BACHELOR THESIS

Environmental change as reflected in sediment cores of the Barsnesfjord, Western Norway

By Niels Kijm

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Hogeschool VHL University of Applied Sciences

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Environmental change as reflected in sediment cores of the Barsnesfjord, Western Norway

Niels Kijm
930412001
niels.kijm@hotmail.com
Environmental science, Nature and Environment
Bachelor thesis

Supervisor:
Matthias Paetzel
Høgskulen i Sogn og Fjordane Sogndal, Norway
matthias.paetzel@hisf.no

Revise:
Astrid Valent
Wim Hilbrants
Hogeschool van Hall Larenstein Leeuwarden, Netherlands
astrid.valent@wur.nl
wim.hilbrants@wur.nl

Opponent:
Leo Bentvelzen
Hogeschool van Hall Larenstein Leeuwarden, Netherlands
leo.bentvelzen@wur.nl

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Image front page: Sediment Core 4, Core 6, and Core 17. Image Niels Kijm.

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Abstract

The Barsnesfjord is located near the small town of Sogndal in Western Norway. A 9 m deep sill separates the periodically anoxic, 82 m deep Barsnesfjord from the oxic, 260 m deep Sogndalsfjord. On this 9 m deep sill the Loftesnes Bridge was built in 1958 and connects Sogndal with Loftesnes. Starting in 2014, Sogndal municipality will replace this old Loftesnes Bridge with a new one. The new construction plan involves a sediment infill on the sill and narrowing of the sill. A research done by the Norwegian Institute of Water Research(NIVA) shows that there are no major influences expected in the Barsnesfjord due to the infill. However, the NIVA report of 2011 suggests further investigations into possible influences the bridge building on the Barsnesfjord ecosystem.

In order to find out what might happen in the Barsnesfjord, this research investigates the sediment of het Barsnesfjord. Three objectives will be answered in this thesis.

1. Is it possible to date sediment cores from the Barsnesfjord on an annual to decadal time scale over the past 30 to 50 years?
2. Can the succession of changing sediment parameters be related to the variability of environmental and climate change during the last 30 to 50 years?
3. Is it possible to construct a box model predicting the influence of expected future environmental change on the Barsnesfjord system, based on the record of environmental change as reconstructed from the Barsnesfjord sediments?

Dating is necessary to put the sediment core in a time scale and correlate it with environmental and climatic settings. The correlation between the changes in the sediment and the variability of environmental and climate change gives a understanding how different fjord processes works and how they interact. On this data, a simple box model is constructed to predict and illustrate how the building of the new Loftesnes Bridge might influence the hydrography and ecology of the Barsnesfjord.

Three new sediment cores, Core 4, Core 6 and Core 17, are taken from the bottom of the Barsnesfjord. Smear slides are used to analyze the sediment cores. The analyzed parameters are: mineral grain size, total organic matter, terrestrial organic matter, marine organic matter, fresh water diatoms, marine diatoms and framboidal pyrite. After analysis, the data is used creating graphs to date the sediment cores and visualize environmental change. With this data a box model is made to predict what might happen to Barsnesfjord after making the sill shallower.

The simple box model shows that the frequency of inflow events that renew the water masses in the Barsnesfjord occur less often causing more often anoxic conditions. A bigger brackish water column, on top of the marine water, absorbs more light before it reaches the marine waters and causes a decrease in primary productivity. The bigger brackish water column, fine mineral matter and terrestrial organic matter have more time to settle to the bottom. An increased sediment accumulation and terrestrial organic matter fraction are expected to be visualized in the future.

A dating is found using Paetzel & 2010 and visualized on a annual time scale. While using graphs and comparing them, sediments could be correlate to the variability of environmental and climate change. With these date a box model is create to predict the influence of expected environmental change on the Barsnesfjord system

Samenvatting

Het Barsnesfjord is gelegen naast het plaatsje Sogndal in het westen van Noorwegen. Een 9 m diepe ophoging verdeelt de, van tijd tot tijd zuurstofloze, 82 m diepe Barsnesfjord van the zuurstofrijke, 260 m diepe Sogndalsfjord. Op deze natuurlijke ophoging is de Loftesnes Bridge gebouwd in 1958 en verbindt Sogndal met Loftesnes. In 2014 begint de gemeente Sogndal met de bouw van een nieuwe brug omdat de huidige brug is verouderd en te klein is. Het bouwplan bevat een ophoging en een vernauwing van de natuurlijke ophoging tussen Sogndal en Loftesnes. Een onderzoek, uitgevoerd door het Noorse intituut voor water ondetzoek(NIVA) verwacht geen grote veranderingen in de waterkwaliteit van het Barsnesfjord door deze ophoging en vernauwing. Echter, het NIVA rapport van 2011 suggereert verder onderzoek naar de mogelijke invloed van dit bouwplan op de ecologie in het Barsnesfjord.

Om uit te zoeken wat er mogelijk gebeurt met het Barsnesfjord, wordt het sediment van het Barsnesfjord onderzocht. Drie doelstellingen worden gesteld in dit afstudeeronderzoek.

1. Is het mogelijk om de sediment kernen van de Barsnesfjord op een jaarlijkse tot tienjaarlijkse tijdschaal te zetten over de afgelopen 30 tot 50 jaar?
2. Kan de successie van the veranderingen in parameters gecorreleerd worden met de veranderingen in milieu en klimaat veranderingen over de afgelopen 30 tot 50 jaar?
3. Is het mogelijk om een box model te maken en hiermee de invloed van de verwachte milieuverandering op de Barsnesfjord systeem, gebaseerd op de vastgelegde milieuveranderingen als gereconstrueert uit het sediment van de Barsnesfjord?

De datering is noodzakelijk om de sediment kern in een tijdschaal te plaatsen en het te kunnen vergelijken met milieu en klimaat eigenschappen. De correlatie tussen de veranderingen in het sediment en de veranderlijkheid van milieu en klimaat verandering geeft inzicht in de werking van fjord processen en hoe deze elkaar beïnvloeden. Deze gegevens worden gebruikt om een eenvoudig box model te maken die weergeeft en voorspelt hoe de bouw van de nieuw brug, de hydrologie en de ecologie van het Barsnesfjord beïnvloed.

Drie nieuwe sediment kernen, Core 4, Core 6 and Core 17, zijn genomen van de bodem van het Barsnesfjord. De volgende parameters zijn geanalyseerd: mineraal korrelgrootte, totaal organisch materiaal, terrestrisch-organisch materiaal, marineorganisch materiaal, zoetwater kiezelalgen, marine kiezelalgen en pyriet. Nadat ze geanalyseerd zijn, is deze data gebruikt om grafieken te maken en met deze grafieken de kernen dateren en de milieu en klimaat veranderingen zichtbaar gemaakt. Met deze gegevens is een box model gemaakt dat voorspelt wat gebeurd met het Barsnesfjord nadat de natuurlijke ophoging verder wordt opgehoogd.

Dit eenvoudige box model laat zien dat de frequentie van momenten waarbij het water massa's in het Barsnesfjord afneemt waardoor het vaker zuurstofloos word. Een grotere brakwater kolom, bovenop het marinewater, absorbeert het meer licht voordat het de marinewater kolom kan bereiken en verminderd daardoor de primaire producenten. Een vermindering in marineorganisch materiaal en marine kiezelalgen wordt hierdoor verwacht. In grotere brakwater kolom krijgt fijne mineraal materiaal en terrestrisch-organisch materiaal meer tijd om te bezinken op de bodem. Een verhoogde snelheid in de accumulatie van het sediment en meer terrestrisch-organisch materiaal wordt verwacht zichtbaar te worden in het sediment in de toekomst.

Een datering is gevonden door de data te vergelijken met de data van Paetzel en Dale 2010 en deze is zichtbaar gemaakt op een jaarlijkse tijdschaal. Met het vergelijken van de grafieken, kon het sediment gecorreleerd worden met veranderlijkheid van milieu en klimaat veranderingen. Deze correlatie is gebruikt om een box model te maken en de invloed van de verwachte milieuverandering in het Barsnesfjord te voorspellen.

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1. Introduction

The Loftesnes Bridge connects the Norwegian Main Road RV5 with the Sogn og Fjordane County Road FV55 crosses the Sogndalsfjord (a northern tributary of the Sognefjord) at the city of Sogndal, Western Norway (Figure 1). The bridge was built in 1958 on a 9 m deep sill that separates the periodically anoxic, 82 m deep Barsnesfjord from the oxic, 260 m deep Sogndalsfjord. Due to the Loftesnes Bridge's aging and small size, the Sogndal municipality decided to replace the old bridge with a new one. Building starts in the autumn of 2014.

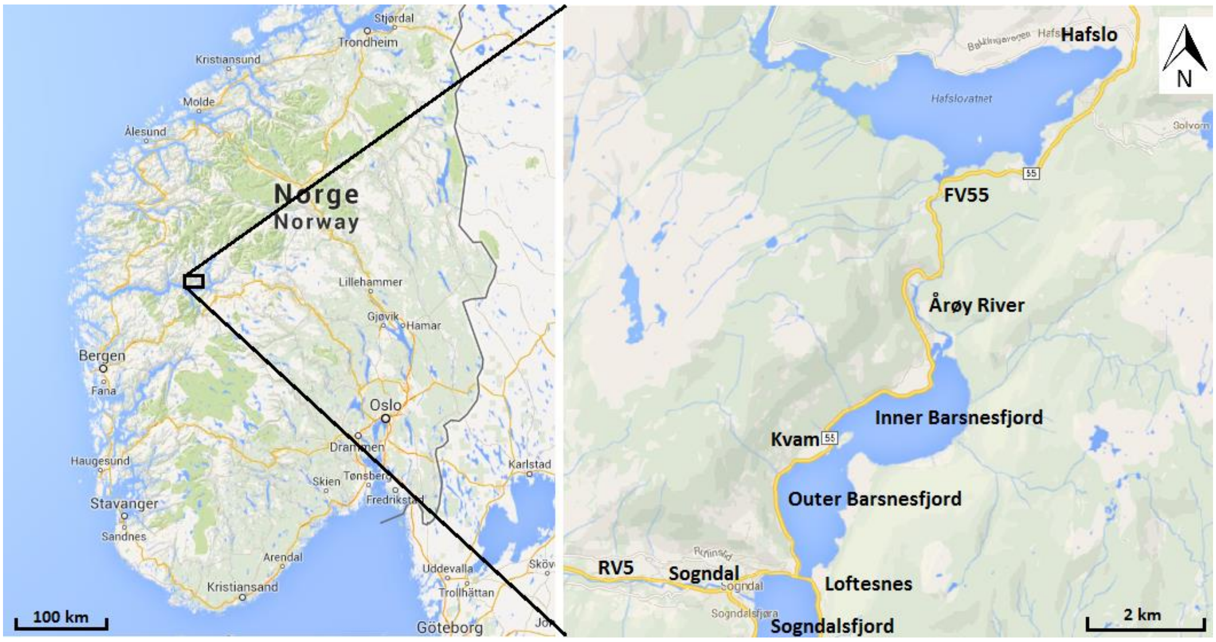


Figure 1 Research area shown in a modified map of Google maps. The left image indicates the location of the Barsnesfjord in western Norway; the right image shows the Inner and Outer Barsnesfjord in detail, including the location of the city of Sogndal and the Loftesnes Bridge.

The shallow sill depth presents the major obstacle for oxygen rich water entering the Barsnesfjord. In spite of this, water masses still pass the sill because of estuarine circulation processes (e.g. Syvitski et al. 1987). This estuarine circulation replaces the low oxygen water masses of the Barsnesfjord with oxygen rich water masses of the Sogndalsfjord with a frequency of about three to four years (Paetzel & Dale 2010). The ecosystem of the Barsnesfjord depends on the frequency of these water exchange events (Torbjørn Dale 2014, *personal communication*).

Prior to the building of the new bridge, the Norwegian State Road Authority (Statens vegvesen) designed a bridge construction plan based on evaluations of the Norwegian Institute of Water Research (NIVA 2003; 2011). The new construction involves a partial infill of the sill mainly due to a larger size of the foundation the new bridge pillars will rest on. The evaluation of NIVA (2003) suggests little or only minor influence of such narrowing on the water exchange processes in the Barsnesfjord. The NIVA report of 2011 suggests further investigations on a possible influence of the bridge building on the Barsnesfjord ecosystem.

