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Natural and anthropogenic deposition in Bøkfjorden

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Abstract

The aim for this study is to characterise and distinguish natural and anthropogenic deposition in Bøkfjorden, and to identify the spreading and the impact of submarine tailings placements on the seafloor. The analyses are based on the integration of swath bathymetry, high-resolution seismics and multi-proxy analyses of four sediment cores

The physical properties, including magnetic susceptibility and wet-bulk density, of the sediment cores were measured with a Multi Sensor Core Logger (MSCL). Element-geochemical measurements were performed with an Avaatech XRF core scanner. In addition, grain-size distribution analyses and measurements of the shear strength was carried out.

The bathymetry reveals a generally northwards sloping of the sea floor that is cut by a channel, which acts as a pathway for submarine tailings placements and the channel follows the deep part of the fjord basin.

The high-resolution seismics data and sediment cores revealed three different sedimentary environment: glacier proximal (deglaciation), open marine (postglacial) and anthropogenic (mine tailings placements). The glacial proximal stratification reflected repeating changes in the depositional environment. The open marine environment is reflected as massive deposits accumulated from mass wasting and suspension settling. Anthropogenic deposits are found in the form of submarine tailing placements. The submarine tailings reflected massive sedimentation and repeated change in the deposition of tailings. The majority of the submarine tailings placements occurs close to the depositional site in the vicinity of the fjord head. However, these deposits became unstable occasionally and the failed tailings were transferred over at least 13.2 km through the channel and into the deeper parts of the fjord.

Acknowledgement

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1 Introduction

1.1 Objectives

The overall goal of the project is to characterise and distinguish natural and anthropogenic deposition in Bøkfjorden and to identify the spreading and impact of submarine tailings placements on the seafloor of the fjord. This goal shall be achieved by:

- Integration swath bathymetry, high-resolution seismics and lithological data, including:

a) Mapping of the seafloor morphology.
b) Studying sedimentary processes and sediment distribution.

1.2 Background for the study

This master projects, together with two other master projects, are a part of the NYKOS (New knowledge on Sea Disposal, https://www.sintef.no/projectweb/nykos/) project, which was started in 2014 by Sintef, NTNU, NIVA, UiT and NGU, in cooperation with the following mining companies: Nussir, Sibelco Nordic, Sydvaranger Gruve AS, Omya Hustadmarmor, Nordic Mining, Rana Gruber and Titania.

The objectives of the NYKOS project are to increase knowledge of the environmental effects of submarine deposition of fine grained tailings from the mineral industry and enable development of new sound environmental criteria and monitoring technologies that prepare for a sustainable mineral industry in Norway.

2 Background information

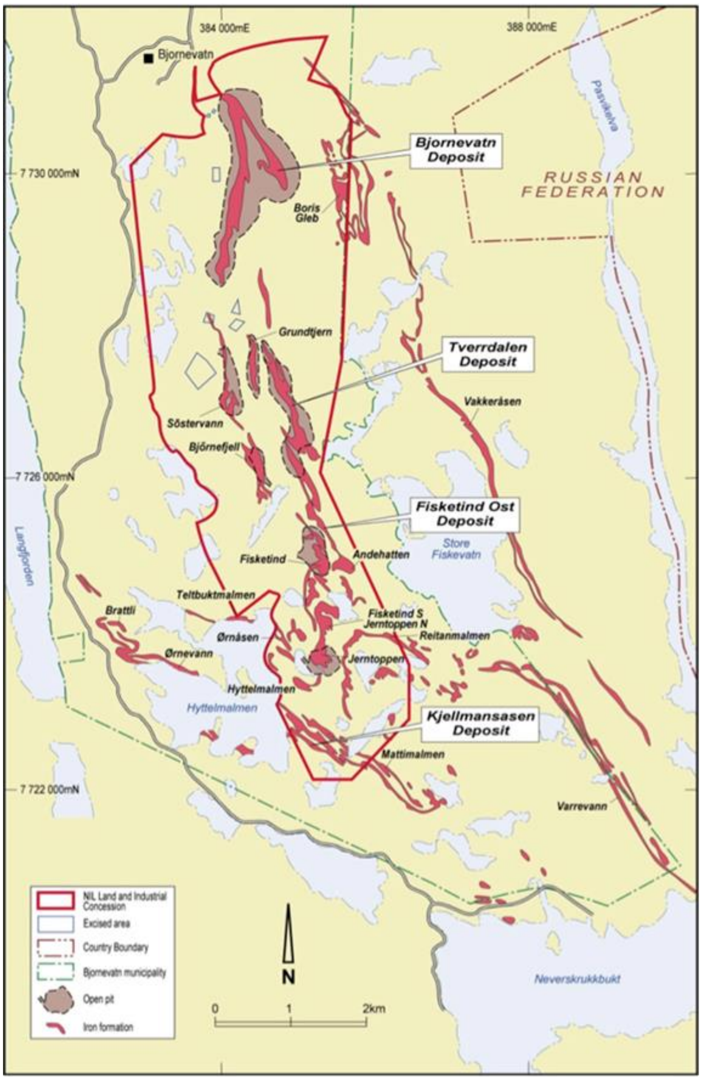

Figure 1: Overview of the mine deposits in Bjørnevatn that Sydvaranger Gruve AS was extracte iron ore from (Picture from Carstens, 2014)

South of Bjørnevatn there are 23 separated iron ore deposits with more than 400 mill. tons ore (Carstens, 2014). 280 mill tons of this iron ore are located in Bjørnevatn, this is the largest deposits as represented in Figure 1. In Bjørnevatn there are three massive zones of ore with up to 35 % iron. This is low compared to other parts of the world like Australia and Brazil that have over 65 % iron. The iron ore is also hard and that make it very costly to extract. The main reason for extracting this ore is that the ore at Bjørnevatn contains magnetite. Nearly all the other mines in the world extract hematite. To transform hematite to steel you need five times as much energy than if you do it with magnetite. The infrastructure around Kirkenes make it easy to transport the ore to the rest of the world with train or ship (Carstens, 2014). It was this iron ore Sydvaranger Gruve AS extracted, the ore was transported to a factory in Kirkenes before the mine tailings was deposited in Bøkfjorden. An overview over the area is represented in Figure 2.

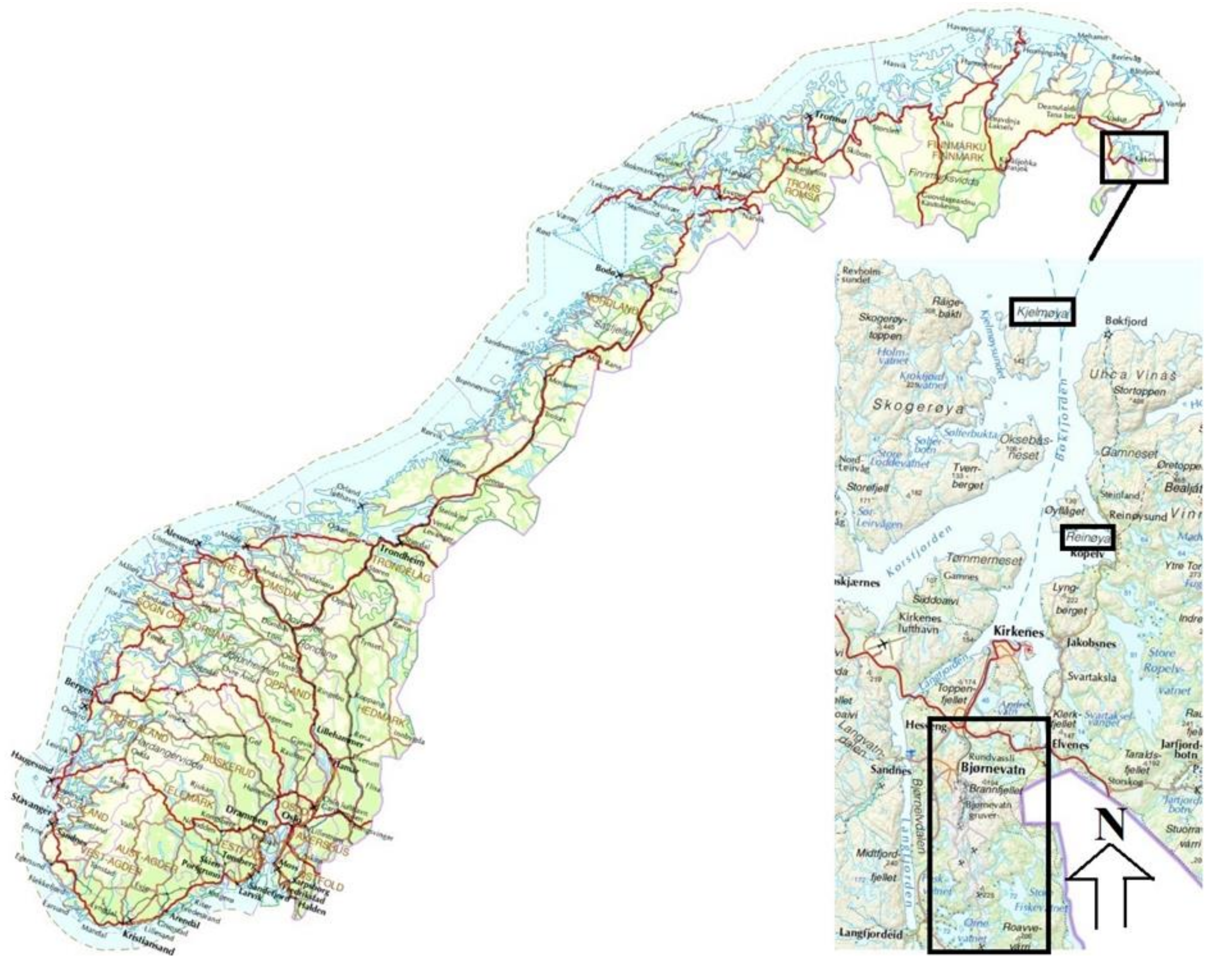

Figure 2: An overview of the area, the mine area is marked in a large square. The two main islands is marked with small squares. Kirkenes, Bøkfjorden and Korsfjorden is also represented in the figure.

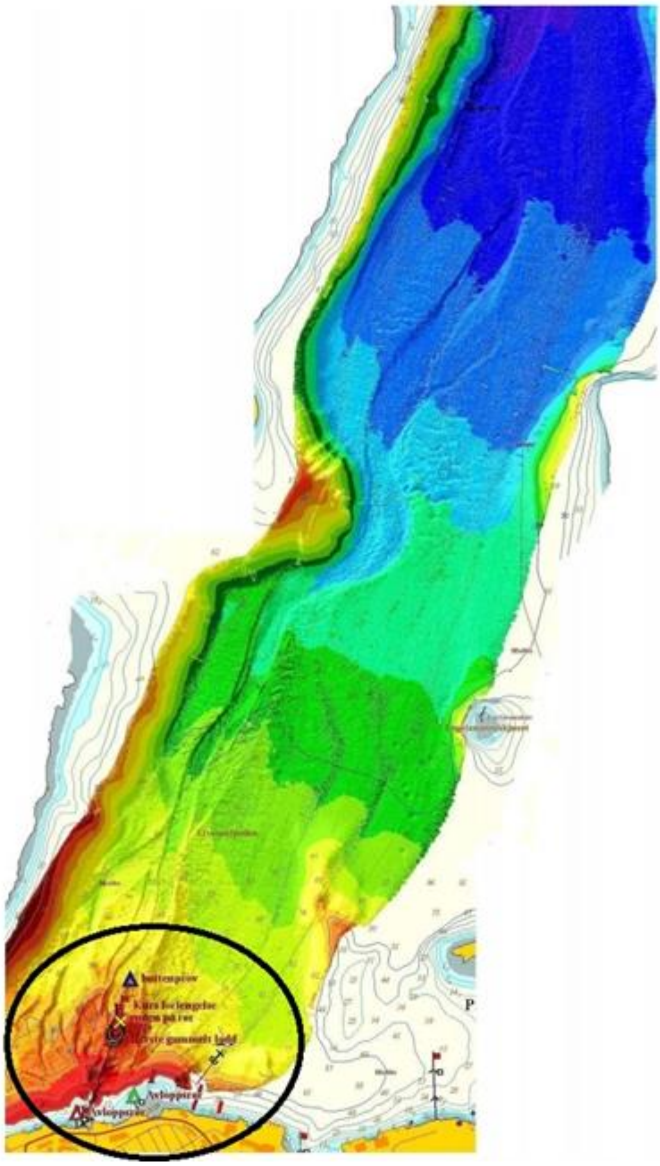

Figure 3: The circle indicate where the mine tailings was last deposited (photo from Øie, 2013)

Before 1976 Sydvaranger Gruve AS deposited mine tailings in Langfjorden and this build up a large slam bank (Kvassnes & Iversen, 2013).The latest deposition site of mine tailings are deposited 450 m from the Sydvaranger dock on a depth of 27 meters as represented in Figure 2 (Toresen & Fosså, 2009; Ramirez-Llodra et al., 2015). Figure 2 also show the channel that are eroded from the mine tailings, the channel stops SW for Reinøya approximately 4.7 km from deposition site (Øie, 2013). Sydvaranger Gruve AS had what is called an open pit mine represented in

Figure 4. In the latest permission Sydvaranger Gruver AS was allowed to deposit 4 mill. tons of mine tailings per year and up to 50 tons flocculation per year whereas 10 tons could be Magnafloc LT38 (Berge et al., 2012; Berge et al., 2014). More information about the flocculation used by Sydvaranger Gruve AS see chapter 4.4.

Figure 4: Open pit mine (Multiconsult, 2008-2009).

3 Previous investigations

In order to obtain the permission to deposit submarine tailings placements on the seafloor of Bøkfjorden, Sydvaranger Gruve AS provided numerous reports addressing how the mine tailing will affect every aspect of the fjord basin. In this chapter the main findings will be presented.

Skei and Rygg presented the first report in 1989 for the Norwegian Water Institute in cooperation with A/S Sydvaranger. This report was taking a closer look on the sediments and the mollusc fauna. Their many findings were summarized in three points (Skei & Rygg, 1989):

- *The sediments were affected by the mine tailings 13 km from Kirkenes with a seafloor areal of 26 km^2.*
- *The seafloor fauna was affected moderate in a radius of 7 km from Kirkenes (Reinøya, see Figure 2)*
- *The likelihood that the seafloor in Varangerfjorden was being affected was close to zero.*

In 1989 Sydvaranger Gruve AS was also allowed to discharge approximately 1.7 tons of mine tailings per year (Skei & Rygg, 1989).

In addition to this report, Skei provided an additional report in 1990 about the particles in the water masses that supports the findings from 1989 (Skei & Rygg, 1989; Skei, 1990). Most of the mine tailings will sink to the bottom because saltwater is pumped into the discharge pipe and the water consists of a high solid solution and traps the mine tailings in Bøkfjorden. The mine tailings create large build-up of material and this will eventually turn into an erosive gravity flow that will make a channel on the sea floor (Skei, 1990).

