as described in Facies 5 (thinly laminated sandstone).

4 Significant stratigraphic markers.

4.1 Conglomerate

4.1.1 Grønfjorden Bed

A conglomerate layer is often observed at the lowermost part of the Firkanten Formation, with its base representing the boundary between the Firkanten Formation and the underlying Carolinefjellet Formation. This conglomerate is referred to as the Grønfjorden Bed , named after its type area in Grønfjorden west of the study area. The bed is considered significant stratigraphic marker. When observed in the cores from the study area, the Grønfjorden Bed is either an intra or extraformational conglomerate, and in the case of core 13-2013 in Operafjellet it is mixed. In Operafjellet, the bed also shows a thicker unit of extraformational conglomerate in core 15-2010 and in the close-by field log OP1-2013, while the other cores have thinner intraformational beds. The intraformational clasts are often fragments of mudrock as a result of erosion on the paleo-river channel, while the extraformational sediments having travelled a greater distance, indicates higher velocities of the river system of Grønfjorden Bed in the areas where there are clasts vs lower velocities in areas where it is absent. The size of the clasts also supports this theory as the intraformational clasts are smaller than the extraformational clasts in the study area.

During fieldwork, a folded section of the Grønfjorden Bed was observed, about 1,5 m in thickness (see Fig. 12) so the bed originally was only a part of that thickness when deposited. In cores, therefore the thickness of the Grønfjorden Bed might be exaggerated thickness due to folding. The logs were not adjusted for this as it was not clear if this went on through the extended area or not.

Fig. 12. A folding of the prominent conglomerate bed, Grønfjorden Bed at the base of Firkanten Formation.

In contrast with Operafjellet, the Grønfjorden Bed in Breinosa is most often extraformational, excluding the core 3-2011, located in the eastern part of Breinosa, which is intraformational. The bed frequently contains small coal fragments between the clasts, and it is mostly polymictic and matrix supported, poorly sorted with clasts sub-angular to rounded.

This conglomerate has often been used as a marker of the Cretaceous / Paleogene boundary in the central Spitsbergen sedimentary basin. The bed is not always seen in drill cores, and other markers found in the underlying Carolinefjellet Formation should in addition be used for aid of marking the boundary. Structures such as fining upwards cross bedded lenses of sand and silt, which are often found in the Carolinefjellet Formation as opposed to more disruptive or sharp sand lenses in mudstone of Firkanten Formation. Furthermore, it is observed by Store Norske Geologists that the zoophycus trace fossils are often observed in Carolinefjellet Formation close to the boundary, and this trace fossil is considerably easy to recognize in a core.

4.1.2 Top Endalen conglomerate

A layer of conglomerate is also observed in the top of the Firkanten Formation. This conglomerate is a quite stable marker for the upper boundary of the Firkanten Formation to Basilika Formation and is found in all the cores in the study area that reach through the upper boundary of Firkanten Formation. It varies greatly in thickness and can be from approximately 20 cm up to over 200 cm thick. Directly above the conglomerate, the green glauconite-rich sandstone of Basilika Formation takes over. In Operafjellet, it is observed a few centimetres above the Bassen seam (the Endalen Member coal seam) but in Breinosa where the coal seam is not present, it is lying directly on the massive sandstone of Facies 8 which will be detailed later. The conglomerate is in most cases extraformational and mostly clast supported, although it can be matrix supported or have medium to coarse sand layers in it. In core 14-2010 an intraformational conglomerate is found on the bottom of the bed or as a separate conglomerate bed beneath the top layer.

4.2 Coal

Coal seams have long been considered important stratigraphic markers and that is not an exception with the coal seams in Firkanten Formation. The five coal seams named and described by Major and Nagy (1972) have been used for correlation in several studies, as well as the two seams that are now added, that are located only in Operafjellet, here the Bassen seam (top of Endalen seam) and the Dirigenten seam (top of Todalen Member seam). All the seams and changes within them will be discussed in detail in the results chapter.

4.2.1. Coal in the study area

Several coal seams are present in the Todalen Member of Firkanten Formation. Most of them are observed in both of the mountains of the field area. They have significant economic potential with Longyear seam currently being mined by Store Norske at Mine no 7 in Breinosa, close to Longyearbyen, and Longyearseam, Svarteper and Askeladden seams are furthermore considered significantly oil prone (Marshall et al., 2012; Marshall, 2013).

However, two new and limited, thin coal seams are now observed in Operafjellet and they will be described in details further in this thesis where their regional distribution will be discussed, a lithostragraphic logging is done on one of the seam and the other will be detailed with chemical laboratory analysis. These coal seams are not extending over the valley and seem to be only present in Operafjellet, at the edge of the basin.

Fig. 13. Endalen/Todalen lithological boundary. The coal seam in top of the Todalen Member and the first cliff forming sandstone of the Endalen Member above it.

5 Results

5.1 Facies description and interpretation

Elleven different lithofacies have been recognized and they are detailed in this chapter starting with a simplified table of all the facies, their description, depositional process and depositional environment. Furthermore, each facies is discussed in detail where a sample of logs and photos of said facies is used to give a better idea of the lithological investigation and the determination of each facies.

Table 4.

Facies description and interpretation

Nr.	Lithofacies	Description	Depositional process	Depositional Environment
1	**Coal and coal shale**	Coal, ash rich coal/coal shale often with pyrite nodules.	Peat formation due to initial decomposition of vegetation, burial and coalification.	Bog, marsh, swamps.
2	**Paleosol**	soil, silt to fine sand with abundant rootlets and burrows.	Vegetation and subaerially formed soil buried under sediment.	Continental depositional setting, such as on coastal/delta plain.
3	**Organic rich mudstone**	Mudstone (silt and clay), Pyrite, organic material, often with small coal fragments visible.	Regular flooding introduces considerable amount of mud into continental system that is deposited from suspension.	Low energy delta, floodplain or tidal flat.
4 **4a** **4b** **4c**	**Heterolithic bedding with ripples** **Lenticular bedding** **Wavy bedding** **Flaser bedding**	Cross laminated sandstone that alternates with mudstone in different rations. Three different bedding types: Lenticular = more mud than sand. Wavy = approximately equal ratio of mud vs sand and Flaser = more sand vs mud.	Deposited during different energy levels. Fluctuating hydraulic conditions, current activity alternating with quiescence stages. Lenticular bedding formed during quiet stages and flaser during higher energy stages. Wavy bedding is the mid stage bed.	Tidal flats in subtidal environments or flood plains
5	**Thinly laminated sandstone**	Sandstone with very fine (0,5-1mm) horizontal plane parallel lamination of silt. Tiny flaky mica is often present in the silt and minor bioturbation is noted in the sandstone.	Formed when wave energy causes a separation between grains of different sizes, silt is deposited from suspension during quiet times of high tides – Cyclic differences in sediment supply.	Formed in coastal environment or mudflats.

6	**Sandstone with crossbedding**	Light coloured cross bedded sandstone with interbedded mud flakes, intraformational clasts, sideritic nodules and coal fragments.	High energy wave activity that transports plant fragments, mud flakes, clasts and nodules.	Wave or storm dominated sandy beach or shoreface
7	**Intensively bioturbated sandstone**	Highly bioturbated sandstone with no primary structures visible. Fine to medium grained, visibly structureless sand with minor silt, coal fragments, mud clasts, mud lenses, sideritic nodules, extra-and intraformational clasts.	The clasts and plant fragments suggest high energy wave activity with lots of nutrition transported for burrowing animals.	Amalgamated sand layers forming at shoreface with both quiet fair-weather sedimentation and storms bringing in nodules, clasts and fragments of plants into the facies.
8	**Massive sandstone**	Light coloured sandstone with no structures observed.	Considerable amount of sand deposited, possibly with initial structures that have completely been destructed by intense bioturbation or initially deposited without any finer or coarser material giving the illusion of massive non structured sand.	Shoreface
9	**Conglomerate**	Intraformational and extraformational gravels and pebbles, mostly matrix supported	Fluvial transportation or basal conglomerates during marine transgression	Tidal channels or ancient beach.
10	**Bentonite**	Bentonite clay	Weathering of volcanic ash	Volcanic ash deposited in a wet surface or a water body.
11	**Ophiamorpha sandstone**	Highly bioturbated sandy substrate, with dominant ophiamorpha fecal pallet lined tube margins burrows.	Dwelling burrows of decapod crustaceans.	Sandy shore

Facies 1: Coal and coal shale

Description

The coal facies consist of coal and very organic rich coaly shale which is a coal with very thin (few mm-1 cm in few places) silty mudstone layers or ash rich coal.

The thickness of the coal varies from 1-2 cm coal lenses to coal seams with thickness of about 3 meters. Most of the coal seams are continuous and can be seen over the whole study area, while others are just localized. The coal facies are typically black with high luster and dull intercalations or striations. It breaks in either conchoidal or cuboidal fractures or most commonly, it is banded and breaks in layers. Parting or splits are present at times and are made up of very dark organic rich mudstone which is here classified in Facies 3. Upper and lower contacts of the coal to the over or underlying rock are typically quite sharp, especially when it is transitioned from paleosol, making it easy to sample the coal in those places without compromising coal samples with traces from the roof or floor of the seam. Pyrite can be present at times within the coal as a post depositional feature seen in between breakage of the coal.

Ash content in the coal seams vary from 3,5% to 51,5%. The ash content is considerably consistent within the same coal seam throughout the study area with minor vertical variations. The sulphur content varies from 0,2%-12,2% and shows a slight increase within each seam from Operafjellet to Breinosa. See tables in Appendix II for mean laboratory result

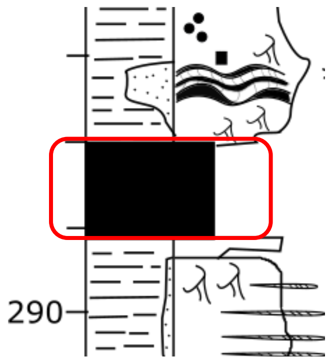


Fig. 14. Facies 1 in log from BH-19-2011

Fig. 15. Core photo of Askeladden seam from core 14-2010.

Fig. 16. Longyearseam from Core 19-2011.

Discussion and interpretation:

General interpretation of Facies 1 is that the coal forms from peat accumulation; burial of vegetated matter, physical and chemical changes of it in bog, mars or swamps and at last coalification which would be the degree of change undergone by the coal as it matures from peat to anthracite (Worldcoal.org).

The organic rich parting rock in the coal and increasing sulphur trend southwards in the coal seams can indicate a deposition closer to marine setting at Breinosa than in Operafjellet.

A dominant feature of bituminous coal is its banded appearance, irregularly alternating layers of different composition called lithotypes (Grimes 1982). Lignite is brown to brownish black coals that commonly retain many of the structures of the original woody plant fragments (Boggs, 2009). Sub-bituminous coal has properties between bituminous and lignite and anthracite is hard, black and dense coal with high carbon content. It is bright and shiny and breaks with conchoidal fracture (Boggs, 2009). In general, the coal seams in the study area show the characteristics of sub bituminous to bituminous coal although few cm layers of coal with the properties of anthracite is observed. Furthermore, the coal seams have different classifications. A more thorough description and interpretation of each of them is found in the discussion chapter.

Facies 2: Paleosol

Description

Facies 2 is a highly bioturbated rooted paleosol with little or no structures and varies in grain size from silt to fine sand. The facies is fine grained silt in lower part, of Firkanten Formation, in Todalen Member, but much coarser, often fine to medium grained sand in the upper part in Endalen Member. It is mostly found around the coal and dark organic rich mudstone.

It is often, but not always, observed beneath the coal seams in Todalen Member but beneath the coal seam in Endalen Member in Operafjellet it is always present as a thick unit of approximately 50-180 cm. The units seem to be thinner in cores 14-2010 and 16-2010 which are located more centre in the mountain while the other cores are more marginal.

Furthermore Facies 2 is usually present beneath the Svarteper seam in both Operafjellet and Breinosa. These units are approximately 50-120 cm in Breinosa but considerably thicker in Operafjellet or approximately 120-200 cm thick.

In the BH 15-2010 from Operafjellet one of the lower paleosol is observed as a very light coloured, almost white (see Fig. 17 and 18), while otherwise it is observed as dark grey in Todalen Member and light brown in Endalen Member.

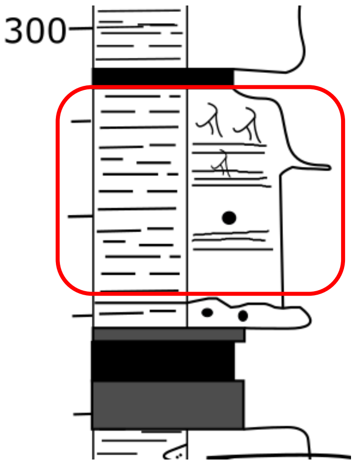


Fig. 17. Facies 2 in log from BH-15-2010

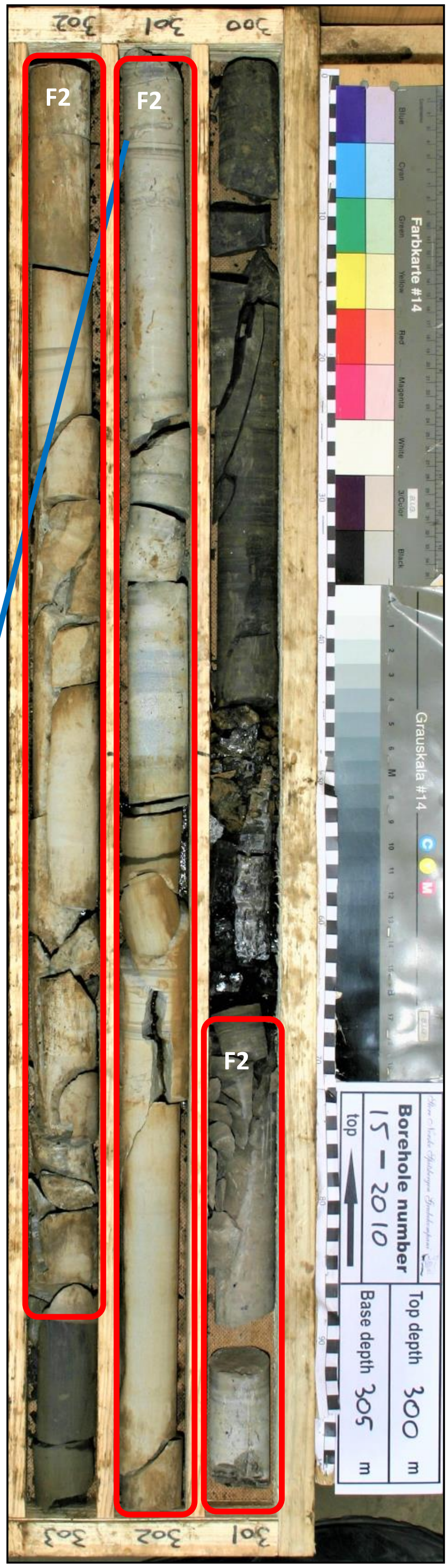


Fig. 18. Facies 2, light coloured paleosol beneath a thin coal seam in core BH-15-2010. The figure to the left shows a closeup of structures and rootlets.

Discussion and interpretation

A paleosol is a fossil soil that often contains many of the characteristics of a modern soil such as fossilised roots, burrows of soil modifying organisms and layers enriched or depleted in certain minerals.

Seatearths which are clay-rich fossil soil found immediately beneath a coal seam, are common in coal measures of north-western Europe and North America and are characterised by a bed of organic matter underlain by a leached horizon of white parent material where iron has been washed out (Percival, 1986, Nichols, 2009). The paleosol in Firkanten Formation is here considered to be seatearth, and the leached seatearth in core 15-2010 indicates high eluvial activity through the soil in the Eastern edge of Operafjellet during the time of soil formation.

Facies 3: Organic rich mudstone

Description

Facies 3 appears in all the drill cores and was also observed in the field. It often appears in the lower part of the Firkanten Formation, in the Todalen Member around the coal seams and often as a parting of coal seams. The facies consist of a dark brown/grey to almost black mudstone with mostly homogenous appearance (see Fig. 19). The clay versus silt content varies throughout but can be difficult to distinguish properly in the core but often slight colour change can be detetcted where the silt grains are more visible. Most commonly F3 is completely structureless with no apparent fissility and a rather blocky or massive texture, but occasionally, it breaks in a dis-organised manner with thin lamination which breaks and weathers in thin shales.

In the Breinosa cores, the mudstone facies varies from ca. 3 cm to approximately 60-90 cm except in core 3-2011 where the thickness of the mudstone reaches up to 3 meters. In Operafjellet, F3 are considerably thicker units or from ca. 3 cm up to 5.3 meters in core 19-2011 and up to ca. 2,5-3-5 meters in the other Operafjellet cores with thicker units that are reaching more than a meter in thickness, appearing more frequently. The units of F3 are often divided by F4, lenticular to flaser bedded mudstone and sandy ripples with mud drapes.

Small coal fragments, small pyrite nuggets and irregulary shaped sediment with what appears to be pyrite as a secondary mineral, is often observed in the mudstone (see log in Fig. 20). Furthermore, very fine lines (ca 1-2mm) of some kind of extremely thin and very irregular light coloured fine grained (silt-very find sand) lenses are observed occasionally. This does not appear as clear ripples or proper regular lenses and no internal structures are to be seen.

Fig. 19. The the left: a close up of the mudstone. To the right: Facies 3, in BH-15-2010.

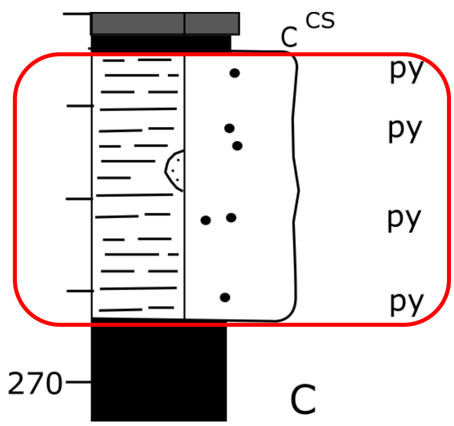


Fig. 20. Facies 3 in log from BH-14-

Discussion and Interpretation

Mudstones are deposited in a calm energy environment where fine grained sediments such as clay and silt are abundant. They can form in river floodplains, lakes and quiet water parts of rivers, along low-energy shorelines (Tucker, 2011) in lagoonal, tidal-flat and deltaic environments but they are particularly characteristic of marine environments where the seafloor lies under storm weather wave base, such as adjacent to major continents (Boggs, 2011).

Organic matter with increasing carbon content in the mudstone results in darker and eventually black colour (Tucker, 2011). F3 appears to be high in organic content, and it is commonly observed around the coal seams. The fine irregular lines found in the mudstone could be very fine sand/silt or even pyrite formed within an animal burrow system. Commonly, pyrite is considered typical for marine muds (Tucker, 2011), however the high content of organic matter indicates a more terrestrial, floodplain or shallow marine environment. Facies 3, therefore seems to be deposited in a low energy environment where both organic material and marine influences are present such as in a low energy delta, floodplain or tidal flat.

Facies 4: Heterolithic bedding with ripples

Facies 4 is divided into 3 subfacies due to the fact that they are produced by similar processes but with different ratios of mud and sand, and they often appear together in the cores. At times the subfacies grade from one to another (see log in Fig. 21 and core photo in Fig. 22 showing gradual change between all three subfacies). They often appear as rather messy examples of bioturbated ripples.

Facies 4 represents ripples of sand and silt that move periodically in some areas of ripple Formation where mud is deposited in suspension at time of slack water, often with double mud drapes. The beds vary from being just a couple of centimetres up to 6 meters. The three subfacies are as following:

F4a: Lenticular bedding; A mud dominated bedding with cross-laminated sandstone that occurs in thin lenses, the ripples of sand are completely surrounded by mud (Reineck & Singh, 1980; Nichols,2009).

F4b) Wavy bedding: A thin ripple cross laminated sandstone alternating with mudrock often in rather equal proportions (Reineck & Singh, 1980; Nichols,2009).

F4c) Flaser bedding: A cross-laminated sand that sometimes has isolated thin layers or drapes of mud, often in the trough of the ripple (Reineck & Singh, 1980; Nichols,2009).

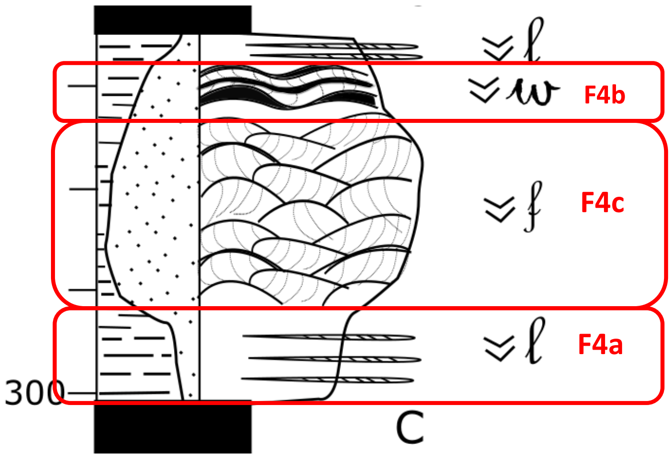


Fig. 21. Facies 4 in log from BH-5-2009

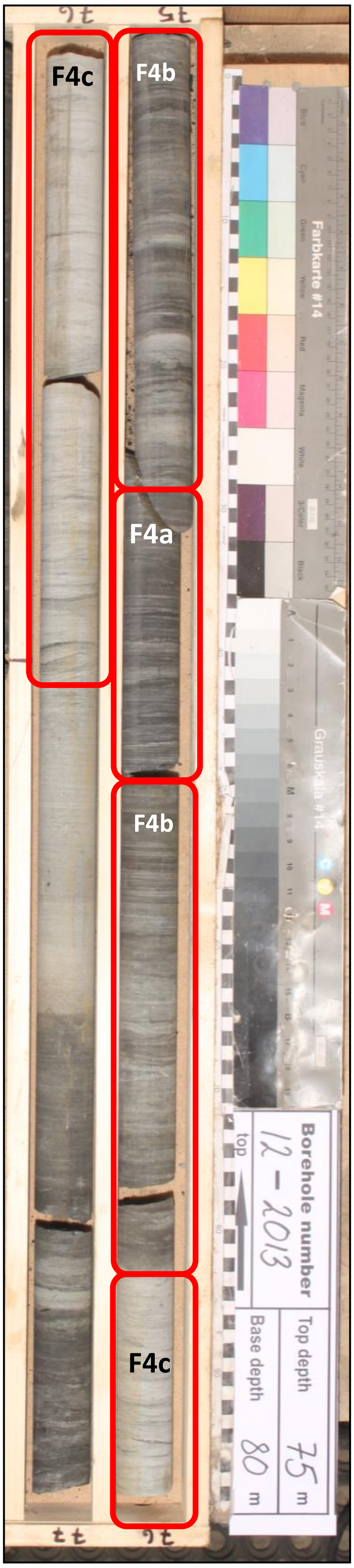


Fig. 22. Facies F4a, F4b and F4c in BH-13-2013. Gradual change between the three facies can be observed.

F4a) Lenticular bedding

Description

Facies 4a consist of dark organic rich mudstone inter-bedded with sand lenses which are often ripple cross laminated. These sand lenses are often discontinuous and isolated both horizontally and vertically (see Fig. 23). The horizontal isolation is not always observed in the core unless the sand lenses are very small and do not exceed the diameter. Some of the ripple structures are disturbed making them harder but not impossible to recognise.

F4 is often found around the coal seams and between F3 in Todalen Member but very seldom in Endalen Member. It is sometimes found as a gradual change from F3 to F5 and/or F6.

In the Operafjellet drill cores the lenticular bedding units are ranging from ca 10-250 cm thick with most of the thicker units approximately 50-80 cm thick, although core 13-2013 (see map X) has F4a units reaching up to 250 m thick and core 19-2011 has a unit reaching 180 cm. Furthermore, the field log OP1-2013 also has considerably thick F4a units, or up to 140 cm and the rest of the cores in Operafjellet have units reaching approximately 80 cm. The frequency of the units varies from 4 to 18 units per core in Operafjellet.

Breinosa drill cores have only 3 to 8 units per core which is considerably fewer than in Operafjellet. The thicknesses of the F4 in Breinosa are also considerably less or 15cm to maximum of 120 cm but most of the thicker units only reach up to 60 cm.

Fig. 23. Close up of lenticular bedding in core 13-2013, the upper core showing small burrows and sand lenses disturbed by bioturbation.

F4b) Wavy bedding

Description

Wavy bedding is formed where thin ripple cross laminated sandstones alternates with mudrock. The boundaries above and below F4b are most often very gradual from lenticular bedding with higher mud to sand ratio or from flaser bedding with higher sand to mud ratio.

F4b is most often only observed in Todalen Member like F4a. It is only observed in Endalen Member in two of the logs from Operafjellet but completely absent in that member in the other ones. These logs, OP1-2013 (field log) and 15-2010 are taken with very short distance between them and they only contain one F4b unit each of 20-35 cm. Due to incomplete Endalen Member in cores from Breinosa it is impossible to be sure if it is also absent in Endalen Member in the whole mountain but those cores that do have the Endalen Member logged do not have any F4b in that upper member of Firkanten Formation.

Fig. 24. Close up of wavy bedding in core 13-2013.

The thickness of F4b units are usually 15-80 cm in both mountains but in the OP1-2013 and 15-2010 in Operafjellet it reaches up to 100 cm in Todalen Member and in the Breinosa core 2-2007 the thickest unit is 200 cm. The frequency of the facies is 3-4 units in each log in Todalen Member, but the facies is occurring considerably more frequently in OP1-2013 than in the other logs or approximately 8 times.

F4c) Flaser bedding (+ trough shaped ripple lamina)

Description

Facies 4c consists of small-scale cross laminated sandstone with thin mud streaks that are mainly in the ripple trough but are also observed partly or completely covering the crests. Quite often the beds are bioturbated and the original structure of ripples becomes hard to recognise (see Fig. 25). Double mud drapes are observed at times in all F4 subfacies.

Facies 6 is abundant in Todalen Member but is also observed in the Endalen Member logs although it is fewer, 1-2 units, and considerably small or 10-50 cm while it is observed in thicknesses in the range of 10 cm up to 600 cm in Todalen Member. It reaches the 600 cm maximum thickness in Breinosa but most frequently it is 10-100 cm in Operafjellet with the thickest units there being 320 cm.

The frequency of each unit of F4c is 3-8 units in Breinosa cores and 4-10 units in Operafjellet cores but varies within the areas.

The lower boundaries are usually either sharp where they over-or underlie coal or mudstone, or they are gradually overlying sandstone facies. Upper boundaries are frequently gradual where it changes into wavy bedding or sandy facies. The flaser bedding can also be found adjacent to the conglomerate where the conglomerate is either or both the upper and lower boundary.

Fig. 25. Flaser bedding in core 15-2010, the lower core shows more disturbed bioturbated beds.

Discussion and interpretation:

Lenticular bedding is produced in environments with alternating supply of sand and mud, in which the conditions favour deposition and preservation of mud over sand (Reineck and Singh, 1980). Lenticular bedding as well as flaser bedding appear to form on tidal flats and in subtidal environments or flood plains, where conditions or current flow or wave action, depositing sand, alternates with slack water conditions when mud is deposited (Boggs, 2011).

Breinosa has been found to contain considerably thinner and fewer units of lenticular bedding than are found in Operafjellet. That and the often-disturbed ripple form in the units indicate calmer or deeper conditions in the depositional area of Operafjellet, allowing for the mud to settle from suspension and burrowing animals to disturb the original form of the ripples.

Wavy bedding: The more frequent occurrences of the F4b in OP1-2013 could be explained by the fact that OP1-2013 is the only on-site field log while all the others come from drill core logging. It has likely been mixed with Flaser or Lenticular bedding forms due to the less details you can see in on-site logs compared to extreme details you can observe and measure in drill cores, it is representing the transitional phase between those two forms and therefore more challenging to distinguish the forms on few mm-cm basis than in cores.

The much thicker unit (200 cm) of F5 in core 2-2007 in Breinosa can be explained by the location of the drillhole (see map) which is located much further to the south from the other cores taken in the study area.