It is the main task of this thesis to use the Barsnesfjord sediment for reconstructing environmental change in the Barsnesfjord mainly by including changes in hydrography and ecology throughout the past 30 to 50 years. Based on the findings, a model will be constructed in order to predict and illustrate how the building of the new Loftesnes Bridge might influence the hydrography and ecology of the Barsnesfjord after the building of the new bridge.

2. Objectives

The development of a future environmental impact model requires the reconstruction of former environmental impact on the area. This will be done by interpreting the sediment record of the past 30-50 years by addressing the following three objectives:

2.1. Objective 1

Is it possible to date sediment cores from the Barsnesfjord on an annual to decadal time scale over the past 30 to 50 years?

Sediment cores from the Barsnesfjord have been dated earlier by Paetzel & Schrader (1991) using the ^{137}Cs fallout from the 1986 Chernobyl atomic power plant accident and also from the 1963 global nuclear weapon tests. In addition, they confirmed this dating by counting seasonal laminae in the sediment. Paetzel & Schrader (1992) related coarser grained sediment fractions of the Paetzel & Schrader (1991) sediment cores to historically documented slide events. An additional dating was gained in Barsnesfjord sediments by correlating the grain sizes of the cores of Paetzel & Schrader (1991) with those of the cores of Paetzel & Dale (2010), thus transferring the dating horizons from the earlier cores to the new cores. The challenge will be to transfer these dating horizons also to the 2013 Barsnesfjord sediment cores of this thesis, thus gaining a 30 to 50 year time schedule of sediment change.

2.2. Objective 2

Can the succession of changing sediment parameters be related to the variability of environmental and climate change during the last 30 to 50 years?

Fjord sediment change reflects signals of environmental and climate change (Syvitski et al. 1987; Howe et al. 2010). Parameters to be affected consist of particulate organic matter and particulate inorganic matter. The particulate organic matter fraction includes the total organic matter fraction, divided into the terrestrial and the marine organic matter fraction. The particulate inorganic matter fraction includes framboidal pyrite, the mineral matter fraction, and grain sizes. All parameters will be investigated by translucent light microscopy using the smear slide technique. The observed changes in these parameters will be related to environmental and climate change. Together with the sediment dating, the parameters will reveal the timing of this change.

2.3. Objective 3:

Is it possible to construct a box model predicting the influence of expected future environmental change on the Barsnesfjord system, based on the record of environmental change as reconstructed from the Barsnesfjord sediments?

Box models represent useful tools for illustrating simple relationships between parameters. They can be constructed qualitatively and quantitatively. In the work at hand, a qualitative model will be designed. The focus will be to understand and illustrate the causes of environmental change in the Barsnesfjord in the past. Using this past record of environmental change, the model will illustrate how a range of expected future environmental change might affect this picture in one or another way. The main emphasis will be put on possible changes that might occur in the Barsnesfjord due to alterations of the sill when building the new bridge at Loftesnes.

3. Environmental Setting

3.1. Bathymetry

The Barsnesfjord is a northeast-directed tributary of the Sogndalsfjord which is connected with the Sognefjord further to the southeast. The Barsnesfjord is located northeast of the small town of Sogndal. A sill of 9 m depth separates the Barsnesfjord from the Sogndalsfjord. The Barsnesfjord itself is divided into the 66m deep Inner Barsnesfjord basin and the 82 m deep Outer Barsnesfjord basin. A 30 m deep sill separates the two Barsnesfjord basins at Kvam (Figure 1 and 3). The main freshwater input to the fjord originates from the Årøy River, which has its inlet in the northeast of the Barsnesfjord. The main source of the Årøy River water masses is the glacier Jostedalsbreen mainly coming from its glacial tributary Austerdalsbreen and in minor quantities from its glacial tributary Langedalsbreen (Figure 2).

Figure 2 The melting water from the glaciers Langedalsbreen and Austerdalsbreen in the north is flowing south to Hafslo and ends in the Barsnesfjord by the Årøy River. These glaciers are the main source of water masses for the Årøy River. Modified map from Google maps.

3.2. Geology

Different types of rock can be found in the area around the Barsnesfjord. These are the autochthonous basement rocks consisting of gneiss granite, and the lower and middle allochthonous rocks of the Caledonian orogeny, namely phyllite and anorthosite. The main source rocks of the Årøy River are gneiss granites.

The fjord basins around Sogndal were formed during the Quaternary ice ages culminating in the maximum of the last, Weichselian ice age (Aa 1982) around 20.000 years BP, i.e. before present (Clark et al. 2009).

During the Holocene, i.e. the past 10.000 years the fjord basins around Sogndal have been filled in with 50 to 100 m sediment (Grønning 1983; Paetzel & Dale 2010).

3.3. History

Four major events have been documented in the Barsnesfjord region that might have had some influence on the Barsnesfjord environment and thus on the Barsnesfjord sediment record (Paetzel 1990; Paetzel & Schrader 1991; 1992; Paetzel & Dale 2010):

- In 1904, an explosion went wrong during road construction and blocked the outflow of freshwater from the Lake Hafslovatnet into the Årøy River (Figure 2), thus reducing the inflow of freshwater into the Barsnesfjord. For the whole of 1904, the Lake Hafslovatnet was dammed with a water level reaching a maximum of 1,5m above normal lake water level. After one year of elevated lake water level, the blockade of rocks was finally removed and the lake water level fell back to its normal position.

- In 1975, an amount of approximately 2000 m^3 of silt and clay slid into the Inner Barsnesfjord near Øyabrekka.
- In the autumn of 1982, several thousand m^3 of silt and fine-grained material from an ice marginal deposit at the mouth of the Årøy River and a gravel dump laying on top of these deposits, slid into the Inner Barsnesfjord. The source of the gravel dump is crushed rock material from the building of the water tunnel for the hydro power station at Årøy.
- Another major event was construction of the hydro power station at Årøy in 1983. The main freshwater flow of the Årøy River was changed from running through the natural riverbed to running through a water tunnel. A minimum water flow of 3,5 m^3/s is still maintained downstream of the water tunnel in order to sustain the salmon population of the lower part of the Årøy River.

3.4. Hydrography

The water in the Barsnesfjord is stratified with water layers of different density. The upper 10 meters of the water column are strongly influenced by the low-density freshwaters of the Årøy River. The low-density freshwater floats on top of the more saline, higher-density marine water masses; these marine water masses originate from the Sogndalsfjord. The temperature of the surface water fluctuates in the summer from 16°C to 10°C and the winter from 10°C to 0°C. Water temperatures below 10 m water depth remain more or less stable at 7°C to 8°C (Kaufman 2014).

Due to estuarine circulation processes (Syvitski et al. 1987), oxygen rich marine water masses enter the deeper parts of the Norwegian fjords via the Norwegian Coastal Current. This high-density water inflow is compensated by the freshwater and brackish water outflow from rivers and runoff. The circulation pattern in the Outer Barsnesfjord is different, though. The 9 m deep sill at Loftesnes blocks the inflowing deep water (Figure 3). Thus, the water exchange is restricted in the Outer Barsnesfjord. This allows oxygen conditions of the deeper fjord waters to decrease to the critical values of 2 mg/l in these periods. Due to this restriction process, deep-water inflow and oxygen renewal occurs only every three to four years (Paetzel & Dale 2010).These events mostly happen in late fall and early winter because of a less stratified water column due to little freshwater. In addition, storm events might destabilize the water masses and press the denser seawater over the sill (Torbjørn Dale 2014, *personal communication*).

The 30 m deep sill at Kvam (Figure 3) additionally restricts water inflow and water circulation in the Inner Barsnesfjord. Low oxygen conditions (from 7 mgO_2/l to 0 mgO_2/l) thus remain in the Inner Barsnesfjord water masses at a water depth greater than 40m, and permanently anoxic conditions ($<2mgO_2/l$) prevail at water depth greater than 60m (Dale & Hovgaard 1993; Kaufman 2014).

Macroscopic benthic life does not survive in fjord waters below the critical value of $2mgO_2/l$. Thus, sediments will settle and accumulate continuously during periods of low oxygen conditions. These sediments will be undisturbed by bioturbation producing a continuous record of laminated sediments as long as these conditions prevail.

4. Methods

A Niemistö gravity corer (Niemistö 1974) was used to retrieve two sediment cores at 82 m water depth in the Outer Barsnesfjord (Core 4 and Core 6) and one sediment core at 61 m water depth in the Inner Barsnesfjord (Core 17) in September 2013 (Figure 3). The Niemistö corer allows sampling sediment cores with undisturbed sediment-water interfaces. Figure 3 reveals the core locations including coordinates.

The samples were taken slightly above a water depth that marks the level of critical oxygen conditions, i.e. <2 mgO_2/l. This sampling strategy allows indicating changing oxygen levels in the sediment when taking samples at the same water depth in future research. The sediment cores were handled in a vertical position during sampling and transport until core opening in the laboratory. This was done to avoid artificial disturbances of the sediment surface.

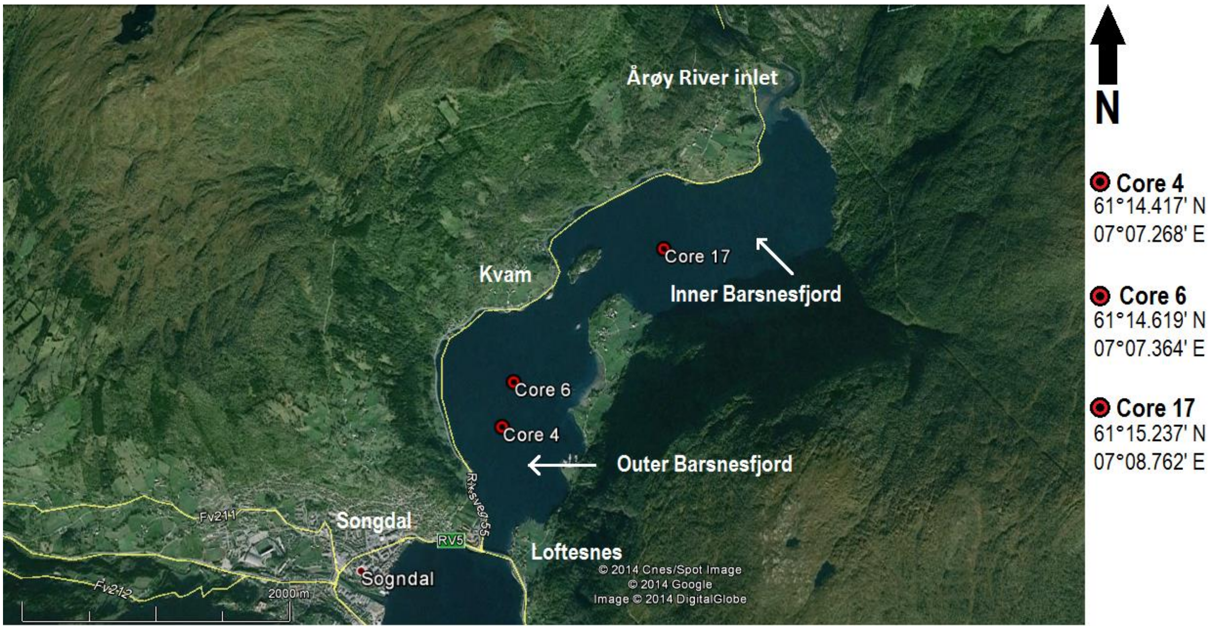


Figure 3 The locations of the sediment cores taken in the Outer Barsnesfjord (Core 4 and Core 6) and in the Inner Barsnesfjord (Core 17). To the right, the coordinates of the locations are given in degrees and minutes. Modified map from Google Earth

In the laboratory, the water on top of the (still vertically positioned) sediment cores was drained off using a water hose and a pipette. The visible sediment surface was secured using paper towels. This allowed placing the sediment core horizontally for opening without destroying the sediment surface.

After cutting the cores in two halves, the core structures were sketched and the colour of the sediments was documented using a Munsell Soil Color Chart (Munsell 1994). Density subsamples were taken continuously at 1.8 cm steps down core using cut off head syringes. Colour and density determinations are standard sediment documentation methods and thus not further used in this thesis. Smear slides were made continuously in 1cm steps down core.