Then in 1995 a new report was completed with the previous reports as a basis (Skei & Rygg, 1989; Skei et al., 1995). The conditions in Bøkfjorden were unchanged but some new findings were discovered (Skei et al., 1995). The report was written because Sydvaranger Gruve AS wanted to increase the discharge amount from 1.7 mill tons per year to 2.2 mill tons per year, as well as the amount of the flotation chemicals from 21 tons per year to 50 tons per year (Skei et al., 1995). The report state that a cloud of deposited material could be seen in a depth of 30- 40 meters (the depth increases away from the deposited site) all the way to the intersection between Bøkfjorden and Korsfjorden as represented in Figure 2 (Skei et al., 1995). Mine tailings in Bøkfjorden are characterized by low organic carbon and high iron contents. Analyses of iron and organic material in Bøkfjorden indicate that the whole fjord system is influenced by mine tailings. The report concluded that it will take fifty years after termination of the mine activities to rebuild the environment, because the natural sedimentation is around 2 mm/year. (Skei et al., 1995).

The next report was written in 2007 when new owners had taken over after the closure of the mine in 1997 (Skaare et al., 2007). The new owners needed to get a new permission to start up the production. Therefore Sydvaranger Gruve AS contacted the Norwegian Water Institute to make a new report. The conditions in Bøkfjorden had changed to the better due to the termination of the mine. The changes could also be seen in the sediments where there was an increase in organic carbon content and the vertical iron content was decreasing (Skaare et al., 2007). The inner part of the fjord also consists of coarser material than before. There was also discovered that red king crab had invaded the area. Making the sediments more stirred and therefore more oxidized. The red king crab also eats the organisms living on the seafloor. The authors were not sure about the long-term effect these red king crabs will have on the environment in Bøkfjorden (Skaare et al., 2007). The main conclusion was that if Sydvaranger Gruve AS was granted permission to start up the mines again, this will probably mean that the conditions on the seafloor will return to the same condition as in the 1990`s.That is why the Norwegian Water Institute is recommending that if Sydvaranger Gruve AS starts up again, a surveillance program should be established to monitor the impact the mine tailings on the environment in Bøkfjorden (Skaare et al., 2007).

Following this recommendation Sydvaranger Gruve AS sent an application about changing the discharge permit to the State Pollution Control Authority (SPT). The application was forwarded to the Institute of Marine Research. Sydvaranger Gruver AS wanted to increase the mine tailings from 4 million tons per year to 9 million tons per year (Toresen & Fosså, 2009). They also wanted to increase the use of Lilaflot D817 (a flocculation chemical). However this chemical is on the SPT red list over dangerous chemicals, because it still unknown the full effect this chemical will have on the environment and the organisms. As Sydvaranger Gruve AS did not include any grain-size analyses into the new application, it was hard to distinguish the ratio between fine-grained and coarse grained mine tailing (Toresen & Fosså, 2009). Further it will be hard to predict the consequence this increase will have on the environment. In Bøkfjorden there are strong tides that can carry the finer grains far out in the fjord. Sydvaranger Gruve AS wanted to make the discharge pipe longer to make the impact of the mine tailings at a minimum (Toresen & Fosså, 2009). The Institute of Marine Research wanted the SPT to look closer on the discharge permit Sydvaranger Gruve AS already had. They also strongly recommended an impact assessment to look at the risk the mine tailing already crated for the environment and organisms (Toresen & Fosså, 2009).

In 2010 a new report complied on the request from Sydvaranger Gruve AS to get permission to deposit up to 4 mill tons per year mine tailings and 35 tons per year of flocculation chemicals (Berge et al., 2011). Right before the work started Sydvaranger Gruve AS discovered that the mine tailings were deposited on 50 m instead of 28 m and that this most likely had been the case for half a year. This is why the result may not show the normal situation for discharge of mine tailings at Sydvaranger Gruve AS (Berge et al., 2011). The condition in a radius of the 4 km from Kirkenes was deteriorated between 2007 and 2010. There was a strong particle influence within the deposited site, without the top 15 m of the water column. This is probably because the mine tailings are sinking. The turbidity maximum for the inner fjord was at a depth of 20-60m (Berge et al., 2011).

There was made a report in 2012 building on the findings in 2011 (Berge et al., 2012). In this report that state that at least the top 20 meters of the water column in the whole fjord system is undisturbed by mine tailings. The influence on the seafloor is still affected negative from Kirkenes- Reinøya (Berge et al., 2012).

Then in 2014 a new report was made to have a closer look on the flocculants the used at Sydvaranger Gruve AS (Berge et al., 2014). Berge et al. used DOC-analyze in the absence of a better method. The conclusion after numerous tests was that the short term and long term effect of this flocculants on the environment was low.

After this report Sydvaranger Gruve AS wanted to increase the use of polyDADMAC (Magnafloc LT 38) from 10 tons per year to 22 tons per year (Christiansen & Moen, 2014). The reason to maintain good enough quality of the iron ore concentrate and the importance of reusing the water. The application was sent to the County Governor in Finnmark. The County Governor is not positive to this increase, mainly because there are few test conducted on polyDADMAC (Christiansen & Moen, 2014). This is already a weakened environment and the County Governor is not sure how much more it can withstand. Since this is on the Finish boarder they also recommend the Norwegian environment agency to treat this according to the Espoo-Convection and send the application to Finland for them to make a statement (Christiansen & Moen, 2014). 17. December the Norwegian Environment Agency receive the recommendation from the County Governor in Finnmark (Sørby & Slaire, 2015). Sydvaranger Gruve AS need to use more flocculates as polyDADMAC to be able to continue to extract iron ore, due to sliding. The Norwegian Environment Agency conclude with that the positive side contemplates the negative. Sydvaranger Gruve AS is granted to increase the use polyDADMAC to 22 tons per year. This shows the mineral law first hand that the county director of Finnmark can promote his point of view, but at the end it is the Norwegian environment agency that make the final decision (Sørby & Slaire, 2015). To read more about the mineral law see chapter 4.2 the mineral law.

4 Description of the mine

4.1 Sydvaranger Gruver AS

Tellef Dahll discovered the iron ore in 1866 that was the start of what later became A/S Sydvaranger in 1906 (Ramberg et al., 2013). A/S Sydvaranger started their production in 1910; due to advanced technology that made it possible to extract the iron ore form the mine (Sydvaranger Gruve AS (a), 2016). In the start the mine was followed by crises, war and business cyclicality. Towards the end of the war, 1944, Germans destroyed the mine because of the Russian invasion of North Norway. After the war the mine was rebuild by the directorate of hostile property company and the state wanted to restart the production and had 43 % of the holdings in the mine. In 1981 the state had brought 87.45 % of the holdings in the mine, because the mine was in desperate need for fresh capital (Sydvaranger Gruve AS (a), 2016). In 1997 when the iron ore prices dropped drastically, due to cheaper and higher- quality ore from other parts of the world. At the end of 2000 Varanger Kraft had brought all of the holdings in the mine. Sydvaranger Gruve was then sold to Tschudi Shipping Company in 2006. The year after Northern Iron Ltd was founded to reopen the mine and the name was changed to Sydvaranger Gruver AS. Under Australian owners the mine was reopened in 2009 and 31. August 2010 the mine was official opened (Sydvaranger Gruve AS (a), 2016). In 2015 the board in Sydvaranger Gruve AS announced a new bankruptcy. The mine was shut down again because of the low iron ore price and the mine could not pay the debt. Sydvaranger Gruver AS will go into the history books as one of giant in Norwegian mining (Ramberg et al., 2013)

4.2 The mineral law

In 2009 a new law was established to promote and ensure the societal justifiable management and follow the principles for a sustainable development (Næring- og fiskeridepartementet, 2009). In Finnmark the law is special strict to ensure that all aspect is taken into consideration. This mean that the Norwegian environment agency needs to consult the landowner, the Sami parlament of Norway, the commune, the county governor and the district board for drift of reindeers before making a decision. If Sydvaranger Gruver AS wanted to change the current amount of deposition per year they need to contact NVE-The Norwegian Water Resources and Energy Directorate to do an assessment of the current condition of the fjord. All the findings were then put into a report and sent in with the other recommendation from the other agency. Then the Norwegian environment agency has to make a decision based on these recommendation (Næring- og fiskeridepartementet, 2009).

4.3 Iron ore – definition and formation

An iron ore is defined by a raw material that has enough iron ore to make metallic iron (Sverdrup, 2009). Often it is also added that there has to be a financial gain for the iron ore to be extracting. The iron ore minerals with highest economic value are hematite and magnetite (Sverdrup, 2009). At Sydvaranger Gruver AS they use magnetite (Fe_3O_4) that have an iron contain of 72.4% (Ramirez-Llodra et al., 2015).

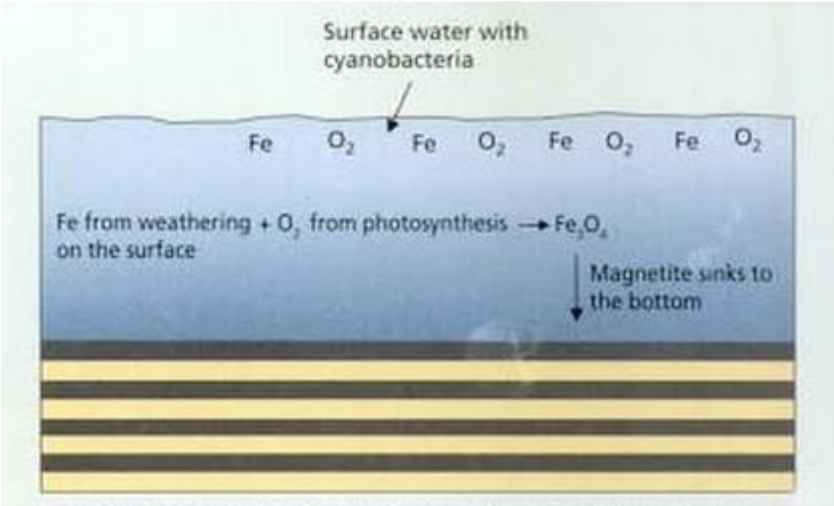

Figure 5: Formation of Bonded Iron formation (BIF) is formed. Iron oxide, magnetite (Fe_3O_4) and hematite (Fe_2O_3), are formed when free oxygen and iron ions are binding together. The dark bands are magnetite/hematite and the yellow bands are jasper. This bands can be from one millimetre up to a few centimetres. (Picture from Ramberg et al., 2013).

This iron ore is believed to have formed from the late Archaean to up to about 1800 million years ago (Ramberg et al., 2013). It is a part of a worldwide group of sedimentary ore deposited often referred to as the Banded Iron Formation or BIF (Figure 5). The BIF was formed due to the release of iron ions (Fe) when the rocks on the continent start to break up, due to the low amount of oxygen in the atmosphere the iron was transported to shallow basins as ions (Fe) (Ramberg et al., 2013). In these shallow basins the iron ions (Fe) reacted with the oxygen (O_2). The oxygen was a waste product from the photosynthesis of cyanobacteria. This reaction formed iron oxides as haematite and magnetite and it will sink to the bottom. When the cyanobacteria bloomed a surplus of oxygen gradually build up. This ended with that many cyanobacteria died and this lead to perception of silicon dioxide in form of jasper. After some time the conditions could change again and a new circle begun. This ended when the oxygen in the atmosphere increase (Ramberg et al., 2013). The iron ore in Kirkenes is what is could a quartz bearing iron ore, one layer of iron ore and on layer of quartz as represented in Figure 6.

Figure 6: Iron ore from Sydvaranger Gruve AS. (Photo from Carstens, 2014).

4.4 Separation process and chemicals

Sydvaranger Gruver AS used a processes called the ”wheat process” to disguise the ore from the rest of the material (Sydvaranger Gruve AS (b), 2016). The raw ore is crushed to fine particles and water is added to separate the iron ore from the rest of the raw material with the help of electromagnets. This process is time consuming and a large amount of freshwater is needed (Sydvaranger Gruve AS (b), 2016). There are no large freshwater resources in the area, so Sydvaranger Gruver AS re-used the water before entering the fjord. Since mine tailings are fine grained material, chemicals and flocculants are added to make the small particles bind to each other so it easier to filtering it out before it entering the fjords (Sydvaranger Gruve AS (b), 2016).

Sydvaranger Gruve AS also used different flocculation chemicals (Berge et al., 2012). In the beginning Sydvaranger Gruve AS used Magnafloc 10, Magnafloc 155 and Magnafloc 1707. Later Sydvaranger Gruve was allowed to change Magnafloc 1707 to Magnafloc LT 38. Magnafloc LT38 is a coagulant and where the active substance, polyDADMAC, have a longer active chain length than polyacrylamide that are the active component in Magnafloc 10 and magnafloc 155 (Berge et al., 2014). Polyacrylamide is a water-soluble polymer of acrylamide. The active component in Magnafloc LT38 is polyDADMAC (2-Propen-1aminium, N,N-dimethyl-N-2-propenyl-chloride). PolyDADAMAC is a water soluble polymer that is used world-wide for water purification (Wilson, 2008). The polymer of PolyDADAMC is very stable and will only change structure due to extreme pH, temperature or UV conditions (Wilson, 2008). On the homepage Sydvaranger Gruver AS state that polyDADMAC is used in shampoo and conditioner and the amount released in Norway is at least 160 tons/year (Sydvaranger Gruve AS (b), 2016).

4.5 Tailing disposal methods

There are many different ways to deposit mine tailings like coastal tailing disposal, submarine tailing deposit disposal, deep-sea tailing placement and some in landfills (Ramirez- Llodra et al., 2015). In the early days riverine deposits was the most common, but after a dam failure in Papua New Guinea the waste was deposited directly in the Ok Tedi and Fly river system. These caused large environmental and societal impact from 1983 – 2013, the consequence was that all countries forbid riverine discharge, without 1 in Indonesia and 3 in Papua New Guinea. After riverine depositing was forbidden in many countries the continued with the landfill (Ramirez-Llodra et al., 2015). Landfill is also competing with other activities including farming, agriculture, recreation etc. Today more and more countries use marine systems for depositing the mine tailings. This seems like a less harmful way then the landfill. Every year there are 2-5 major dam failure and 35 minor. This because the landfilled are put in dams that are constructed in naturally depressions zones. Often there are poor management of this dams that lead to failure, leaching of toxic chemicals and heavy metals and acidification of waterways. The dams are also very vulnerable to natural changes e.g. earthquakes and precipitation (Ramirez- Llodra et al., 2015).