Wavy bedding is usually observed as a gradual change between lenticular bedding (F4a) to flaser bedding (F4c) where the mud vs sand ratio is changing during fluctuations in sediment supply or level of current or wave activity. These types of bedding are common as tidal-flat and delta-front deposits. The occurrence of wavy bedding in fining upward units of fine-grained sandstone in repeated fining upward units overlain by mudstone can be interpreted as lower intertidal deposits with overlying shales as intertidal deposits (Boggs, 2011). According to Walker (2006) wavy bedding with such discontinuity of ripple layers, suggests limited sand supply and long periods of mud deposition between sand emplacement.

Flaser bedding indicates deposition under fluctuating hydraulic conditions. Current activity alternating with quiescence stages are the processes behind the deposition of the rippled sand and the mud. With repeated episodes of ripple current activity, previously deposited ripple crests are eroded allowing new ripples to bury, form and preserve rippled beds with mud flaser in the troughs (Boggs, 2011). The mud flaser between the ripples that separate the ripples from above and below ripples form during occasional slack water when more mud can deposit from suspension.

Superimposed migrating ripples can produce a series of cross laminae. The ripples climb on one another and the crest of vertically succeeding laminae become out of phase and seem to be advancing upslope. When cut normal to the wave crest in an outcrop or a core this process can result in cross bedded units with the general appearance of waves and when the section shows the cut in other orientations, the laminae can either just appear horizontal or through-shaped. This depends furthermore on the orientation and the shape of the ripple (Reineck and Singh, 1980, Boggs, 2011).

The subfacies of F4 are deposited during different energy levels, fluctuating hydraulic conditions, current activity alternating with quiescence stages. Wavy bedding is the mid stage bed often representing the gradual environmental change from quiet stages of when lenticular bedding is formed to higher energy stages of which flaser bedding derives from.

The criteria for the formation of F4 can fit both tidal flat sediments and the facies and its sub-facies are considered here to be formed in a tidal flat in subtidal environment or floodplain.

Facies 5 – Thinly laminated sandstone.

Description

Facies 5 is composed of sandstone with very fine laminations of silt. This lamination is often horizontal or slightly dipping, plain-parallel continuous lamination (see log in Fig. 26 and picture of core with a closeup in Fig. 27), but it can be discontinuous as well. Of oucrse, continuous lamination in a core are only noted for the diameter of the core. Discontinuous structures noted in a drill core is therefore very short or only few mm to couple of cm. The fine silty material is often associated with mica lying parallel to the lamination and is easily observed in plain view, in fractures, and weakly observed in profile view around the core with the naked eye. This mica rich silt makes it easy to break the core at its boundary with the sandstone.

This facies is not abundant in the cores but appears in both Endalen Member and Todalen Member in most cores. In Endalen Member the facies is approximately 40-70 cm thick units that can be traced throughout most of the cores.

The F5 units are from approximately 10 cm thick to 120 cm thick in Operafjellet, where the thickest unit, 120 cm thick, is found in the Todalen Member in North-Western part of Operafjellet in Core 13-2013. The F5 in Operafjellet are occurring from 5-13 times in each core with most occurrences in 19-2011.

In Breinosa the F5 facies is found at fewer occasions than in Operafjellet in each core except in core 1-2011 where it is found 10 times in Endalen Member. In other cores it is only found 2-5 times in Endalen Member and 0-5 times in Todalen Member. The thickness of the facies in Breinosa is varying from 10 cm to 120 cm.

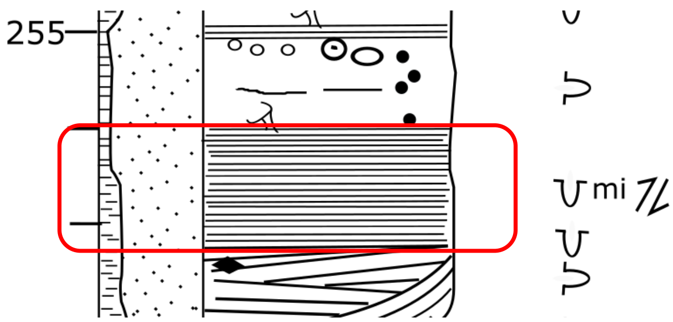


Fig. 26. Facies 5 in log from BH-13-2013

Fig. 27. To the left: A closeup of the lamination in F5. To the right: Facies 5 in BH-13-2013.

Discussion and interpretation

The thinly laminated sandstone of facies 5 is suggested to be formed in the foreshore where the slightly dipping sediment is deposited parallel to the foreshore slope with a seaward inclined laminae. The heavy and light- mineral laminae we have in F5 can be the result of traction deposition by swash and backwash on beaches or transport of sand in rivers of at high flow velocities (Harms and Fahnestock, 1965; Allen, 1984; Bridge and Best, 1997, Boggs, 2011). F5 is considered here to have the former definition of processes due to lack of evidence of fluvial processes around the facies.

When the F5 units are occurring often in a core, it often is due to F8 splitting two or more smaller F5 units. As will be discussed for facies 8, the massive sandstone might actually have structures that are just not visible due to lack of different material to make it visible or it can be heavily bioturbated in those places. This can arguably open up for more questions, where the F5 units are originally much thicker than observed and is it perhaps the same facies apart from the fact that the first order structures have been erased by bioturbation. Or, perhaps they are actually present but can only be seen on macroscopic level. That means that during the deposition of F5 there could have been periods where fine material was lacking or calmer periods with higher bioturbation rates in between faster sedimentation rates with lack of bioturbation and abundance of fine silt to be deposited with the sand.

Occasional discontinuousness of the structure occurring at times in the facies, might furthermore be due to the same reason as mentioned before, a bioturbation where burrowing animals (which can be abundant in beach environments) have disturbed the primary structure of the facies and only left a part of it to be observed. Or even that finer dark particles were not abundant enough to show prominent visible structure.

Core 3-2011 is very close to 1-2011 but unfortunately the core stops in the lower part of Endalen Member so logs from the upper part does not exist but it can be assumed that F5 is more abundant in the northernmost part of Breinosa just like it is more abundant in Operafjellet than in rest of Breinosa. This shows an abrupt decrease in the facies from the northernmost part of Breinosa to the middle of the mountain, but quite similar occurrences in Operafjellet across Adventdalen and to the absolute northernmost part of Breinosa.

Facies 6 - Sandstone with low angle crossbedding

Description

Facies 6 contains cross beds that are most often light-coloured massive sandstone with very thin dark grey or brown mudstone layers (≤mm) defining the crossbedding (see Fig. 29).

The boundaries to other facies are most often gradual from plane parallel lamination or massive looking sandstone with no visible structures but occasionally sharp boundaries are observed as reactivation surfaces (mudstone layer) between sets or defining the bottom or top of the facies (see log in Fig. 28).

Approximate frequency of Facies 6 is 9-10 units in Todalen Member and ca 5 occurrences of the units in Endalen Member. Noticeable difference between the mountains is not observed like in F5.

Mud flakes, intraformational clasts and sideritic nodules are often observed within Facies 6 and occasionally coal fragments and rootlets. The coal fragments and rootlets are not in situ and are usually not observed close to the coal seams.

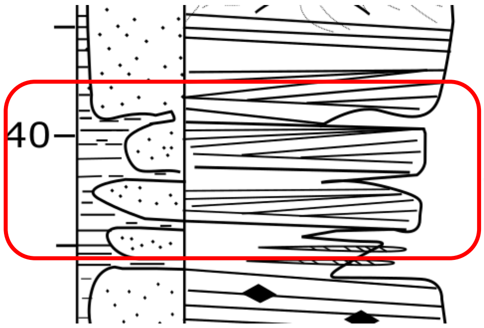


Fig. 28. Facies 6 in log from BH-12-2013

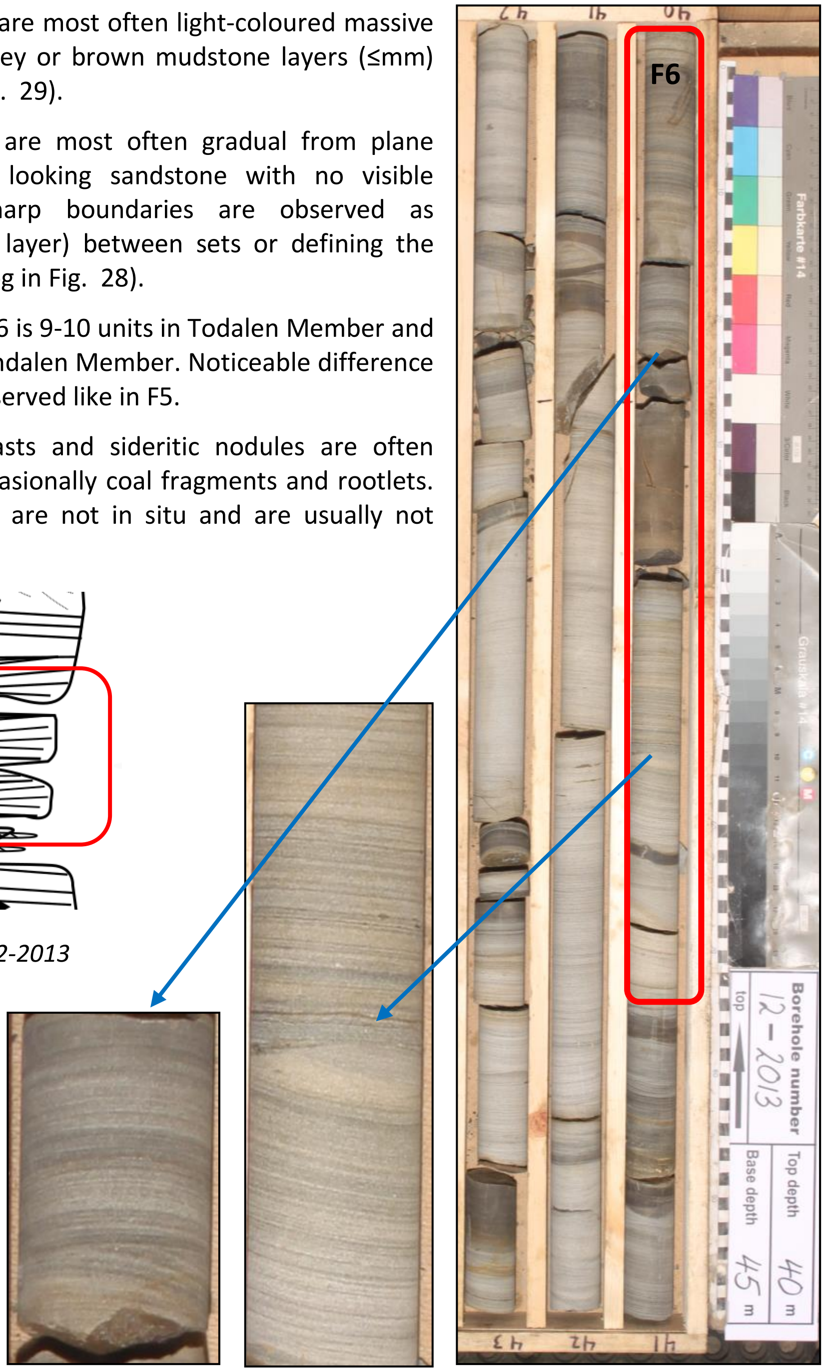


Fig. 29. Facies 6 in core BH-12-2013, with close ups of the cross bedding in to the left.

Discussion and interpretation

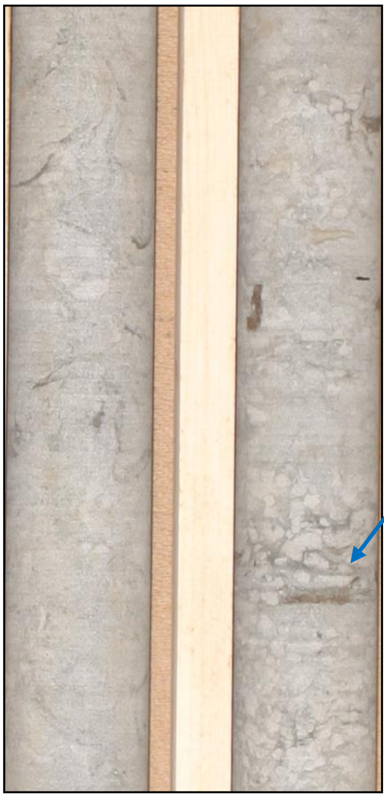
Middle shoreface deposits form under high-energy conditions due to wave break and longshore and rip currents. Sediments forming in the middle shoreface are usually fine to medium grained sand with minor silt or shell amounts. Both landward and seaward dipping trough cross beds and sub-horizontal plane parallel lamination can occur in this area and trace fossils such as Ophiamorpha nodosa commonly occur (Boggs, 2011). Furthermore, sideritic nodules found within the facies are common diagenetic minerals in both shales and sandstones, it commonly forms at shollow burial depths and its elemental composition is often related to the sediments in the depositional envirornment it is formed within (Mozley, 1989). This description and interpretation fits very well to Facies 6.

Facies 7 – Intensely bioturbated sandstone

Description

Facies 7 consists of mostly fine- to medium-grained sand with some amounts of dark silt present in places, making the facies look at bit darker. Some small intervals may have a medium/coarse grain size or very fine to fine grained sand. No sedimentary structures are observed, but unidentified burrows are present in several places and so is plant material, such as scattered rootlets and other small coal fragments. The burrows are most often undifferentiated (orientation uncertain, not horizontal nor vertical), or horizontal but occasionally vertical burrows are observed. At times the burrows cannot even be seen properly, and the sandstone is completely disturbed by bioactivity (see Fig. 30). Furthermore, coal fragments, mud clasts, mud lenses, sideritic nodules and both extra and intraformational clasts are abundant but variable within the facies in all the cores.

This facies is thick and abundant in various intervals in Endalen Member of the Firkanten Formation but it is also quite common in Todalen Member. The thickness of the units is ca. 30-300 cm in Todalen Member in Operafjellet and 50-150 cm in the same member in Breinosa. In Endalen Member the units vary from 80-1100 cm in Operafjellet and 100-900 cm in Breinosa with one unit reaching up to 600 cm thickness in core BH 1-2011 with only thin layers of F9-conglomerate and F5-Thinly laminated sandstone dividing it up. These two facies often divide F7 up with very thin (few mm to few cm) units, if those were not present then the F7 units would measure even thicker.



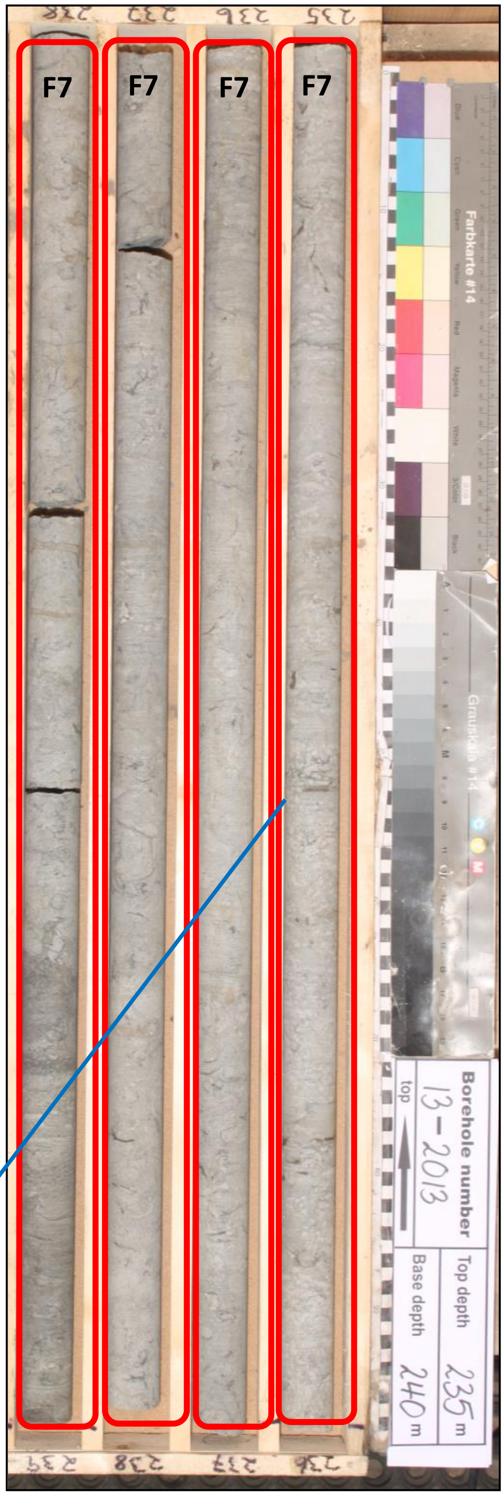


Fig. 30. To the left: A closeup of the facies. To the right: Facies 7 in BH-13-2013

Facies 7 is most often found at the boundary of Todalen Member and Endalen Member representing the first 3-4 meters in the Endalen Member, where it often is succeeded by the crossbedding of facies 6. Conglomerate, nearly always extraformational, is often found dividing apart the beds in Endalen Member and coal fragments, mud clasts, mud lenses and sideritic nodules are found scattered throughout the facies (see representation in log in Fig. 31). Facies 5 and 6 are often found below or above the F7 beds.

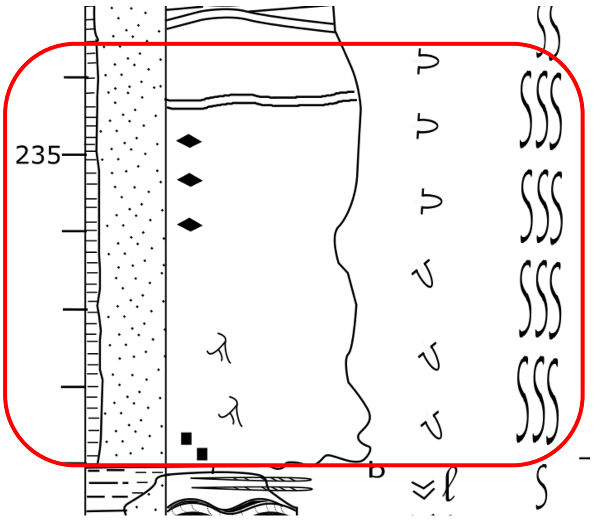


Fig. 31. Facies 7 in log from BH-13-2013

Discussion and interpretation

Looking at the fact that in this facies both plant material and burrows are present in highly bioturbated sandy substrate, the interpretation of the depositional environment of facies 7 would not suggest an aerial exposure. Plant debris is easily transported material, so plant rich sediments are not uncommon (Tucker, 2011).

Bioturbation is a very common feature in sedimentary rocks and the bioturbation in F7 is Grade 5 to 6. Grade 5 means intense bioturbation, where 80-95% of bed is bioturbated, bedding is completely disturbed (but just visible) and Grade 6 means complete bioturbation, 95-100% of the bed is bioturbated, sediment reworked due to repeated overprinting (Tucker, 2011). In a bed with Grade 6 bioturbation it is often difficult to recognize that bioturbation is present at all. In those cases, the sediment might just appear to be structureless with the only evidence of bioturbation or trace fossils to be disturbed sediment, perhaps with patches of different grain sizes (Nichols, 2009).

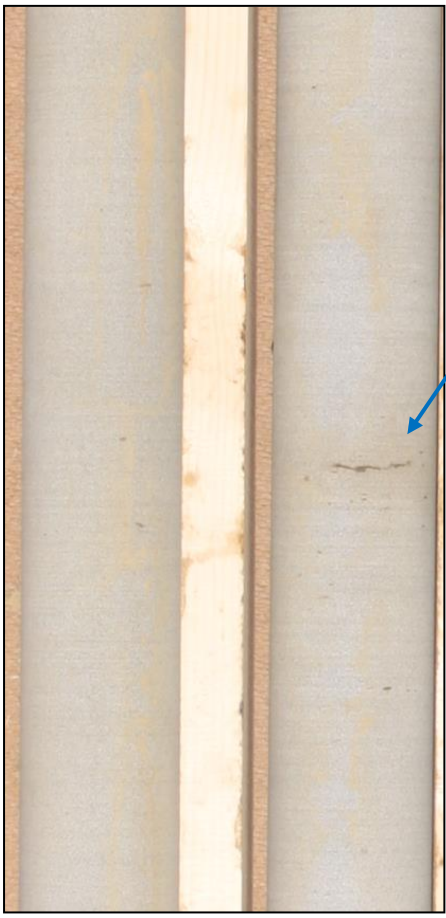
Facies 7 is here interpreted as amalgamated sand layers forming at shoreface with both quiet fair-weather sedimentation with time for intense borrowing and deposition during storms bringing clasts, nodules and coal/plant fragments into the facies although it should not be dismissed that the sideritic nodules could have been formed at the shorface and not necessarily brought by storms.

Facies 8 – Massive sandstone.

Description

Facies 8 consist of well sorted very fine to fine-grained, light-coloured sandstone with no structures observed (see fig. 32) It seems to be homogenous, but very fine-grained mud can be observed using a hand lens. This finer material is in small amounts and is not structured in organized matter but is well distributed within the sand. Smal clasts can also be observed distributed in unorganized matter within the facies.

The units are normally ca 100 cm in Endalen Member in Operafjellet and 50-300 cm in Todalen Member. In Breinosa the units are ca 100-200 cm thick in Todalen Member and ca 100-500 in Endalen Member. The facies is often associated with F5 and F6 such as the often-adjacent facies 7.



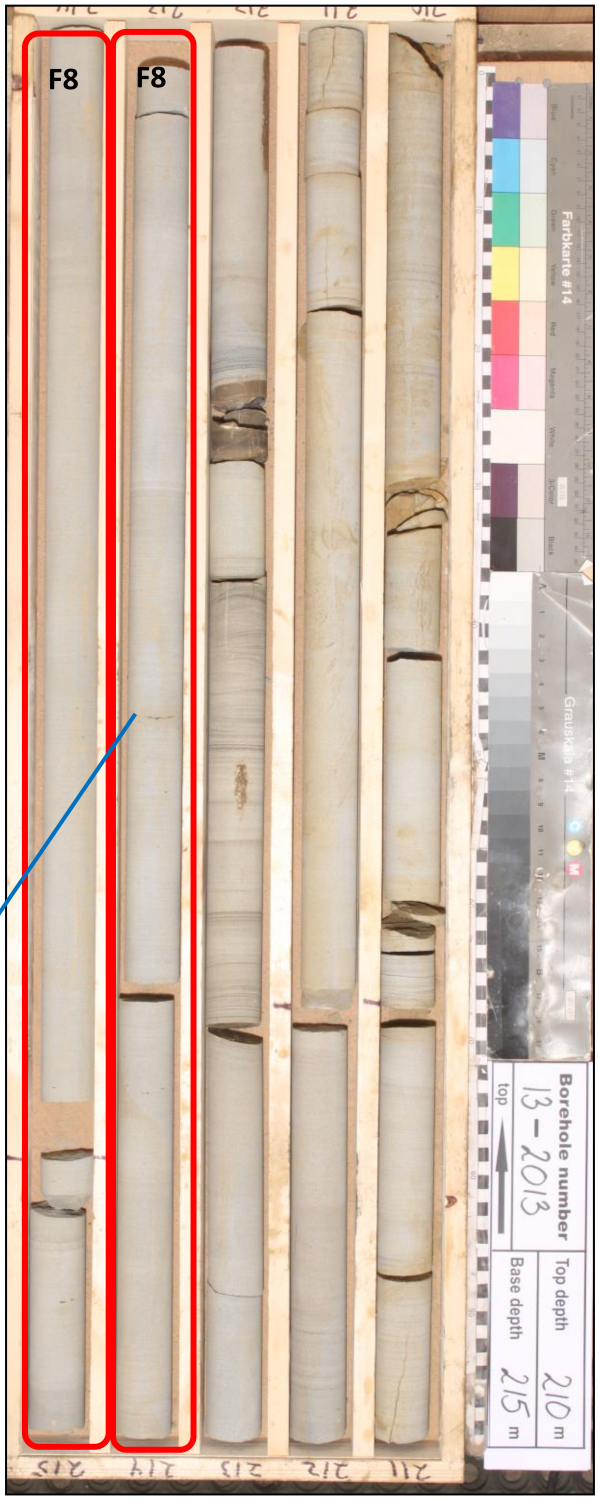


Fig. 32. To the left: A closeup of the Facies. To the right: Facies 8 in BH-13-2013.

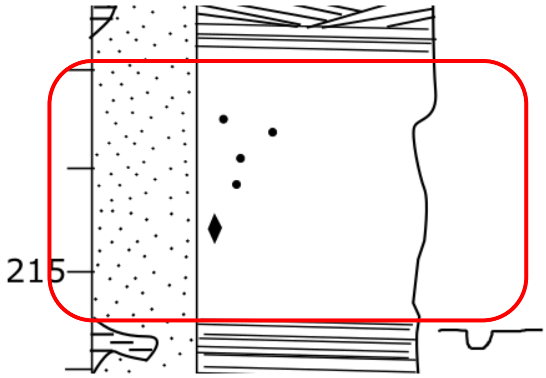


Fig. 33. Facies 8 in log from BH-13-2013

Discussion and interpretation

Due to its massive appearance, this facies can be interpreted in two ways; either the sediment is extremely well sorted and therefore lack of visible structures. This does not mean they are not present but further research on mineral level would be needed. X-radiography techniques and etching and staining methods often show that these kind of beds often do contain faintly developed structures (Boggs 2011). The second interpretation of the facies is that the sandstone is deposited on Shoreface under stable energy conditions with extreme bioturbation. The very well sorted sediment combined with grade 6 bioturbation (95-100% bioturbation) has eliminated all signs of primary visible structures making it look homogenous and massive looking.

Facies 9 - Conglomerate

Description

The clasts in the conglomerates observed in the cores are typically moderately to well rounded. Conglomerate beds are observed regularly throughout the whole formation and are both intraformational and extraformational conglomerate which are here divided into two subfacies.

F9a) Extraformational conglomerate

Extraformational conglomerate is often observed as a matrix supported conglomerate bed of ca 5-30 cm thickness (see Fig. 34 and 36), although the Grønfjorden Bed and the conglomerate bed that marks the top of Endalen Member can reach up to approximately 100 cm. It is most often polymictic (containing clasts of many different lithologies, Nichols, 2009), sub-angular to sub-rounded and considerably poorly sorted although no boulder size rocks can be seen in a core. It sometimes shows trends of fining upwards or in some cases coarsening upwards. It is often found above the uppermost coal seams and is abundant in the Endalen Member but few extraformational conglomerates are observed in Todalen Member.

F9b) Intraformational conglomerate

Intraformational conglomerate is often observed as matrix supported in thin lenses of 0,5 -2cm, but on occasions it reaches up to approximately 10 cm (see Fig. 35 and 37). The conglomerate is quite often observed as very small, well-sorted, monomictic and sub-rounded to rounded clasts, which are commonly elongated. These intraformational conglomerates are more abundant in the Todalen Member in Operafjellet.

In some cases, both intra- and extraformational clast build up the conglomerate bed. Imbrication is not observed. F9 is found within Marine sandstones of Facies 4, 6, 7 and 8.