Smear slide

Smear slide analysis is a technique to examine sediment particles smaller than Sand *in situ*, using a small sample size of maximum 1-2mm^3. Simple tools are required to make a smear slide. This makes it a fast, easy and cheap method and it even allows repeating the examination of samples from archived cores without damaging them. A new sample can be taken from the same spot as often as necessary since only a small amount of the sample is needed. It is the primary investigative tool for initial analysis of cored sediment (Rothwell 1989).

Sampling occurred continuously down core on 1 cm sediment slices, giving a resolution of 1 to 2 years of deposition per smear slide sample, corresponding to the results of Paetzel & Dale (2010) who determined averaged sedimentation rate of 0,75 cm/year for the Outer Barsnesfjord and 0,85 cm/year for the Inner Barsnesfjord.

Smear slides are made by homogenizing 1 cm thick sediment slices. Then, a small amount of these mixtures, about the size of a needle head, is placed on a microscope cover glass together with one drop of distilled water. The sample should be mixed until the material is has disintegrated in the drop of water. Next, a drop of Kodak Photo Flo is added to reduce the surface tension of the water, allowing the sample to spread over the entire cover glass. Half a centimeter of space is left on the two long sides of the cover glass, allowing the cover glass to be held without the fluid running down the fingers. Finally, the sample is dried and the cover glass is mounted onto a pre-heated microscope object glass with the use of Naphrax (Brunel Microscopes Ltd) as mounting medium. The Naphrax refractive index of >1.74 makes it possible to observe diatoms in the smear slides. A drop of Naphras is put on the microscope object glass. The cover glass should be mounted on the microscope object glass by inverting it and allowing the Naphras touching the cover glass. The cover glass will stick to the microscope object glass. Then invert the microscope object glass again and return it to the heat plate. After readjusting the cover glass, the slide is heated to 100°C until the solvent of the mounting medium drags out of the slide in long bubbles. When the bobbling slows down, the slides are removed from the heat plate to cool down.

After the smear slides where created they are analyzed under the microscope. It is important that a single individual performes the smear slide analysis of the single parameters in order to avoid biasing the results.

The following parameters were analyzed in the smear slides:

- Grain size was divided into clay (< 2 µm), silt (2-63 µm) and sand (>63 µm to 2 mm) according to the Udden-Wentworth grain size classification (Wentworth 1922). All three sizes added up to a total of 100%.
- Organic matter was determined versus the mineral matter fraction, totaling 100% of the material.
- The organic matter fraction was further divided into the terrestrial organic matter and marine organic matter fraction, both adding up to 100% of the organic matter. Terrestrial organic matter is all the organic matter that originates from land, recognized by its dark

brown to black colour, strong cell walls, and/or fibers. The marine organic matter has a light brownish colour and more diffuse shapes.

- The most common diatoms were counted and classified according to their environment. These were for freshwater environment indicator: *Tabellaria flocculosa*, and for the marine environment indicators: *Skeletonema costatum* and *Chaetoceros species* as used and described by Paetzel & Dale (2010).
- Pyrite was compared with 100% of the mineral matter fraction. Pyrite occurs in its round, framoidal form as a result of organic matter decomposition in anoxic conditions.

Microsoft office 2007 software Excel and PowerPoint was used to creating graphs.

The grain size graphs were correlated with two cores taken by Paetzel & Dale (2010) in the Barsnesfjord in 2007, Core MF2007-1 for the Inner Barsnesfjord and MF2007-2 for the Outer Barsnesfjord. Grain sizes are the most conservative sediment parameters. This allows transferring the dating of the 2007 sediment cores done by Paetzel & Dale, to the 2013 sediment cores by relating dating lines to grain size peaks, occurring at similar sediment positions in both investigations.

The results from the sediment parameters analyses were placed in an estimated timeframe and interpreted in relation to other and their possible sources.

Finally, a box model was constructed to indicate how each parameter is influenced by its sources. Such a box model allows predictions to be made on how future environmental events might influence the fjord environment.

5. Results

5.1. Particulate matter

At first, the results will be shown for all particulate matter but the diatoms within the single cores, i.e. Core 4 (Figure 4), Core 6 (Figure 5), and Core 17 (Figure 6). Also, correlative peaks will be indicated marked with a blue rectangle. All parameters are presented versus sediment depth on a 100% scale.

Core 4 Outer Barsnesfjord

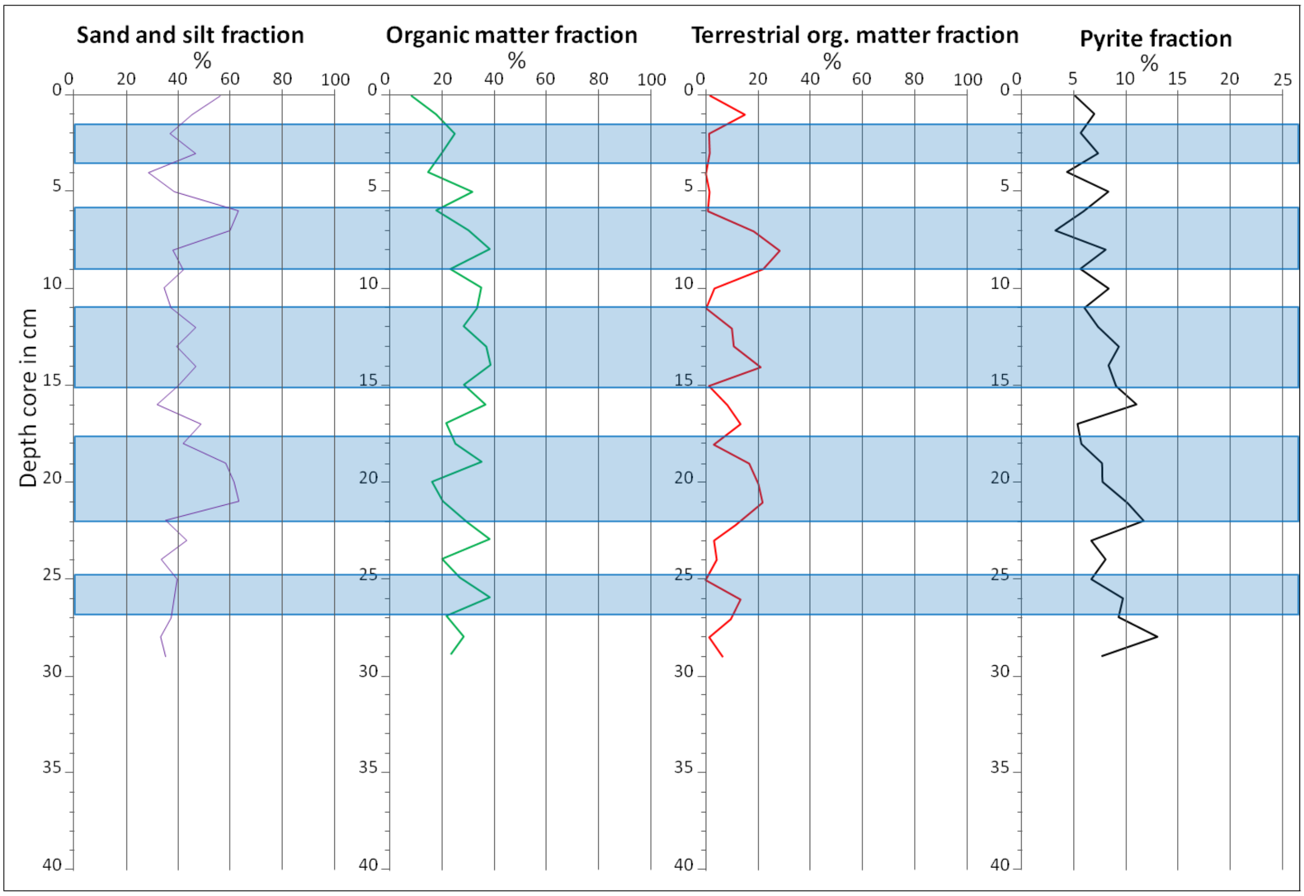


Figure 4 The results of Core 4, Outer Barsnesfjord. Sediment parameters presented are Sand and silt (in % of the total mineral grain size); organic matter (in % of the total particulate matter); terrestrial organic matter (in % of total organic matter); pyrite (in % of the total mineral matter).

Core 4 revaeled a reasonable good correlation between the coarse grain sizes (sand and silt) and terrestrial organic matter, indicating that both fractions are of terrestrial origin and transported by runoff into the fjord. In addition, the total organic matter fraction seems to show to some extent the opposite trend of the coarse grained fraction. This is reasonable as over 80% of the organic matter fraction is of marine origin and does not depend on terrestrial processes other than nutrient supply. The pyrite fraction does not show a clear relationship with the other graphs.

Core 6 Outer Barsnesfjord

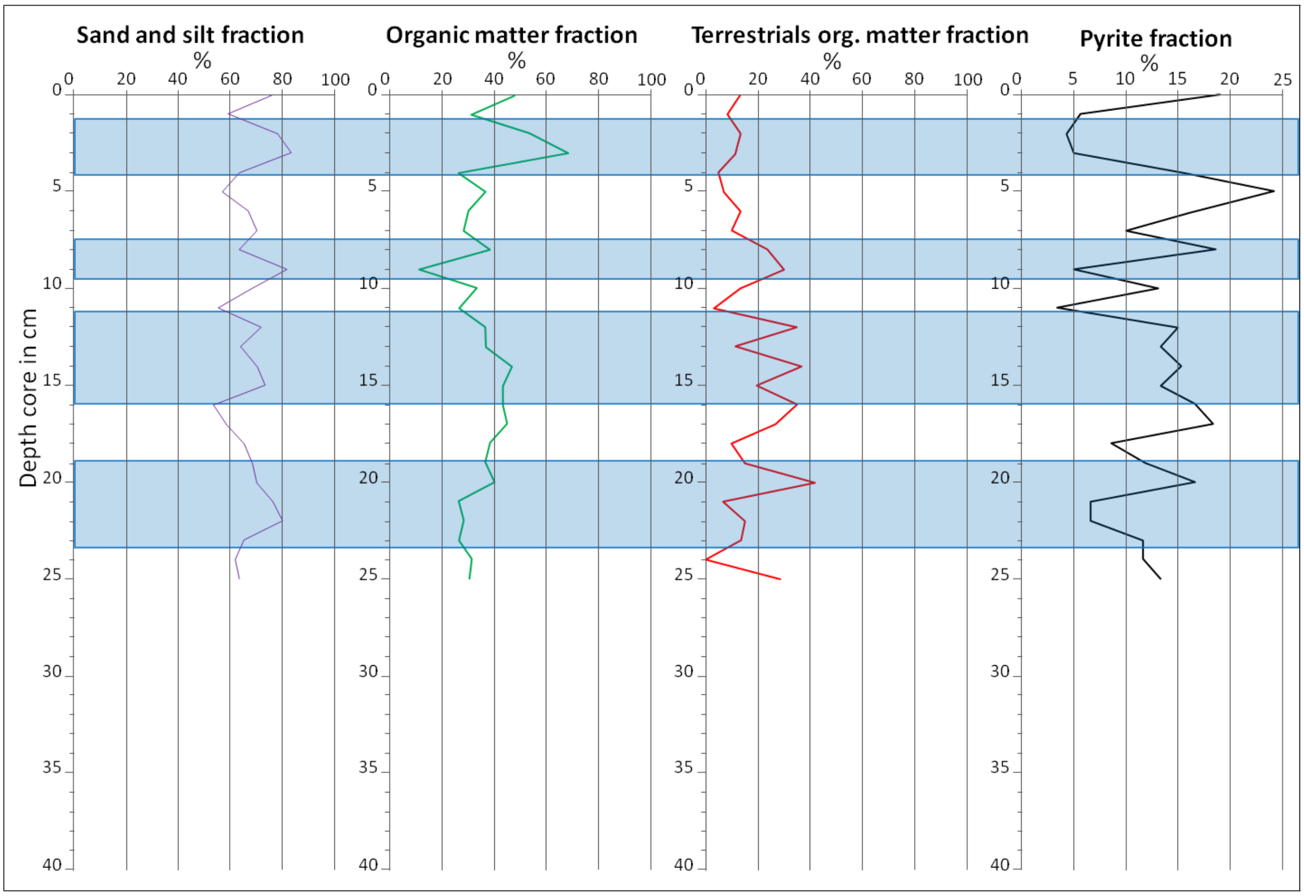


Figure 5 The results of Core 6, Outer Barsnesfjord. Sediment parameters presented are Sand and silt (in % of the total mineral grain size); organic matter (in % of the total particulate matter); terrestrial organic matter (in % of total organic matter); pyrite (in % of the total mineral matter).