There are three ways to deposited mine tailings into the marine environment, Coastal Tailing disposal (CTD), Submarine Tailing Disposal (STD) and Deep-Sea Tailing placement (DTSP) represented in Figure 7.The CTD is when the tailings are deposited in the water surface in the euphotic zone. There is some debate if this is the best because of the consequence for the diversity of life in the euphotic zone and the impact on the shoreline (Ramirez- Llodra et al., 2015). This practice is still used in Papua New Guinea. DSTP is when the mine tailings are deposited in waters deeper than 100 meters through a submerged pipeline below the euphotic zone. The mine tailings create a gravity flow and are deposited on the seafloor below 1000 m depth. With sub marine tailing the pipeline deposited mine tailings on shallow water (<100 m) that submerged water depths in the euphotic zone (Ramirez- Llodra et al., 2015). This mine tailings will submerge the euphotic zone. These mine tailings are deposit quite fast and this can create a turbidity flow. A turbidity flow can have a velocity up to 25 m/s and a thickness of several hundred meters (Ramberg et al., 2013). These gravity flows can result in that the mine tailings submerged all the way to the fjord bottom (Ramirez-Llodra et al., 2015). This is common in fjord basins in Norway, Canada and Greenland. STP was the tailing disposal methods Sydvaranger Gruve used. The mine tailings from Sydvaranger Gruver AS mainly consist for quartz, amphibolite and some magnetite (Berge et al., 2011). Sydvaranger Gruve AS says on their homepage that they believe that sea fill is less harmful to the environment than other deposition methods (Sydvaranger Gruve AS (c), 2016). Further, they say that is very important to know all the aspects within the fjord, like water temperature, chemical composition and know as much as possible about the mine tailings. This will reduce the risks of harming the environment unnecessarily. At Sydvaranger Gruver AS the ore is oxidized and, therefore, does not contain any heavy metals (Sydvaranger Gruve AS (c), 2016). Heavy metals are very dangerous for the habitat, because some of it is bioavailable (Ramirez-Llodra et al., 2015). This means that they can be stored in the animals that may die because of the contamination/pollution.

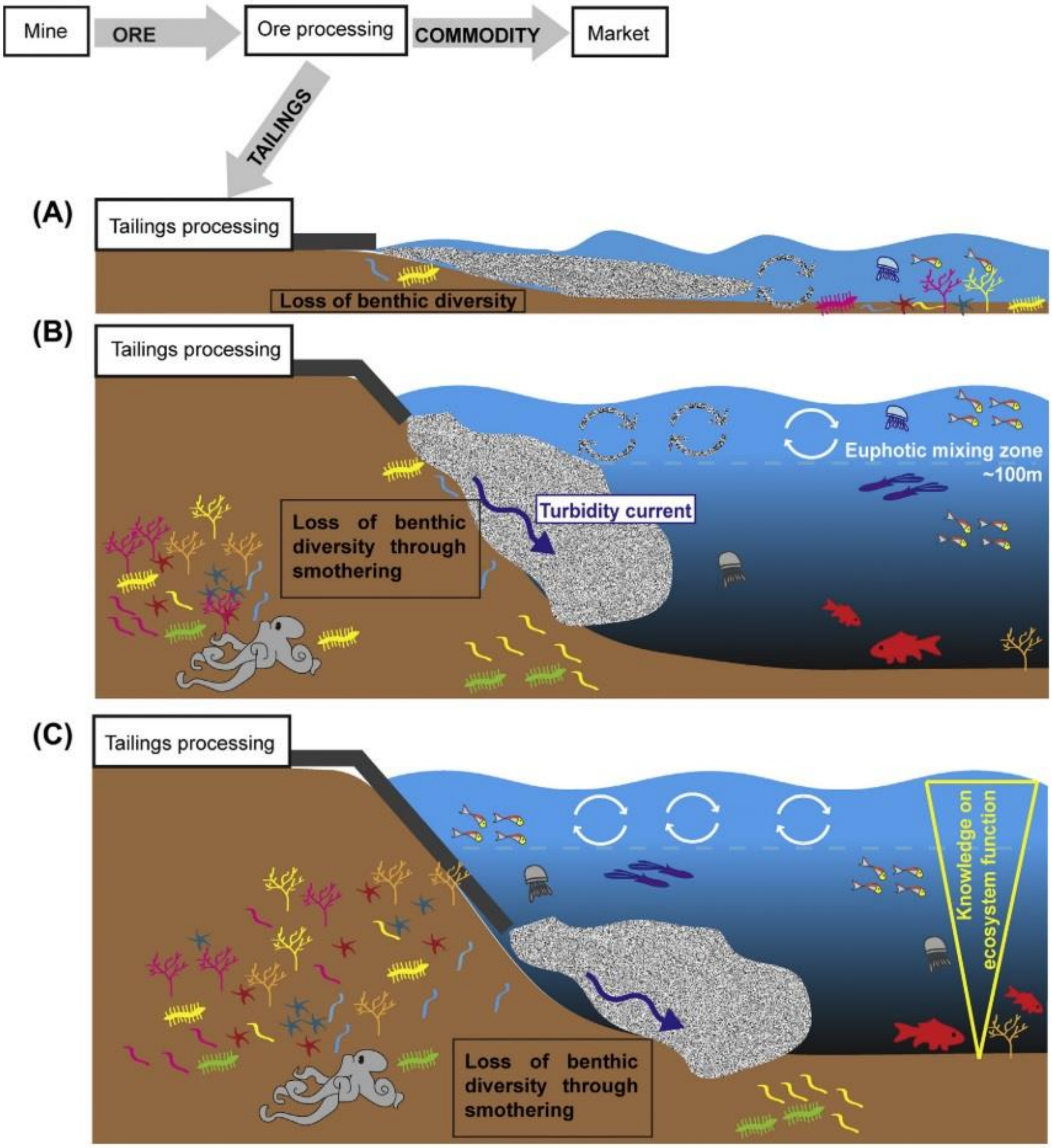

Figure 7: Different Mine Tailings: A) Coastal Tailing Disposal B) Submarine Tailing Disposal and C) Deep-Sea Tailing Placement (photo from Ramirez-Llodra et al., 2015).

5 Description of the area

5.1 Physiographic setting

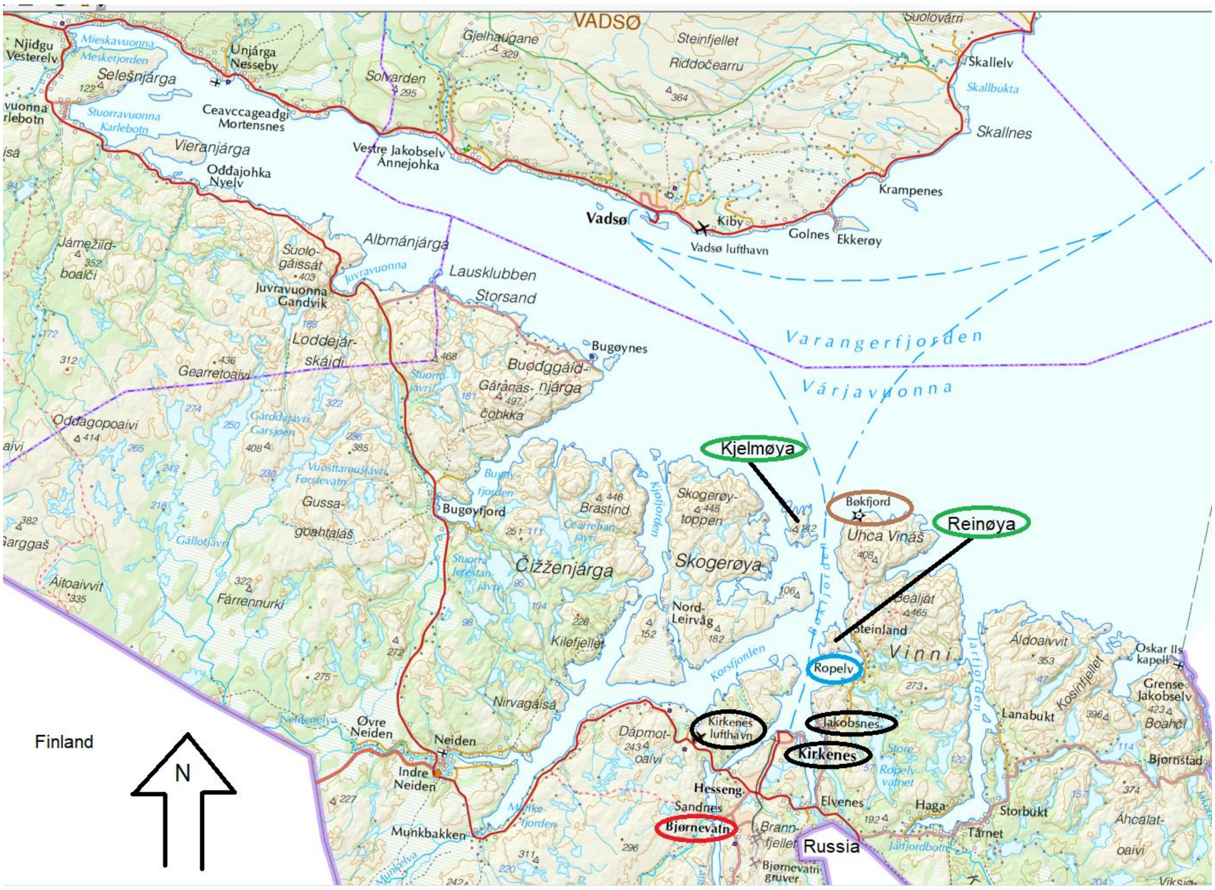

Figure 8: The area around Bøkfjorden. The black circle is important, green circle is the islands and the reed circle is the mine, the blue is one of the rivers in the area and the brown is the Bøkfjorden lighthouse. Korsfjorden and Varangerfjorden is also represented.

Bøkfjorden (69.83362 N, 30.053345 E- 69.875310N, 30.113416E) is a north-south directed fjord in the northern part of Norway and the southern fjord arm of Varangerfjorden (Figure 8). The fjord is 23 km long and between 0.6- 2.5 km wide. The depth varies from 9 m in the inner most part of the fjord to around 254 m in the outer most part. A sill is separating Bøkfjorden from Varangerfjorden; it limits the water exchange between the two fjords (Berge et al., 2012). In Bøkfjorden there are two large islands Kjelmøy in the outer part and Reinøya in the inner part represented in Figure 8. Approximately 10 km south of Kjelmøy and just west for Reinøya, Korsfjorden merges together with Bøkfjorden. Korsfjorden has an open water pathway to Kjølfjorden and Neidenfjorden. In the inner most part of Bøkfjorden the town of Kirkenes is located. Bøkfjorden continues on the eastern side of the town and end in the settlement of Elvenes near Russian boarder. At Elvenes the Finnish originated Pasvik River has its outlet, with an average discharge of 180 m^3/s (Bjerkeng, 1999; Berge et al., 2012). On the western side of Kirkenes Langfjorden continues all the way into the settlement of Bjørnevatn 10 km from Kirkenes. Sydvaranger Gruver AS is located in Bjørnevatn represented in Figure 8.

5.2 Formation of the fjord

Syvitski et al., (1987) defines a fjord as "high latitude estuary, which has been or presently being excavated or modified by land- based ice". Syvitski et al., (1987) says further that estuaries are ephemeral geologic features and fjords are the deepest of all estuaries. Fjord systems are non-steady state system that will change over short periods of time.

The formation of a fjord starts with a river. The river finds zones of weakness in the bedrock and starts to erode these into V- shaped valleys. During a glacier the land is covered by ice (Syvitski et al. 1987). The ice will continue to erode the V- shaped valleys into large parabola shaped valleys. When the ice retreats the sea level will increase rapidly. After a while the isostatic uplift will follow and the water in the parabola is trapped (Syvitski et al. 1987)

5.3 Vegetation and other influences on the fjord system

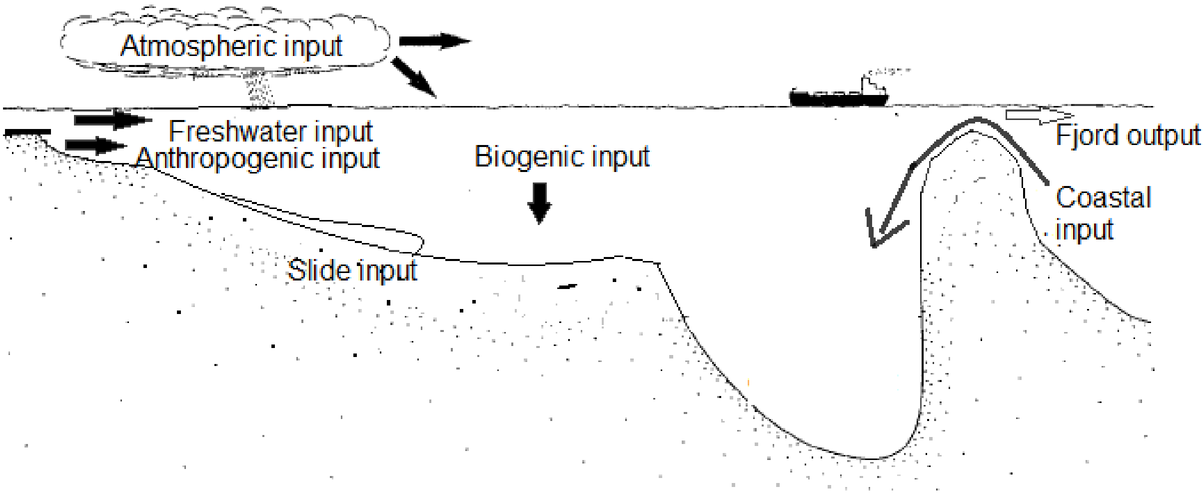

Figure 9: Different input source to the fjord system (Figure is modified from Syvitski et al., 1987)

Today the fjord is mainly influenced by the Pasvik River for sediment and freshwater supply. There are also found a lot of bigger and smaller lakes in the area. The largest lake in the area is Store Ropelv-vatnet and Ropelva is transporting mainly water to Bøkfjorden right south of Reinøya. The elevation in the area varies between 100 to 400 meters. The largest top is Stortoppen at 408 m in the outer part of Bøkfjorden, the tops are flat most likely because of ice erosion. The eastern side of the fjord has the highest elevation and steepest incline. There are also more settlements on the eastern side of the fjord.

The vegetation in the surrounding area is large influence by the bedrock and the snow cover during winter (Høgda et al., 1995). In the area there are acidic bedrocks e.g. gneiss so the oligotrophent vegetation community types dominating the area (Høgda et al., 1995). A habitat that are oligotrophent means that the habitat is low in nutrients (Lacoul & Freedman, 2006). The linchen dominated heath and woodland vegetation cover types are dominating where there is a small amount of snow cover

(Høgda et al., 1995). Birch dominating the area close to Bøkfjorden. There are also found pine forests, bogs and mires in the area. The mountain tops have sparsely vegetation (Høgda et al., 1995). This can influence the bioaccumulation in Bøkfjorden.

The area along the dock of Kirkenes is heavily polluted with cobber, PAH (Polycyclic aromatic hydrocarbon) - compounds and TBT (tributyltin) due to Kimek AS (Berge et al., 2012). Kimek AS repair ships and other industrial services (https://www.kimek.com/). The polluted are from Kimek is approximately 1 km from the discharge pipe that was used by Sydvaranger Gruve AS. The pollution levels decreased away from the shipyard and this indicate that the pollution is coming from shipyard activities or from terrestrial sources (Berge et al., 2012). This will also increase the spreading from ship hulls that traffic the area (Salomonsen et al., 2011). The industrial area of Kimek is registered as a ground contamination side that have drainage directly into the fjord (Salomonsen et al., 2011). The sewage from the community of Kirkenes are mainly discharge directly into Bøkfjorden at shallow depths without any purification (Berge et al., 2012). There are salmon butchery located at Jakobsneset approximately 3 km east of Kirkenes (Figure 8) that take in processes water at 20 m water depth and discharge it at 30 m water depth. This can also increase the bioaccumulation if the water is poorly purified. Another problem is the red king crab as mention early that can resuspension material (Berge et al. 2012).