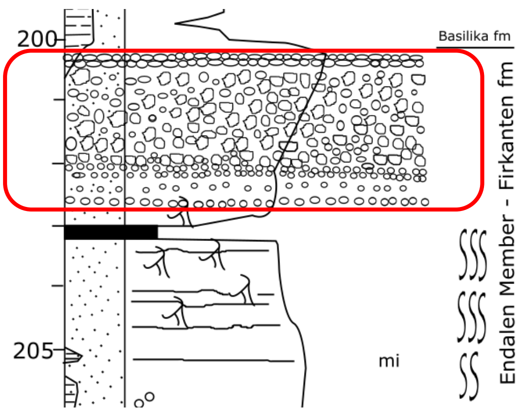


Fig. 34. Facies 9a in log from BH-19-2011

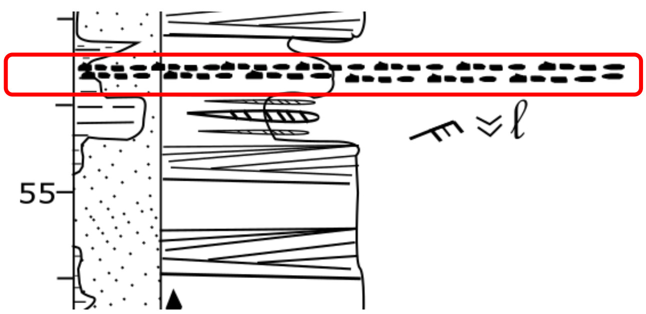


Fig. 35. Facies 9b in log from BH-19-2011

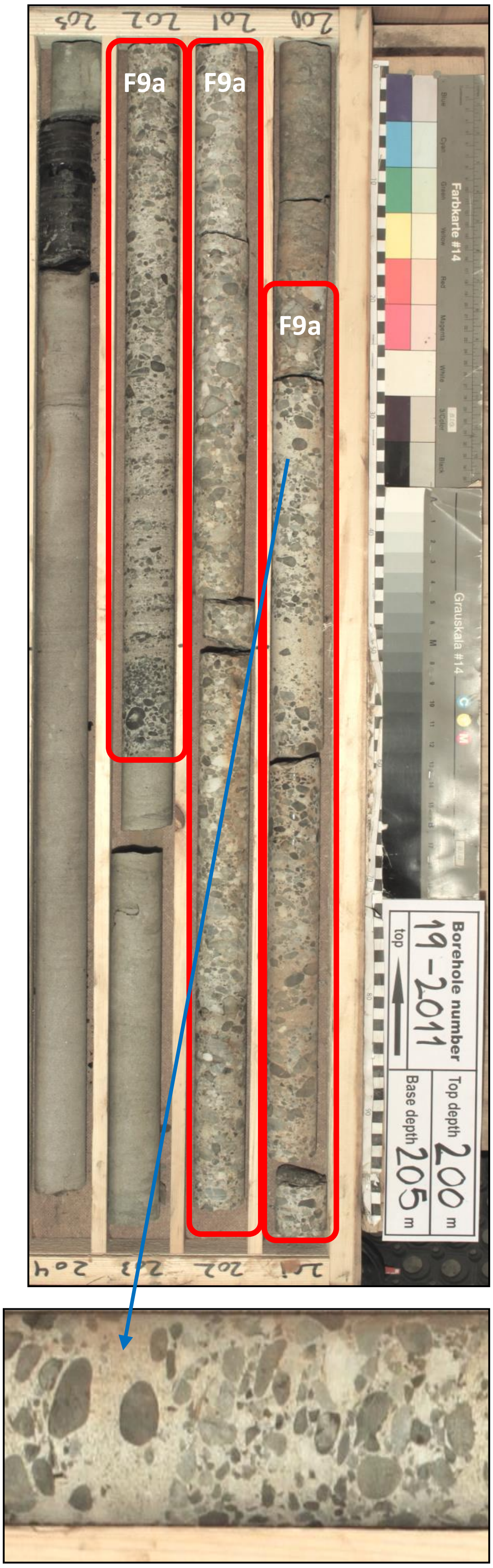


Fig. 36. Above: Facies 9b in BH-12-2013. To the right: Close up of F9B.

Fig. 37. Above: Facies 9a in BH-19-2011. To the right: A close up of the facies.

Discussion and interpretation

As Facies 9a is derived from a source outside the depositional area. It is almost exclusively associated with different facies of marine sandstone, shoreface to foreshore, so the conglomerate can be interpreted as a lag deposit, channel fill in tidal channel, as shallow marine conglomerate or it can be a beach sediment formed during marine transgression.

Facies 9b, Intraformational conglomerates contain clasts composed of the same material as the matrix or shortly transported material from the same area, it is the result of reworking of sufficiently lithified sediment soon after deposition (Nichols, 2009). It is mostly found in tidal flat deposits of the Todalen Member and can be interpreted as tidal channel deposit.

Facies 10: Bentonite

Description

The bentonite layers are clearly identifiable, they have a sharp contact to the over and underlying strata, are light brown or grey coloured and very fine grained. The bentonite consists of very soft material that can easily be to cut with a knife and when watered, it absorbs the water in a very efficient way, often bulging out and making the core itself look wider (see Fig. 39).

Thin units of only approximately 5-10 cm of facies 10 are observed clearly in a few of the cores. In cores 14-2010, 15-2010 and 13-2013 from Operafjellet, the bentonite is observed just below the boundary of the Endalen and Todalen Members. In Breinosa it is only observed in core 4-2009 several meters below the boundary of the two members.

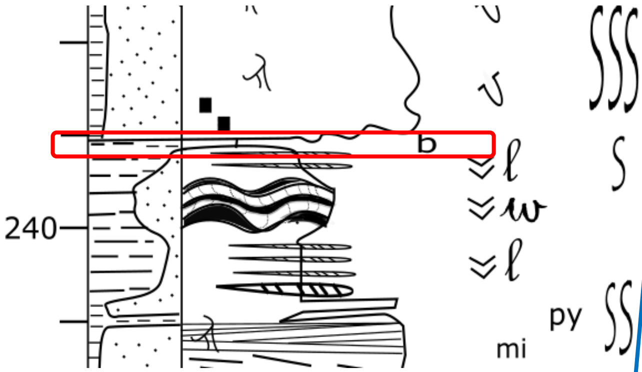
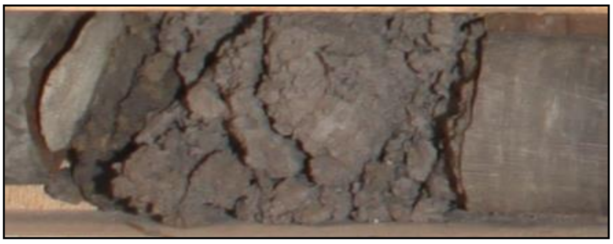


Fig. 38. Facies 10 in log from BH-13-2013



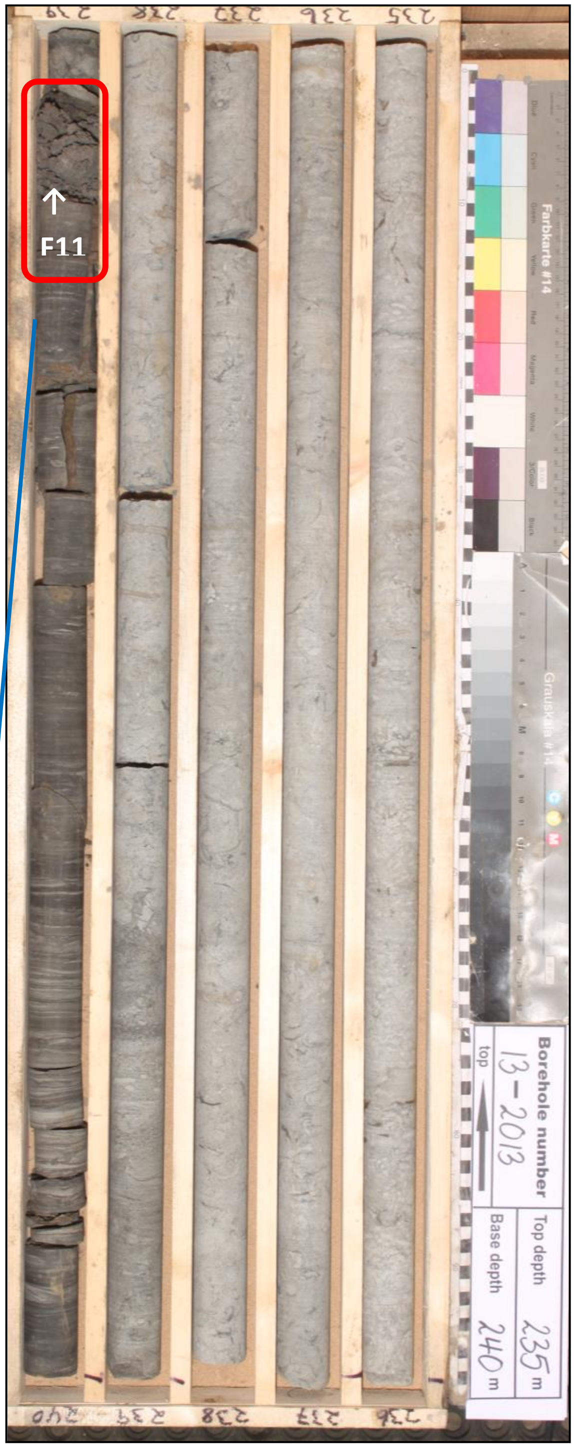


Fig. 39. To the Left: Facies 10 seen up close, before water test. To the right Facies 10 in BH-13-2013

Discussion and interpretation

Bentonite is a product of volcanoclastic sediment that is mostly composed of smectite clays which are alteration products of basaltic rock (Spears, 2003, Nichols 2009). To find the origin of the sediment where the original volcanic material has been altered, the mineralogy of the clays in the mudrock, such as high proportions of smectite presence, can be the only clue. Mineralogy study in the Firkanten Formation bentonite has not been done in this investigation but the formation of the bentonite here is suggested to be due to volcanic ash transported by wind and then settling in suspension where burial and diagenesis occurred.

Although the bentonite is several meters below the Endalen-Todalen boundary in core 4-2009 from Breinosa, it is approximately the same meters above the Askeladden coal seam in the core where Askeladden is observed in (core 13-2013). This might indicate that core 4-2009 had higher sediment rates and/or greater accommodation space during the time of deposition of the sediments in the upper part of Todalen Member, above the bentonite unit.

The absence of the facies in most of the cores does not necessarily indicate that it has not been there before. It is important to note that it is possible that some bentonite layers were not noted during logging as they might have been very thin or mistaken for being mudstone. It is also possible that it has been subjected to erosion, been blown away if it did not deposit on a wet and calm area or even washed away during drilling due to its fine grained material that easily turns into soft mud when subjected to water, and water needs to be used in abundance during core drilling.

In a thorough study of the Palaeocene bentonites of the Central Basin, Jones et al. (2016) investigated the bentonite layers in the drill cores from Store Norske and from within Svea Nord Coal mine. Most of the layers were found in Todalen Member of the Firkanten Formation although their research also investigated other formations. In his research a total of 50 sub samples from cores within the basin were analysed and Bentonite was found in 9 cores with bentonite layers ranging from 2-9 occurances. They concluded this to be an indication that the deposition of some tephra layers did not cover all the cores and/or that some ash layers were eroded before they were buried in some of the locations of the cores.

The abundance of layers in the Firkanten Formation could be explained by the fact that volcanic ash layers have higher preservation potentials in floodplains and outer shelf environments than in delta fronts and sand-bar complexes but they also do address the possibility that sediments in other formations and the Endalen Member could have been deposited during quiet periods of volcanic activity.

The result from Jones et al. (2016) yield that the bentonite in Todalen Member is characterized by evolved trace element compositions, strongly negative Europium anomalies and moderate LREE enrichment. The likely sourced of the bentonites in Firkanten Formation according to their study, are the rift-related alkaline volcanic provinces of North Greenland and Ellesmere Island (Jones et al. 2016).

Facies 11: Massive Sandstone with Ophiamorpha burrows

Description

Only one of the cores contains Facies 11. That is core 2-2007 (Fig. 40 and 42), located south of Breinosa. This facies is found within similar facies as to facies 7, a highly bioturbated sandstone but has additionally clear Ophiamorpha nodosa (see Fig. 41). Facies 7 occurs four times, in four different horizons, within the Todalen Member but as the Endalen Member is not present in this core/log it cannot be excluded that it might possibly be present there.

Facies 11 is first observed approximately 1 meter above the lowermost coal seam and then 3, 4 and 9 meters higher up in the core other Ophiamorpha nodosa horizons are present. Sandy lithology is present all around the facies with high bioturbation rate (facies 7) or non-bioturbated sandy cross beds (facies 6).

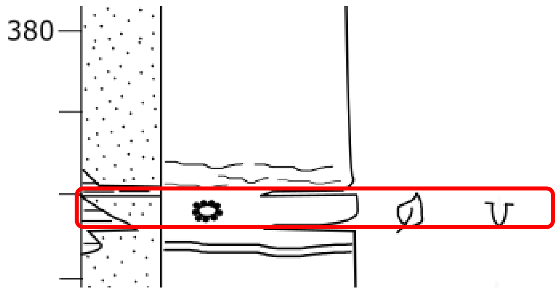


Fig. 40. Facies 11 in log from BH-2-2007

Fig. 41. Clear image of Facies 11 with abundance of Ophiamorpha, shown in a core from Todalen Member outside of the study area.

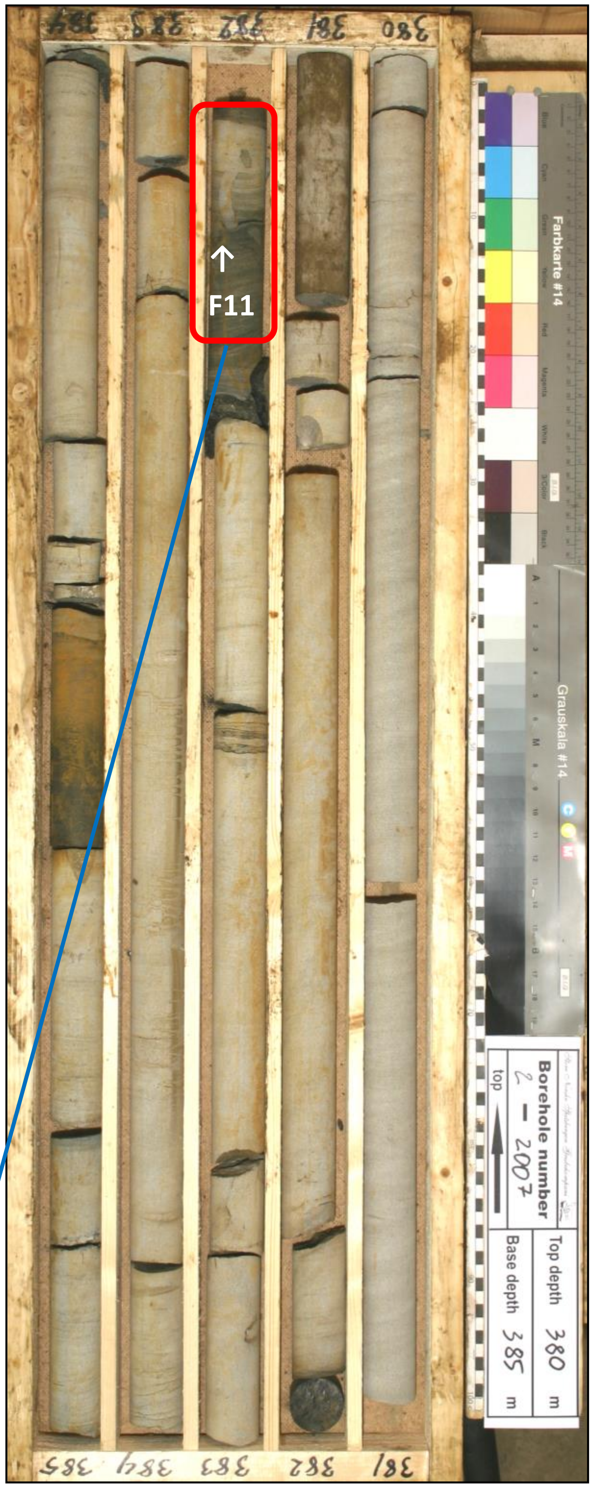


Fig. 42. Above: Facies 11 in BH-02-2007. To the left: Close up of Facies 11 showing both vertical and horizontal burrow within two different beds.

Discussion and interpretation

Ophiamorpha is one of the most common ichnogenera found in the Skolithos Ichnofacies. Skolithos ichnofacies is typical of foreshore to upper-and middle-shoreface environments of wave dominated shorelines. It is common in delta front deposits, in distributary channels of subaqueous delta plain. (Buatois and Mángano, 2011).

Commonly, horizontal traces are not preserved in fossil examples of the Skolithos ichnofacies due to intense erosion that usually only allows deeper vertical traces to be conserved in the sediment (Buatois and Mángano, 2011). With that in mind, the possibility of original presence of Ophiamorpha in the northern part of Breinosa and in Operafjellet has to be considered.

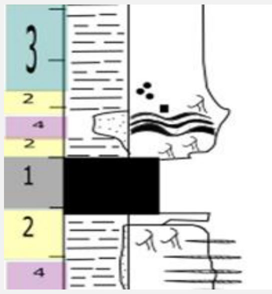
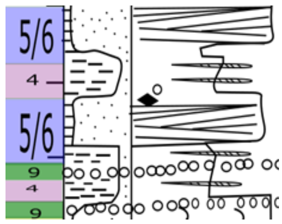
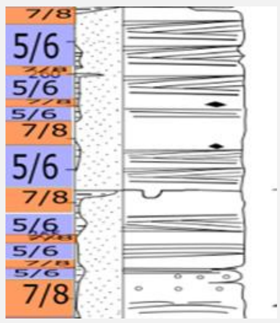
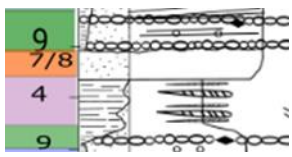
If there was a high sediment input from the north-eastern side of the basin during a fall in relative sea level, the sediment above the first coal seam in Operafjellet and Breinosa were deposited more landwards during basin-ward translation of the coastline position with subaerial erosion on the northern part of the study area in which the Ophiamorpha facies would have been eroded away. Unlike facies 7, facies 11 does not have abundance of clasts which indicate more aerial exposure and channel formations.

5.2 Facies associations

Based on the relative position of facies in the logs, 4 main facies associations are recognised and presented in the following table. The table identifies the costal sub-environment for each association, which facies are included in the association, a description of the association and an interpretation. Furthermore, a sample of how the facies are associated in the logs is presents.

Table 5.

Facies associations and interpretation

	Facies Associations	*Facies*	*Description of facies*	*Interpretation of processes and depositional environment*	*Example of facies association in logs with facies no. in colour*
1	Backshore tidal flat	1, 2, 3 and 4	Coal and Coal shale, mudstone, heterolithic ripple bedding and paleosol	Sediment deposited in quiet paralic environment on Backshore tidal flat from the middle tidal range of intertidal to supratidal zone. Deposition with significantly large tidal range with the area regularly flooded, bringing more sand into the system forming ripples.	
2	Upper shoreface to foreshore	4, 5, 6 and 9	Heterolithic sandstone, ripple beds, thin plane parallel lamination, larger scale cross beds and occasional conglomerate mostly intraformational.	Sedimentation influenced by strong tide or wave processes with silt, sand, granules and sediments up to large pebbles on lower tidal range of intertidal to subtidal zone on tidal dominated upper shoreface to foreshore. Tidal ripples and the occasional plane parallel lamination forming during quieter stages and some bigger crossbedding forming during stormier weather.	
3	Proximal Lower shoreface	5, 6, 7 and 8	Homogenous looking, plane parallel laminated sandstone, cross laminated sandstone, highly bioturbated and massive sandstone bodies.	Strong wave or tidally influenced sedimentation on proximal lower shoreface on the subtidal zone with intense bioturbation during periods of fair weather.	
4	Distal Lower shoreface	4, 7, 8 and 9	Intensively bioturbated or massive looking sandstone, heterolithic sandstone w. ripples often bioturbated, conglomerate.	Deposition under high energy marine condition with calm periods allowing for bioturbation in lower intertidal to subtidal zone. Coarser material such as conglomerate can be washed up and deposited during storms.	

5.3 Paleo-environmental analysis and geochemistry of the coal seams.

Svea seam

The lowermost coal seam of the Firkanten Formation is the Svea seam. It is present throughout Breinosa but only occurs in the eastern most part of Operafjellet in cores 19-2011 and 15-2010, it is possible that it is present where core 16-2010 was taken but as the core itself does not reach to the lower boundary of Firkanten Formation it is not registered in that core.

The thickness of the Svea seam in Operafjellet where it is observed is quite great or 116-196 cm thick but parting present in core 15-2010 is 312 cm. In Breinosa the coal thickness measured in the cores is 130-172 cm with 1-79 cm partings. Further south in the study area (2-2007) the seam is measured only 15 cm with no parting (see Fig. 43).

Under the coal seam, a paleosol is observed, and above the seam in Breinosa is heterolithic flaser-wavy bedding but in Operafjellet there is a bleached paleosol above the seam. The partings in the seam are made from organic rich mudstone or paleosol.

No lithotyping was done on this seam as the cores where Svea seam is present are older than from 2013 and the coal therefore already sampled from the drill cores.

The ash content in the seam peaks around Adventdalen, in core 15-2010 at the southernmost part of Operafjellet and at 3-2011 but decreases southwards within the seam in Breinosa (see Fig. 44). This could indicate a considerable amount of inorganic material coming into the system from North to South and the leached seatearth/paleosol above the seam in core 15-2010 indicates high fluvial activity through the soil in the Eastern edge of Operafjellet during the time of soil formation. A fluvial transportation of sediments which could be the cause of higher amount of inorganic material in the seam.

The sulphur content is extremely low in Operafjellet and fluctuates a bit in Breinosa but keeps relatively low (see Fig. 45). This indicates that there might have been a very large peat formation relatively far away from marine influences, with ocean front south of Breinosa.

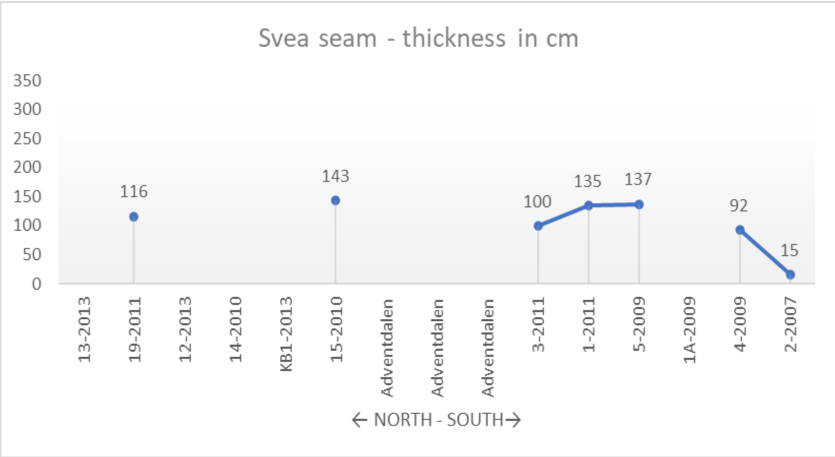


Fig. 43. Thickness of the Svea seam across the study area from north to south. The seam is only present in the Easternmost part of the Operafjellet mountain.

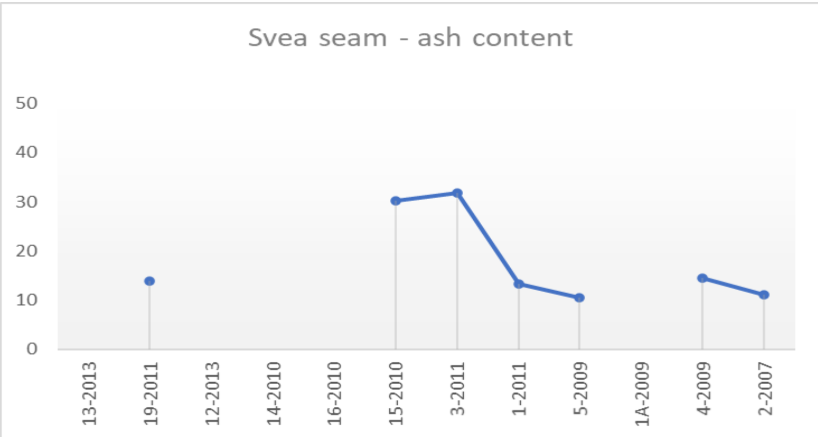


Fig. 44. Ash content in Svea seam across the study area from north to south showing peak in southern part of Operafjellet and Northernmost part of Breinosa.

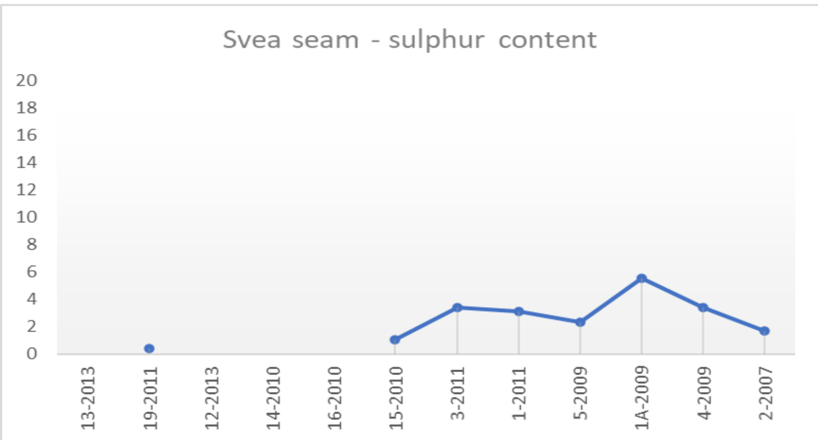


Fig. 45. Sulphur content in Svea seam across the study area from north to south showing slight relatively low and fluctuating sulphur content with an absolute low in Operafjellet.

Todalen seam

This seam is very thin in the study area and it is the lowermost seam in Operafjellet. No measurements for Todalen seam are found for BH-16-2010 as the drill hole did not reach down to the seam but another drill hole was made on a cliff right next to the location of 16-2010, core KB1-2013 so measurements form Todalen seam from that area is taken from that cliff drill hole.

The thickness of the seam is 13-47 cm in Operafjellet, thickest on the east side of the mountain. And in Breinosa it measures only 5-30 cm thick in the cores (see Fig. 46). No parting is observed in the seam and the above and below facies is most often mudstone but paleosol on occasions in Breinosa and wavy bedding in Operafjellet. Lithotyping has been done in few of the cores in Operafjellet and it shows that the coal is vitrain rich in the top indicating wetter conditions with clarain in the lower part indicating a slightly dryer condition at the base of the seam gradually becoming wetter conditions upwards.

Looking at the sulphur and ash content of the seam (see Fig. 47 and 48), it shows a spike in inorganic material in the southern part of Operafjellet in cores 14-2010 and 15-2010. This spike seems to continue across the valley where it decreases at the middle of Breinosa towards core 1A-2009 where it increases again southwards.

The sulphur content is quite stable across the study area apart from a bit lower values in BH-19-2011 in Operfjellet. It decreases southwards in Breinosa from the northernmost tip of the mountain towards the middle of the mountain at core 1A-2009 from where it has a big increase in sulphur content southwards, just like the ash content. This could indicate a closer proximity to marine environment with quite a bit of inorganic sediment coming into the system at the southernmost part of the study area and in the centre of it around the Adventdalen valley.

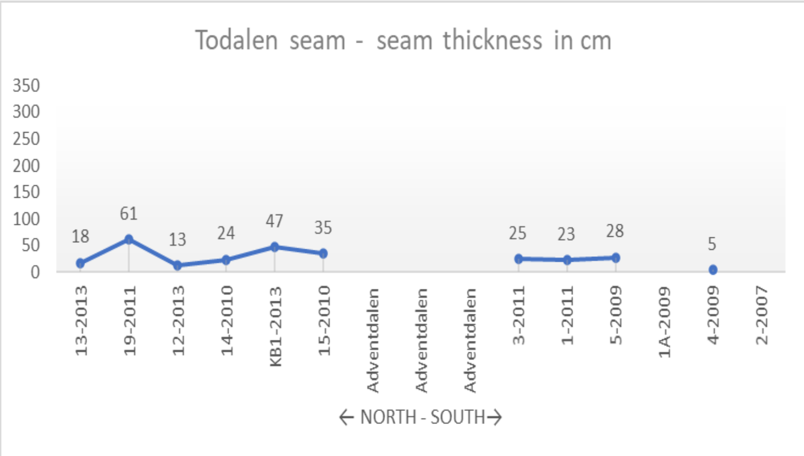


Fig. 54 46. Thickness of the Todalen seam across the study area from north to south.