Also Core 6 revealed a reasonable good correlation between the coarse grain sizes (sand and silt) and terrestrial organic matter, also here indicating that both fractions are of terrestrial origin and transported by runoff into the fjord. However, the total organic matter fraction seems to partly show the same trend as the coarse grain size and the terrestrial organic matter. In addition, the percentage of the organic matter fraction is somewhat higher than in Core 4. This pattern might indicate that Core 6 is located closer to the major terrestrial source area of the Årøyelv River than Core 4. The pyrite fraction indicates similarities with the organic matter curve below 7 cm and no relationship above 7 cm sediment depth. The framboidal pyrite fraction indicates anoxic conditions in the sediment and is thus related to increased concentrations of mainly marine organic matter.

Core 17 Inner Barsnesfjord

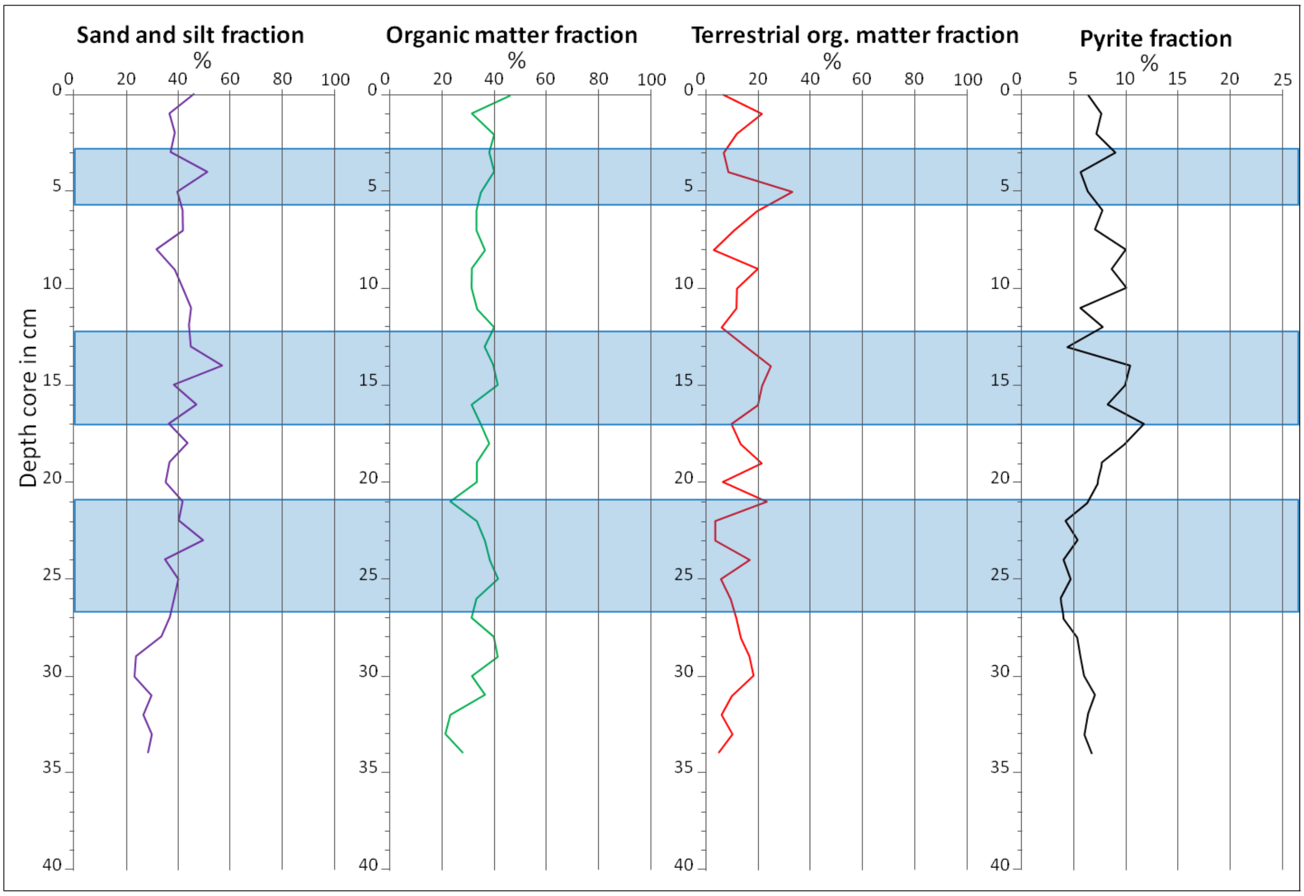


Figure 6 The results of Core 17, Inner Barsnesfjord. Sediment parameters presented are Sand and silt (in % of the total mineral grain size); organic matter (in % of the total particulate matter); terrestrial organic matter (in % of total organic matter); pyrite (in % of the total mineral matter).

The middle 12 to 18 cm indicates a similar increase in all four parameters of Core 17. Variations elsewhere are too small to reveal clear trends in this core. In the coarse grain size is a sudden decrease from 40% to approximately 30% at a depth of 27 cm and below.

After having observed this data it seems that grain size, organic matter, and terrestrial organic matter are more or less connected by the same source. Only pyrite does not follow this tendency. This might indicate that pyrite is influenced by a different source.

5.2. Dating

A core-to-core correlation between Core 4 and Core 6 on one side and the dated core MF2007-2 of Paetzel & Schrader (2010) on the other side will profide a dating. The Core 17 has a core-to-core correlation with core MF2007-1. These core-to-core correlations require two prerequisites. (a) The grain size graphs of these cores show a similar pattern, and (b) the correlation takes care of the fact that the dating of the sediment surface of MF2007-2 core ends six years prior to the deposition of the sediment surface of Core 4 and Core 6. Figure 7 shows the correlation of the grain size graphs the Outer Barsnesfjord Core 4, Core 6 with the grain size graph of the Outer Barsnesfjord core MF2007-2. Figure 8 shows the correlation of the grain size graphs in the Inner Barsnesfjord between Core 17 and MF2007-1.

Core 4, Core 6 and MF2007-2 sand and silt fraction, Outer Barsnesfjord

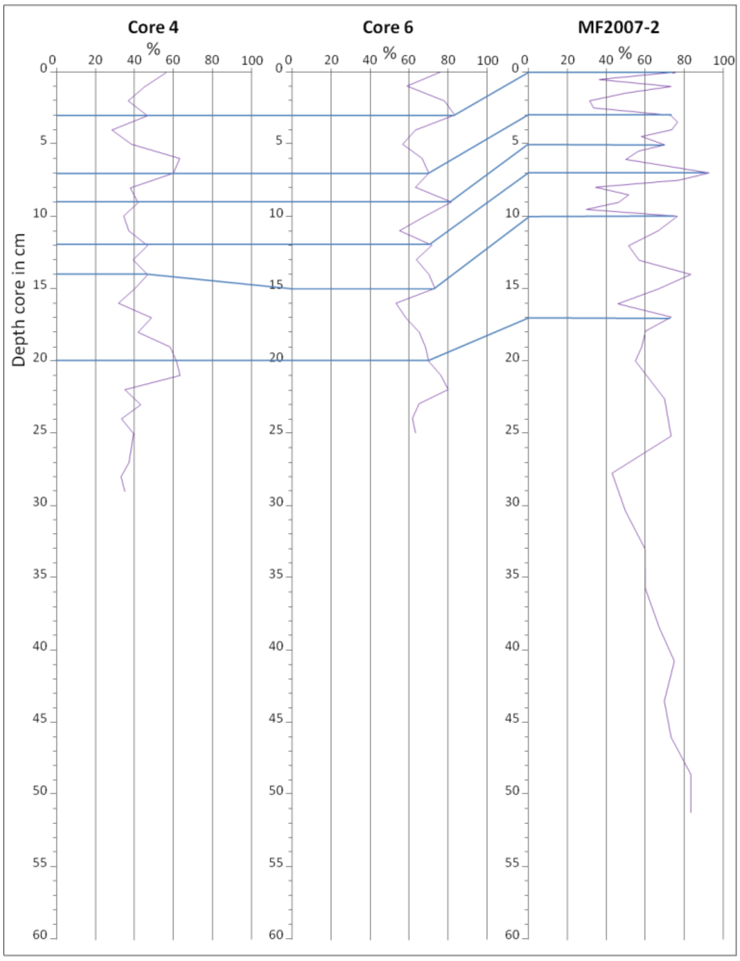
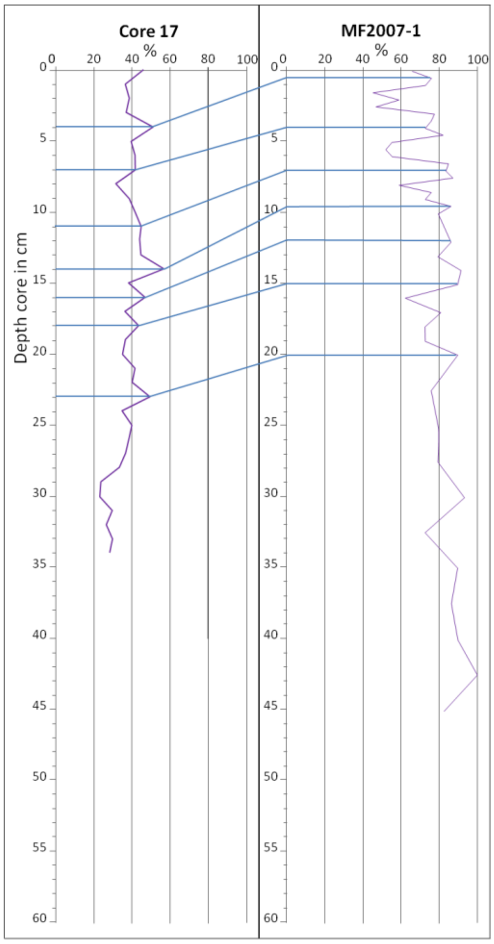


Figure 7 Correlation between the sand and silt fraction of Core 4, Core 6 and MF2007-2. . The blue lines indicate correlative peaks deposited at the same time.

Core 17 and MF2007-1 sand and silt fraction Inner Barsnesfjord



Figuur 8 Correlation between the sand and silt fraction of Core 17 and MF2007-1. The blue lines indicate correlative peaks deposited at the same time.

Paetzel & Dale (2010) dated the peak at 17 cm of core MF2007-2 to being deposited around the year 1983. For core MF2007-1 the dating is the peak at 20 cm, being deposited around the year 1983. As the grain sizes of all cores can be correlated to each other, the same time horizon of 1983 would occur at 20 cm in Core 4, at 20 cm in Core 6, and at 23 cm in Core 17. This would result in sedimentation rates of 0,67 cm/year for the Outer Barsnesfjord (Core 4 and Core 6) and 0,77 cm/year for the Inner Barsnesfjord (Core 17). These sedimentation rates are reasonable as they are similar to those proposed for the two Barsnesfjord basins by Paetzel & Dale

(2010), i.e. for the Outer Barsnesfjord core MF2007-2 a rate of 0,75 cm/year is shown and for the Inner Barsnesfjord a rate of 0,85 cm/year is shown by core MF2007-1.

5.3. Precipitation and Temperature

Additional confirmation of the dating can be gained by relating the graphs of the coarse-grained fraction to their direct source, i.e. runoff triggered by the local precipitation pattern. Paetzel & Dale (2010) found such relationship in their cores of 2007. Figure 9 indicates a correlation between the annual precipitation pattern at the nearby meteorological Station at Hafslo (Figure 1 and 2) and Core 4, Core 6 and Core 17. The correlative time horizon of 1983 is indicated as a red line in the graph. In a year of increased precipitation it is predictable that the fraction of more coarse grains should increase. Therefore the dated cores are aligned next to the precipitation with a line on the year 1983, a correlation should be visible and confirm our dating.