5.4 **Bedrock**

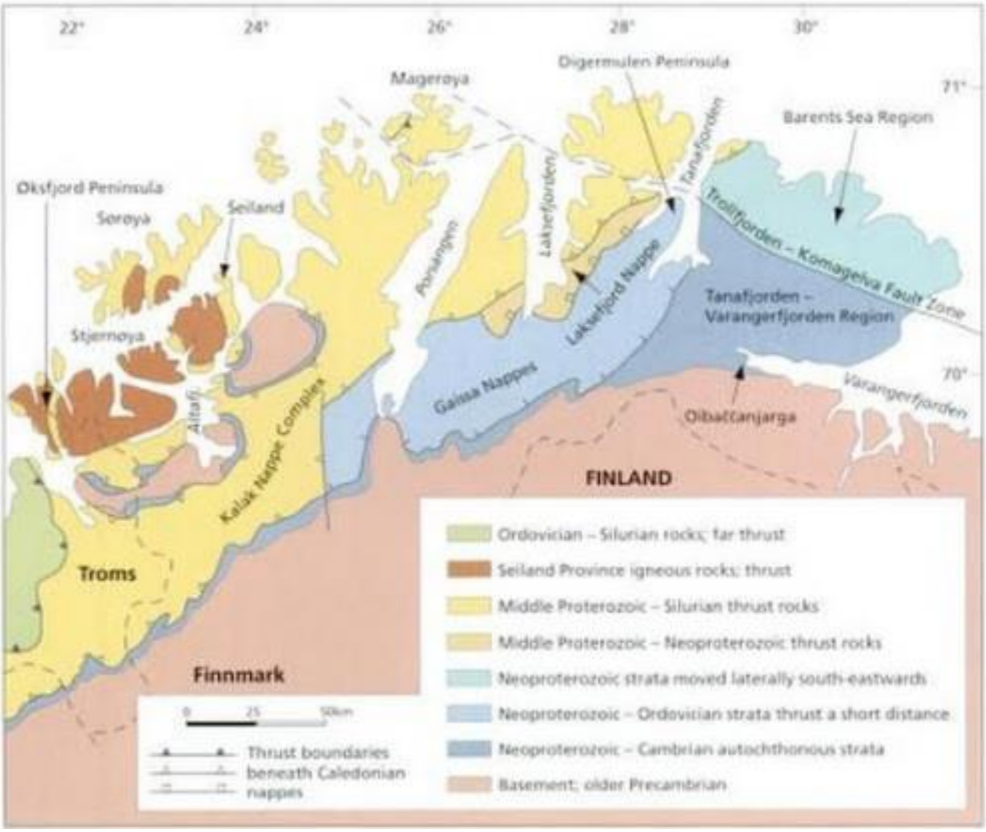

Figure 10: Overview over the bedrock in Finnmark. (Picture from Ramberg et al., 2013).

Two main geological regions occur in eastern Finnmark the Tanafjord-Varangerfjord-region and the Barents Sea region as represented in Figure 10 (Ramberg et al., 2013). There have been large changes in the area trough time from the Varangerian Ice age depositing glacial deposits to the warm period where deep weathering on the basement and carbonate banks on shallow sea (Ramberg et al., 2013).).

In eastern Finnmark the Neoproterozoic succession offers a well- preserved documentation of the Timanian Marginal zone in Baltica (Ramberg et al., 2013). An important structure in this Timanian Marginal zone is the Trollfjorden- Komagelva fault zone that divides the Varanger Peninsula diagonally from northwest to southeast. This fault zone originated form the Precambrian and it was already a weakness zone when Rodinia split up around 700 million years ago (Ramberg et al., 2013). Rodina was a supercontinent that formed around 1300 million years ago and on one time nearly included the entire seven continents that we know today. This divided Finnmark into the two geological areas mentioned earlier the Tanafjorden-Varangerfjorden and the Barents Sea region. On the southeast side of the fault zone the succession in largely autochthonous. This means that the strata are deposited directly on top of the basement rocks. This is not the case for the Barents Sea Region where the rocks were transported an unknown but long distance (Ramberg et al., 2013).

Sør- Varanger belong to baltic shield that is characterized as a bedrock area of Precambrian age (Bakkejord & Lebesbye, 1985). The oldest rock in this area is around 2 800 million. This consist of granitic gneisses and the Jarfjordgruppa consisting of migmatite, mica- and garnet gneisses. The Bjørnevatngruppa is around 2 700 million years and consist of biotite, hornblende gneisses, quartzite, mica schist and some conglomerate (Bakkejord & Lebesbye, 1985). It is in this formation the iron ore is found, that was used by Sydvaranger Gruve AS. The youngest bedrock is around 1800 million year and part of the Petsamogruppa consting of “Neverskrukk”-conglomerate and andesitic metabasalt. Before the Petsamogruppa the bedrock was intruded by sills/dikes consisting of granite, pegmatite, mangerite and monzonite. The bedrock also went through one to three phases of folding and metamorphism (Bakkejord & Lebesbye, 1985). After this the area had some diabase (sills/dikes) with an orientation of N 20-30 W and N 20-30 E. Later there was also large fault zone with an orientation of N 5-12 E and N 41-58 E. The strike in the bedrock is mainly towards southeast-northwest (Bakkejord & Lebesbye, 1985).

The bedrock in the Kirkenes area consists many of migmatite (gneiss) of Precambrian age this is represented in Figure 11. In Bjørnevatn where the Sydvaranger Gruver AS is located the bedrock is mainly composed of quarts, feldspar, muscovite shale and gneisses, and in between these some iron ores and amphibolite. It is this iron ore Sydvaranger Gruver AS extracted from their mine.

Figure 11: Map over the bedrock around the Kirkenes area. (Picture from Geological Survey of Norway).

5.5 **Hydrology and oceanography**

Fjords will have an estuarine circulation. The level of stratification is based on the balance between the buoyance forces set up by inflowing fresh water and ocean processes as tides and waves that work to mix the fresh water with the denser and saltier sea water (Syvitski et al., 1987). The surface layer strongly depends on the influx of the fresh water. In Bøkfjorden the surface layer is supported by fresh water from Pasvik River. This freshwater layer has a strong layering and dominating the top layer 0-6 m (Berge et al. 2011). Under this layer there is a layer of brackish water down to around 8 m. Under 8 m there are deep water, the deep water in Bøkfjorden is normally very cold during winter due to the limited renewal (Bjerkeng, 1999). Sea ice can occur in Bøkfjorden from December to April. The thickness of the ice rarely exceeds 30-35 cm in Bøkfjorden (Salomonsen et al., 2011). Bøkfjorden have large tidal differences and this will make the area less sensitive for smaller pollution discharge. At Kirkenes the tide have a large amplitude around 4m (Salomonsen et al., 2011). There is no distinct sill before 17 km from Kirkenes; the sill lies at 100 m water depth. This limits the water exchange between the deeper part of Bøkfjorden and Varangerfjorden as mentioned earlier. The sill will also act like trap concealing the mine tailings in Bøkfjorden and limit the effect on Varangerfjorden (Skei & Rygg, 1989; Skei, 1990; Berge et al, 2011; Berge et al., 2012)

From 1950- 1980 the Pasvik River was regulated and this probably changed the composition of the water masses because of the lack of freshwater input (Bjerkeng, 1999). Heavy metals discharge on the Russian side of boarder have influence the Pasvik River and the sediments in Bjørnevatn (Rognerud, 1990). Nickel, copper, mercury and some cadmium are the main element of pollution from the Russian side.

5.6 Turbidity

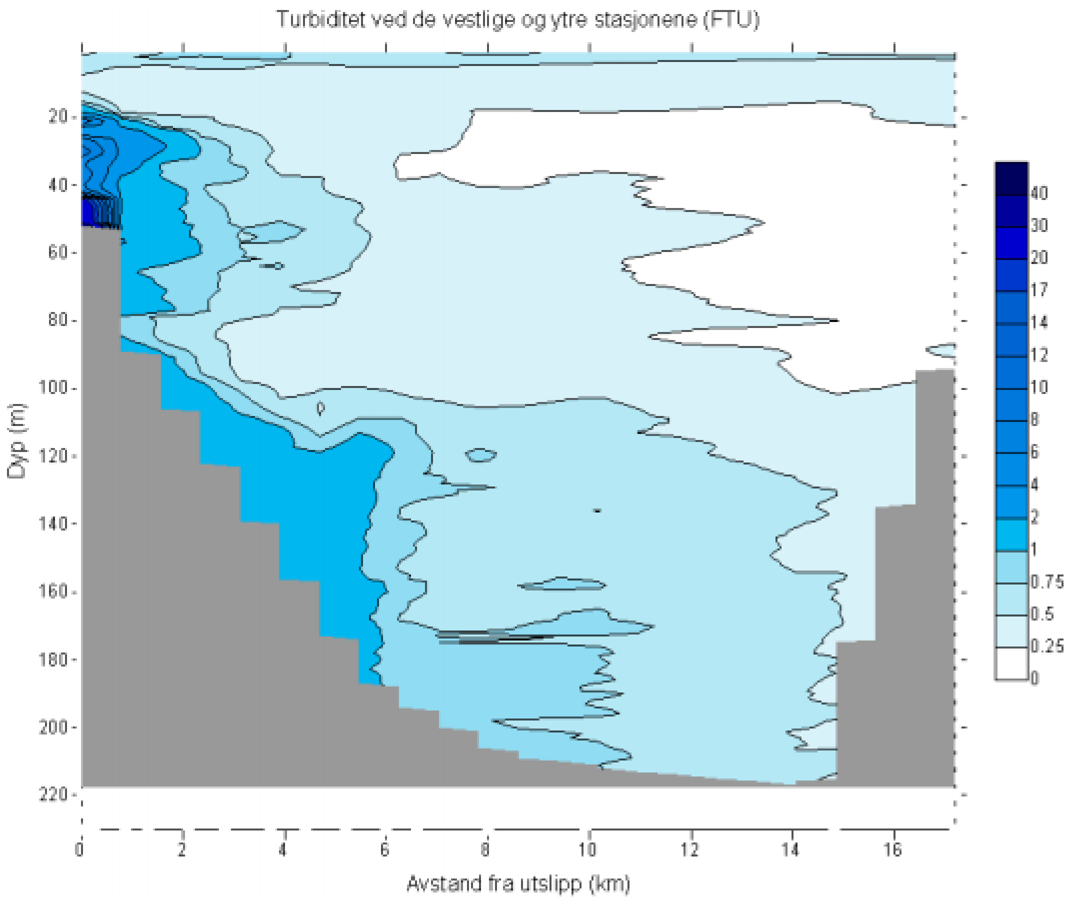

Figure 12: Horizontal and vertical overview of the turbidity in Bøkfjorden. (Picture from Berge et al., 2011).

Turbidity in the water column can indicate how many particles that are located in the water column (Berge et al., 2012). If the turbidity is measured numerous times on several locations this can indicate how the cloud of particles moves from the discharge point and how far it can be identified (Berge et al., 2012). When no material is discharged the turbidity is low and nearly same level throughout Bøkfjorden (Berge et al., 2011). The report from 2011 concluded with that particle concentration in the western part was higher than the eastern part, this was also validated in 2012 at least for the 3 km from the discharge point (Berge et al., 2011; Berge et al., 2012). Figure 12 represented horizontal and vertical distribution of turbidity on a section on western side of the fjord with regards to water depth on the y axis and distance from the discharge point on the x axis (Berge et al., 2011). In the top 20-80 meters depth there was observed relatively high values of turbidity but this was decreasing towards 6 km from the depositional side. The turbidity maximum was normally observed between 20- 60 m depth (Berge et al., 2011). Beyond 6 km from the depositional side there seems to only limit turbidity influence in the bottom 100 meters. In the top 20 m there are relatively low turbidity in the whole fjord and quite similar to the reference locality in Varangerfjorden (Berge et al., 2011). In the report from 2011 there was discovered resuspension around the area of Reinøya limited to the lowest 100 meters of the water column, it is believed that this is due to local currents (Berge et al., 2011). These findings indicate that the mine tailings sink more and more out of the water column over the threshold level further away from the depositional side. Most of the mine tailings are deposited within a radius of 6 from the depositional side (Reinøya), but there are found turbidity values over the background level as fare as 8- 10 km from the depositional side in large depth than 100 meters (Berge et al., 2011). New measurements were performed a year later to valid the findings from the report in 2011, because of the problem with the dropping of the discharge pipe from 28 m- 50m for half a year in 2010 (Berge et al., 2011; Berge et al., 2012). Figure 13 shows the interpolation of the data from the report in 2012 (Berge et al., 2012). This figure should be use with some caution, but it gives a quantitative picture of the vertical and horizontal distribution of particles in the western part of the fjord. Since Figure 13 have a logarithmic scale is not that is to correlate with the Figure 12 from the report in 2011, but the overall trend is the same. The 2012 report back up the turbidity findings from 2011 (Berge et al., 2011; Berge et al., 2012).

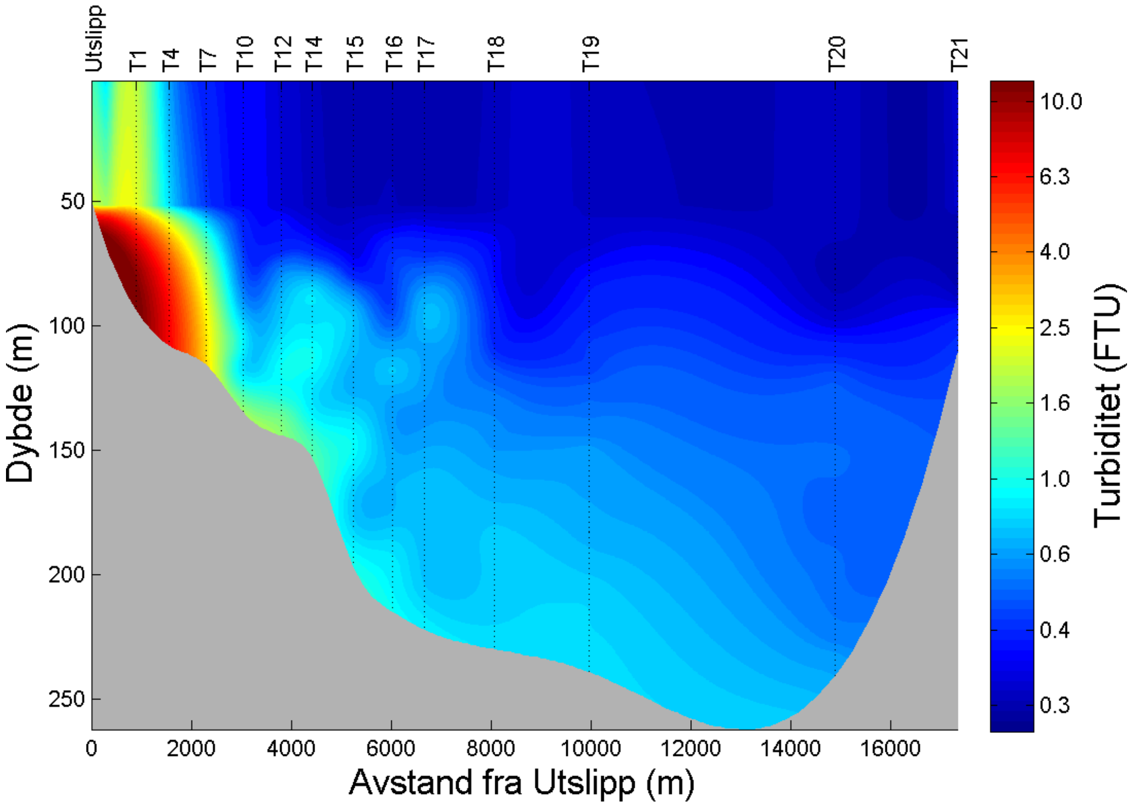

Figure 13: Horizontal and vertical overview of the turbidity in Bøkfjorden. (Picture from Berge et al., 2012).