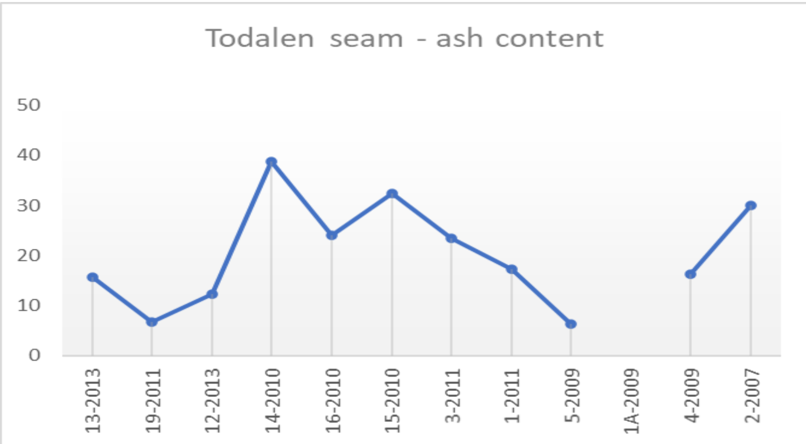


Fig. 55 47. Ash content in Todalen seam across the study area from north to south showing peak in southern part of Operafjellet with slight decrease towards middle of Breinosa where it increases again southwards.

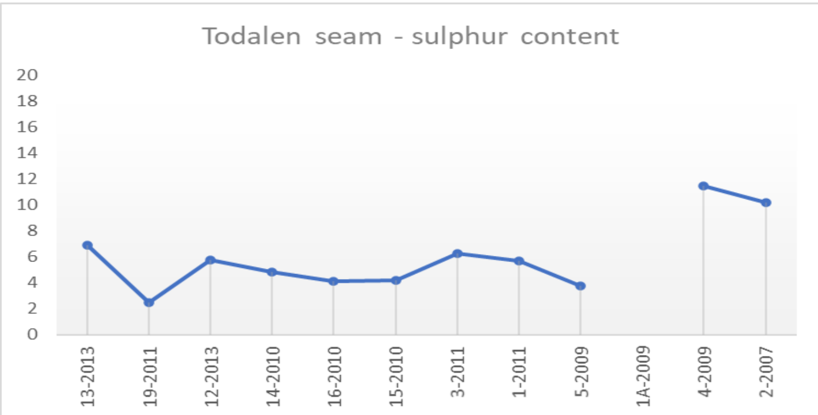


Fig. 56 48. Sulphur content in Todalen seam across the study area from north to south showing southwards increase in sulphur from middle of Breinosa.

Longyear seam

The coal seam that is mined today in Mine 7 in Breinosa is called the Longyearseam. The thickness of Longyearseam in Breinosa is from 90-165 cm without including the partings. In the southernmost part of the study area, in core 2-2007 the seam only measures 13 cm of coal with 6 cm parting (Fig 49). Its thinning out is quite prominent. Parting measured in the Breinosa cores are 25-185 cm thick and is most often made up of mudstone although three of the cores have a parting made up by a bit coarser material, heterolithic bedding with ripples (1A-2009, 5-2009 and 2-2007). Several smaller partings are present within the seam in Breinosa oppose to the usual one parting that is common in Operafjellet. The thickness of Longyearseam measured in the Operafjellet cores is between 138-228 cm thick often with partings that can range from 20-143 cm in thickness and is made up of organic rich mudstone (facies 3). The mudstone is also the under and overlying facies and it occasionally contains thin disrupted and discontinuous sand lenses.

Lithotyping of the Longyearseam was done in few of the cores from Operafjellet, 12-2013, 13-2013 and finally Kb1-2013 which is only used in this study for its lithotyping as it is a small and short core taken from the mountainside next to 16-2010. The lithotyping showed that several small interval changes from vitrain to clarain with durain rich clarain on very few occasions although Kb1-2013 shows a bit more vitrain rich coal than the other two cores and its top contains ash rich coal while the other cores contain durain rich clarain in the top. Vitrain is formed under more moist conditions than clarain and very scarce presence of durain. The coal seam shows small cycles in moisture content with dryer conditions at KB-2013 at the easternmost part of Operafjellet, opposed to the wetter depositional conditions in the western part of the mountain.

Looking at the ash and sulphur content of Longyear seam (see Fig. 50 and 51), it shows increase in both southwards through the study area. The relatively low sulphur and ash values from Operafjellet and the seams thickness there indicates that Longyearseam could possibly have better economic potential in Operafjellet than the same seam that is currently being mined from Breinosa

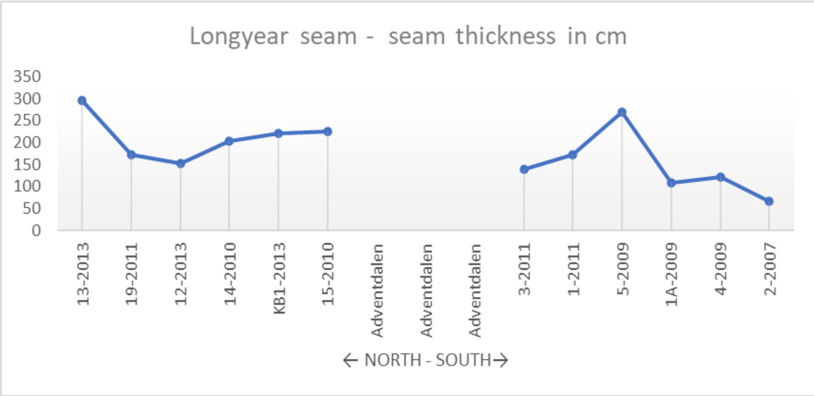


Fig. 49. The thickness of Longyearseam across the study area from north to south. The drill holes on the left of Adventdalen on the graph are from Operafjellet, and on the right side is from Breinosa.

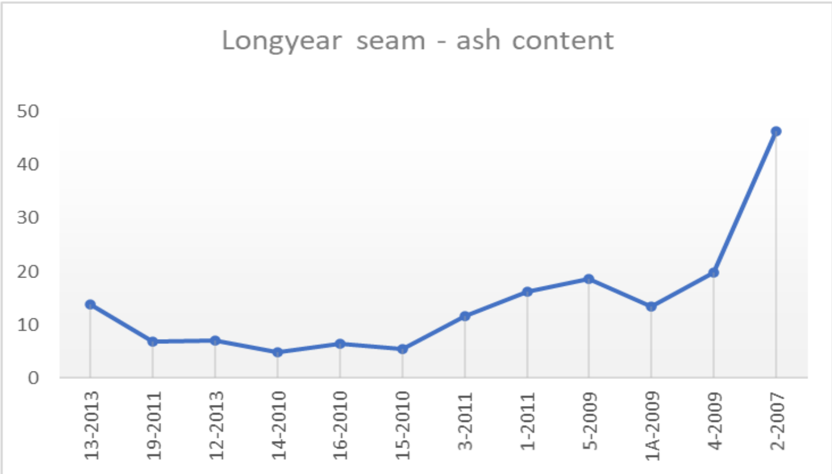


Fig. 50. Ash content in Longyearseam across the study area from north to south showing southwards increase in inorganic material within the coal

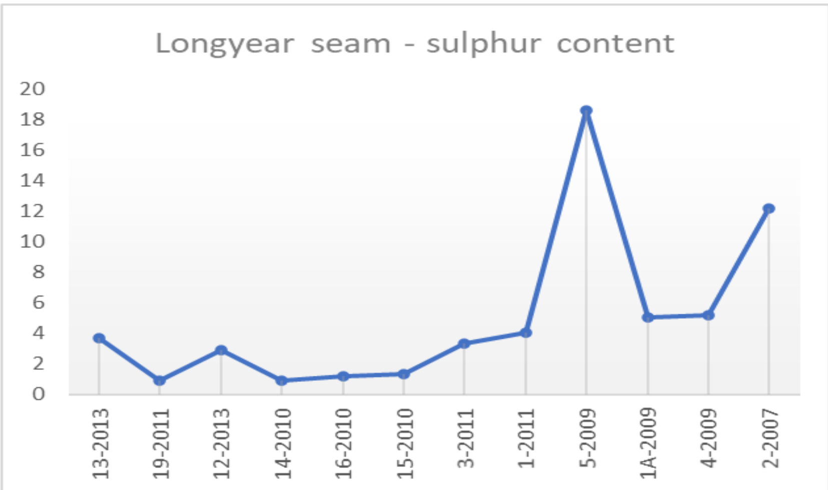


Fig. 51. Sulphur content in Longyearseam across the study area from north to south showing southwards increase in sulphu content

Svarteper and Askeladden seams

These seams will be grouped together here due to their similar characteristics, high sulphur and ash content and their proximity to one another. In Breinosa the two coal seams are separated with heterolithic sediment, usually in this order: lenticular-wavy-flaser-wavy-lenticular-beddings, so it is coarsening upwards from Svarteper and then fining upwards again before reaching Askeladden (see Fig. 52). This makes it quite easy to identify the two seams from others. In Operafjellet on the other hand only small unit of lenticular bedding or pure mudstone is between the two seams if there is any at all. It seems like the rock that is parting the two seams, wedges out and disappears northwards from Breinosa to Operafjellet but another parting appears in the south-western part of Operafjellet. In the north-western part of the mountain the two seams seem to either combine or one of them disappears leaving only one seam in that area.

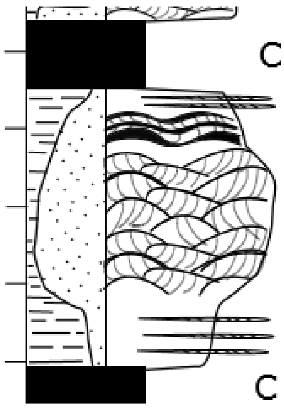


Fig. 52. Shows the coarsening-fining upward cycle between Askeladden and Svarteper in Breinosa.

The thickness of the seam or combined seams in Operafjellet is 124-266 cm with its thickest part at the southernmost tip of the mountain and thinning towards north-west. Rock partings are found to be from none to 4 partings and they are measured with the combined thickness of 0-131 cm. No parting is in the core 13-2013 which was taken from the north-westernmost part of the mountain.

In Breinosa where the seams have easily distinguishable parting rock, the thickness of Askeladden is reaching from 56-140 cm where it gradually disappears southwards while the thickness of Svarteper however varies between 45 cm in the northernmost part of Breinosa and slightly thickens southwards.

Lithotyping was done in core 13-2013 for Askeladden and/or Svarteper in Operafjellet. In that core, no prominent parting is observed so it will be referred to as one seam here. At the very bottom of the seam vitrain is observed, above that a thin coal shale layer. The middle part contains mostly clarain or vitrain rich clarain. Another thin layer of coal shale is found on top of that and at the very top of the seam there is very ash-rich vitrain. Vitrain at the bottom of the seam indicates high-moisture content, which decreases upwards where you got more ash rich and a bit dryer (clarain rich vitrain) coal.

The very ash rich part of the top of the seam could indicate that Askeladden is still present with the usual rock parting only being coal shale now beneath the ash-rich part and in the lower part the coal shale could be the rest of the parting that has been observed within the meant Svarteper seam.

Furthermore, looking at the ash and sulphur distribution in the core throughout the study area the ash content in Askeladden is unusually low in Operafjellet but increases a bit southwards, with higher values in Breinosa. Svarteper shows however higher values in Operafjellet which decrease southwards towards Adventdalen valley, it peaks in BH-3-2011 which is located on the northernmost tip of Breinosa (see Fig. 53 and 54). This could suggest a sudden input of inorganic matter into the system in that area and then possibly also where Adventdalen is today.

Sulphur content in both Askeladden and Svarteper shows very slight increase from the Northernmost part of Operafjellet to the Southernmost part of Breinosa. A slight dip in sulphur around BH-19-2011 and 12-2013 suggests more freshwater.

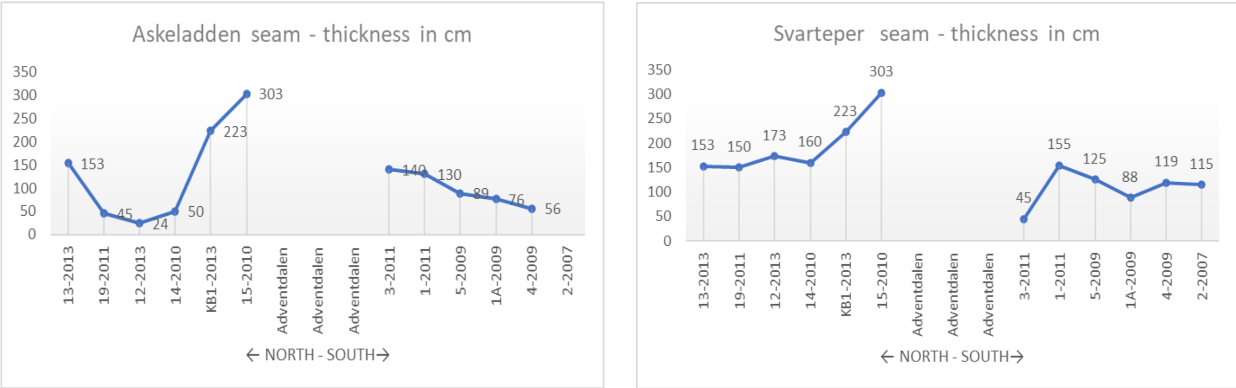


Fig. 53. Thickness of Askeladden and Svarteper, thickness is combined in Operafjellet in three drillholes.

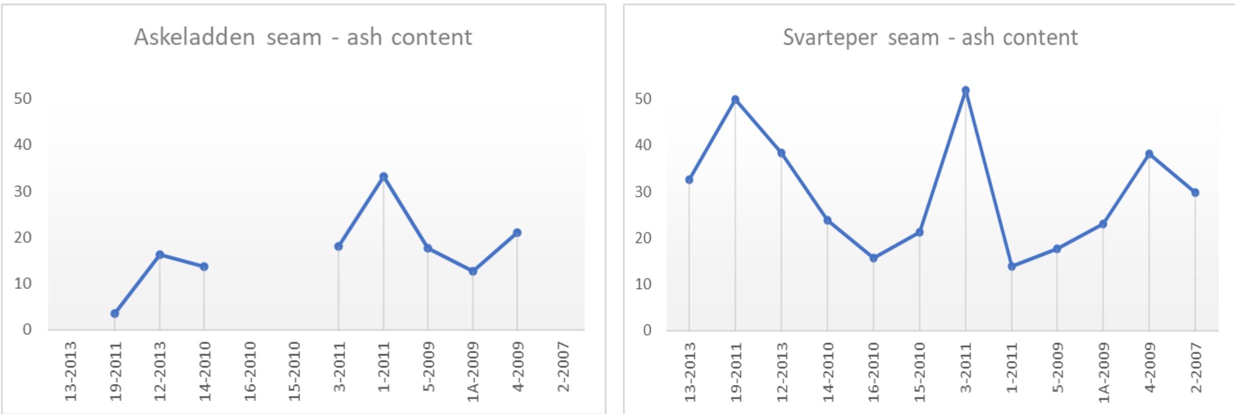


Fig. 54. Inorganic content in Askeladden and Svarteper coal seams.

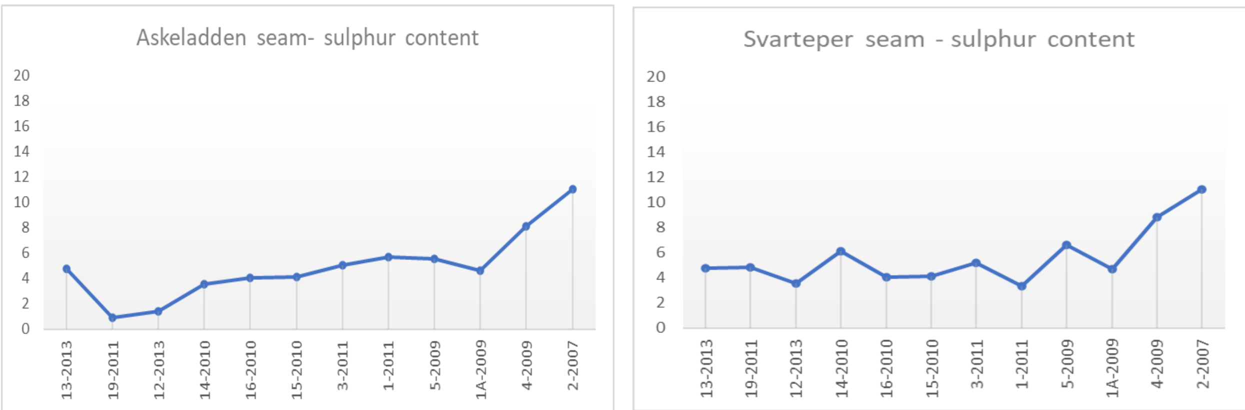


Fig. 55. Sulphur content in Askeladden and Svarteper coal seams.

Dirigenten seam

The second highest coal seam (fig. 7) of the Firkanten Formation is situated in in upper part of the Todalen Member, often close to the boundary to the Endalen Member. It is 4-50 cm thick with its thickest part in the northern part of the mountain and thinning out considerable towards south-east (see Fig. 56). Below the coal seam, there is a rooted paleosol, and directly above there is mudstone with sand lenses, except for in core 14-2010 where there is cross stratified sandstone directly above the seam. This coal seam might have been mixed up with Askeladden and/or Svarteper in the past due its location within the formation as it is the highest/youngest coal seam in Todalen Member although it is situated some 15-20 meters above the true Askeladden or Svarteper seam. Lithotyping of the seam was done in core 13-2013 where you have vitrain in the bottom then a thin lens of coal shale and durain rich vitrain in the upper part.

The Dirigenten seam is mostly made up by vitrain, a coal that has a shiny appearance and relatively high moisture. Vitrain is mostly made up by Vitrinite, a maceral originated as wood or bark and is a major constituent to bright coals (Boggs, 2011). In the upper part of the seam the coal becomes duller and is made up by coal shale and durain rich vitrain. Durain is mostly made up by inertinite, a maceral composed of woody tissue, fungal remains or fine organic debris and is known to have high carbon content. Vitrain is deposited in peatlands with higher moisture content while durain is considerably deposited under dryer conditions, so the lithotyping shows a drying upwards section.

Looking at the ash and sulphur content in the seam (see Fig. 57 and 58) there is a slight southward decrease in ash (inorganic material) while there is a southward increase in sulphur content, the sulphur content is slightly higher than the average content in coal in Operafjellet, and the trend is that sulphur usually becomes higher southwards in the study area. Coals formed under freshwater conditions have a very low total sulphur content while coals formed under marine influences present higher content on sulphur (Chatterjee, 1940). The relatively high sulphur content in the Dirigenten seam might therefore suggest proximity to sea. The ash within the seam suggest sediment input from north with considerable amount of inorganic material coming into the depositional area. If the distribution of the seam and its sulphur content is mapped where the highest sulphur content is in core 14-2010 and also considerably high in 19-2011 and 16-2010, and the seam itself is not present in 12-2013 and 15-2010, the landscape at the time of deposition could indicate a delta environment with embayment bringing marine water just east of BH-19-2011.

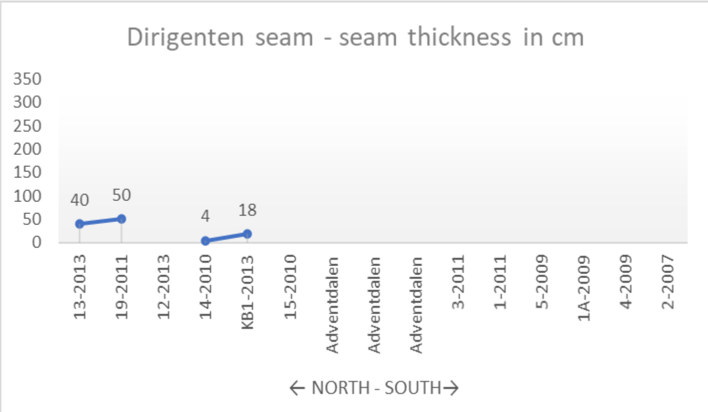


Fig. 56. Diagram showing the thickness (in cm) and distribution of Dirigenten seam in the study area

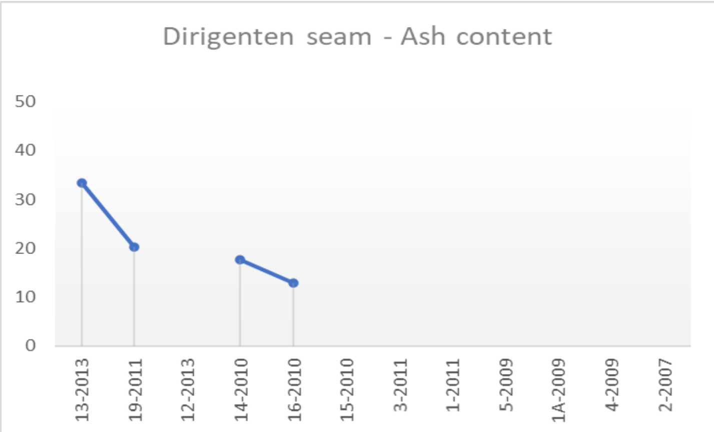


Fig. 57. Diagram showing the ash content in Dirigenten seam throughout the study area

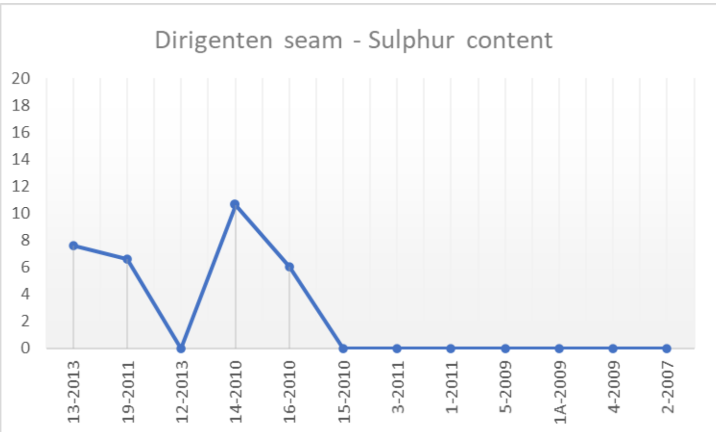


Fig. 58. Diagram showing the sulphur content in Dirigenten seam throughout the study area

Bassen seam

It seems that there has not been made any detailed descriptions of coal in Endalen Member in published literature, but a little-known thin seam is now observed in the top of the member in the Operafjellet drill cores. This coal seam, which seems like is more of a regionally limited lens, looks to be absent in the southern side of Adventdalen but is quite prominent in Operafjellet.

The seam is observed in the top of the Endalen Member, right before the boundary to Basilika Formation. This seam has only been observed in Operafjellet drill cores and is measured ca 4-30 cm thick (see seam thickness graph for the study area in Fig. 59). The seam is at its thickest at the eastern part of the mountain in cores 19-2011 and 16-2010 and thins out southward in the mountain and is completely absent in the western part of it. The seam has possibly not been observed in the field due to its limited distribution and sparce thickness.

The Bassen seam (Fig. 7) was logged thoroughly with lithotyping in mind. The coal was mostly clarain with vitrain properties present in places. It has a high luster, and it switches between ca 1-2 cm layers that are breaking in conchoidal fractures and breaking into cubics. Where the coal breaks into cubics, the coal is also finely laminated. Pyrite is abundant in the seam and clearly visible pyrite bands are observed. The underlying lithology is rooted sandstone or with or without paleosol above the coal, there is a dark, organic-rich sandstone that grades upwards into most often a thick and extensive conglomerate, which is commonly found at the boundary to the overlying Basilika Formation. Furthermore, traces of glauconite were observed in the sand just above the seam during further analysis of BH 19-2011.

Geochemical analysis of the seam does not exist due to its limited thickness and distribution and therefore non economical potential for Store Norske but due to this the coal was never sampled which made lithotyping possible on older cores.

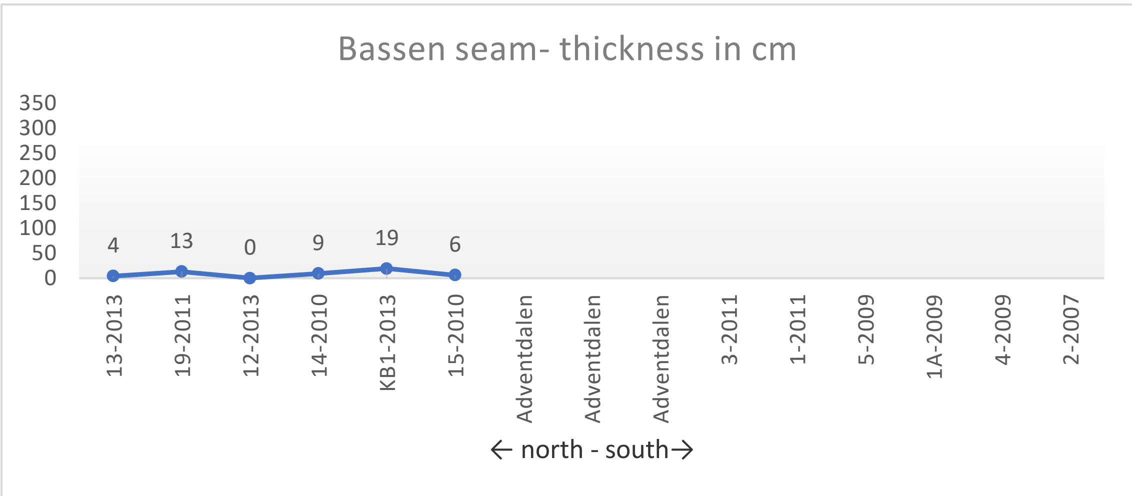


Fig. 59. Diagram showing the thickness and distribution of Bassen seam in the study area

Both the prominent pyrite in the coal itself and the Glauconite in the sand above Endalen seam indicate that the seam is formed under marine influences. Possibly in a salt marsh, a swamp or rheotropic mires that are formed in places where there is a flow of groundwater and some clastic sediment input. They are referred to as salt marshes if the water input is saline and the saline water will then contain sulphates that lead to the formation of sulphides (Nichols, 2009), such as the pyrite found in the seam. Note that it cannot be excluded that the seam had better distribution at time of deposition and has been eroded away.

5.4 Vertical and lateral architecture

5.4.1 Correlation

The correlation was supported by lab results from the coal provided by Store Norske (see appendix II for tables). Especially the ash and sulphur contents of each seam. This supports the correlation of the coal seams from one drill core to another based on stratigraphy alone.

The correlations of the coal seams were done first based on facies associations following from Operafjellet to Breinosa. The cores chosen to represent the correlation and therefore the depositional environment were picked to make the straightest line across Adventdalen and the best cover of Firkanten Formation (see Fig. 60).

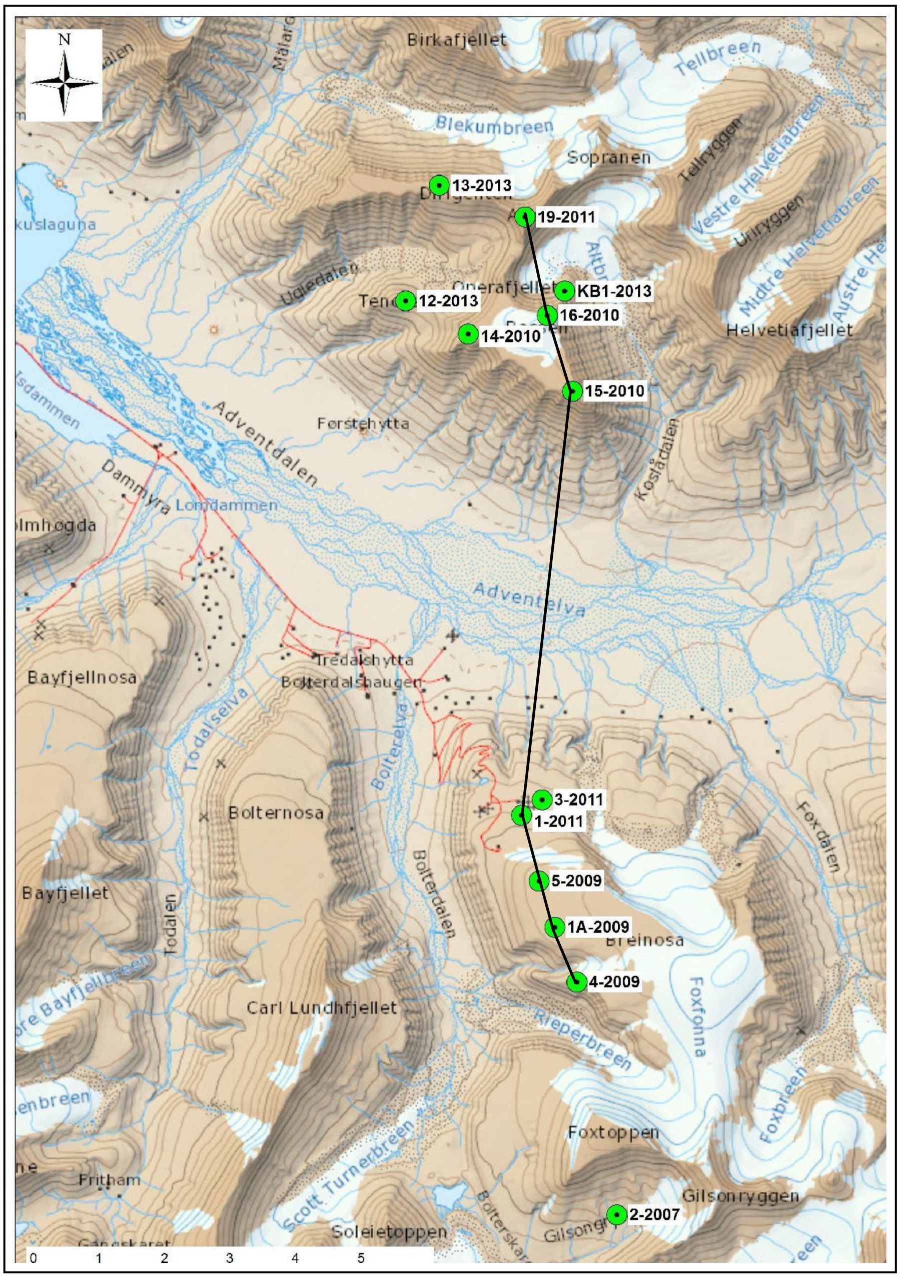


Fig. 60. Map of the study area, black line indicating path of correlation throughout the study area.