Precipitation compared to the sand and silt fraction after dating

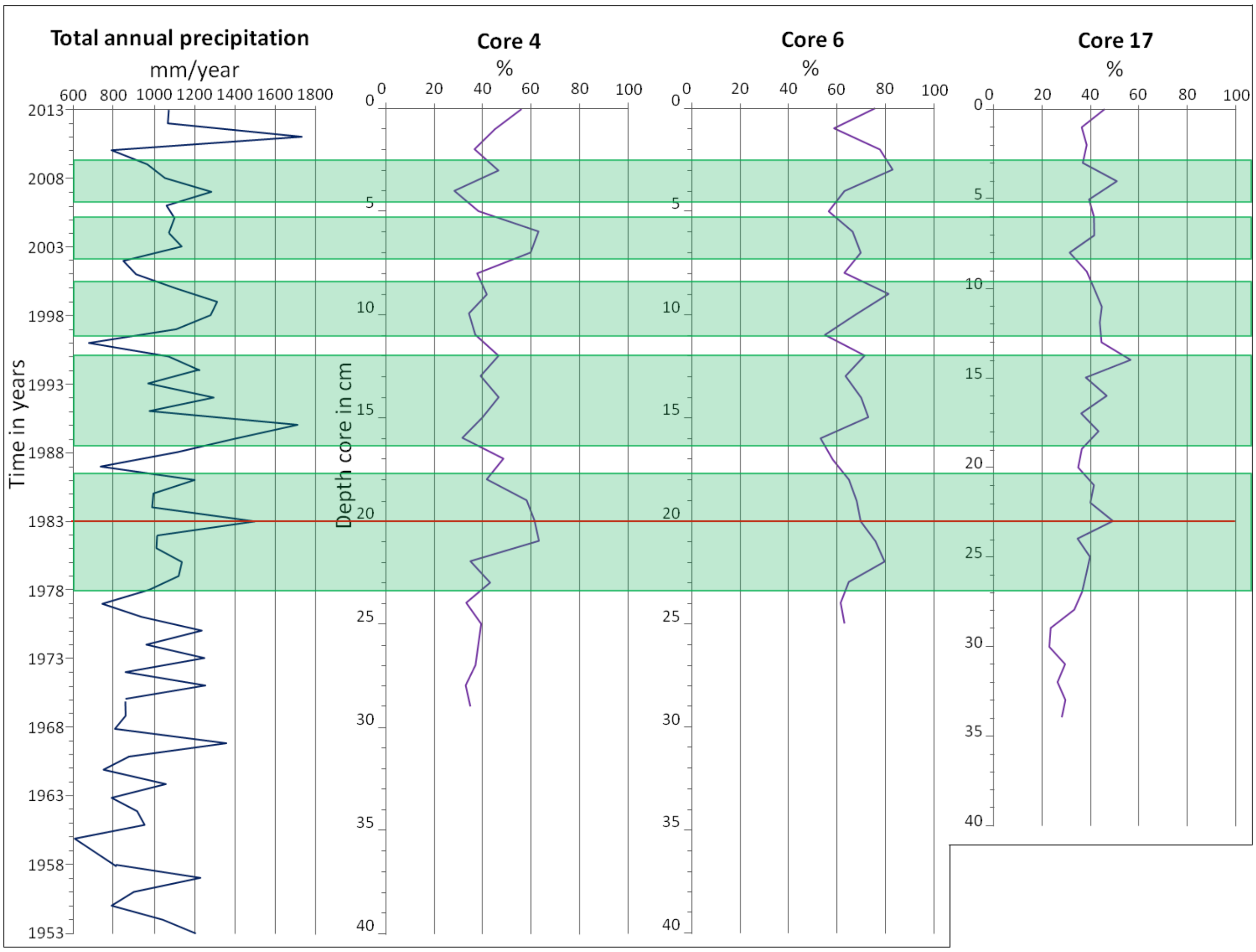


Figure 9 The annual precipitation graph of the Hafslo meteorological station compared to the dated grain size graphs of Core 4, Core 6, and Core17. The red line shows this dating line of 1983. Note that the precipitation graph is presented on a time scale while the grain size graphs are presented on a depth scale. The green boxes show similar peaks and patterns in graph variability.

Comparing the graphs with each other in Figure 9, confirms the overall dating of the graphs (Figure 7 and 8). They also show a clear correlation between precipitation the sand and silt fraction of grain sizes. In particular Core 17 shows a strong correlation in the variability.

Paetzel and Dale (2010) found in addition a correlation between the coarse grain sizes, precipitation, and temperature. Figure 10 confirms the correlation with temperature also for Core 4, Core 6, and Core 17. However, the relationship is less strong than shown for the precipitation. The temperature of the year 2005 is not available and thus missing in the graph.

Temperature compared to the sand and silt fraction after dating

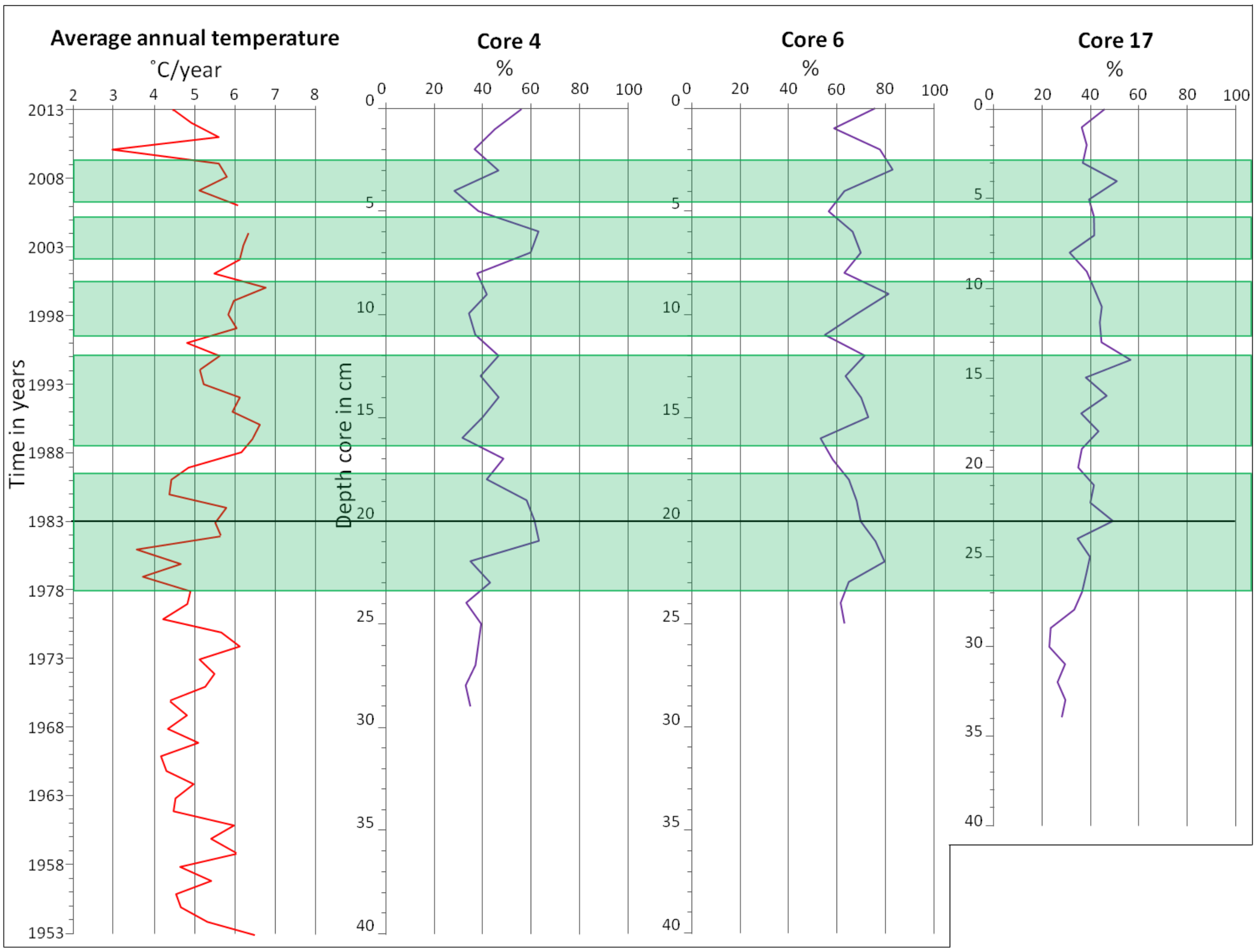


Figure 10 The annual temperature graph of the Fjærland meteorological station compared to the dated grain size graphs of Core 4, Core 6, and Core 17. The black line shows the dating horizon of 1983. Note that the temperature graph is presented on a time scale while the grain size graphs are presented on a depth scale. The green boxes show similar peaks and patterns in graph variability.

Also comparison of the annual precipitation pattern with the deposition of the terrestrial organic matter fraction of Core 4, Core 6, and Core 17 (Figure 11) indicates a strong relationship. The overall dating of Core 4, Core 6, and Core 17 seems thus utterly to be confirmed.

Precipitation compared to the terrestrial organic matter fraction after dating

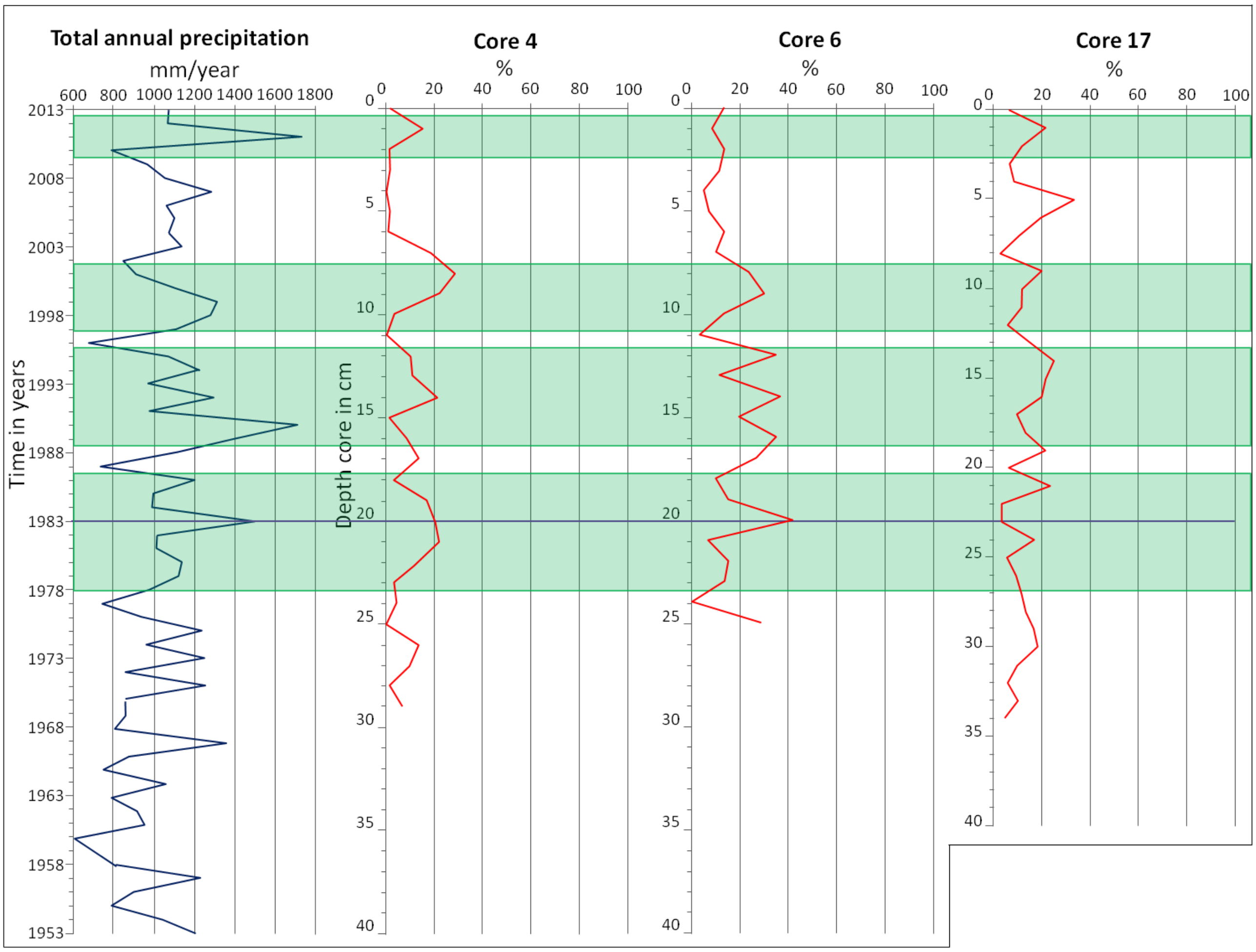


Figure 11 The annual precipitation graph of the Hafslo meteorological station compared to the dated terrestrial organic matter graphs of Core 4, Core 6, and Core 17. The purple line shows the dating horizon of 1983. Note that the precipitation graph is presented on a time scale while the terrestrial organic matter graphs are presented on a depth scale. The green boxes show similar peaks and patterns in graph variability.