5.7 **Climate**

Fjords are sensitive to environmental change and this is largely influenced by climate (Syvitksi et al. 1987). Climate is defining weather in a 30 years period. In the past there have been large climatic variation e.g. glaciation. This can affect the weathering of the rock; if the mechanic weathering is high it will create a larger surface for chemical weathering. At the same time the climate can affect the vegetation in the area. This will contribute to the sediment yield. Climate also controls the type and amount of precipitation, runoff and water temperature which, in consequence, influence, styles of estuarine circulation .Wind also can influence the sediment supply and the distribution of sediments (Syvitksi et al. 1987).

The climate in the area are subarctic with cold winters and relatively warm summers and with an average perception of 450 mm per year (Salomonsen et al., 2011). The dominant wind direction is from south and south-east, with an average speed of 5 m/s. Higher wind velocity are more common in the winter than in the summer time (Salomonsen et al., 2011) .

Figure 14 present the monthly variation in perception and temperature in the last climatological normal from 1960-1990 for Kirkenes airport. Kirkenes airport is located approximately 6 km from Kirkenes to the west. The lowest temperature in the area are in January with -12 ºC and highest in July 12 ºC. The precipitation rate is highest during the summer months, with a peak of 62 mm in August. In the spring the perception is lowest with nearly no perception in April.

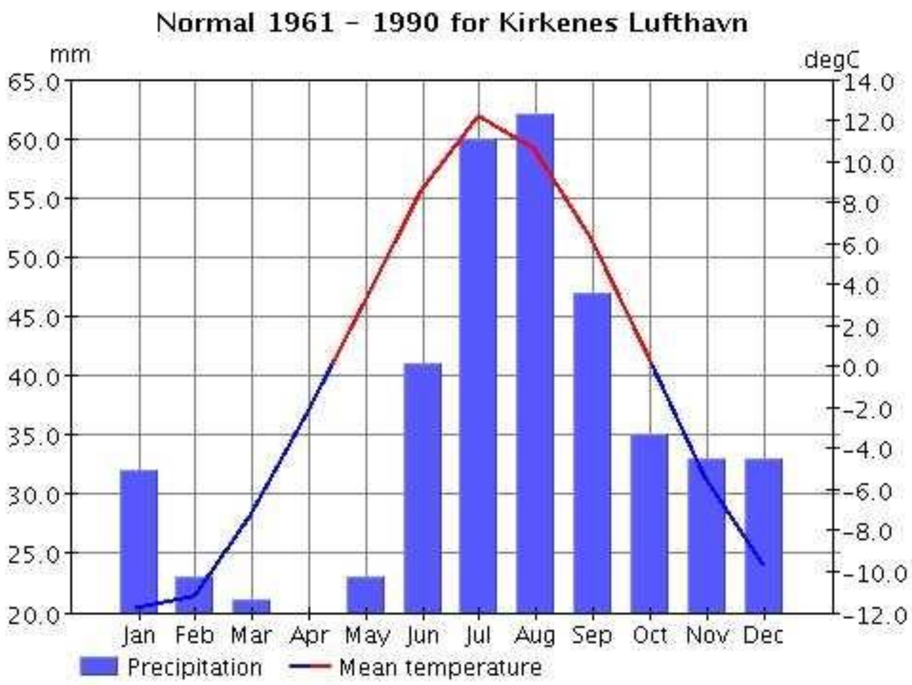

Figure 14: The last climatological normal from 1961-1990 at Kirkenes Airport (Figure from Meteorologisk institutt, 2018)

6 Material and Methods

This chapter describes what material and methods were used for preparation for the results. All the laboratory work was carried out in the lab at the Department of Geosciences at the Arctic University of Norway in Tromsø (UiT).

6.1 Description of the sediment cores

Table 1 provides an overview the four cores used in this master thesis. Three gravity cores (IG16-1798 GC, IG16-1835 GC, IG16-1811 GC) from UiT (the Department of Geosciences) were retrieved with R/V Helmer Hanssen during a scientific cruise within the frame of the Environmental Waste Management (EWMA) project between November 4th to 9th 2016. One Niemestö core (P1505011) from the Geological Survey of Norway was retrieved during a cruise with FF Seisma between May 18th to 22nd 2015 during a cruise within the frame of New Knowledge on Sea Disposal (NYKOS)

Table 1: Information about the retrieved cores from UiT and NGU used in this thesis.

Core ID	**Location**	**Latitude**	**Longitude**	**Water depth (m)**	**Core length (cm)**
IG16-1798 GC	Inner fjord	69 44.594626` N	30 04.297591 E	103.48	182
IG16-1835 GC	Middle fjord	69 46.332838` N	30 05.403604 E	171.86	397
IG16-1811 GC	Middle/outer fjord	69 48.353220` N	30 06.436402 E	229.81	157
P1505011	Outer fjord	69.84.311499º N	30.11.922100 E	243	31

6.2 How to retrieve a gravity core?

Before lowering e.g. a gravity core it is important to survey the seafloor, because the gravity core can penetrated soft sediments only. This survey is often performed by a chirp or TOPAS, i.e. with high- resolution seismic system. When the seafloor conditions are acceptable the gravity core is lowered slowly to the point where it is just a few meters over the ocean floor. Here it is ensured that the gravity core is straight up before penetrating the sediments. There is a weight on top of the gravity core and in the end there is a hard cone to make the penetration easier. Inside this cone there a core catcher that traps the sediments so it can be transported back to the boat.

6.3 Laboratory Work

6.3.1 X- Radiography

Figure 15: The X-ray instrument at UiT. (Picture from UiT, 2018).

At UiT there is a Geotek x-ray core imaging system shown in Figure 15. This system provides information about internal structures that cannot be seen with the naked eye. This can be shell fragments, stones, bioturbation etc. The material density influences the absorption of the x-rays and this is an indication that something is denser or less dense than the surroundings. High-density objects are normally associated with a darker colour. X- Radiographs were acquired from whole and half cores. In your case it was used on whole core, expect IG16-1798GC that was processed again after splitting the core due to unclear image. One section was put in at the time and it did not take too long before the results were ready. The picture could be used right away but some of them need some adjustments to see the internal structure better.

6.3.2 Splitting the core

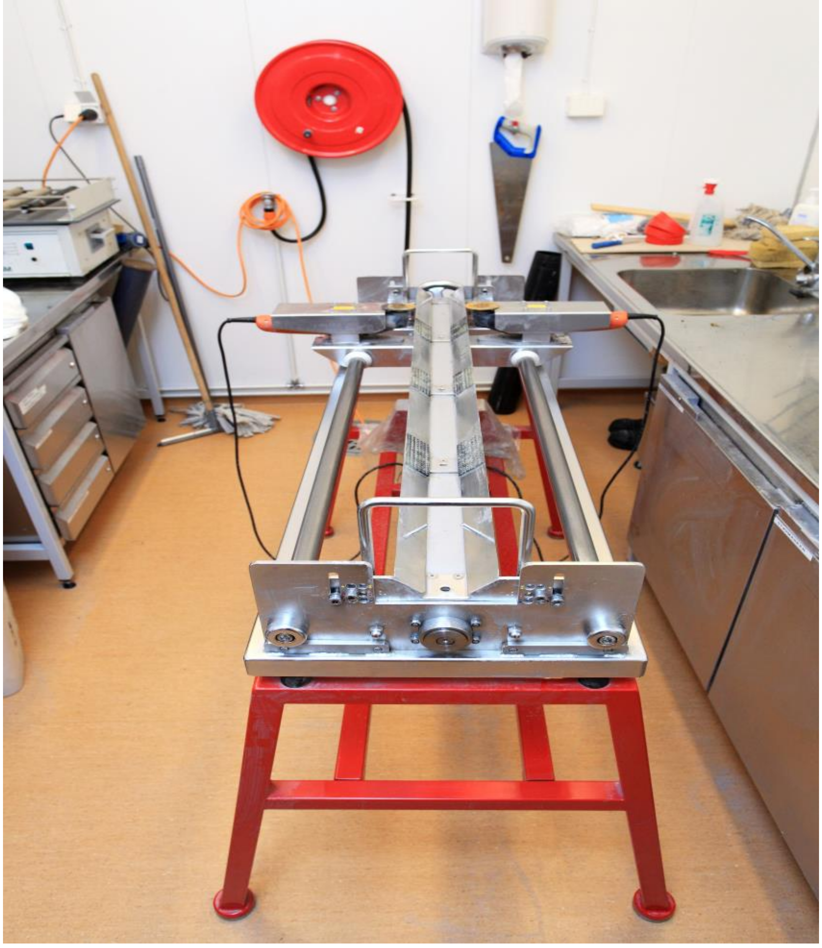

Figure 16: The core line saw at UiT. (Picture from UiT, 2018).

A core liner saw was used to split each core section lengthwise (Figure 16). Then to totally separate the two parts an osmotic knife and a steel wire where used. It was very difficult to separate the two parts of the core and the tendency was that one part nearly got all the sediments. The part with the most sediments became the working part and the other the archive part. All the part of the core was proper marked and then the archive core was wrapped in plastic, put in a plastic bag and taped up to be put in a cold storage room. Important to wrap the working core and store it in a cold room as well otherwise it can dry out.

6.3.3 XRF (X-ray fluorescence scanning) - Scanning

The principle of XRF- scanning is that the X-ray collides with a matter and then the matter will generate second radiation i.e. fluorescence (Forwick, 2013). This will determine the qualitative and quantitative element composition of the matter; if it is solid, liquid or powder. An X-ray tube is the source of the x-rays. Inside the X-ray tube is a vacuum chamber with an anode (+) and a cathode (-). The anode is made of rhodium (Rh). Heating of the cathode leads to emitting of electrons that are drawn towards the anode. When the electrons collide with the anode X- rays are emitted in form of Rh- radiation. The electric current in the cathode controls the emission of the electrons, high electric current means high emission rate. The voltage (U) between the anode and the cathode determine the acceleration of the emitting electrons: the higher the voltage the higher the acceleration (Forwick, 2013).

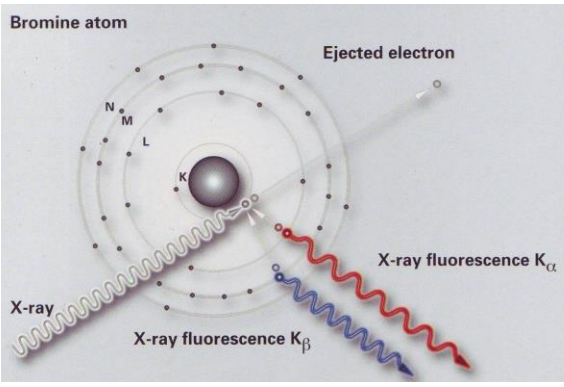

Figure 17: Bohr's atomic model and the generation of secondary radiation. (Figure from Forwick, 2013).

To understand how secondary radiation is generated it is important to have a look on Bohr's atomic model (Figure 17). An atom is build-up of a positively charged nucleus with negatively charged electrons in an orbit around the nucleus. In reality this is much more complicated, but this is just to understand the simple principal about the energy state of the electron. Electrons can be ejected when an X-ray and an atom collide. This leaves a vacancy in the K orbit represented in **Error! Reference source not found.**. The electrostatic forces between the nucleus and the surrounding orbits lead an electron from a higher orbit to fill this vacancy e.g. from the L orbit. When the electron jumps for a higher orbit to lower orbit energy is released and this energy is send out as a secondary radiation or fluorescence. The energy released when the vacancy is filled depends on with orbit the electron came from, i.e. if it was the L orbit or the M orbit (Forwick, 2013).

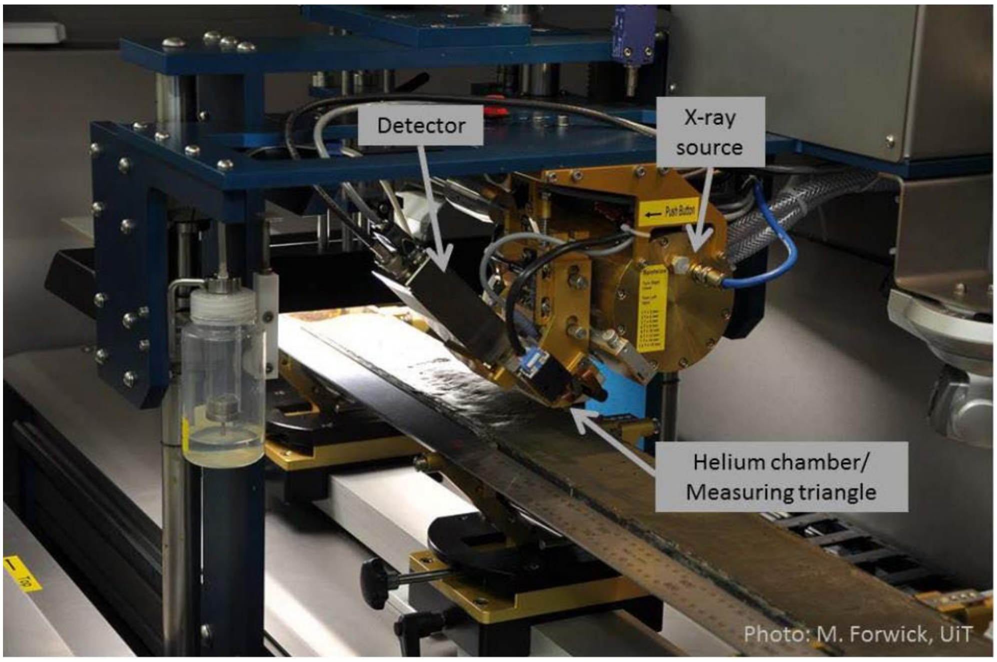

Figure 18: The Avaatech XRF core scanner setup. (Picture from Forwick, 2013).

Avaatech – XRF core scanner was used. It consists of an X- ray source, a helium chamber/ measuring triangle and a detector represented in Figure 18. To avoid contamination the core is covered with a 4 μm thick foil. This is because the measuring triangle lands on the core. The He-chamber was added by the manufacturer because He exposes smaller friction than air on secondary radiation. This makes it easier to detect lighter element as Al, Si, and eventually Mg (Forwick, 2013). The XRF scanner will provide an overview on the most abundant elements in the sample from Mg- U. The various elements require a range of energy to excite so the measurements are performed in multiple runs. The different runs provide different currents, voltages and filters (Forwick, 2013).