5.4.2 Distribution of facies associations

Dominating facies association in Todalen Member is FA1 in the lower part of the member in Operafjellet and FA2 in the upper part of it. In Breinosa FA3 becomes quite prominent in addition to FA1 and FA2. This suggests the lower part of Todalen Member in Operafjellet to be Backshore tidal flat which gradually but interfingering goes into foreshore and upper shoreface in the upper part of the member. Breinosa on the other hand transitions more into foreshore to proximal lower shoreface (Fig. 61- Correlation diagram). In other words, the faceis associations from north to south, reveal a shoreline to the north and more off-shore facies to the south.

A several meters thick lens of FA2 is quite prominent in the middle of the Todalen Member in the southernmost tip of Operafjellet (see Fig. 61 – correlation), and transitions into FA3 across Adventdalen valley over to Breinosa. This can represent a small transgression from the south reaching only the southern part of Operafjellet. This lens is considerably thicker in Operafjellet and thins out towards Breinosa, suggesting relatively higher accumulation rate in the upper shoreface or foreshore north of Adventdalen and gradual decreases in the proximal lower shoreface south of Adventdalen (Fig. 61- correlation).

In Operafjellet, the Endalen Member has mostly FA3 to FA4 with a thin unit of FA2 in the middle of the member in the northernmost part of the mountain and then again throughout the whole study area in the top of the member. Furthermore, F1 is present in the top of the Endalen Member in Operafjellet and in the lower part of it. This suggests that the Endalen Member is deposited in the proximal part of the lower shoreface with a small transgression from south indicated by foreshore to upper shoreface facies in the middle of the member and again in the top allowing for backshore tidal flat deposits in Operafjellet (Fig. 61- correlation).

The Endalen Member in Breinosa has a very similar lithology as the Endalen Member in Operafjellet, although less complicated and without FA1 suggesting less continental influence than in Operafjellet. FA3 and FA4 are the dominating facies associations and in the middle and top of the Endalen Member in Breinosa, FA2 is present, suggesting lower-shoreface deposits (interfingering proximal and distal shoreface deposits) and the occurrence of FA2, upper shoreface deposits, in the middle and top of the member which reaches throughout the whole mountain (Fig. 61- Correlation diagram).

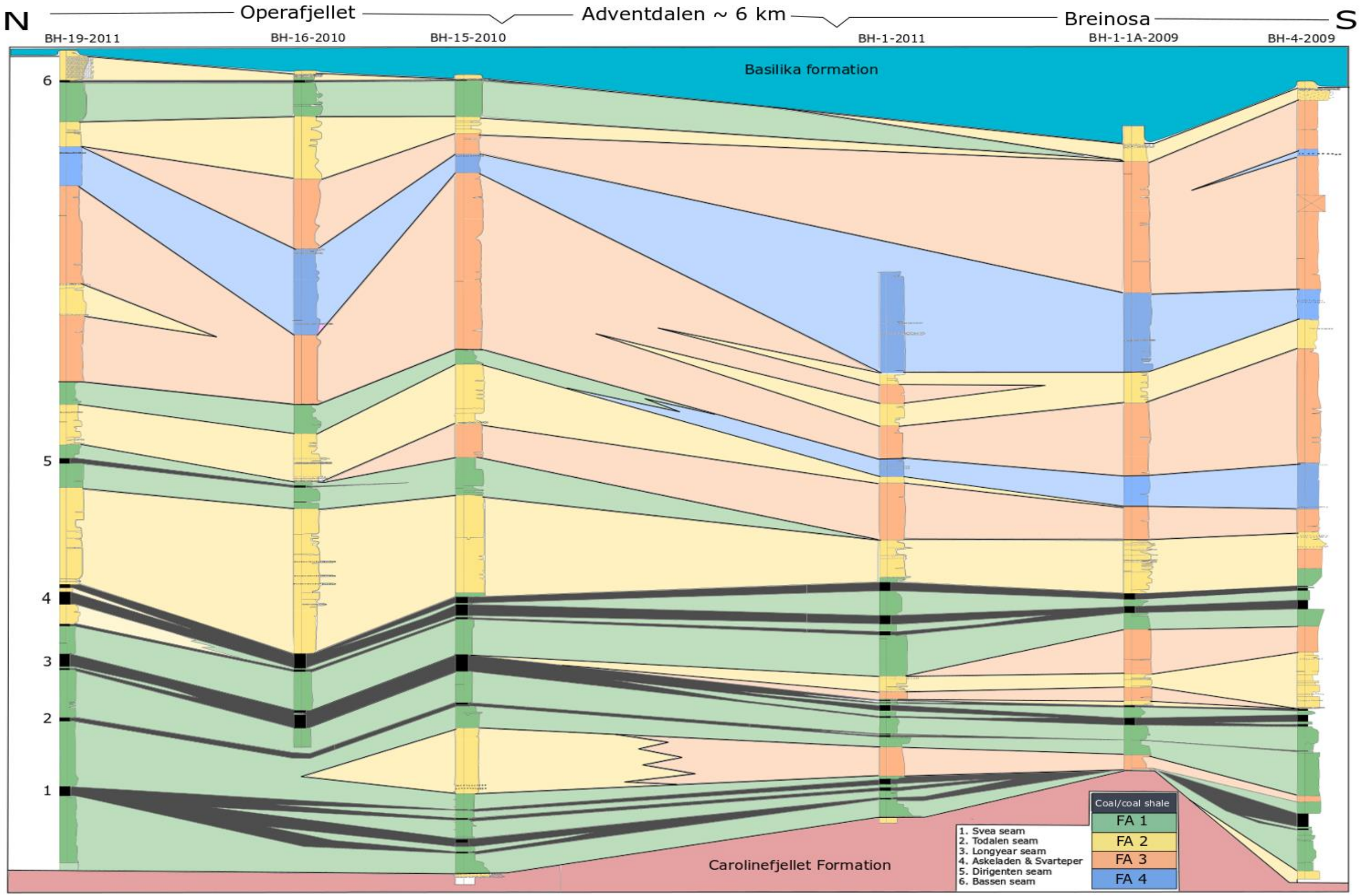


Fig. 61. Correlation across the study area. 1. Svea seam, 2. Todalen seam, 3. Longyear seam, 4. Svarteper & Askeladden-seams (Askeladden on top). 5. Dirigenten seam, 6. Bassen seam. FA1: Backshore, tidal flat. FA2: Upper shoreface to foreshore. FA3: Proximal Lower shoreface. FA4: Distal Lower Shoreface.

6 Discussion

6.1 Paleoenvironmental interpretation

The Todalen Member in Operafjellet is here suggested to be deposited on a backshore tidal flat with interfingering upper shoreface deposits, and in the same member further south in Breinosa there is evidence of deeper-water deposition of foreshore to proximal lower shoreface deposits between periods with subaerial exposure and peat accumulation on tidal flats. Looking at the correlation, it is quite clear that flooding of the tidal flats is greater in Breinosa at the southern part of the study area than in Operafjellet in the northern part where shoreface deposits are almost absent. However, upper shoreface deposits are found in the upper part of the Todalen Member and in the middle part of the member in the southernmost part of Operafjellet where it transitions across Adventdalen to proximal lower shoreface deposits which then thins considerably southwards.

The Endalen Member is suggested to be deposited in a lower to upper shoreface environment throughout the whole study area, with a small regression indicated in the uppermost part of the Endalen Member allowing for backshore tidal flat deposits in Operafjellet but continued marine setting in Breinosa. Above the backshore deposits in the top of the member in Operafjellet, there is evidence of upper shoreface deposits that can be traced through the study area.

The study of Grasdal (2018), which focuses on the Endalen Member in the Adventdalen area, gives a detailed sequent stratigraphic analysis of the Adventdalen area and documents evidence of the presence of a coastal plain environment with a flooding surface at the top of the member which fits well with results presented in this study. Furthermore, he mentions that the entire area above the uppermost coal layer, the Bassen seam, is directly overlain by a wide alluvial plain, which covers the study area with fluvial conglomerate and coarse, stratified sandstone. This is also briefly documented in a paper by Bruhn and Steel (2003). However, while investigating the Bassen seam in detail for this current study, quite prominent and abundance of pyrite was found in the seam, and directly above the seam, in the sandstone and conglomerate above, there is a clear evidence of glauconite. This suggests that the seam was formed under strong marine influence as mentioned in the chapter about the Bassen seam, with transgression during relative rise in sea level and fast landwards translation of the coastline after peat deposition indicated by conglomerate or marine lag deposits above the coal grading quickly into prodelta sediments of the lower Basilika Formation.

The coal seams in Operafjellet tend to be thicker than in Breinosa, with sulphur and ash content generally (with some exceptions), being relatively lower in Operafjellet than in Breinosa. This is a trend that runs through all the coal seams and therefore strongly support greater marine influences in the southern part of the study area through the depositional period of the formation. Furthermore, looking at the coal and considering the F3 and F4 facies, which together with F2 make up FA1, which is considerably much thicker and more frequent in Operafjellet than in Breinosa and the fact that those three facies are more abundant in the Todalen Member and almost absent in the Endalen Member, the evidence suggests that there was intense sediment input and/or more accommodation space, during build-up of the lower part of Firkanten Formation, derived from north or north-west of the basin with considerably lower depositional rate and/or accommodation space in Breinosa than in Operafjellet at the same time. This fits to the results of Lüthje (2008), who suggested depositional material coming from north and north-west and gives a new insight into the environment at the northeast edge of the basin.

This investigation of the facies agrees well with other studies of the Firkanten Formation (Svinth, 2011; Serigstad, 2011, Grasdal, 2018, Lüthje, 2008) with minor exceptions. The established facies, facies associations and correlation diagram, show a clear thinning of proximal facies associations (backshore to upper shoreface) units southwards in the study area in both the Todalen and Endalen Members, while the distal facies associations (proximal to distal lower shoreface) shows the opposite. The distal facies are thickest in Breinosa in the southern part of the study area and thin out towards the north.

This observation, along with the observations of southwards-increase of sulphur within in the coal deposits indicate a coastline in NW-SE orientation. These findings correspond to the findings of Grasdal (2018) who shows the same evidence of proximal and distal shoreface facies indicating NW-SE trending shoreline prograding in a south-western direction. Furthermore, Bruhn and Steel (2003) also mention that the thickness trends of the incised shoreface sandstone body in their study reflect a general NW-SE orientation of the coastline.

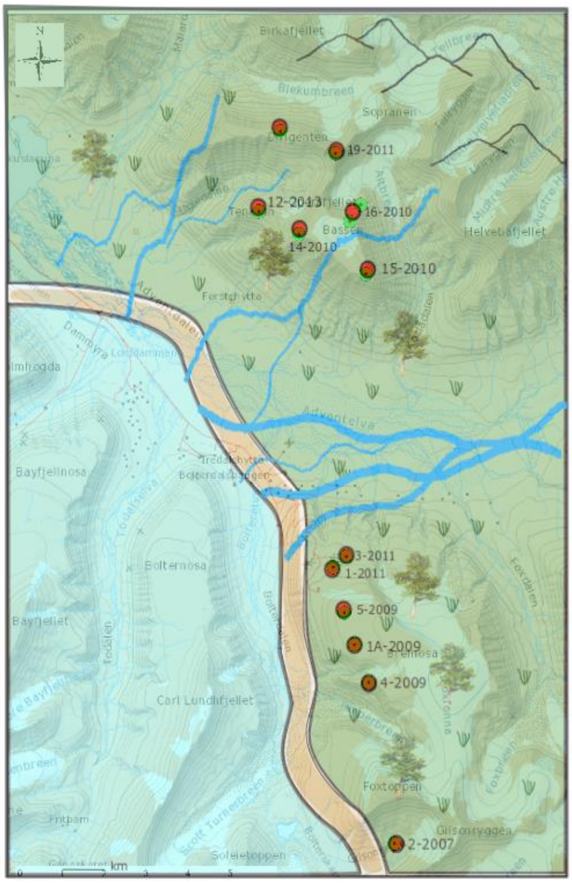


Fig. 62. The coastline during landward translation of it at the time of deposition of Askeladden and Svarteper peat deposits in middle of Todalen Member.

The Palaeocene deposits, including the lowermost Firkanten Formation in the Central Tertiary Sedimentary Basin are interpreted by Bruhn and Steel (2003) to reflect eastward-migrating, landward-stepping, peripheral-bulge-derived succession with transgressive-regressive cycles. The deposition was controlled by the position and height of a thrust-load-generated peripheral bulge. The regressive phases are a response to uplift and basin-ward translation of the peripheral bulge, caused by increased thrust-wedge build-up (see Fig. 63). Furthermore, the regressive phases are characterized by relatively thick, wedge-shaped strata reflecting both increased erosion and unconformity development along the basin margin, and increased creation of accommodation space in the basin (Bruhn and Steel, 2003).

In this current study it is clear that in general, the accumulation of sediments at the northeast edge of the basin suggest more accommodation space and/ or a relatively higher accumulation rate of sediments at Operafjellet than in Breinosa. This correlates on certain levels with the studies of Bruhn and Steel but recent evidence of greater deposition at the basin edge should be recognised and considered that

Todalen Member and lower Endalen Member deposits could also be sourced from peripheral bulge and perhaps the passage and relaxation of the initial peripheral bulge did not happen at the same extent at the basin northeast edge, such as seen in part B for upper Endalen Member in Fig. 63.

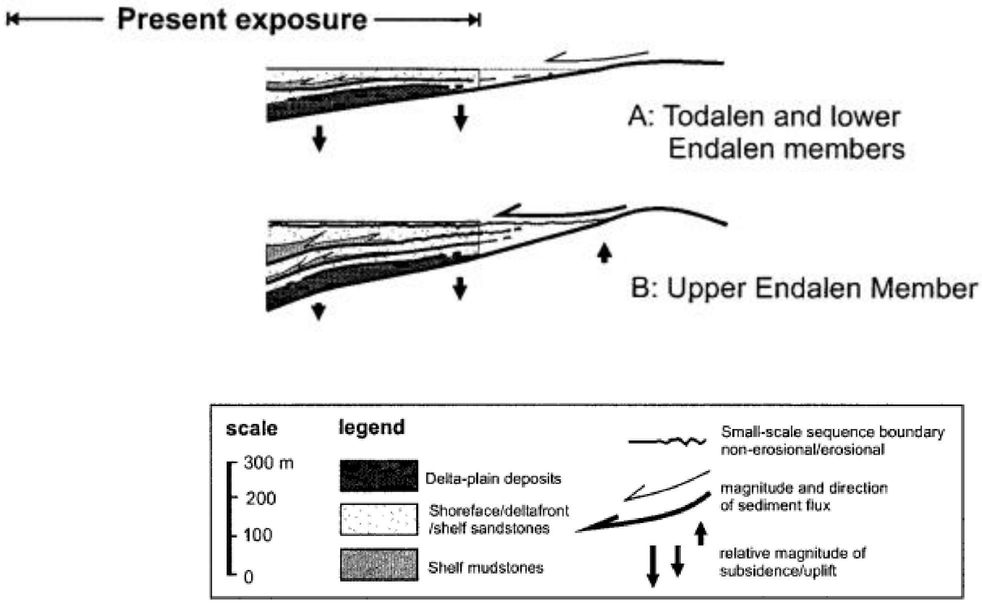


Fig. 63. A Tabular, small scale sequence onlap the basal unconformity on the distal basin margin in Todalen to lower Endalen Member depositional time, after passage and relaxation of the initial peripheral bulge. B. Deposition of basin-ward-stepping, wedge-shaped, small-scale sequences takes place during upper Endalen Member depositional time in response to uplift and basin-ward migration of the peripheral bulge. (Fig. from Bruhn and Steel 2003).

The increase in ash and sulphur southwards in the study area, which is especially prominent in the Longyear seam, together with the fact that there are fewer partings of the coal seams in Operafjellet suggests a greater quality and higher ranked coal at the northeast edge of the basin. It is possible and should be mentioned here that due to the location of Breinosa closer to the ocean during peat deposition, either seasonal fluctuations of groundwater table or extended flooding events interrupted peat formation and brought more inorganic matter to the peatland (Siavalas et al., 2004). All the while the peatland in the Operafjellet area was more protected from such flooding and groundwater fluctuations. As lithotyping is used to determine the moisture of the peatland, this could possibly be determined with lithotyping of new coal from Breinosa for further comparison.

For additional areal coverage, core 2-2007 (Fig. 60) was included in this study to show the significant changes from the study area and the area to the south of it. This core is not representative of the Firkanten Formation stratigraphy in the Adventdalen area but correlations between coal seams and facies associations are possible and showing that considerable changes are happening in the area throughout Operafjellet all the way south to core 2-2007 (see thickness, sulphur and ash graphs for all coal seams in results). It is important to mention that Ophiamorpha (facies 11) is only found in core 2-2007. It is found between the coal seams, indicating the possibility of small transgressions in the south of the study area towards Breinosa occurred between subaerial exposure and coal formation. These transgressions would have reached the point where the placement of core 2-2007 in the southernmost part of the study area was situated.

7 Summary and conclusions

- Results show that the Firkanten Formation is of coastal plain to shallow marine setting and significant lithological differences are observed in the two mouontains in the study area despite their relatively short distance, this is especially noticeable in Todalen Member where you have coal deposits of higher quality and greater thickness and relatively thicker foreshore to backshore deposits in Operafjellet than in Breinosa.
- The Todalen Member in Operafjellet is suggested to be deposited on backshore tidal flat interfingering with an upper shoreface deposit. In same member further south in Breinosa, there is suggested deposition on foreshore to proximal lower shoreface. The Endalen Member is suggested to be deposited on lower to upper shoreface with regression at the top of the member allowing for backshore tidal flat deposits in Operafjellet with a marine transgression with flooding event following at the uppermost part of the formation.
- Facies associations and coal seams in Operafjellet are considerably thicker than in Breinosa, suggesting greater accumulation rate and/or accommodation space at the northeast edge of the Central Spitsbergen Tertiary Basin than few kilometers to the south. It is also suggested increased sediment input during the build-up of Firkanten Formation from the north/north west into the basin.
- Facies association distribution along with sulphur and ash conserved within the coal seams strongly support greater marine influence in the south of the study area, this indicates a general NW-SE orientation of the coastline which corresponds to previous studies done on the Firkanten Formation.
- Two new coal seams were recognised in Firkanten Formation and thoroughly described, Bassen seam in the uppermost part of Endalen Member close to the boundary of Firkanten Formation and Basilika Formation, and Dirigenten seam just below the boundary of Endalen Member and Todalen Member. These seams have very limited lateral extent. The Bassen seam is very thin and could have been deposited in greater area but been subjected to erosion. The Dirigenten seam is considerably thicker but has most likely been mistaken for Askeladden or Svarteper seams in the past as they are the upper most seams in the Todalen Member in other areas than Operafjellet, they have similar content of inorganic material, but the Dirigenten seam has much higher sulphur content indicating possible marine proximity greater than during deposition of Askeladden and Svarteper. Moreover, the Dirigenten seam is located some 15-20m above the true Askeladden and Svarteper seams.
- Lithotyping of the coal facies in Operafjellet indicate mostly a mixture of clarin and vitrain. Vitrain is considered to represent higher moisture content during peat formation and be mostly made of the maceral group vitrinite, and durain is considered to represent dryer conditions and to be made of the maceral group inertinite. Clarain has mixed properties of vitrain and durain (Dr. Christopher Marshall, pers. Comm). This suggests that the peatland in Operafjellet was also considerably moist but without major fluctuations such as could be found in Breinosa.

8 Suggestion for further work

- The Firkanten Formation in Operafjellet and Breinosa has undergone tectonic activity and considerably many faults are easily found in the area. Thorough mapping of the faults, especially in Operafjellet would be useful further investigation. During the fieldwork in Operafjellet, some folding was observed in the uppermost Carolinefjellet Formation with Grønfjorden Bed affected. It would be interesting to investigate this folding and follow the lower boundary of Firkanten fm in the mountain and register if folding in this level is happening all through the mountain and even further. Furthermore, researching this tectonic activity to see if it has affected the accommodation space at the Northeast edge of the Central Spitsbergen Tertiary Basin.
- A thorough trace fossil analysis might make a good project to compare with studies for the development of the Central Tertiary basin. Most interesting would be to research the fauna in the mudstone facies and see if high salinity, brackish or freshwater taxa is dominating. This could be done over a wide area and connected to make up a proper model showing, throughout the basin, where more freshwater or marine influences are present.
- As further research of paleosol can give more thorough information about the climate dominating during soil formation, this could be interesting subject for future studies. Looking into the type of paleosol, such as if it is, for example, aridosol or ultisol gives information about if the soil formation was under desert conditions or warm, moist conditions (Boggs, 2011).
- Active search for the Dirigenten and Bassen seams further to the west of Operafjellet and therefore greater mapping of the seams could be an interesting project.
- As lithotyping is used on the coal, to determine the moisture of the peatland during deposition, this could possibly be done in detail with new coal from Breinosa for further comparison of the coal seams in the two mountains.

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Store Norske Spitsbergen Grubekompani. Malte Jochmann & Bjarki Friis. Borehole maps of Operafjellet and Breinosa.

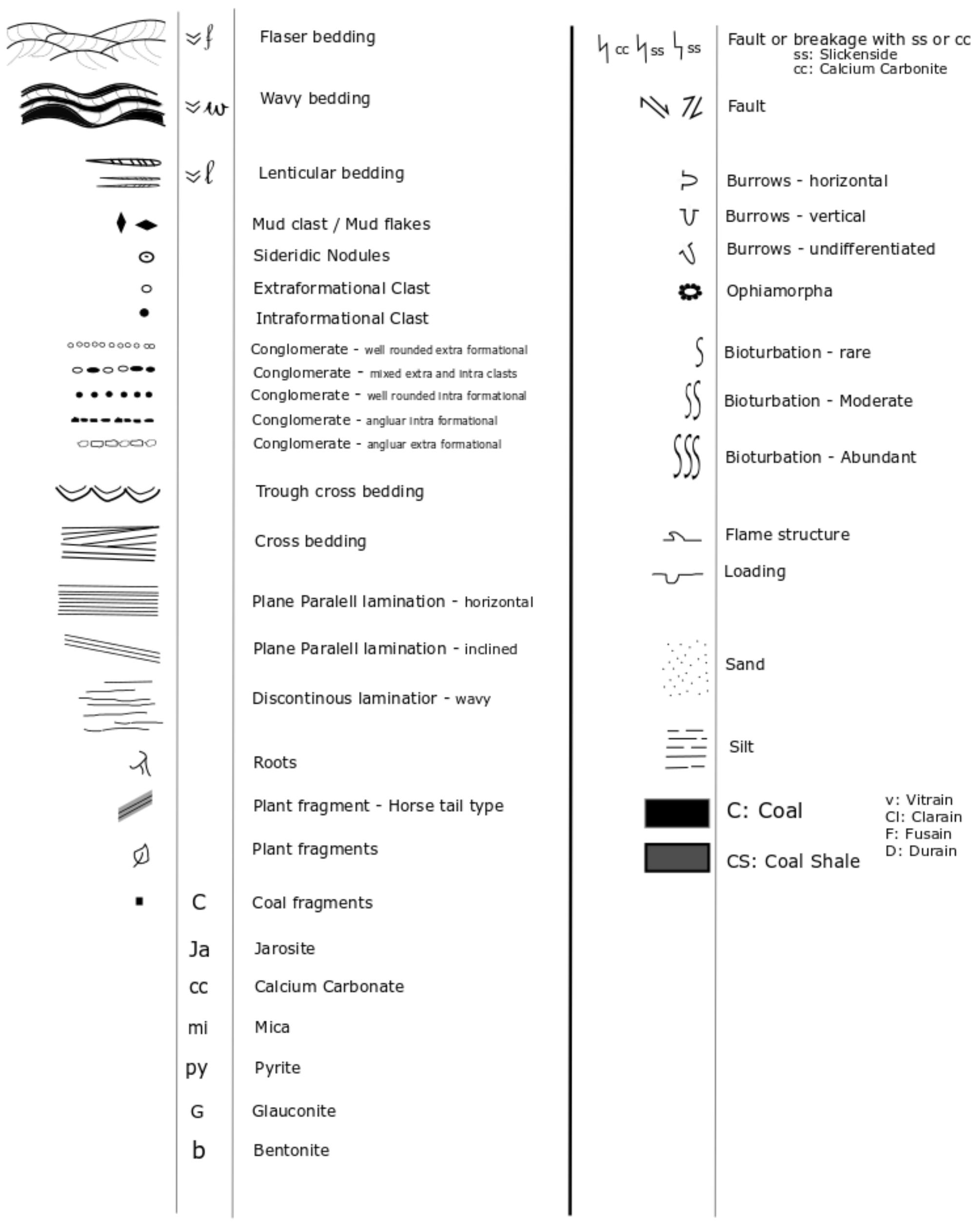
Appendix I

Log overview

Location

Operafjellet	13-2013	19-2011	12-2013	14-2010	16-2010	15-2010	Op-2013
Breinosa	3-2011	1-2011	5-2009	1A-2009	4-2009	2-2007	