Figure 11 shows a visual correlation between terrestrial organic matter and precipitation. This means that runoff from precipitation most probably is the main source for terrestrial organic matter, and for the variability of the sand and silt fraction as shown earlier.

5.4. Diatoms and organic matter

Figures 12, 13 and 14 show the variability of the marine diatoms compared to the variability of the marine organic matter in Core 4, Core 6, and Core 17 respectively. The overall pattern of these graphs is similar (in varying degree). The counted marine diatoms are indicators of high primary productivity. Thus, the production of marine organic matter and therefore the formation of organic matter peaks can be related to an enhanced supply of nutrients. As the marine organic matter fraction does not correlate with the coarse-grained fraction, it can be concluded that the nutrients originate from estuarine circulation rather than from terrestrial runoff. The total organic matter shows some similarities to the marine organic matter and marine diatoms but not a clear correlation. The reason for this is that a part of the total organic matter is terrestrial, thus some precipitation signals are in the total organic matter disturbing the marine signals.

Core 4 Outer Barsnesfjord

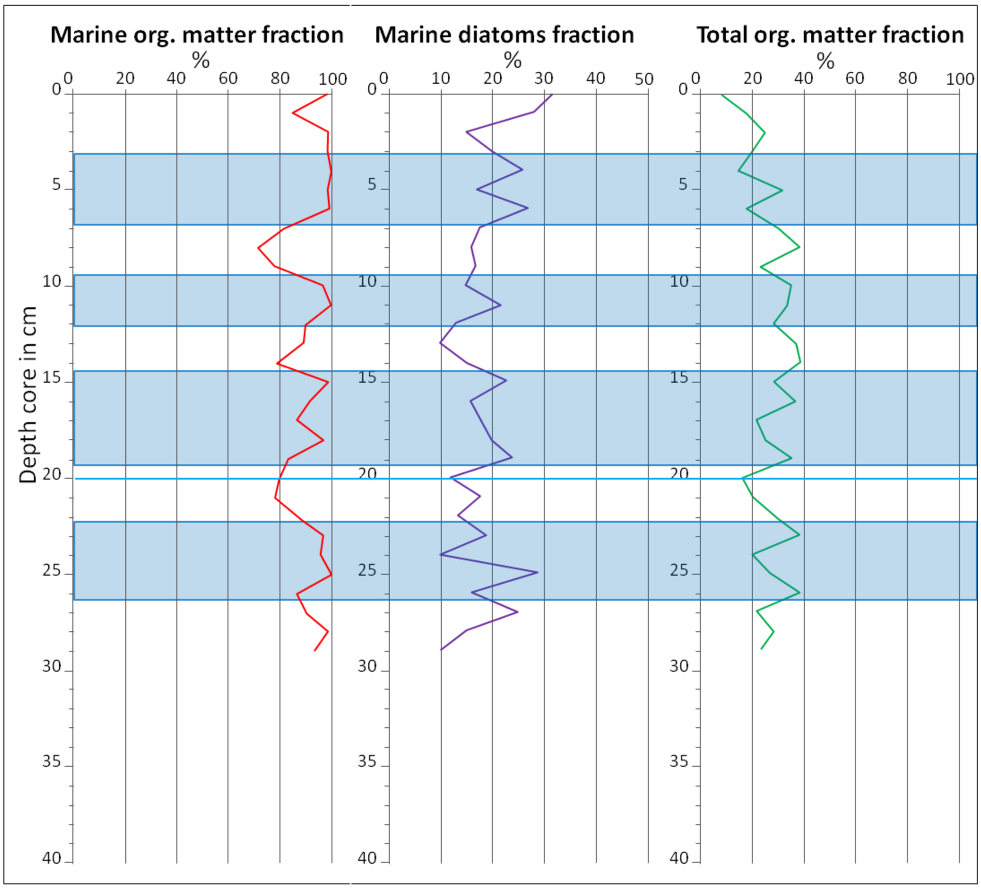


Figure 12 shows the similarities of the marine organic matter and the marine diatom fraction and total organic matter of Core 4. The blue line shows the dating horizon of 1983. The blue boxes are showing similar peaks and patterns in graph variability.

In Figure 12 there is a similarity between 10 and 20 cm depth. Especially marine organic matter and marine diatoms show the same pattern and follow the same trend.

Core 6 Outer Barsnesfjord

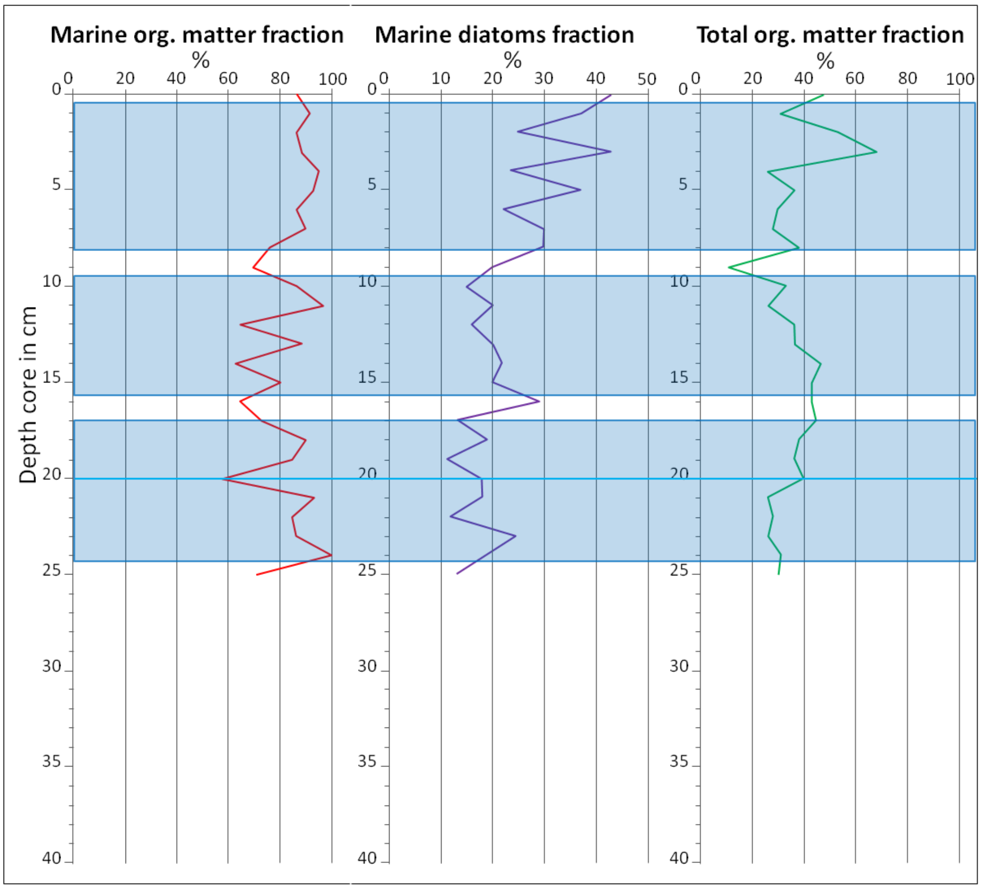


Figure 13 shows the similarities of the marine organic matter and the marine diatom fraction and total organic matter of Core 6. The blue line shows the dating horizon of 1983. The blue boxes are showing similar peaks and patterns in graph variability.

Figure 13 shows no correlation between the variability of the core. However marine organic matter and marine diatoms show a similar pattern. A decrease from 0 cm to 10 cm depth, a more or less stable part at 10 cm to 16 cm depth and a slight increase from 16 to 25 cm depth.

Core 17 Inner Barsnesfjord

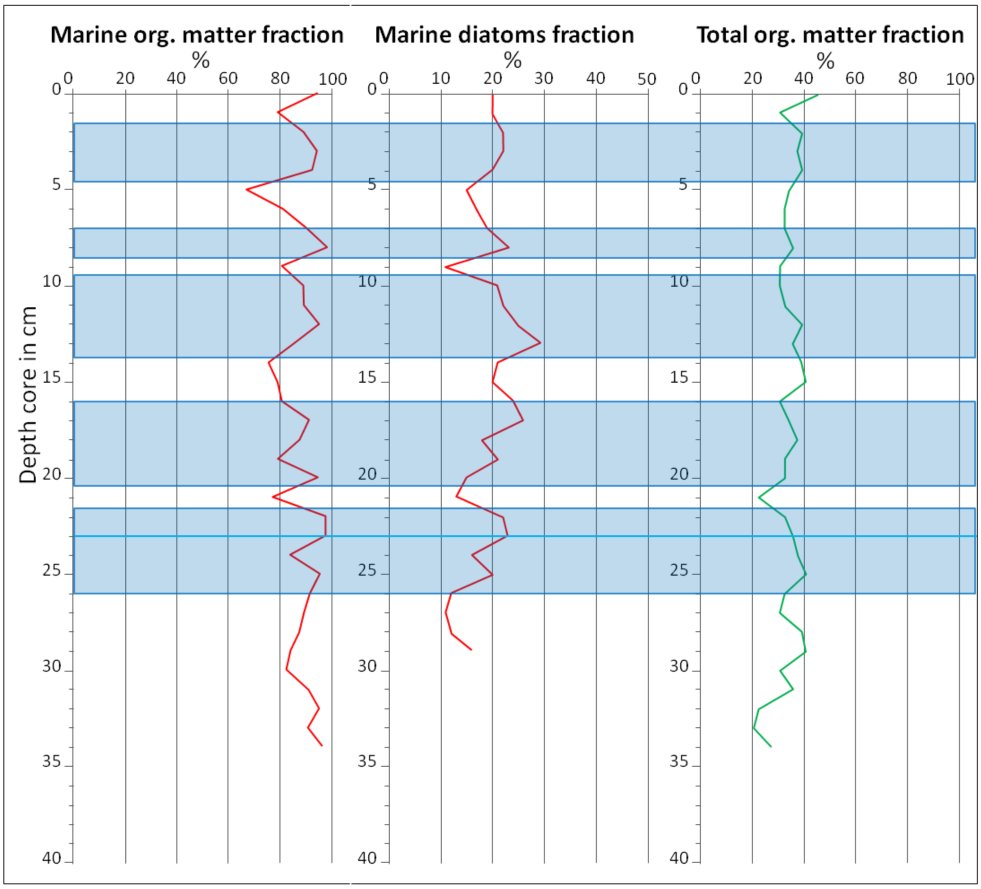


Figure 14 shows the similarities of the marine organic matter and the marine diatom fraction and total organic matter of Core 17. The blue line shows the dating horizon of 1983. The blue boxes are showing similar peaks and patterns in graph variability.

A clear correlation is visible between marine organic matter and marine diatoms in Figure 14. Also total organic matter shows a similar pattern in the variability of the core.

Figures 15, 16, and 17 show a clear relationship (in varying degree) between the freshwater diatom fraction and the terrestrial organic matter fraction of Core 4, Core 6, and Core 17, respectively. This confirms the relationship between precipitation and the enhanced supply of land and freshwater derived organic matter and diatoms due to enhanced runoff. When Core 17 is observed on the coarser grain size, it looks like that there is an increase of the coarse-grain fraction around the year 1981. This might be due to the building of the hydropower plant at the inlet of the Årøy River, and the successive changes in the river water flow.