Table 2: Avaatech XRF core scanner standard settings. (Forwick, 2013).

Elements measured	**Voltages (kV)**	**Current (µA)**	**Filter**
Lighter (Mg-Co)	10	1000	No filter
Medium-Heavy (Ni- ca Mo)	30	2000	Pd (thick)
Heavy (ca Mo-U)	50	2000	Cu

In addition this settings was used:

- P1505-011: The size of the area measured was 5mm cross core and 5 mm down core and with a measurements distance of 5mm. The counting time for each point was 30 sec for all current and voltage settings.

- IG16-1798 GC, IG16-1811GC, IG16-1835GC: The size area measured here was 10 mm cross core and 10mm down core with a measurements distance of 10 mm. The counting time on 10 kV and 30 kV was 10 sec and for the 50kV it was 20 seconds. In intervals with a lot of lamination the same settings as for P1505-011 was used. This was the case for IG16-1798 GC and for some of core IG16-1811 GC.

The measurements took some hours depending on the size, so the gravity cores took the longest.

The data was processed and put in to an excel document, this was kindly done by Karina Monsen at the UiT lab. This data was used to make element ratio. This because if one single element is plotted against depth and the curve drop, this can be misinterpreted to be a result of climatic or oceanographic changes (Forwick, 2013).

6.3.4 XRF spectrometer

Figure 19: XRF spectrometer at UiT. (Picture from UiT, 2018).

The instrument used at UiT is the Bruker S8 Tiger (Figure 19) this determines the main elements over > 0.5 % and the trace elements in a sample by the way of the wavelength dispersive XRF measurements. This measurement was carried out by Nikolai Figenschau for further information have a look at his Master thesis (Figenschau, 2018).

6.3.5 MSCL - Multi sensor core logger

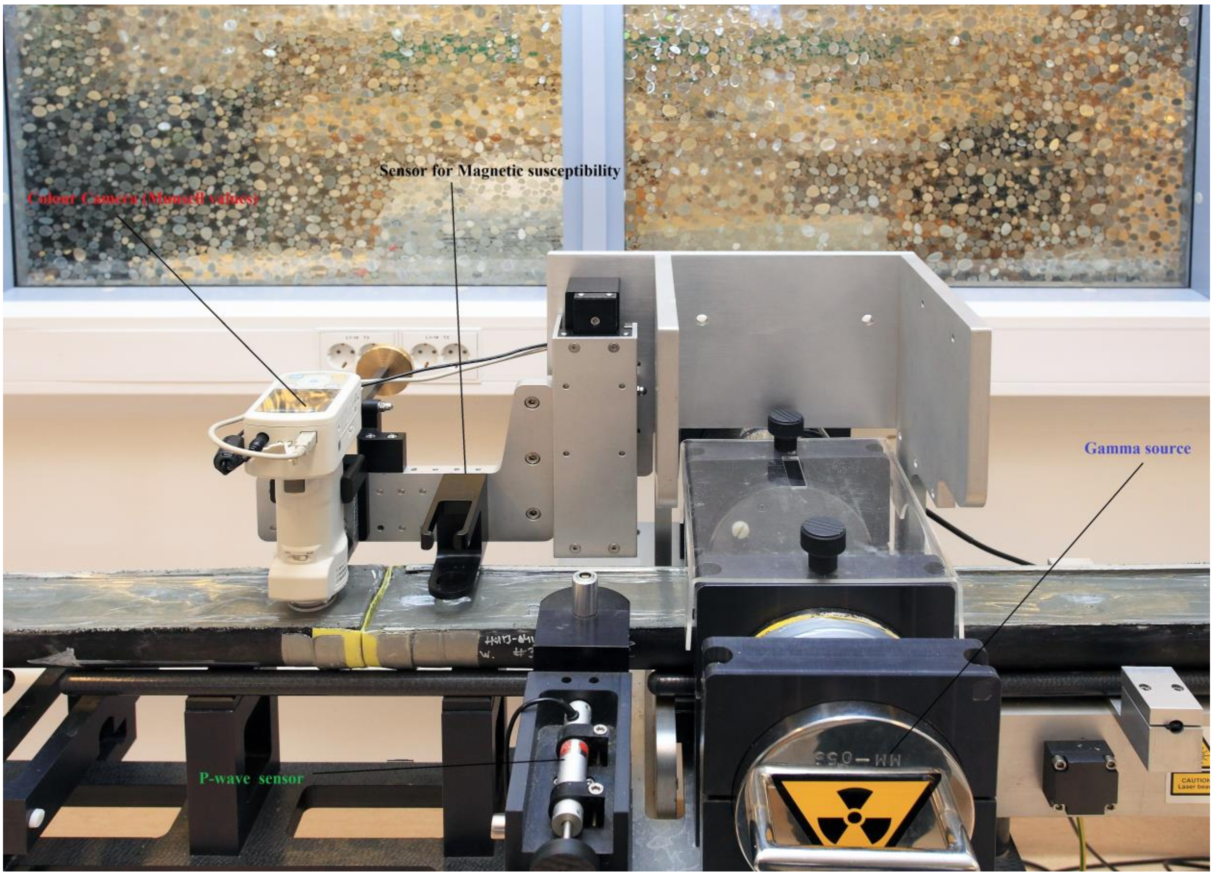

Figure 20: Multi sensor core logger at UiT. (Picture is modified from UiT, 2018).

MSCL stands for multi sensor core logger (Figure 20). The MSCL provides valuable information about physical properties as wet bulk density, p-wave velocity, p-wave amplitude, magnetic susceptibility, and temperature. The physical properties can change due to temperature (Weber et al. 1997). To avoid any temperature differences the cores was stored at room temperature the night before the measurement. This was carried out on the whole and later on the half core. The magnetic susceptibility and density was used in these thesis. Therefor the measurements from 23.11.16 on the whole core was used for both wet-bulk density and magnetic susceptibility.

Magnetic susceptibility is a proxy that describes how easily a material can be magnetized (Dearing, 1994). The inherent electrons in the atom control the magnetism of a material. A magnetic field is created when the electron spin around their own axis. The magnetic energy of an atom is determined by the different ways the electrons spin. Magnetic behavior is often divided into five different group: ferromagnetism, ferrimagnetism, antiferromagnetic, paramagnetism and diamagnetism. Magnetite is part of the ferromagnetic group that exhibit strong positive magnetic susceptibility. Other minerals like water, quartz, calcium carbonate all in the diamagnetism group exhibit weak or negative magnetic susceptibility (Dearing, 1994).

6.3.6 Shear strength

The shear strength is the maximum shear stress a material can withstand before it breaks/fails. To measure the shear strength a fall cone was used. This was lowered so it just did not touch the sediments. The undisturbed shear strength was measured direct on the core. Sediments from this measurement was transported to a little cup to find the disturb shear strength. Three values for undisturbed shear strength and disturbed shear strength was carried out each time. This was used to calculate the average and afterwards to calculate the sensitive shear strength. Sensitive shear strength= Undisturbed shear strength/disturb shear strength (S_u/S_d) (Skempton, 1953).The higher value for the sensitive shear strength the higher likelihood for sliding.

6.3.7 Grain- size analyses

1. **Preparation**

For the grain size analysis samples were taken from all four cores, with different intervals. All samples from IG cores were taking from the work halves. However, from core P1505011, samples were also taken from the archive half, due to earlier sampling for other purposes. The samples were around 2 grams. IG16-1798 GC samples was collected every 2 cm for the upper 140 cm and from 140- 174 cm every 5 cm. Due to disturbance in section 1 the sample at 100 cm were taken at 101 cm. In total there was taken 78 samples from IG16-1798 GC. In IG16-1811 GC the sediments were also disturbed in the top part, the first sample was collect at 4 cm. The core was sampled every cm for the first 40 cm and then every 5 cm to 155 cm. In total 62 samples was collected from IG16-1811 GC. From IG16-1835 GC samples was were taken every 20 cm but because of some interesting areas there was also additional samples were taken samples at 85 cm, 90 cm, 333 cm, and 370 cm. Here a sample was taken at 97 cm instead of 100 cm because of an interesting spot and some disturbances in the bottom of the section. All together 25 samples were taken from this core. The last core P1505011 a Niemistöcore there was taken every cm and here the archive core was also used due to earlier sampling by NGU. Here 31 samples was used.

2. **Acid treatment (HCl) and oxidation with hydrogen peroxide (H_2O_2)**

This treatment is used for removing calcium carbonate ($CaCO_3$) and other organic matter from the samples before it was put into the Beckman Coulter LS 13 320 Particle Size Analyser (see below). A list of 14 points was applied before the samples could be analysed by the particle size analyser. First the samples were put into “reagent” tube and filled with HCl just to cover the samples. The samples were then put in a fume hood for a proximally 24 hours. After the 24 hours the samples was centrifuge for 4 minutes/4000 rpm three times (Maybe more if there still have some acid, HCl, left). In between every centrifuge the waste product was discharged and filled up with distilled water. Then the samples was made ready for the thermal bath with adding 20 % H_2O_2 and then covering the samples with aluminium foil. In the aluminium foil hole was made for air to escape. The thermal bath was set on a temperature at 85 °C, the temperature decreased to 79 °C when the lid was opened to put the samples in. The samples had a strong reaction to the H_2O_2 so to avoid any dangerous situation just a few samples was put in the thermal bath at the same time. If the samples had not reacted in 30 min, they would react. After the thermal bath the same centrifuge procedure was used as earlier mentioned. Then the samples were put in plastic cups and put into the dry cabinet at 32 °C. Then 0.2-0.5 gram depending on the grain size, were left in the cup and the rest was put into a plastic bag. Then it was filled with 20 ml of water and put on the shaking table for a day. Before it was put into the analysed machine 1-2 drops of Calgon was added and put into an ultra-bath just to be sure that all is dissolved to get a more accurate result.

IG16-1798 GC: Reacted before the thermal bath: 139,161,166,171. Did not react: 88

IG16-1811 GC: Reacted before thermal bath: 31, 32, 37, 38, 39, 100, 145, 150, 155

IG16-1835 GC: Reacted before thermal bath: 0, 280. Did not react: 360

3. Laser particle size analyser

Instrument used for this was a Beckman coulter LS 13320.This machine is used to determine the particle distribution in fine grained sediments. The technique is based on deflection of a laser beam when the beam hits the particle. Then the angel of deflection depends on the size of the particle. The particles need to be in a range from 0.04- 2000 microns for the best resolution, reproducibility and accuracy. There were three runs per samples and all of them was put into an excel sheet where the average was measured. This was done for every sample. Then it was put into Gradistat and that provides a grain size distribution. This is presented in the result chapter.

7 Results

7.1 Bathymetry

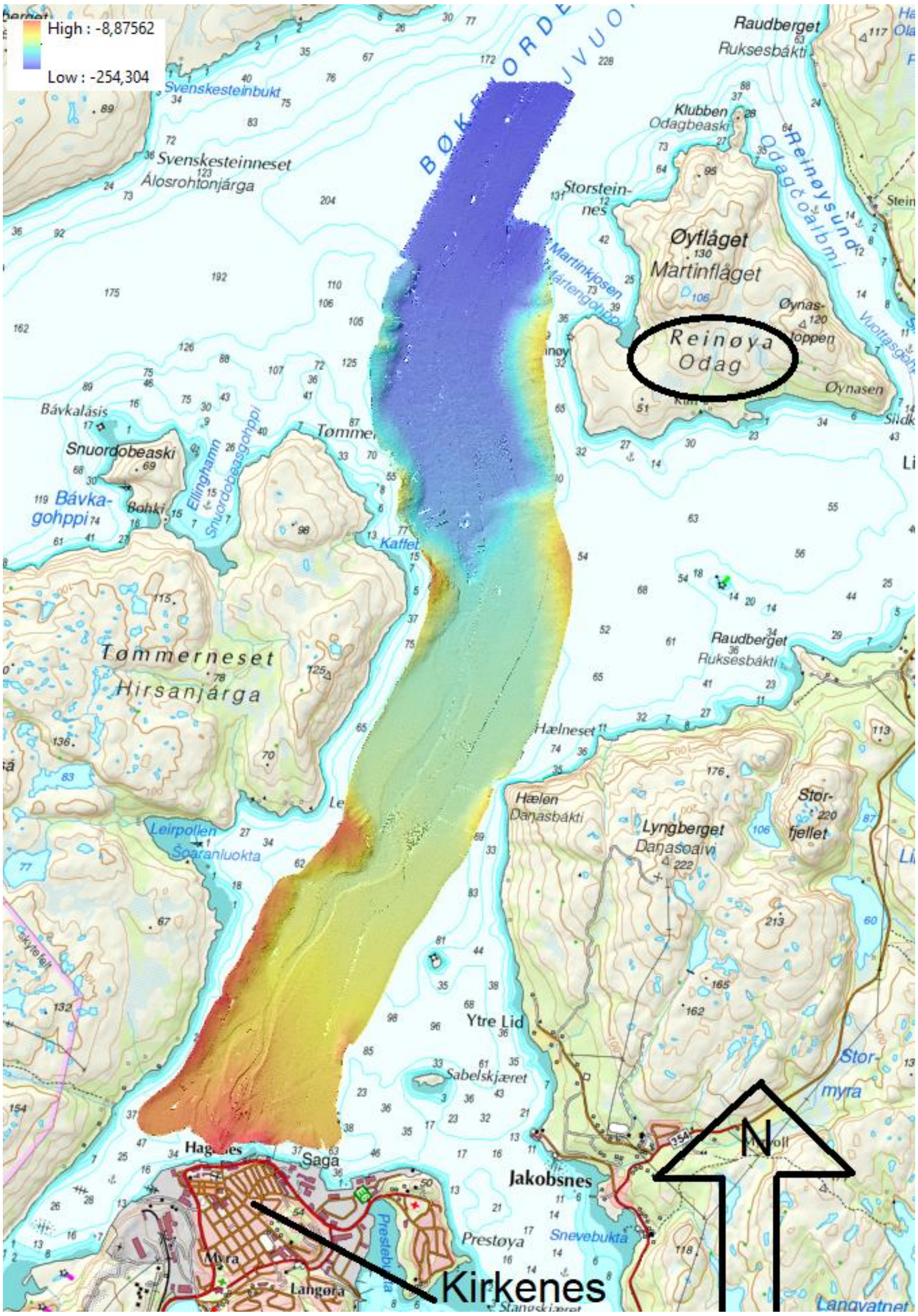

Figure 21: Bathymetry map over the innermost part of Bøkfjorden

The bathymetry data cover the southern parts of a main basin from Kirkenes to northwest for Reinøya (Figure 21). The colour codes in the map indicate the water depth with red being shallow and blue as deeper, with a maximum water depth of 254 m and a minimum water depth of 9 m as mention earlier. The fjord basin is generally smooth and inclined towards the north. However, a step occurs southwest of Reinøya, here the water depth increases from around 160 m to approximately 190 m. The most prominent bathymetric feature is a system of linear incisions extending from Kirkenes and 5 km towards the deepest part of the study area. This system consist of some smaller incisions of up to 77 m wide and 30 m deep close to Kirkenes that merge into one major incision 1.5 km north of Kirkenes. 3 km from Kirkenes the major incision widens due to an obstacle. This major incision has a sinuous shape, is approximately 5 km long, up to 270 m wide and up to a depth of 150 m.