LEGEND



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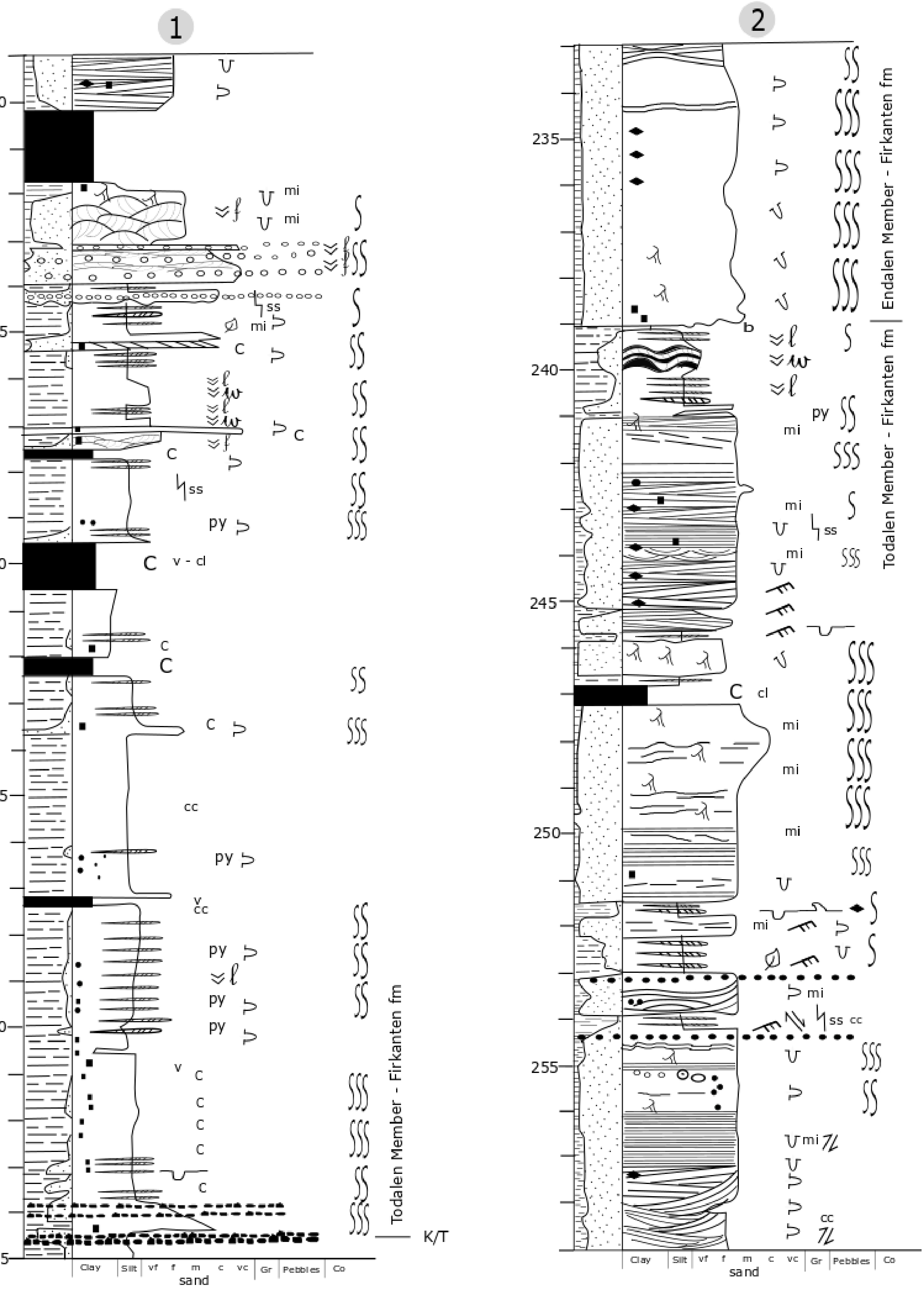

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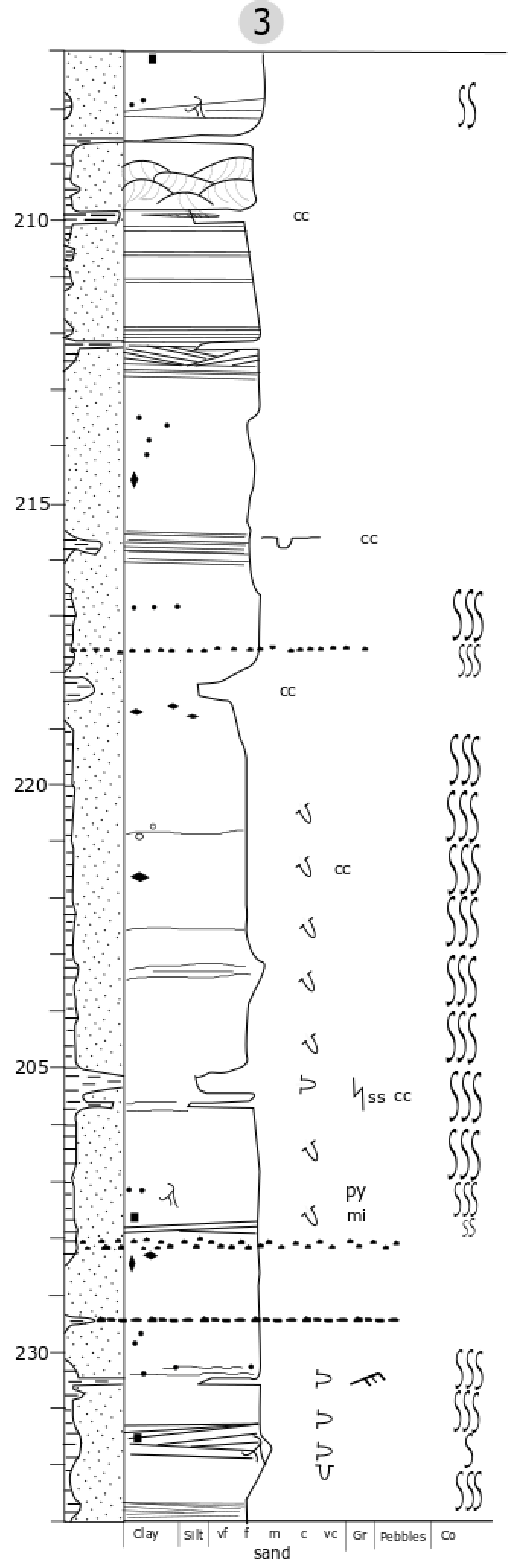

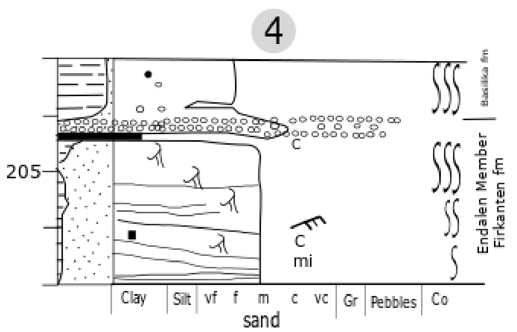

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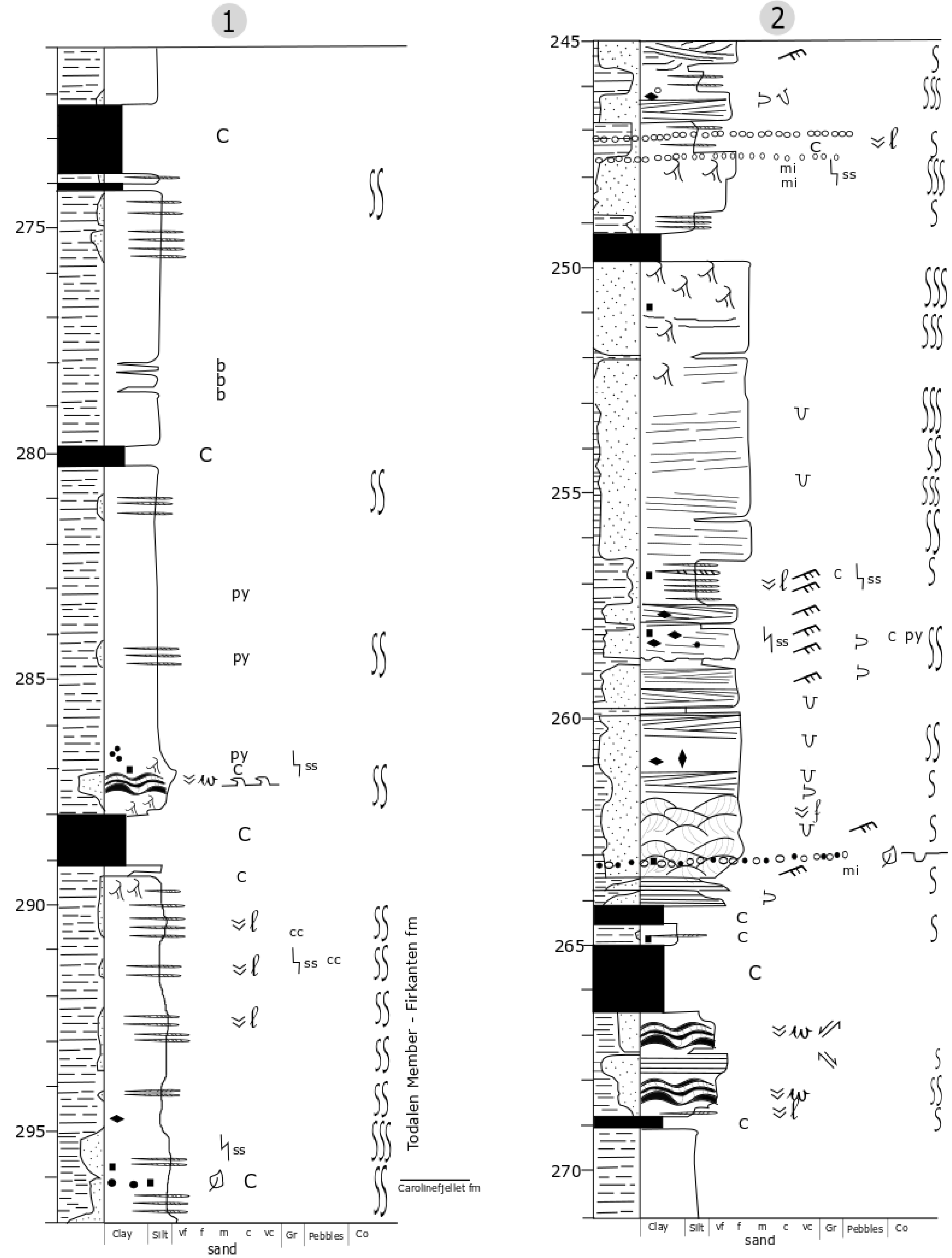

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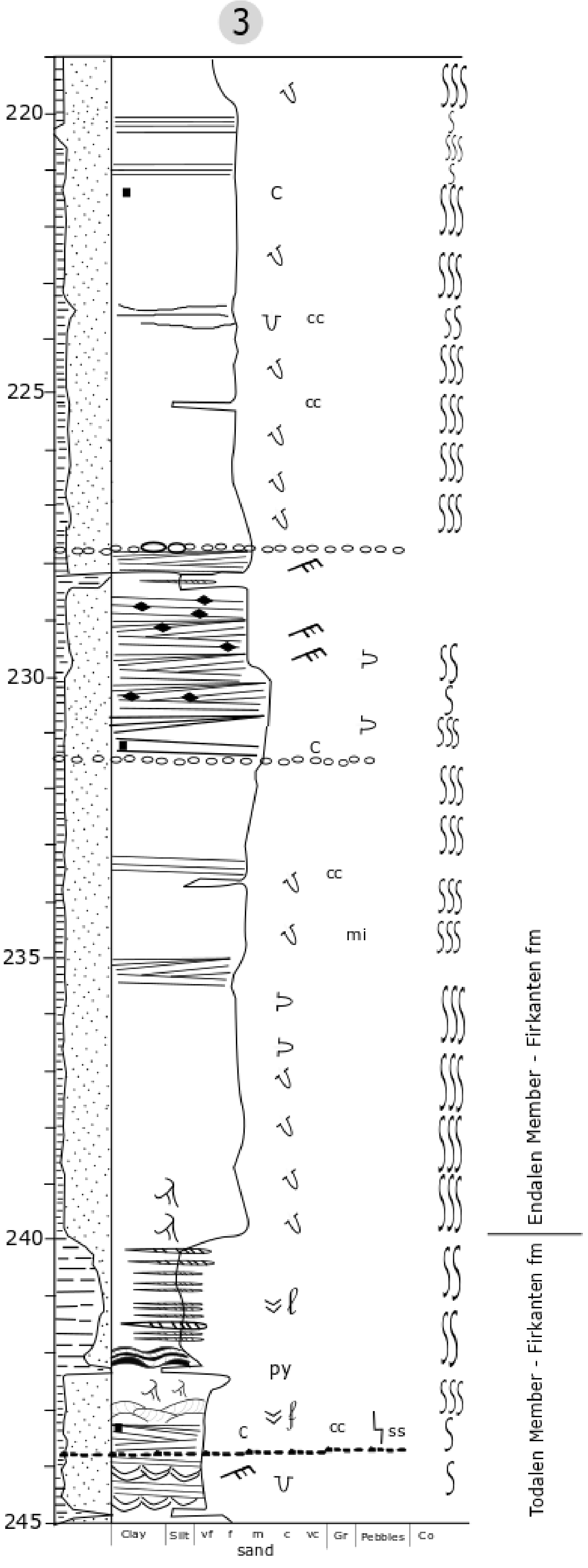

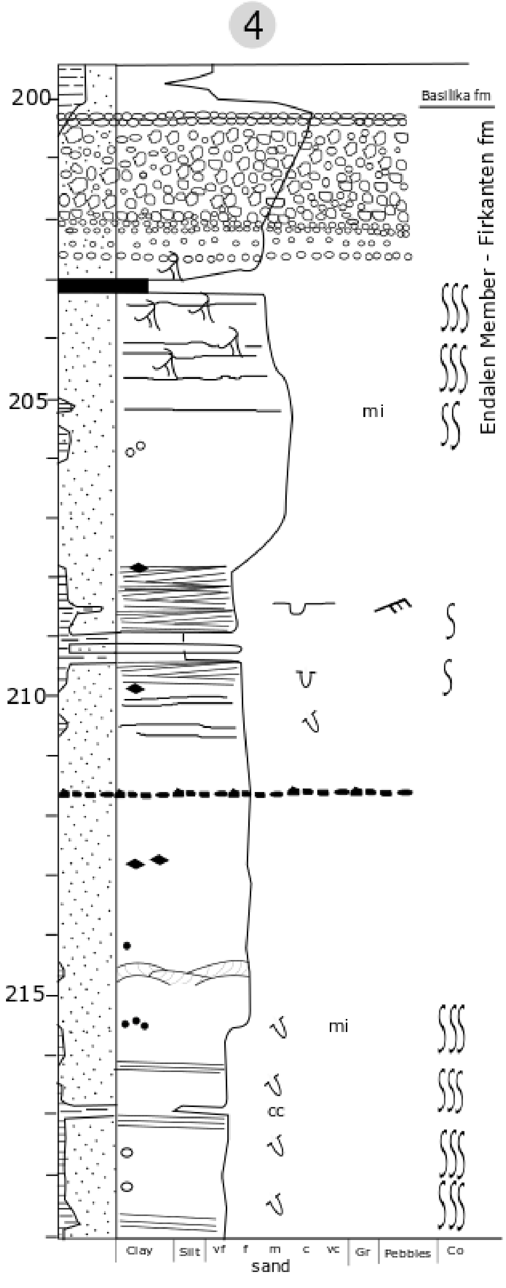

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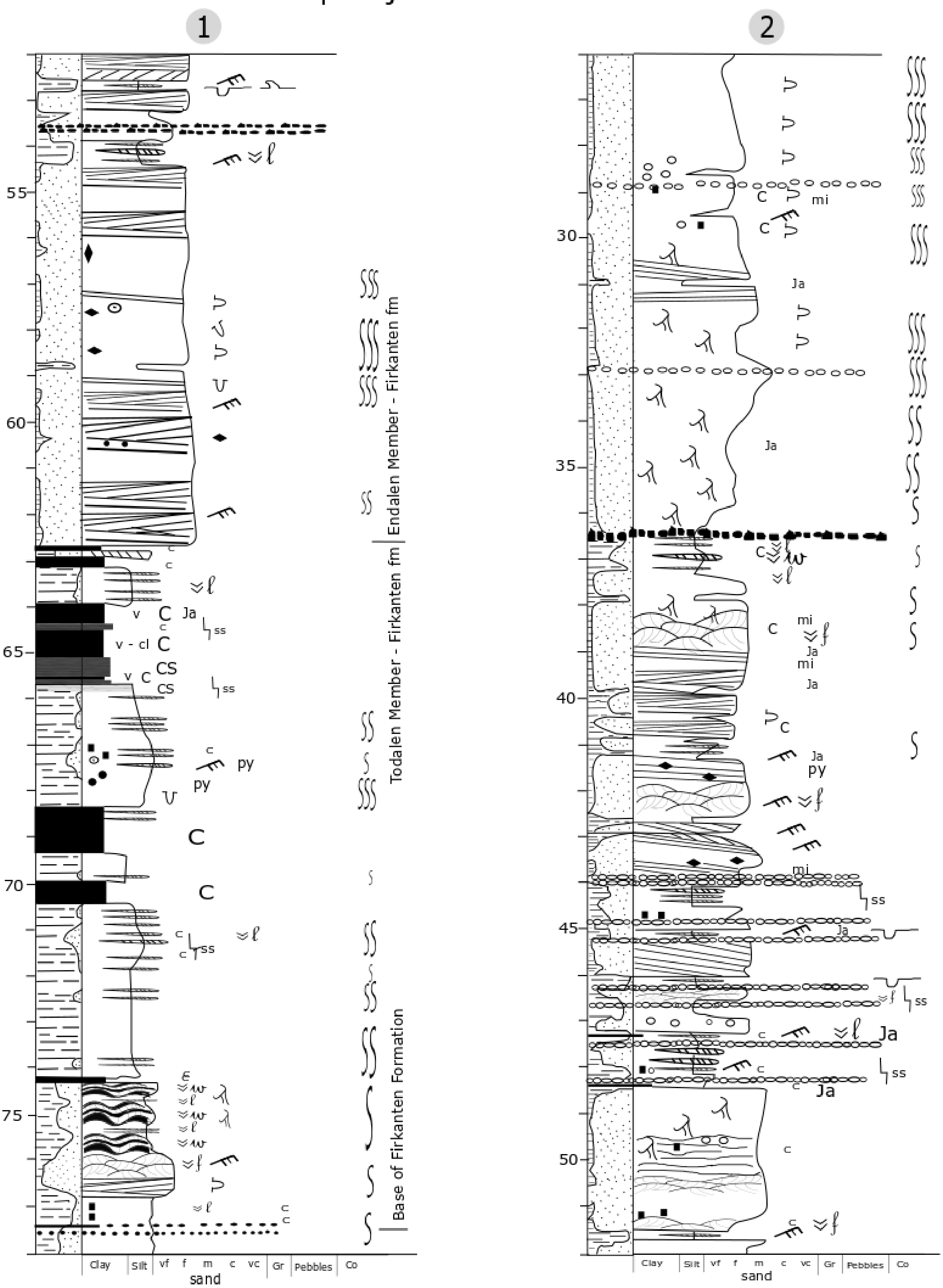

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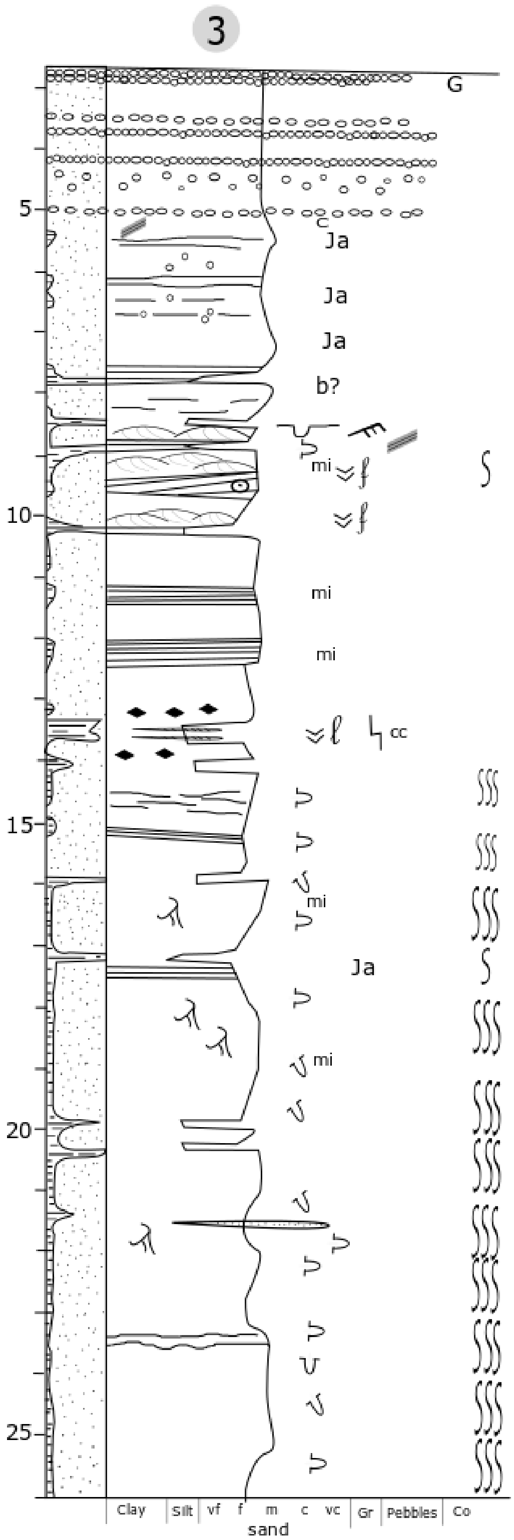

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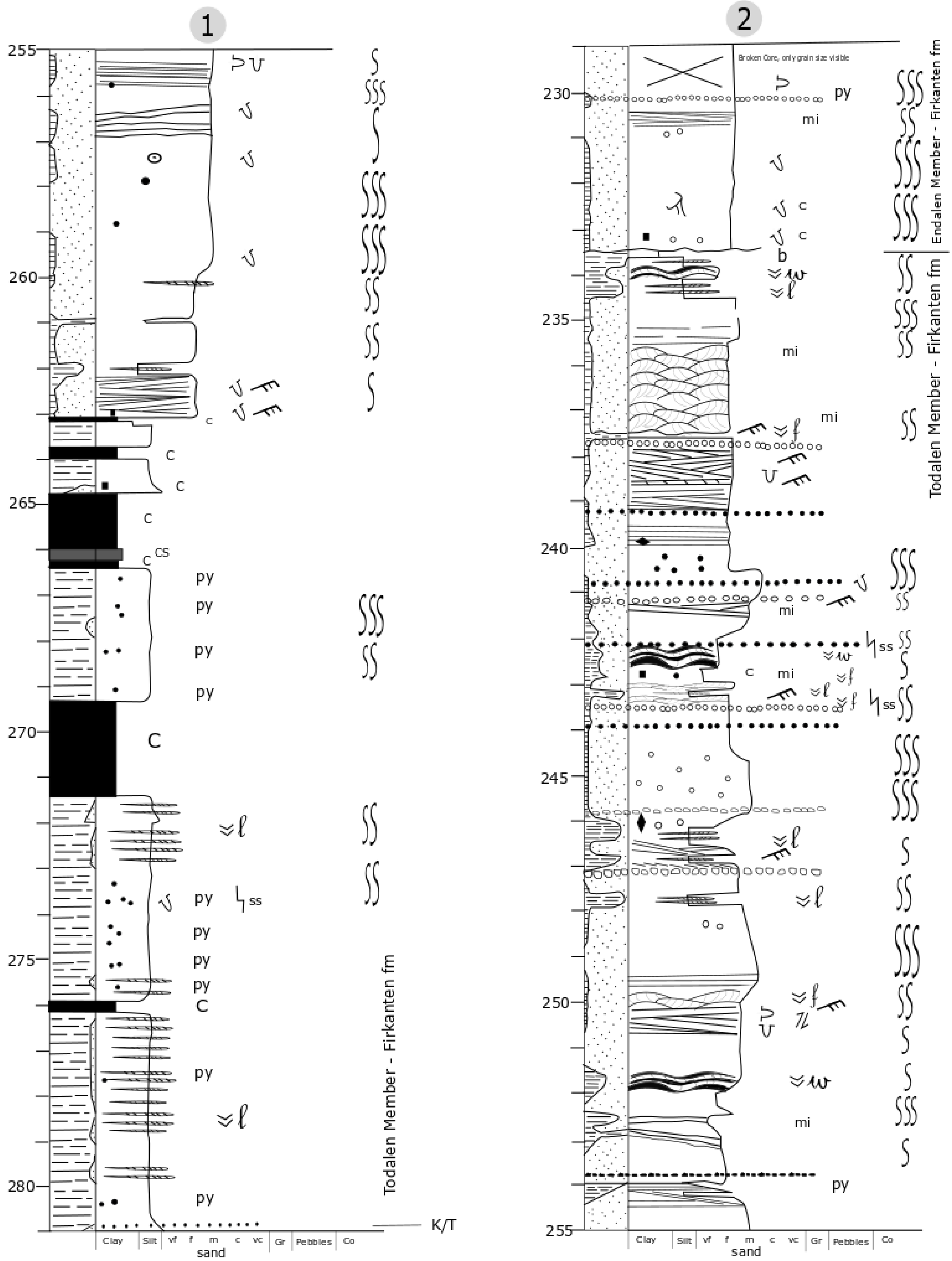

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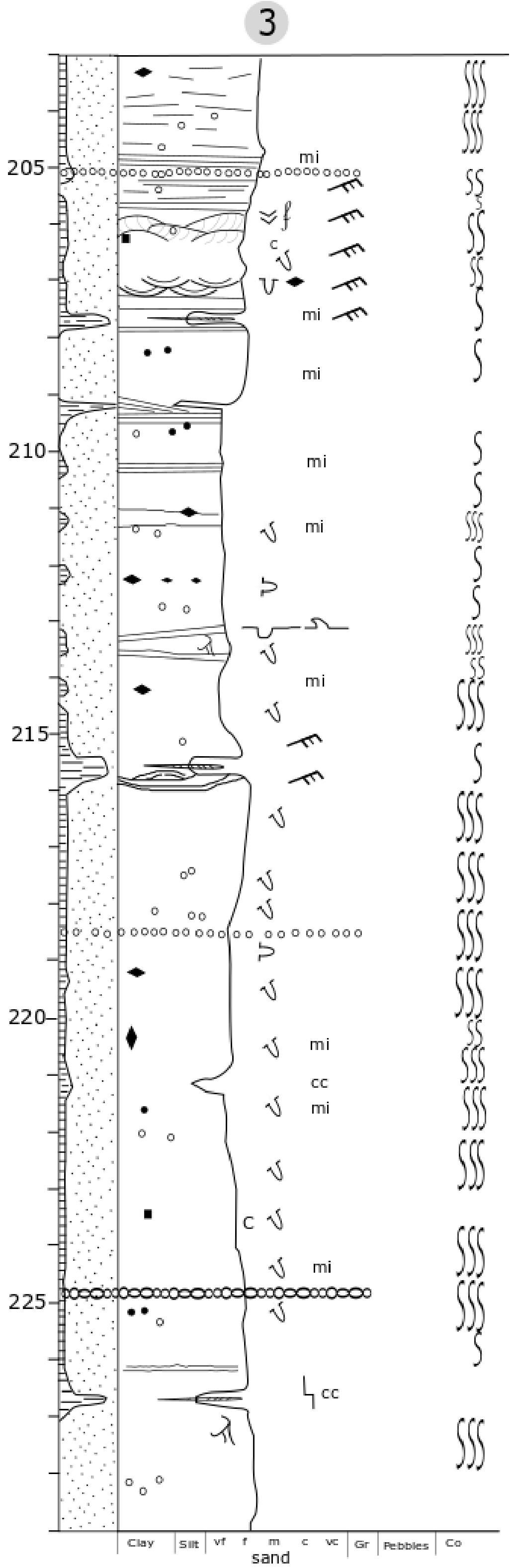