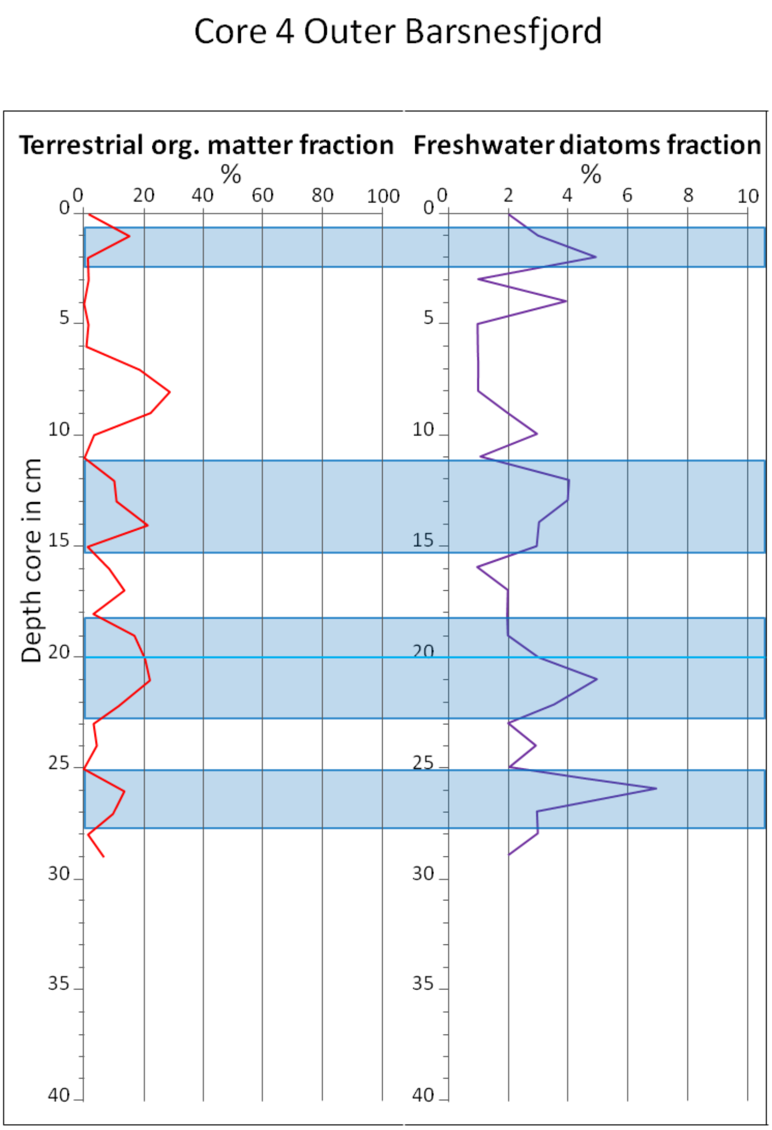


Figure 15 shows the similarities of the terrestrial organic matter and the freshwater diatom fraction of Core 4. The blue line shows the dating horizon of 1983. The blue boxes are showing similar peaks and patterns in graph variability.

Figure 15 shows a clear correlation in the Core 4 between terrestrial organic matter en freshwater diatoms. Only from 3 to 10 cm this correlation in variability is not as clear as the rest of the core.

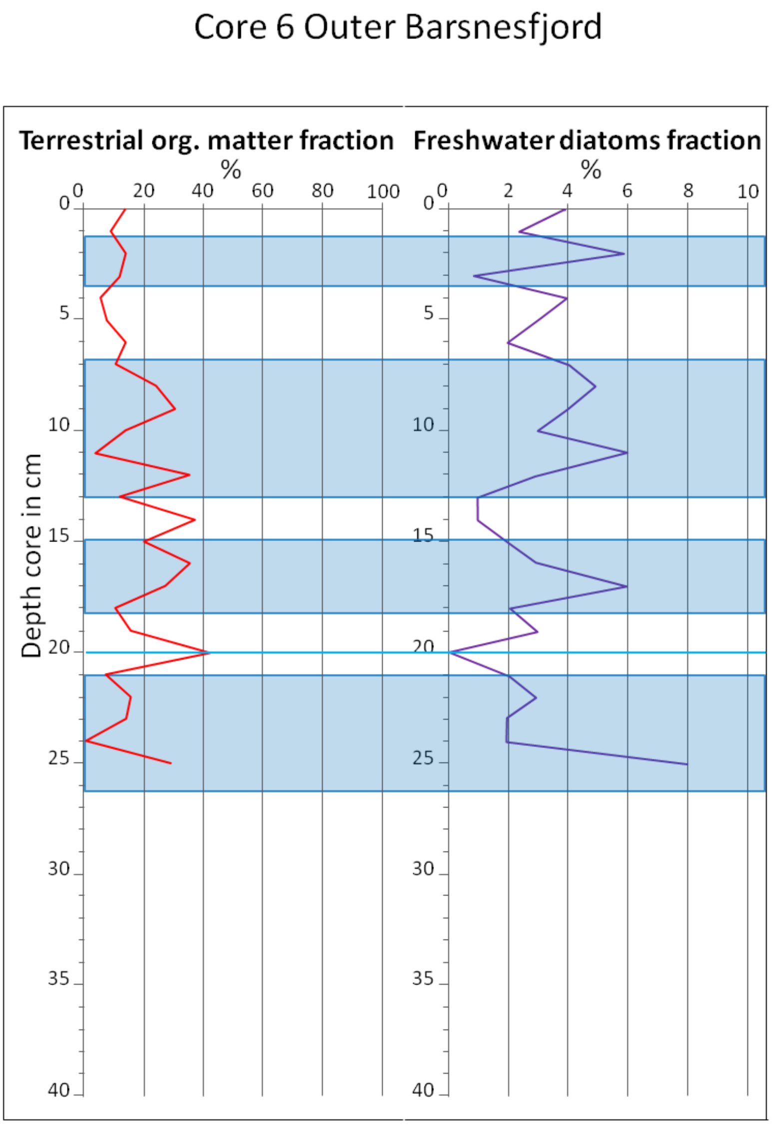


Figure 16 shows the similarities of the terrestrial organic matter and the freshwater diatom fraction of Core 6. The blue line shows the dating horizon of 1983. The blue boxes are showing similar peaks and patterns in graph variability.

Like in Figure 15, Figure 16 shows a clear correlation between terrestrial organic matter and the freshwater diatoms. Only at 20 cm depth is an opposite peaks is visible.

Core 17 inner Barsnesfjord

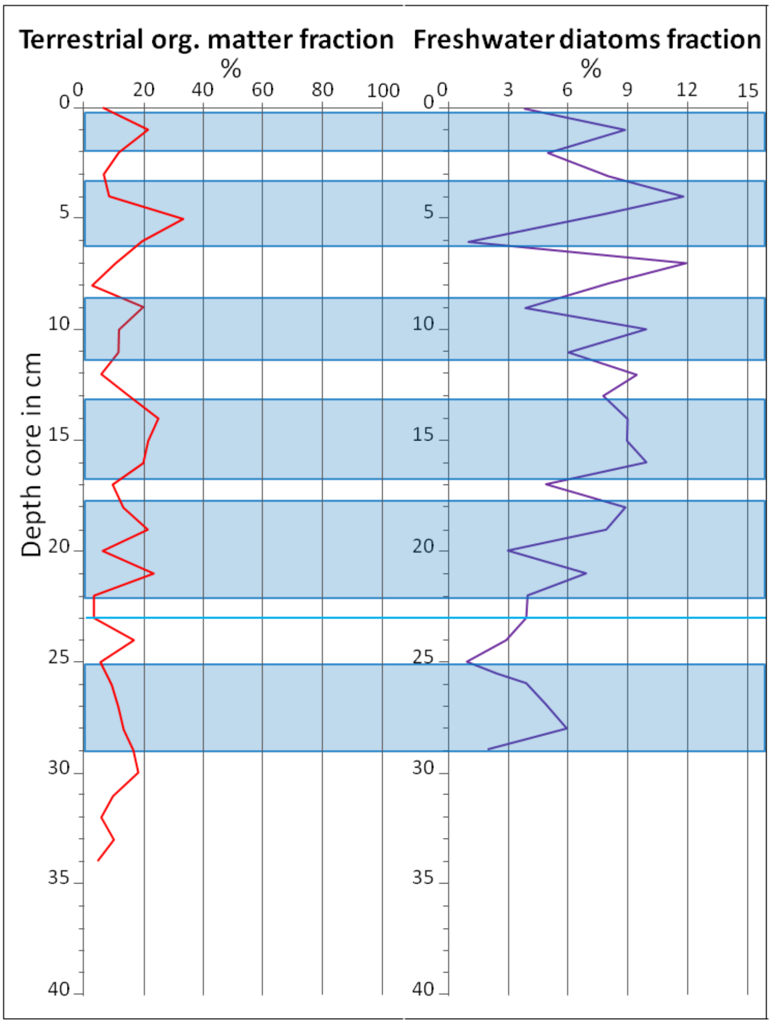


Figure 17 shows the similarities of the terrestrial organic matter and the freshwater diatom fraction of Core 17. The blue line shows the dating horizon of 1983. The blue boxes are showing similar peaks and patterns in graph variability.

Figure 17 shows a clear correlation between terrestrial organic matter en freshwater diatoms. This correlation in the variability is clearly visible in all three cores.

6. Discussion

Paetzel and Dale (2010) show a good correlation between clay sized particles of their cores and precipitation. This correlation implies that more clay particles enter the Barsnesfjord in times of enhanced precipitation. The dataset of the thesis at hand implies the opposite: during times of enhanced precipitation more erosion would occur, transporting a higher amount of coarse grained particles into the fjord. The relationship between runoff and the transport of coarse-grained particles has been documented in a variety of transitional areas between land and sea (see Syvitski et al. 1987 and Howe et al. 2010 for a review). Thus, also the focus of this thesis is put on the relationship between coarse particle-inflow at times of enhanced precipitation.

Not all the correlative lines of Core 4 and Core 6 are straight-line connections with one another. This can be explained by the fact that they are taken at different locations. Even slight differences in sedimentation rates might let correlative sediment horizons occur at different sediment depth even in nearby fjord locations (e.g. Paetzel & Dale 2010). The same is true for setting up relationships between sediment parameters presented on a depth scale and independent variations presented on a time scale. Sedimentation rate are different from year to year, and even from season to season. This implies that differences will occur when compared with evenly spaced (time-)data. Thus, it is in this context more correct to talk about relationships and correlative horizons between the independent datasets rather than discussing statistic correlations.

The first couple of centimeters of the cores do not give an as clear signal as the sediment found at greater depth. The explanation is that the first couple of centimeters contain more water than the remainder of the core, leading to an artificially high sedimentation rate within the top sediment layer. These unconsolidated very recently deposited sediment surfaces would consolidate within a year, revealing lower sedimentation rates and thus clearer signals as the water content reduces (Syvitski et al. 1987).

Figure 10 shows the correlation between temperature and coarse grain sizes. This correlation is less strong than the one in the precipitation and coarser grain sizes. The reason for this is that the temperature and precipitation are linked to each other. So they both show a correlation, but the precipitation is the real source of the variability of the coarse grain size.

6.1. Box model

This box model illustrates the main processes in the Barsnesfjord and how these will be documented in the sediments. To make a box model it is important to know which parameters are linked to one another and to which sources. So, a short statement will be made on every parameter.

Grain size: the sand and silt fraction seem to be strongly influenced by precipitation (Figure 9).

Organic matter: The total organic matter fraction contains terrestrial and marine organic matter (Figures 12, 13 and 14). The marine organic matter fraction seems to have the dominating influence on the total organic matter.

Terrestrial organic matter: the terrestrial organic matter shows a clear correlation with the precipitation in Figure 11 and with the freshwater diatoms in Figure 15, 16 and 17. It also shows a slight correlation with organic matter in Figure 4, 5 and 6. It makes sense that freshwater diatoms and terrestrial organic matter are linked together. Terrestrial organic matter is supplied via runoff from rivers, lakes, and glaciers.

Marine organic matter: marine organic matter shows a relationship between marine diatoms and total organic matter in Figure 12, 13 and 14. Since marine organic matter is the other part of the terrestrial fraction, it should show a reversed correlation with precipitation and freshwater diatoms.

Pyrite: no relationship with pyrite was found. However, such relationship should exist as framboidal pyrite easily forms in times of anoxic sediment conditions (Syvitski et al. 1987). The reason for the missing relationship might be the fact that the pyrite fraction was estimated as part of the total mineral fraction (as pyrite is a mineral). However, the framboidal pyrite forms on organic matter and mostly on the marine organic matter fraction. Thus, framboidal pyrite should have been estimated as part of the marine organic matter fraction.

Precipitation: the precipitation shows a strong correlation to the temperature. A year with increased temperature is in most cases also a year with more precipitation as precipitation requires clouds and a cloud cover would effectively reduce the emission of heat into space (Paetzel & Dale 2010).