Interpretation: This system is interpret to be a channel created by gravity flows composed off and triggered by the deposition of the mine tailings.

7.2 TOPAS

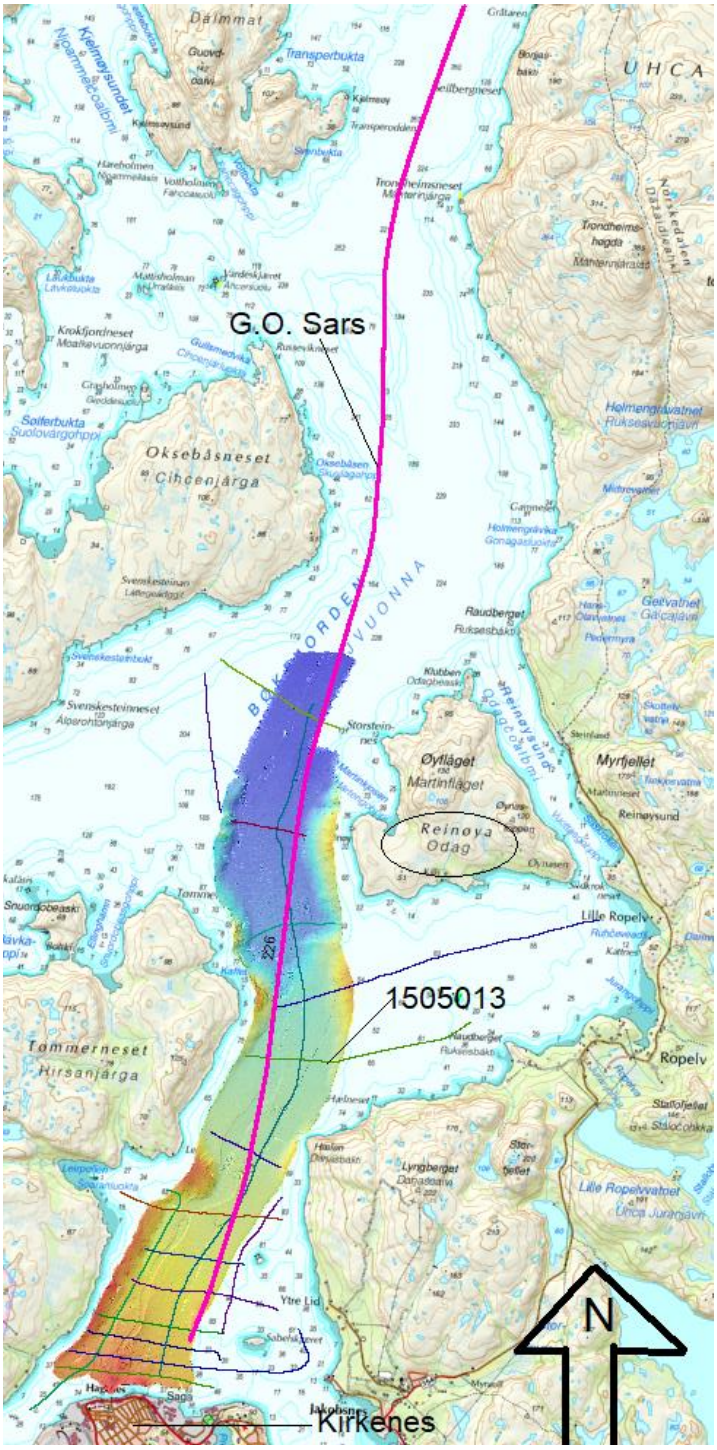

Figure 22: Show the two lines used for TOPAS high-resolution seismic profiles in Bøkfjorden, these are called 1505013 and G.O. Sars.

The sediment basins in fjords commonly hold a high temporal resolution that mirror land- and marine based processes In this chapter a closer look on two TOPAS profiles is being represented, 1505013 (Figure 23) and G.O. Sars (Figure 24). The TOPAS profile is divided into three units (Unit 1, 2 and 3). In TOPAS profiles it is often difficult to separate bedrock from moraine (Hjelstuen et al., 2013).

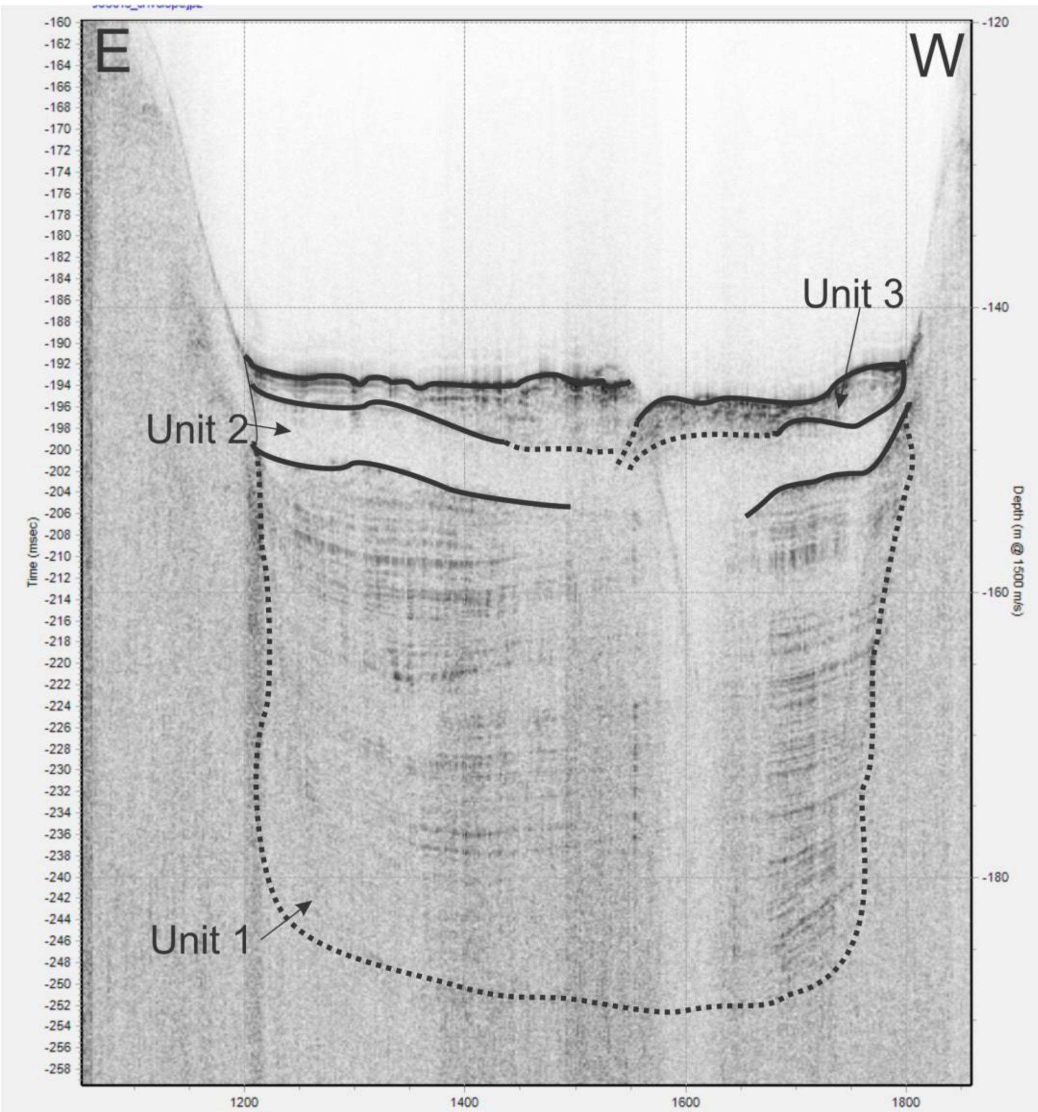

Figure 23: The TOPAS high-resolution seismic profile 1505013 E-W with different units.

Unit 1 in Figure 23 is a massive and acoustically well laminated unit with parallel to sub-parallel reflectors. The reflectors are also characterised by closely spaced continuous to discontinuous reflections. In the middle of the profile unit 1 nearly look transparent and it appears that unit 2 is penetrating into unit 1. The reflectors look stronger and more prominent towards the west. The upper boundary is not well defined in the middle part of the profile, but more prominent on the western side. The lower boundary is not clearly defined therefore a dotted line marks where the acoustic basement may be. Unit 2 is thinner than unit 1 and consisting of an acoustic transparent layer with no internal structures. The unit is thinning out towards the west and in the middle unit 3 drapes into unit 2. The upper boundary is not well defined. The top unit 3 is the thinnest of the units and consists of grey sequence with acoustically laminated layers on top. This layers seems to be more prominent on the east side and are hard to spot on the west side. This reflectors are parallel to sub parallel and characterised by very closely spaced continues to discontinues reflections. The west side seems more massive with hint of lamination. The top boundary is well defined without one point in the middle of the profile look like it penetrating downwards.

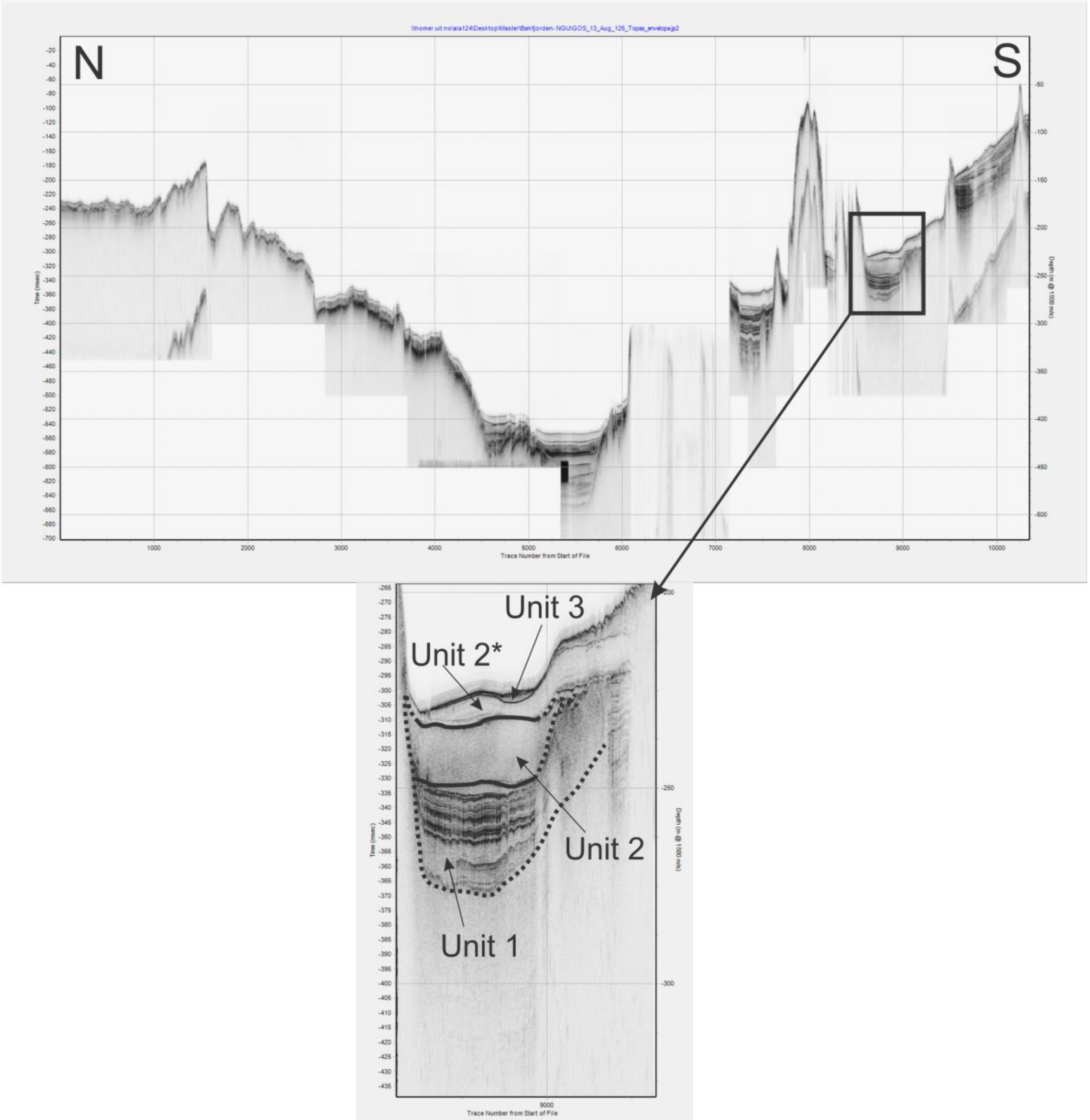

Figure 24: The TOPAS high-resolution profile G.O. Sars N-S with different units.

Unit 1 in Figure 24 consists of an acoustically well laminated layer, but there are also two distinct transparent layers. One in the lower part that is thinning out towards the north and one marking the top boundary of this unit. After the first transparent interval the lamination gets more prominent. The reflectors are parallel to sub- parallel. The south- north boundary is not well defined. The lower boundary seems the quite well defined. Unit 2 is acoustically transparent with no internal structures. The thickness of this unit 2 is nearly the same as unit 1. The appearance of unit 2 on the TOPAS profile is somewhat darker than unit 2*. Whereas unit 2 has a relatively uniform thickness, unit 2* is thinning towards the north. There are some hint of lamination at the north side and here there are a clear upper and lower boundary here. This unit 2* have no distinct boundary to the south. Unit 3 is very thin, making it hard to see if there are any internal structures. Unit 3 appears massive with a clear top boundary. Unit 3 is also thinning towards the north.

Interpretation of 1505013 and G.O Sars: Unit 1 with the acoustic stratification is believed to be a result of frequent lithological change in a proximal glacimarine environment (Forwick & Vorren, 2010). This may be a result of mass- transport activities, as well as temporal and spatial variations in ice rafting and/or sediment supply from one or several sources (Forwick & Vorren, 2010). This glacimarine package is larger in 1505013 than in G.O Sars. The transparent package, unit 2 and unit 2*, is interpreted to be a slide debrites (Hjelstuen et al., 2013). Unit 2* separated from unit 2 just to indicate that in the G.O Sars profile there seems to be two separated sliding events. Where unit 2* seems to have a smaller extent than unit 2. These slide debrites are a result of recurrent mass failure, which may be a result of large unstable sediments packages or pressure release from the last glaciation (Hjelstuen et al., 2013). The grey sequence in unit 3 is most likely reflecting hemipelagic suspension after the postglacial sliding events and the laminated sequence may indicate mine tailings. The lamination show repeated change in the deposition of mine tailings. The point in the middle of unit 3 on the TOPAS profile 1505013, is believed to be an erosive channel where the turbidity current transported the mine tailings. On the side of the channel there may be levees created when large amounts of mine tailings are discarded and creating turbidity currents with high velocity so that the mine tailings splash over the channel bank and are deposited (Amundsen et al., 2015).