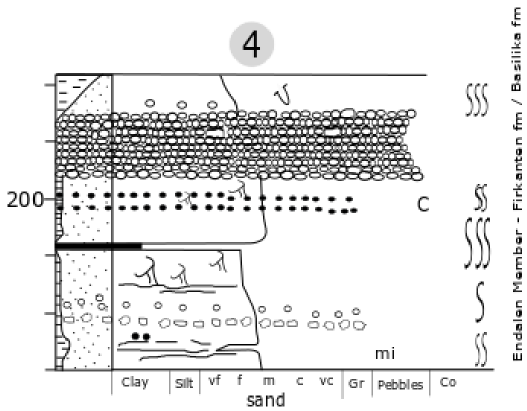

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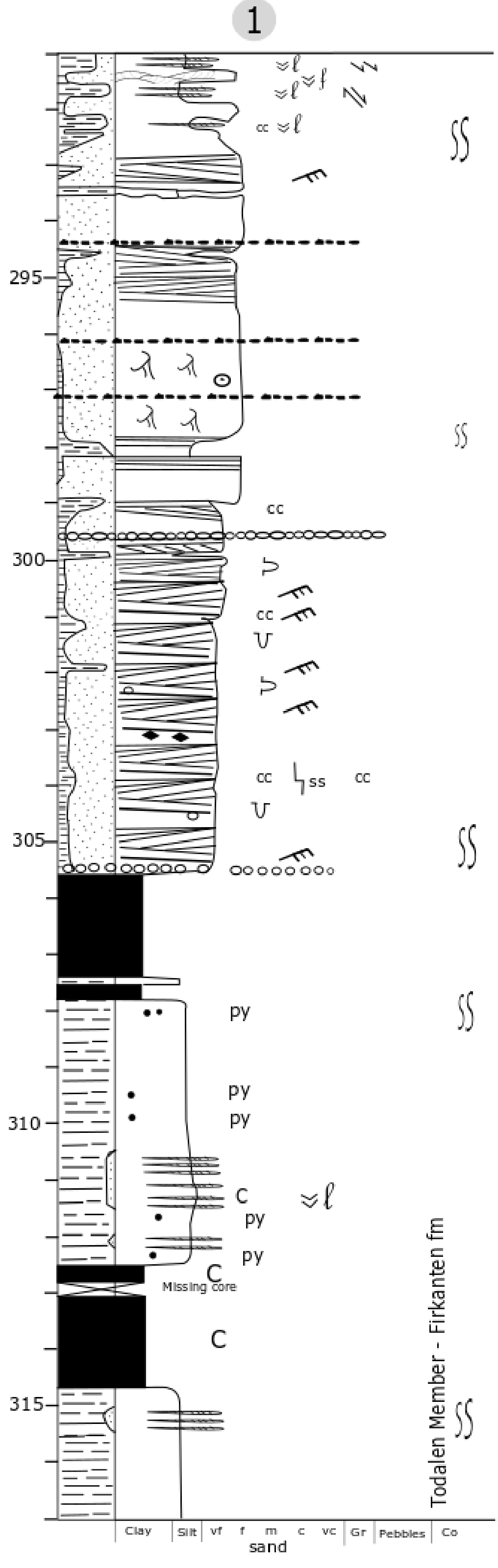

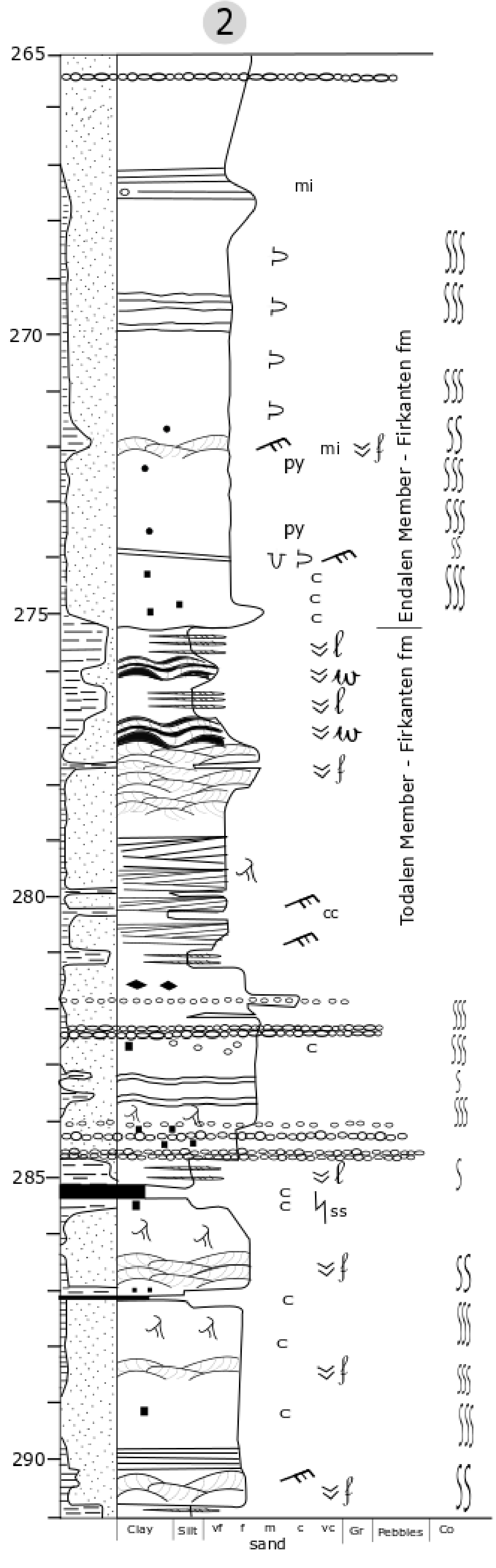

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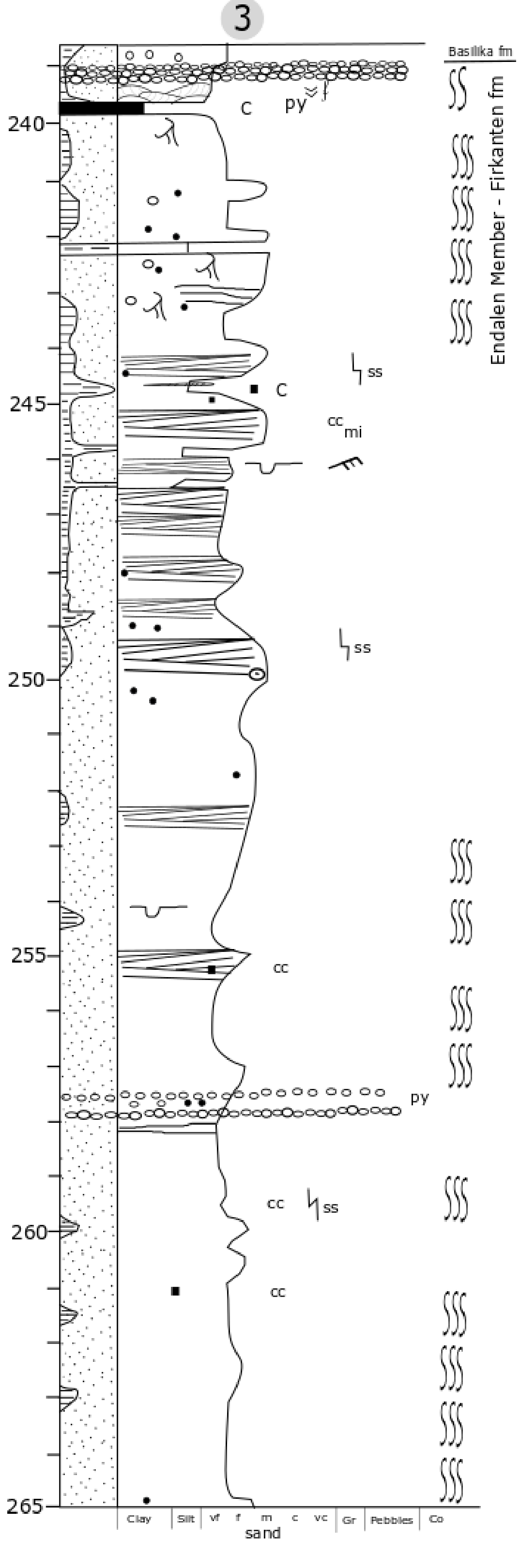

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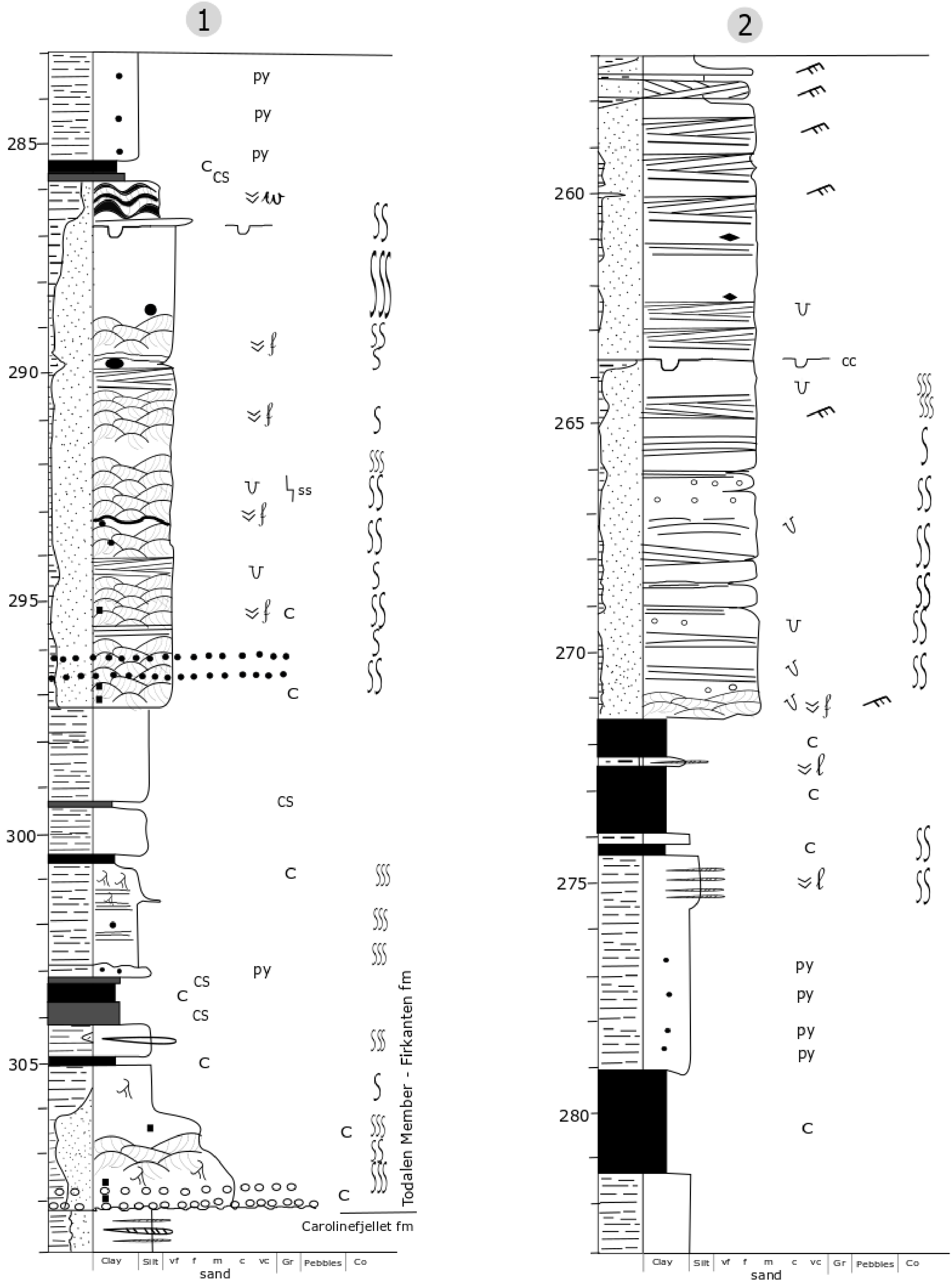

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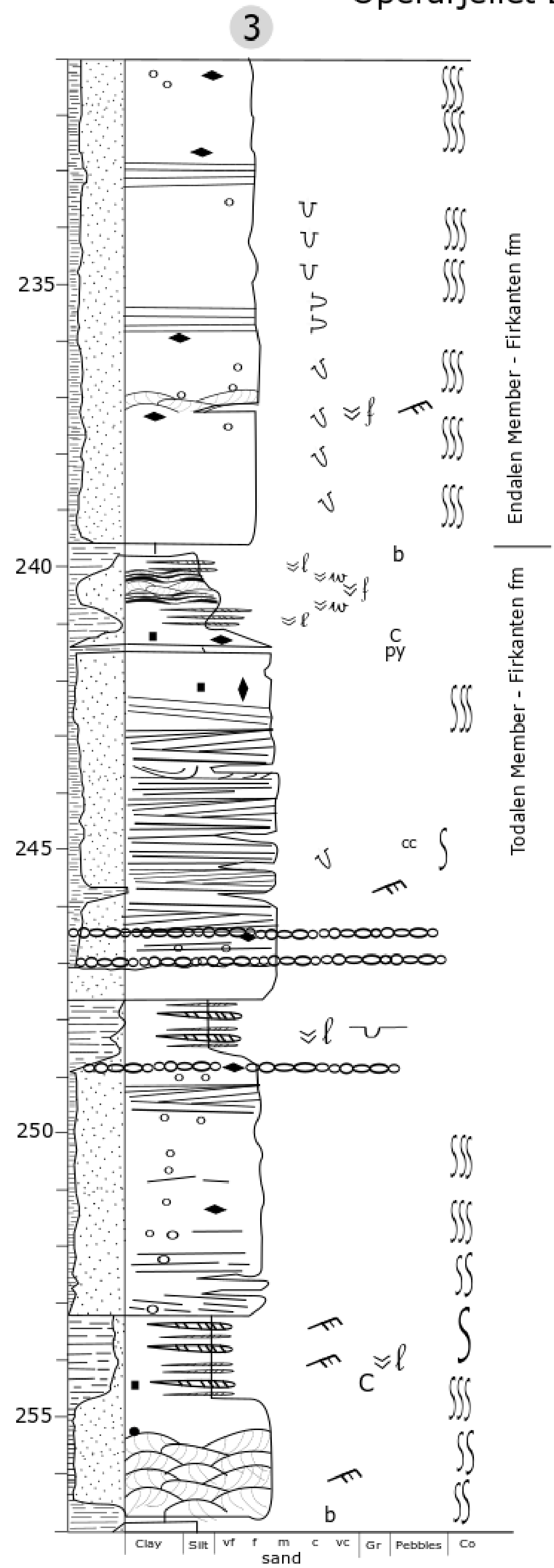

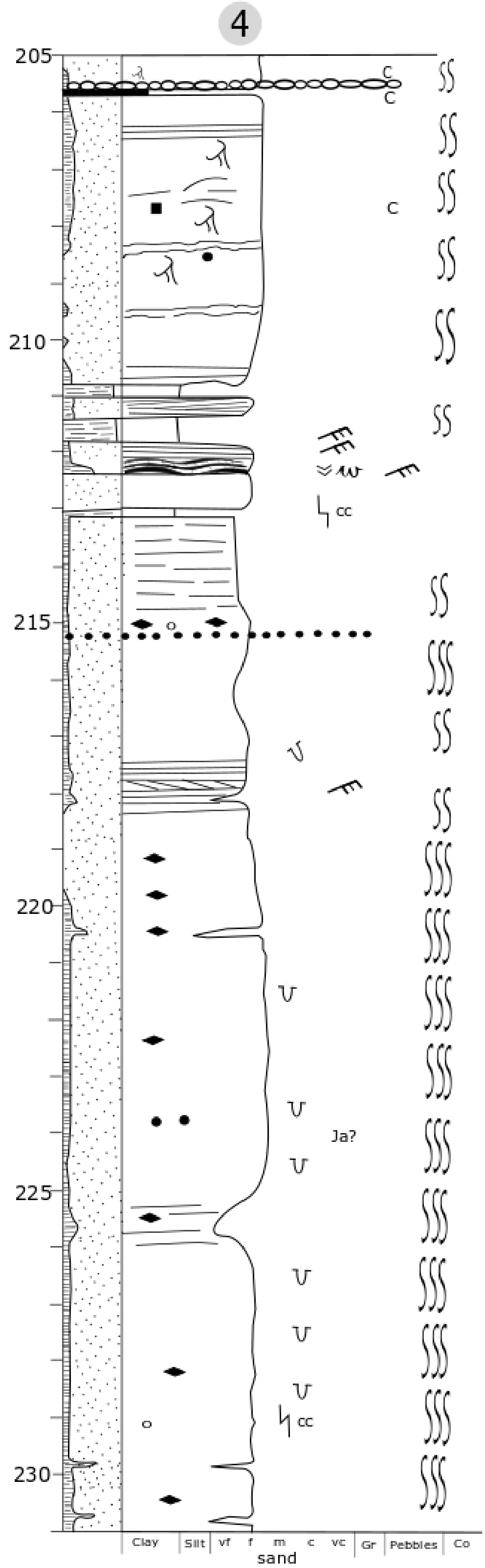

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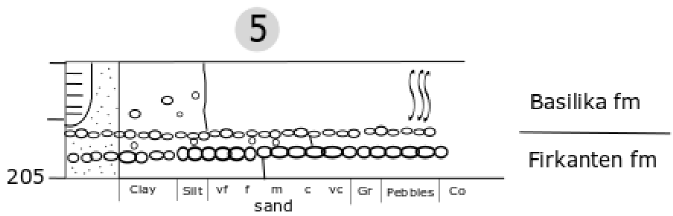

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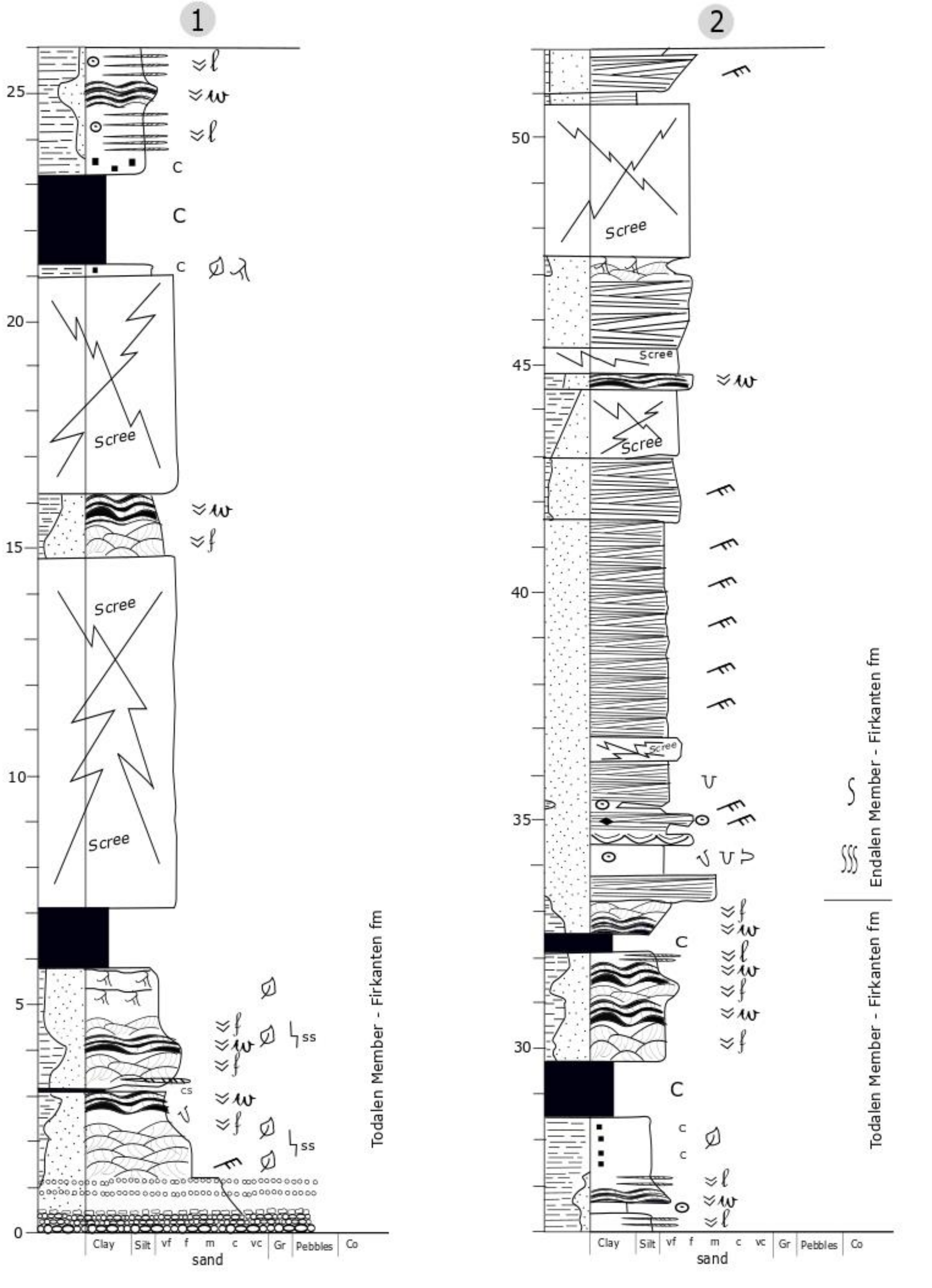

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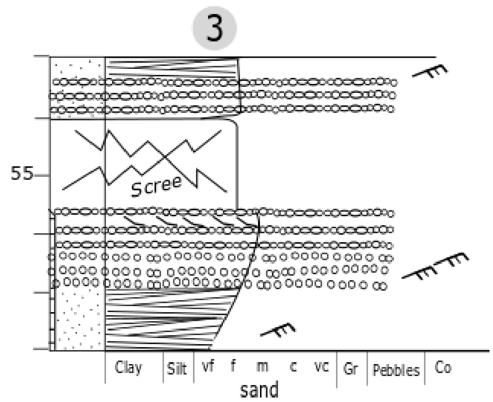

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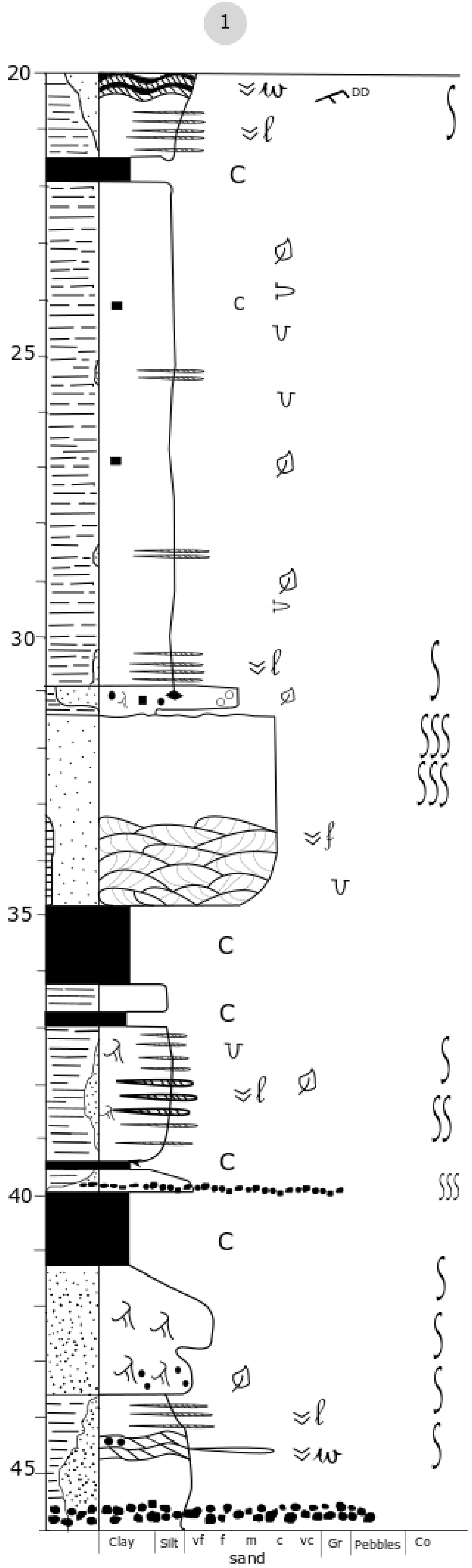

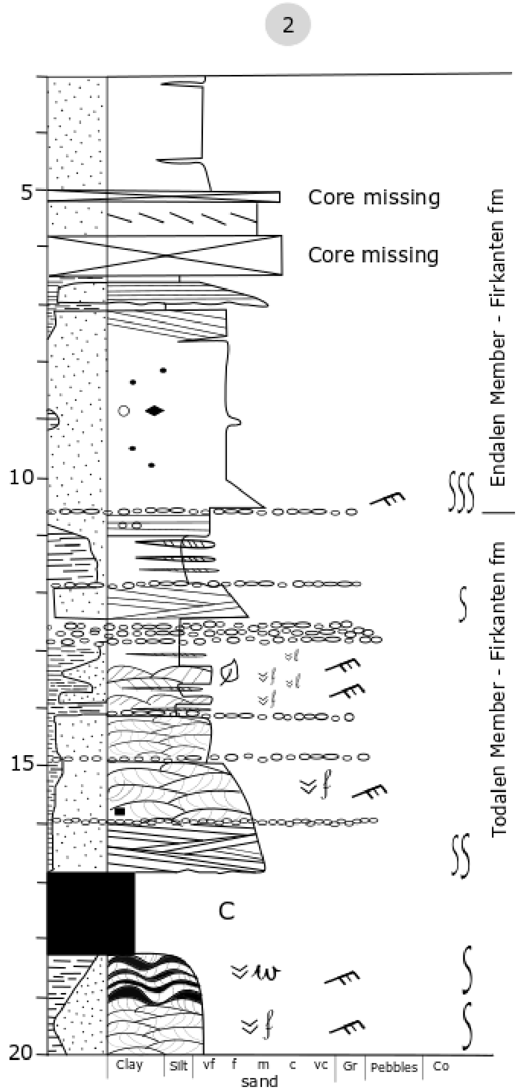

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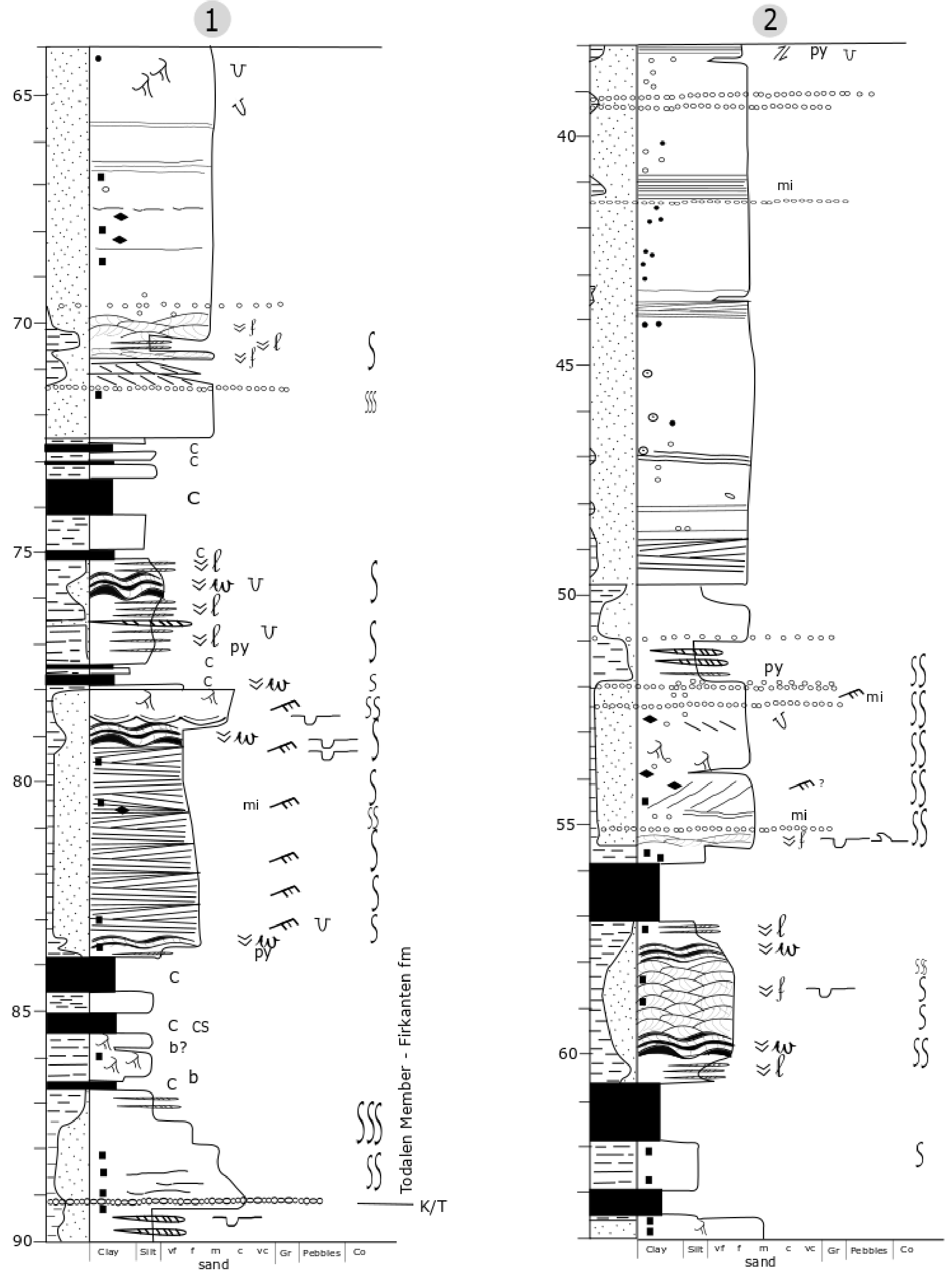