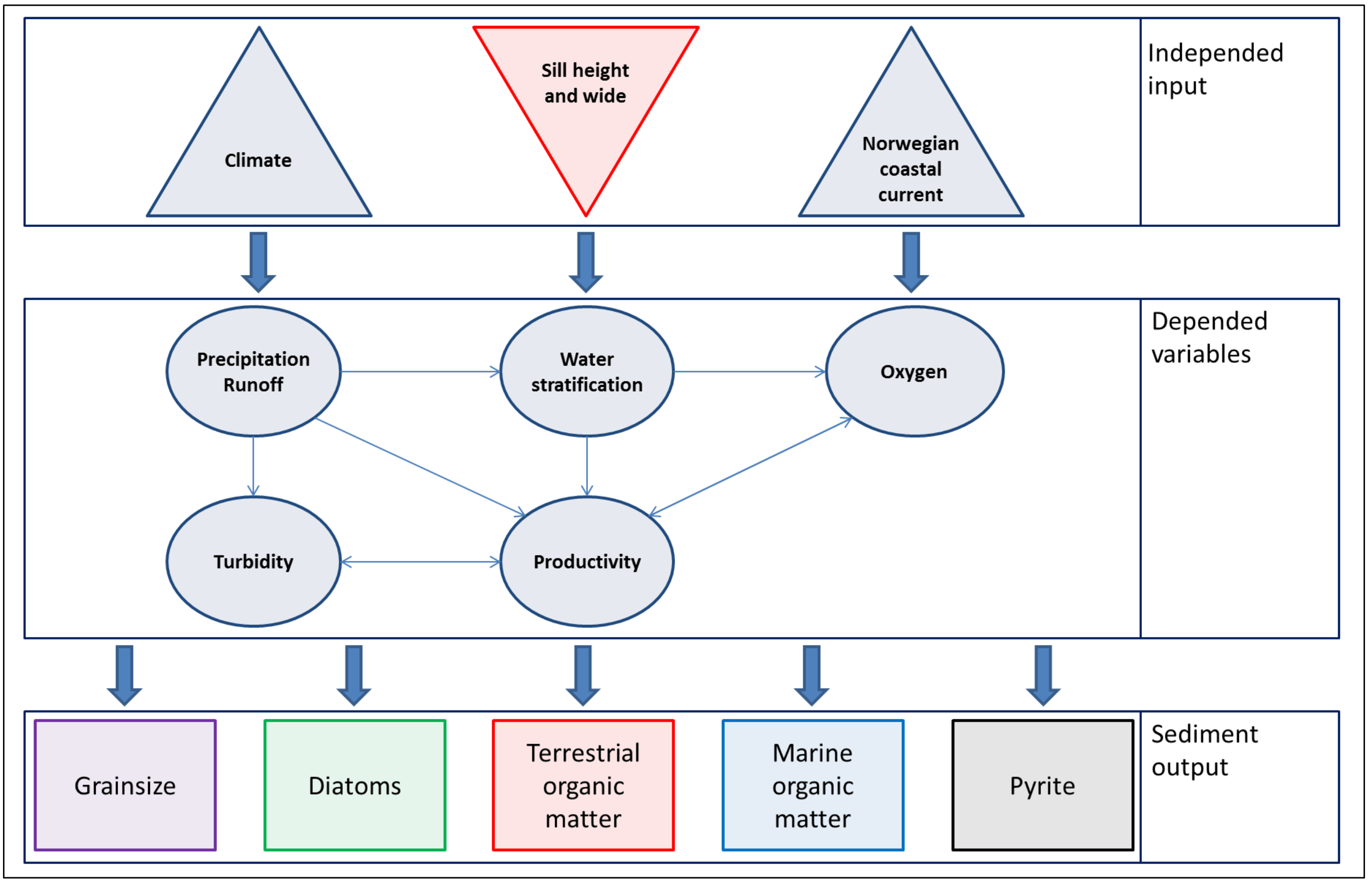


Figure 18 shows the box model. The upper triangles are the main independent sources that influence the particulate matter composition in the fjords. They have a major influence on the middle circles with dependent variables inside the fjord system. The dependent variables will define the sediment output (lower boxes).

In order to explain all the processes in this model (Figure 18), all the links and processes will be discussed in the following chapter according to the influence of the fjord independent variables climate, sill height and depth, and the Norwegian Coastal Current.

6.1.1. Climate

Climate is an important factor for the processes in the fjord and leaves a lot of traces behind in the sediment (Howe et al. 2010). Climate is here documented in terms of precipitation, temperature and seasons. The precipitation has a strong influence on the variability of the grain size and terrestrial matter, as shown in Figure 9 and 11. Increased precipitation causes a larger fraction of the coarser grain sizes and a larger fraction of the terrestrial organic matter fraction to enter the fjord via rivers, lakes and glaciers, leaving its trace in the fjord sediment.

Runoff defines the amount of freshwater that is coming down from the mountains, including the influence of precipitation and glacial runoff. This freshwater will enter the fjord surface waters mix with the waters from the Norwegian coastal current by the process of estuarine circulation (Syvitski et al. 1987). Because this current is blocked by the 9 m deep sill at Loftesnes this mixing process is interrupted in periods. In years with higher precipitation, the brackish water column encroaches to deeper parts of the Barsnesfjord because the increased amount of fresh water mixes with the marine water making more brackish water. The brackish water flow out to the Sogndals fjord and the sea. Thus, the amount of marine water is declining until a new inflow event replaces the old, less saline, and oxygen poor Barsnesfjord basin waters with new, more saline, and oxygen rich seawater (Kaufmann 2014).

In years with increased precipitation the runoff is higher, eroding and transporting more particles. This gives the fjord an increased turbidity. The increased turbidity decreases the penetration depth of light in the fjord water, thus reducing primary production (Dale and Hovgard 1993; Torbjørn Dale 2014, *personal communication*). This is a disadvantage for marine plankton since they cannot live in the upper fresh and brackish water layers.

In years of increased primary productivity, more organic matter will slowly sink to the bottom of the fjord. While sinking to the bottom, a lot of organic matter will be decomposed by biodegradation. This process also uses a lot of oxygen. When the organic matter reaches the fjord bottom and starts to accumulate, the oxygen levels in the sediment might even drop below the critical level of below 2 mgO_2/l (Syvitski et al 1987). Below this level live is not possible. In the Barsnesfjord this process causes the Outer Barsnesfjord to be partly anoxic and the bottom of the in Inner Barsnesfjord to be anoxic (Dale and Hovgaard 1993; Kaufmann 2014). Since there is less oxygen available, more organic matter starts to reach the bottom. The increased amount of organic matter and the low oxygen level allows forming of framboidal pyrite. Thus, during anoxic conditions, an increase of pyrite should be visible in the sediment (Matthias Paetzel 2014, *personal communication*).

Years with an increased temperature are correlating with years of increased precipitation. Seasons also have their influence on the fjord. In the spring and summer there is an increased runoff of melting snow and ice from the mountains. This melt water flow to the fjord and mixes with the marine fjord water to form brackish water and flows eventually to the sea.. In times of increased freshwater, originating from snowmelt in the mountains, the fresh and brackish water layer increases in depth and the marine water column decrease to a greater depth in the fjord. During winter, the freshwater input is significantly decreased. This process increases the chances of basin water renewal in the Barsnesfjord during winter (Dale & Hovgaard 1993; Kaufmann 2014). In addition, western storms could press the more saline waters over the sill into the Barsnesfjord during autumn and winter (Torbjørn Dale 2014, *personal communication*).

6.1.2. Norwegian coastal current

The Norwegian coastal current supplies most of the oxygen and marine water to the fjords. The temperature of this water remains constant at approximately 6 to 7°C (Kaufmann 2014). The high salinity of the marine water causes strong water stratification, separating the saline deeper fjord water masses from the brackish surface waters. This stratification together with the sill, blocks possibility for marine water to flow into the Barsnesfjord, thus restricting the renewal of the basin waters.

6.1.3. Changes at the sill

The influence of sill depth and width on the water inflow can be summarized by simple comparisons: (a) the narrower the sill, the faster the speed of the inflowing water. Increasing turbulence could lead to a stronger mixing of the surface waters (Golmen 2003); and (b) the shallower the sill, the smaller the possibility of deep water renewal in the Barsnesfjord (Matthias Paetzel 2014, *personal communication*).

Due to the building of the new Loftesnes Bridge in 2014, it is that the frequencies of inflow events into the Outer Barsnesfjord basin will decreases, thus restricting the water renewal of the fjord waters. Oxygen levels are expected to stay low or even further decrease in the deeper parts of the Barsnesfjord. Under such conditions, the deepest waters layers of the Inner and Outer Barsnesfjord can more often reach levels below 2 mgO_2/l. These conditions would make it impossible for organisms to live. It will favour the forming of framboidal pyrite causing an increase in the pyrite fraction in the future.

There is also the possibility of the brackish surface water layer remaining longer in the Barsnesfjord, thus increasing water stratification caused by an increased brackish water column. This effect might increase the probability the formation of ice cover during winter. Further, an increased water column of brackish water will slow brackish water flow to the Sogndalsfjord and thus extend the time it remains in the Barsnesfjord. The longer the brackish water remains in the Barsnesfjord, the more of the fine grained mineral grain sizes would settle and accumulate in the sediment.

In addition, the increased brackish and freshwater layer might block the sunlight. Sunlight is crucial for marine primary productivity. Reduced primary productivity would imply less consumption of oxygen due to less decomposition of organic matter. This should show up in the sediments by a decrease of marine organic matter, a decrease in marine diatoms, and in a lesser degrease of total organic matter. The brackish and freshwater layers are bigger allowing more primary productivity for freshwater organisms. An increase of freshwater diatoms is predicted. The fraction of terrestrial organic matter is expected to increase as well which is caused by the extended time it takes to settle in the Barsnesfjord and the decrease in marine organic matter.

To summarise, the planned infill of the sill between the Sogndalsfjord and the Barsnesfjord is expected to influence the hydrography leaving traces in the sediment.

7. Conclusion

It is possible to date the sediment cores from the Barsnesfjord on an annual to decadal time scale over the past 30 to 50 years.

The succession of changing Barsnesfjord sediment parameters can be related to the variability of environmental and climate change of the last 30 to 50 years.

A box model has been constructed in order to predict the influence of expected future environmental change on the Barsnesfjord system, based on the record of environmental change as reconstructed from the Barsnesfjord sediments throughout the last 30 to 50 years.

References

Clark P.U., Dyke A.S., Shakun J.D., Carlson A.E., Clark J., Wohlfarth B., Mitrovica J.X., Hostetler S.W. & McCabe A.M. 2009: The last glacial Maximum. Science 325 (5941), 710-714.

Golmen L. G., Lundmark K. & Åtland Å. 2010: New bridge at Loftesnes in Sogndal. Environmental consequence assessments, Norwegian Institute for Water Research, NIVA Rapport Nr 5899 Loftesnes-Sogndal.

Golmen L. G., Molvær J. & Bjerknes V. 2003: A prestudy for the propose of the new Loftesnes bridge in Sogndal, Norwegian Institute of Water Research, NIVA Rapport Nr 4718-2003.

Kaufman S. 2014: A 100 year hydrographic record of the Barsnesfjord, Western Norway and its environmental application.

Niemistö L. 1974: A Gravity Corer for Studies of Soft Sediments. Merentutkimuslait, Julk/Havsforskningsinst, Skr. 238, 33-38.

Paetzel M. & Dale T. 2010: Climate proxies for recent fjord sediments in the Inner Sognefjord region, western Norway. *In:* Howe, J. A., Austin, W. E. N., Forwick, M. & Paetzel, M. (eds) Fjord Systems and Archives. Geological Society, London, Special Publications 344, 271-288.

Paetzel, M. & Schrader, H. 1991: Heavy metal (Zn, Cu, Pb) accumulation in the Barsnesfjord: Western Norway. Norsk Geologisk Tidsskrift 71, pp. 65-73.

Paetzel M. & Schrader H. 1992: Recent environmental change recorded in anoxic Barsnesfjord sediments, western Norway. Marine Geology 105, 23-36.

Rothwell R.G. 1989. Minerals and Mineraloids in Marine Sediments: An optical identification guide, Elsevier Applied Science, London, 279 pp.

Syvitski J.P.M., Burrell D.C. & Skei J.M. 1987: Fjords. Springer-Verlag, New York, 378 pp.

Wentworth C.K. 1922: A scale of grade and class terms for clastic sediments. Journal of Geology 30, 377-392.