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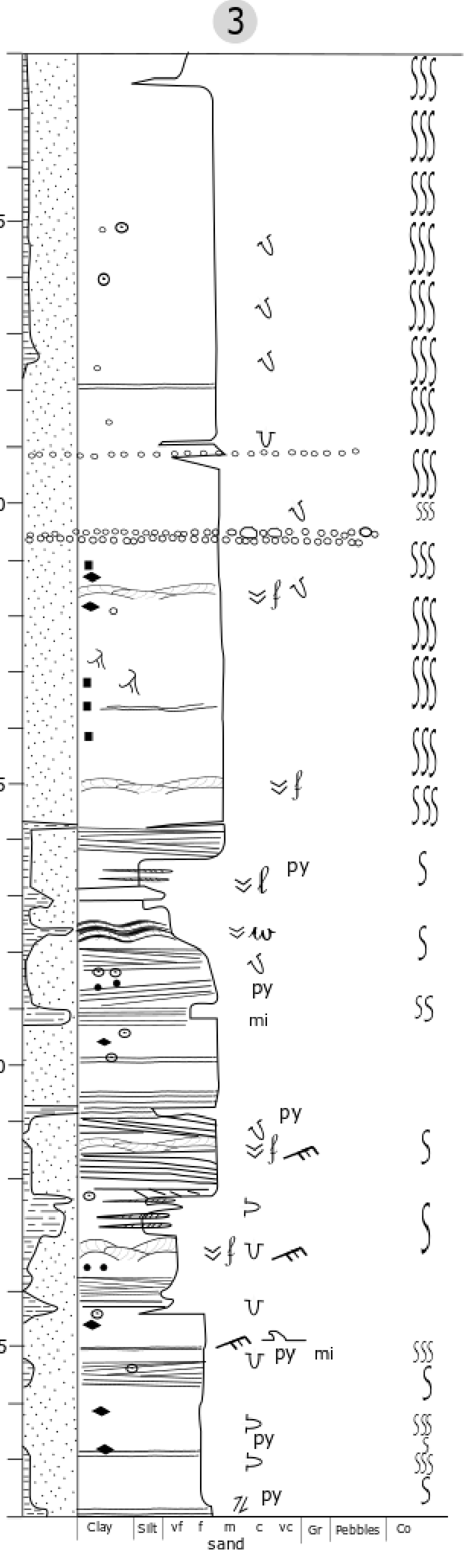

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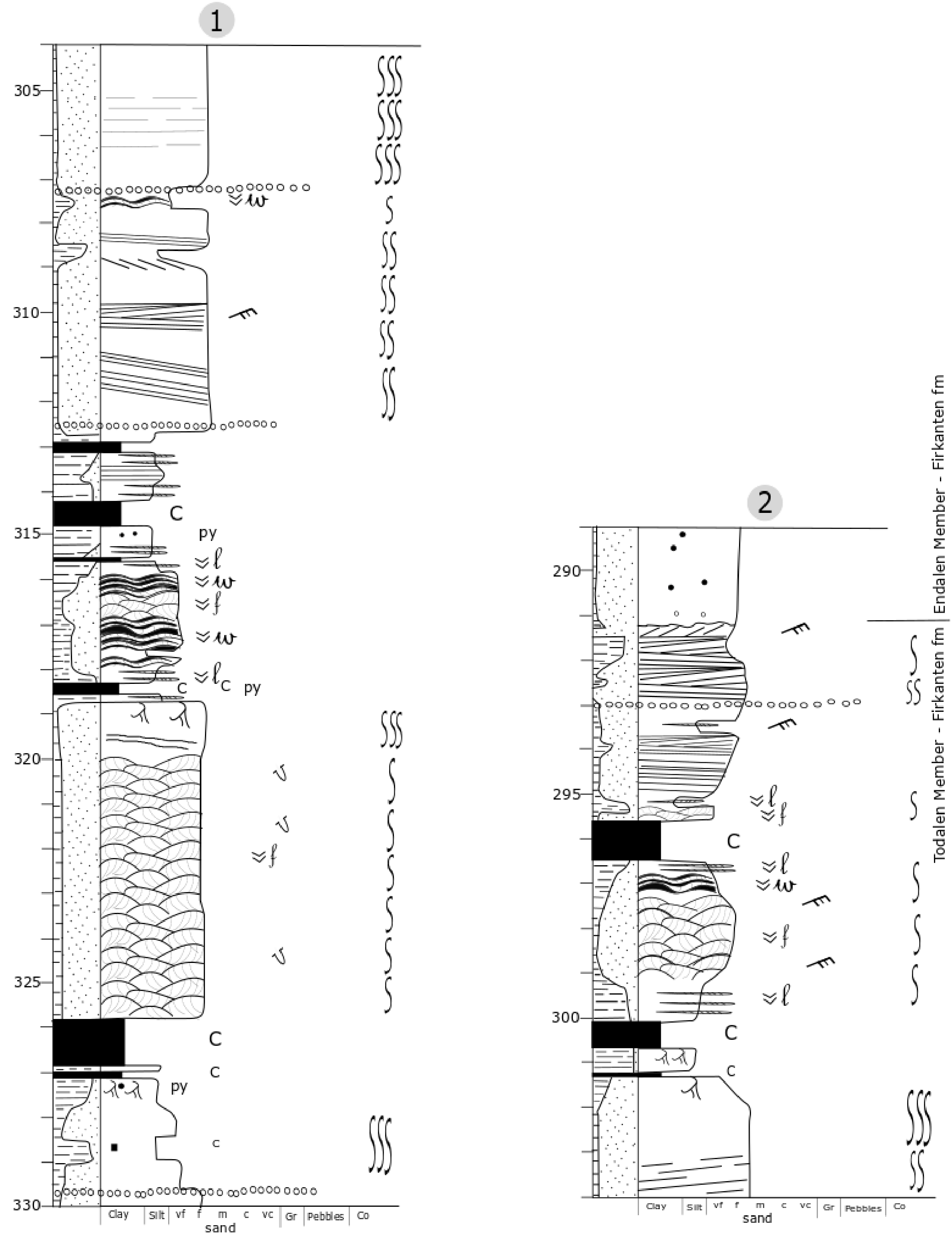

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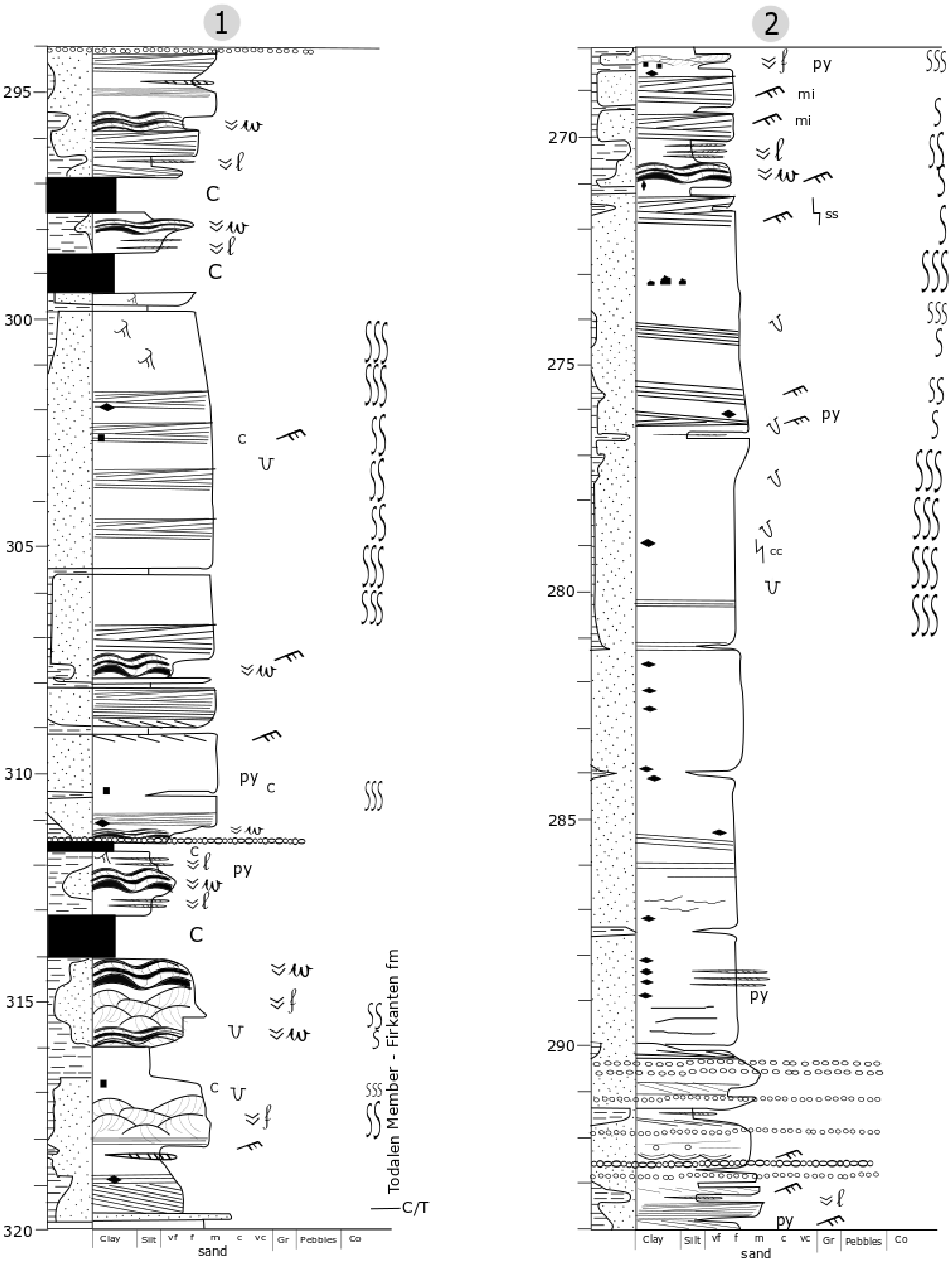

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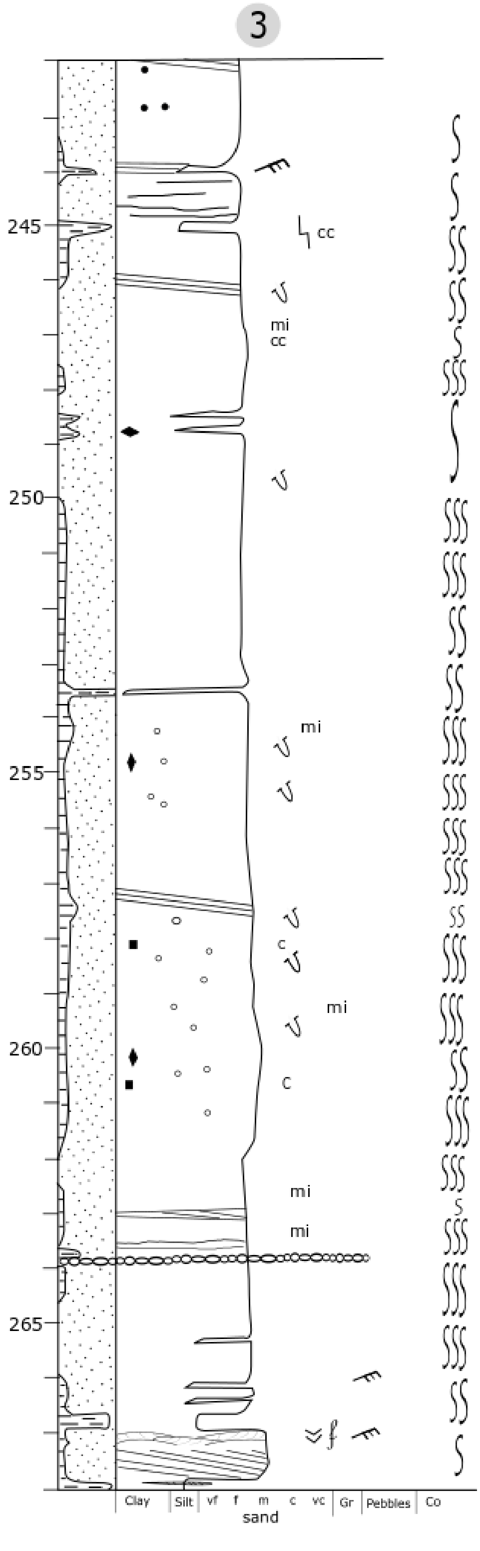

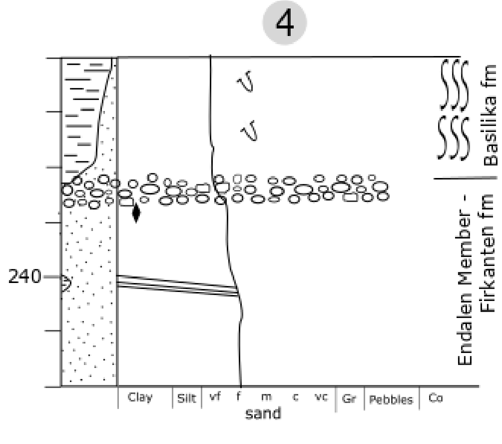

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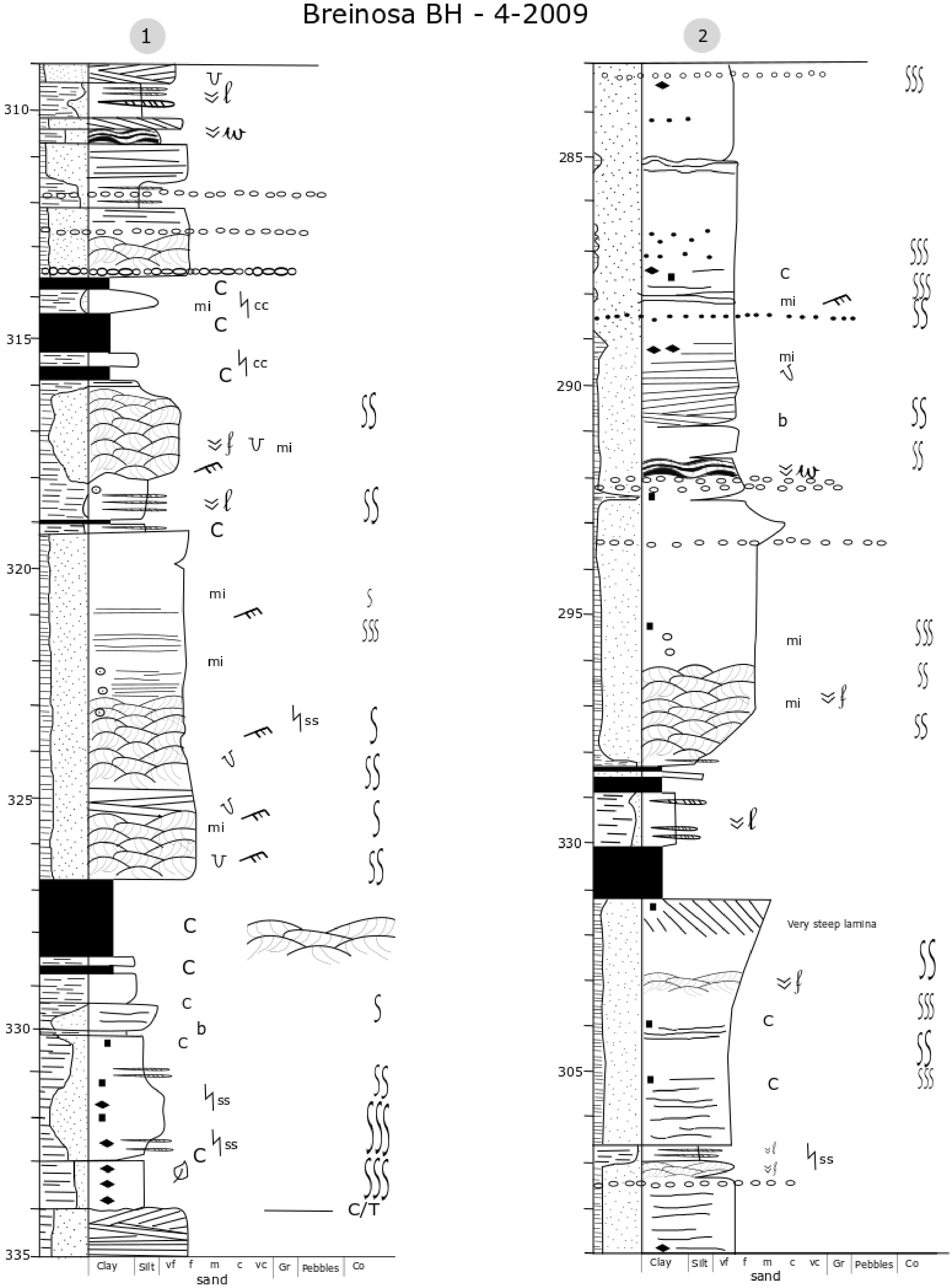

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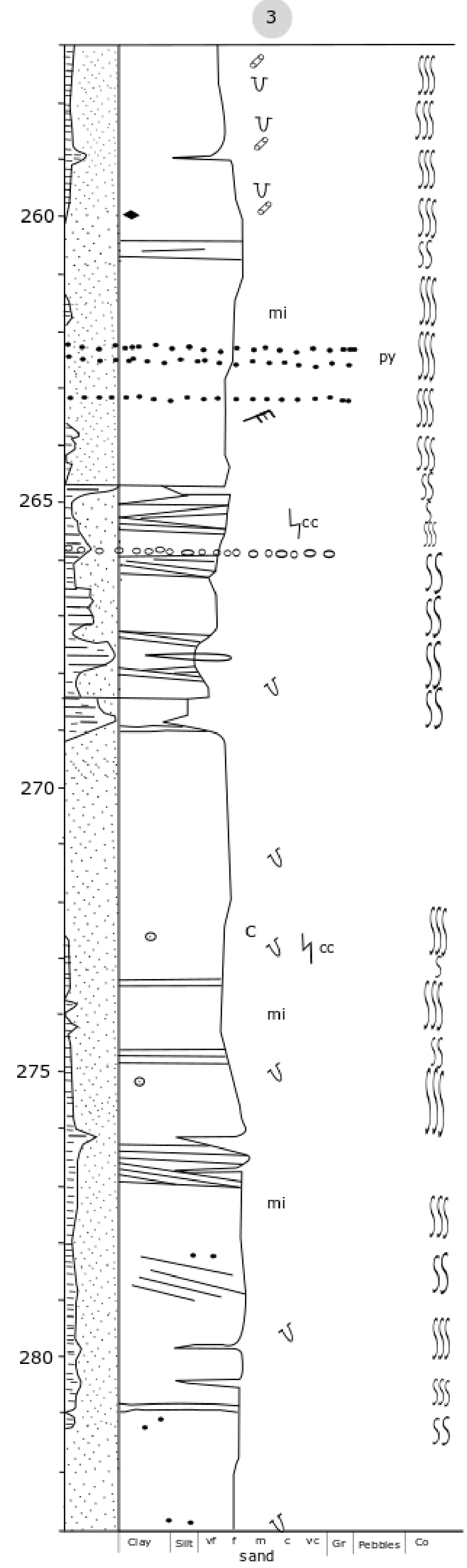

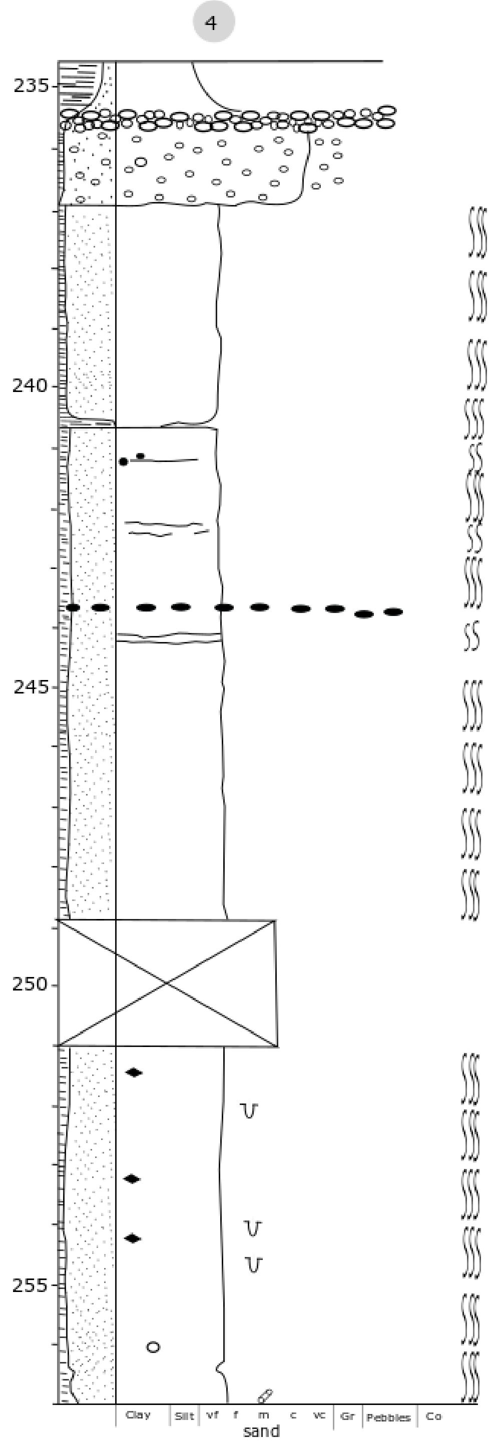

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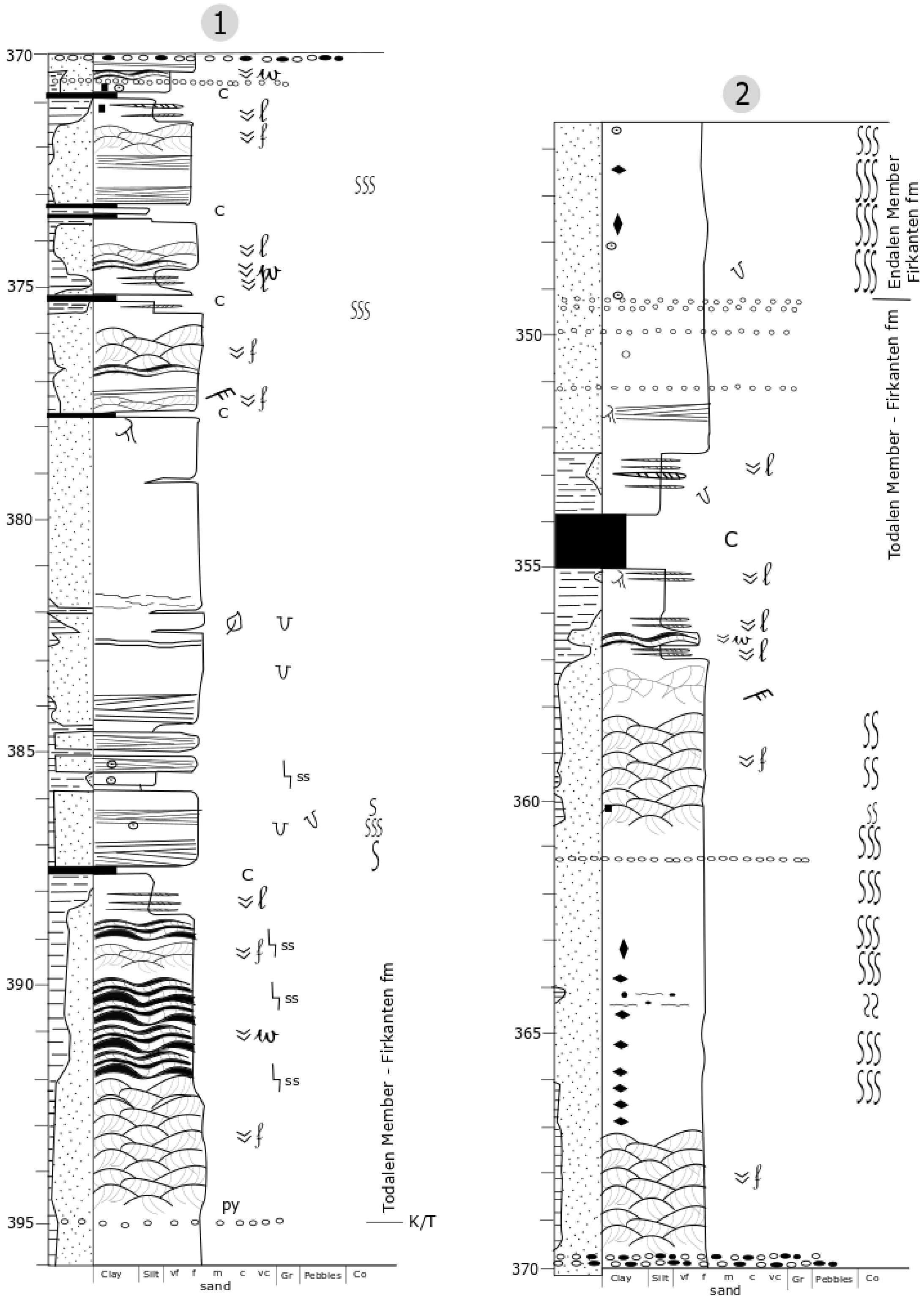

Appendix II

Overview tables for coal samples

Ash	13-2013	19-2011	12-2013	14-2010	16-2010	15-2010	3-2011	1-2011	5-2009	1A-2009	4-2009	2-2007
Dirigenten	33,4	20,3		17,6	12,8							
Askeladden		3,5	16,2	13,7			18,10	33,1	17,6	12,6	21,1	
Svarteper	32,6	49,8	38,34	23,9	15,6	21,3	51,80	13,85	17,6	23	38,2	29,8
Longyearseam	13,8	6,9	6,97	4,9	6,4	5,4	11,70	16,3	18,61	13,5	19,7	46,3
Todalen Seam	15,7	6,8	12,2	38,7	24	32,3	23,40	17,2	6,3		16,3	30
Svea seam		13,9				30,1	31,70	13,2	10,6		14,4	11

Mean inorganic (ash) content in coal samples. Sudden peaks in ash might be due to roof, floor or parting being sampled with the coal. This was taken into account and the laboratory data was cross referenced with logs and photgraphs. The coal is sampled in approximately 20 cm samples where the average is presented in the above table.

Sulphur	13-2013	19-2011		12-2013	14-2010	16-2010	15-2010	3-2011	1-2011	5-2009	1A-2009	4-2009	2-2007
Dirigenten	7,59		6,6		10,6	6,02							
Askeladden	4,76		0,9	1,41	3,5	4	4,1	5,01	5,7	5,5	4,6	8,1	11,04
Svarteper	4,76		4,8	3,52	6,1	4	4,1	5,16	3,33	6,6	4,7	8,8	11,04
Longyearseam	3,65		0,9	2,92	0,9	1,2	1,3	3,33	4,05	18,6	5,01	5,2	12,2
Todalen Seam	6,87		2,5	5,76	4,82	4,13	4,2	6,24	5,68	3,77		11,47	10,2
Svea seam			0,4				1,04	3,41	3,1	2,33		3,4	1,68

Mean sulphur content in coal sampes. The coal is sampled in approximately 20 cm samples where the average is presented in the above table.

Thickness

	13-2013	19-2011	12-2013	14-2010	KB1-2013	15-2010	3-2011	1-2011	5-2009	1A-2009	4-2009	2-2007
Dirigenten	40	50	0	4	18	0						
Bassen	4	13	0	9	19	6						
Askeladden	153	45	24	50	223	303	140	130	89	76	56	
Svarteper	153	150	173	160	223	303	45	155	125	88	119	115
Longyearseam	296	172	153	203	220	224	140	171	269	107	122	67
Todalen Seam	18	61	13	24	47	35	25	23	28		5	0
Svea seam		116				143	100	135	137		92	15

The thickness of coal seams in each core without partings.