7.3 Sediment cores

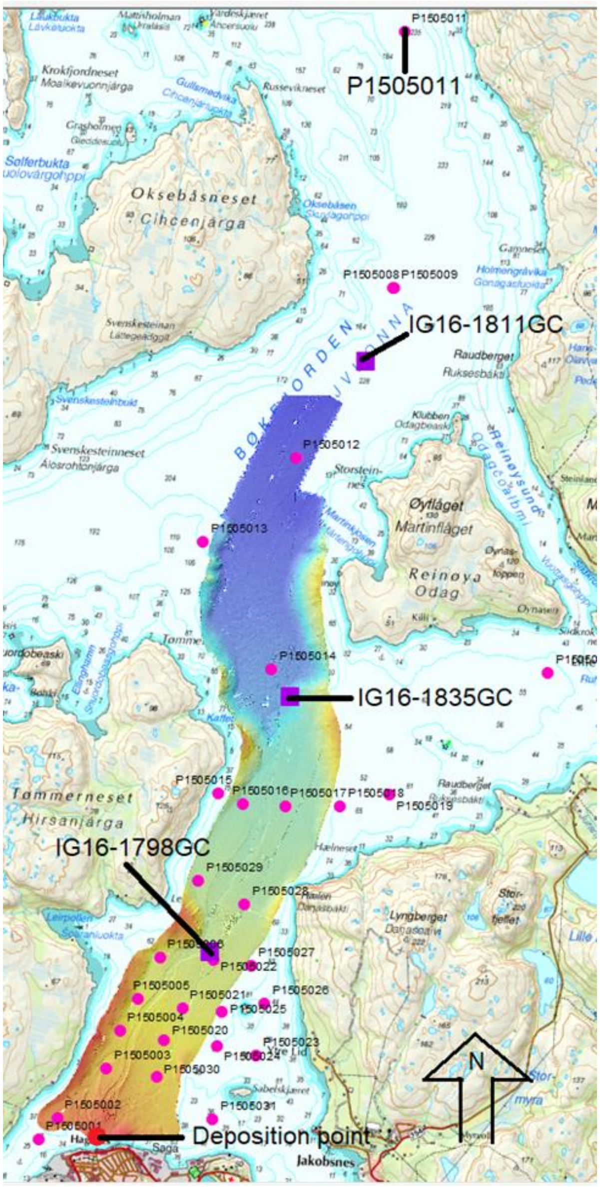

Figure 25: The location of the cores in Bøkfjorden

The location of the cores is represented in Figure 25. Core IG16-1798 GC is located on the edge of the canyon 2.3 km from the deposition side. On the threshold south west of Reinøya approximately 5.4 km from the deposition side core IG16-1835 GC is located. Then 9 km from the deposition side with the intersection between Bøkfjorden and Korsfjorden core IG16- 1811 GC is located. The linear distance to P1505011 is approximately 13.2 km from the depositional side.

7.3.1 IG16-1798GC

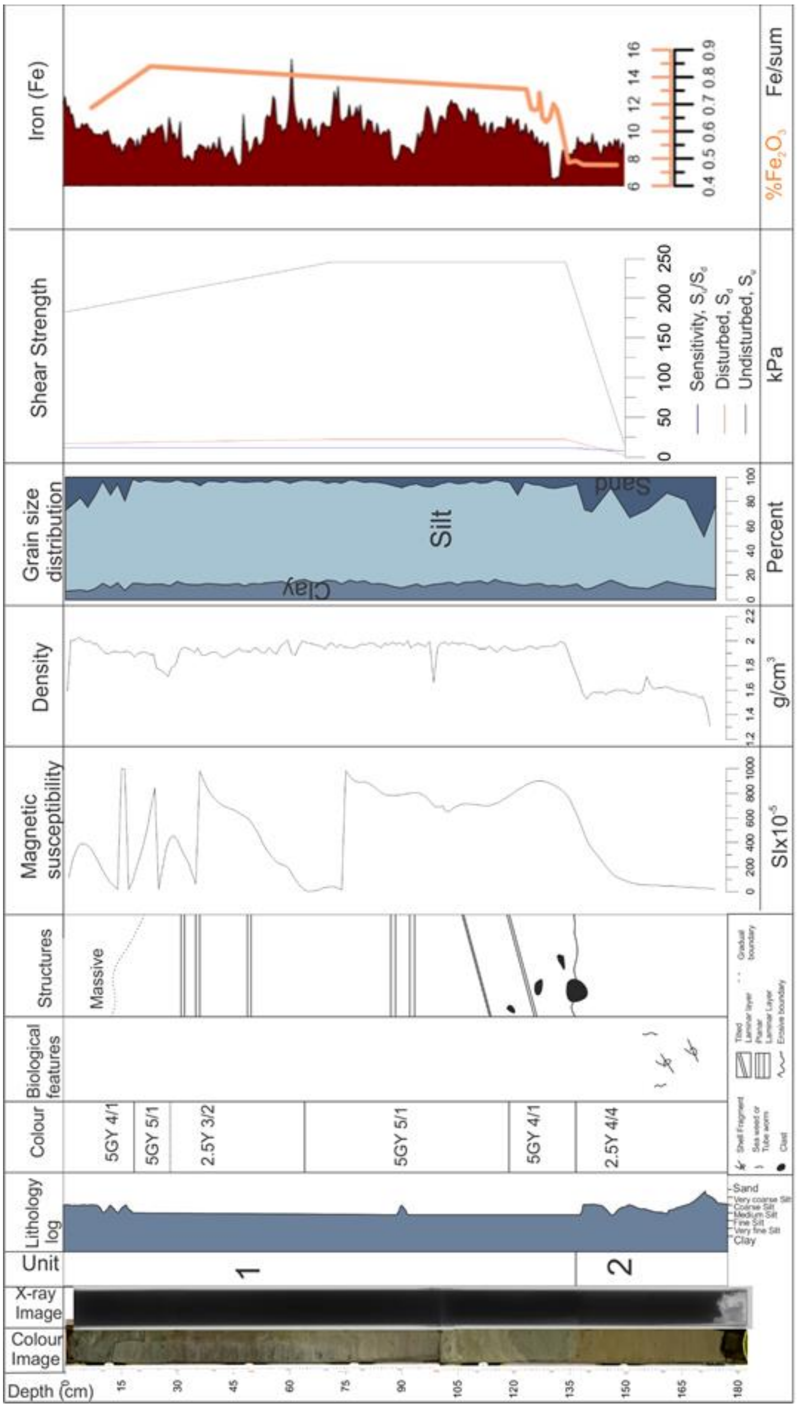

Figure 26: Core IG16-1798GC with all the result from different analyses. The Iron (Fe) was made by Nikolai Figenschau.

Core IG16-1798GC is 182.5 cm long and divided into two units (Figure 26).

Unit 1 from 0-136.5 cm is mainly composed of unimodal poorly sorted mud, the most dominant grainsize is medium silt. Between 2- 8 cm a coarser area occurs with sandy mud and a dominant grainsize of coarse silt. Whereas the predominant sediment colour is greenish grey and dusky red. The coarser area from 2-8 cm has a darker greenish colour. Between 80- 100 cm there are some wavy laminae. Further, from 106-126 cm there are some greyish layers dipping to the left. In addition some drop stones where found at 117 cm, 128 cm and 133 cm. The wet-bulk density varies between 1.66 g/cm^3 and 2.02 g/cm^3, with the lowest value at 99 cm and the highest value at 3.5 cm. There are more frequent fluctuations in the magnetic susceptibility than in wet- bulk density. The magnetic susceptibility varies between 2 SIx10^{-5} and 1000 SIx10^{-5} with lowest value between 65.1-66.9 cm and highest value at 15 cm. The quantitative iron characteristics (%Fe2O3) shows small variations, while the qualitative iron (Fe/sum) characteristics show more frequent fluctuations. The values vary between 0.425 and 0.8 with the lowest value between 131.5-133 cm and the highest value at 61.8. The shear strength in this unit is fairly stable, before a significant decrease at 133.9 cm. There is an erosive boundary between unit 1 and unit 2 with a large drop stone marking the boundary.

Unit 2 from 139-182.5 cm mainly compose of trimodal very poorly sorted sandy mud, the most dominant grain size is coarse silt. The unit has only one colour that is olive brown. From the X-radiograph, bioturbation is seen throughout the unit: At 156.5 cm and 158.5 cm some black long mater is found. Shells are also discovered in the throughout unit, especially in the bottom parts. Both of the measured physical properties decrease in the top parts before they stabilizes and continue down- core with small variations. The wet-bulk density varies between 1.32 g/cm^3 and 1.72 g/cm^3, with the lowest value at 172.5 cm and the highest value at 155.5 cm. The magnetic susceptibility varies between 20 SIx10^{-5} and 620 SIx10^{-5} with lowest value at 173.9 and highest value at the boundary at 137 cm. The Fe/sum varies between 0.51 and 0.59 with the lowest value at 142.2 cm and highest value at 144.8 cm.

Interpretation: The overall trend in this core is that unit 2 have lower values and less fluctuation when it comes to wet-bulk density, magnetic susceptibility and Fe/sum ratios. The erosive boundary between unit 1 and 2 indicates a rapid change in depositional environment, this is also supported by the distinct colour change. In unit 1 the sensitivity and iron values are dropping around 133 cm, this can be due to a drop stone. However, the sensitivity decreases throughout unit 2, indicating that the shear strength decrease is probably not due to the drop stone. This rapid drop in especially sensitivity shear strength can make the material unstable and more exposed for sliding and in a worst-case scenario this can have devastating effects both on the marine and terrestrial environment. Based on these observation unit 1 is interpreted to be mine tailing deposit. In unit 2 some black long mater was inspected with a microscope and it is believed that this is a tubeworm. Tubeworms are indicators for bioturbation. There are also found many shells throughout this core. All of these findings in unit 2 support that this is natural sediments deposited in an open marine environment.

7.3.2 IG16-1835GC

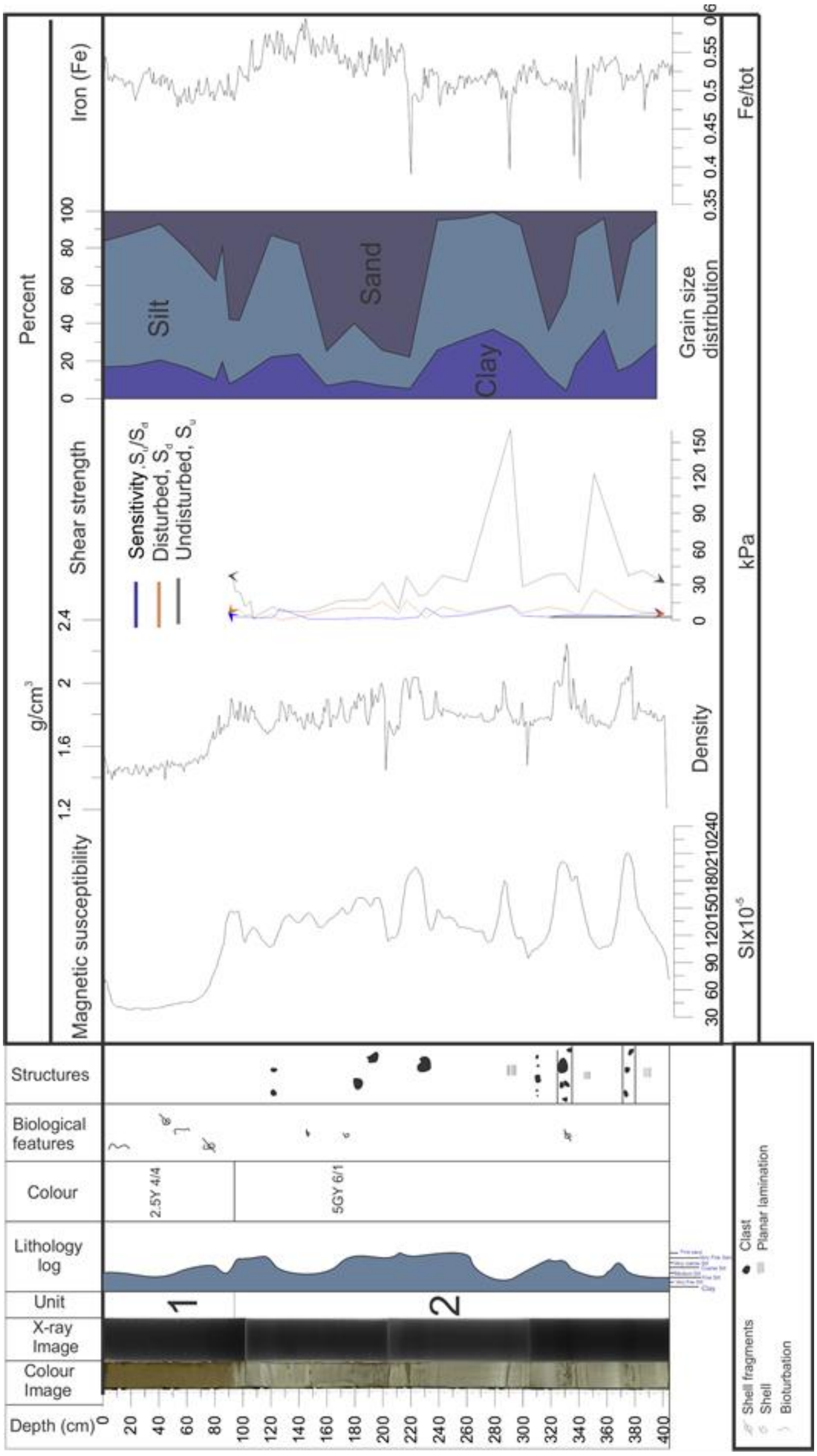

Figure 27: Core IG16-1835GC with all the result from different analyses

Core IG16-1835GC is 404 cm long and divided into two units (Figure 27).

Unit 1 from 0-94 cm is mainly composed of a polymodal, very poorly sorted sandy mud, with medium silt as the most dominant grainsize. The predominant sediment colour is olive brown. From the X-radiograph bioturbation is spotted throughout unit 1. Unit 1 also consist of many shells fragments. The wet-bulk density varies between 1.38 g/cm^3 and 1.90 g/cm^3, with the lowest value at 44.4 cm and the highest value at 91.7 cm. The magnetic susceptibility varies between 38 $SIx10^{-5}$ and 147 $SIx10^{-5}$ with lowest value at 19 cm and highest value at 91 cm. The lowest iron values is 0.48 found at 53.5 cm and the highest is 0.53 found at 33.5. There are unfortunately not taken many shear strength measurements in this unit, but there seems to be a decrease in sensitive shear strength towards the boundary to unit 2. There is a gradual boundary to unit 2.

Unit 2 from 94-404 cm compose mainly of polymodal very poorly sorted mud- sandy mud with fine silt as the dominant grainsize. The grainsize varies a lot throughout this unit 2 from very fine silt- fine sand. A coarser area between 97- 120 cm consist of muddy sand with a dominant grainsize of very fine sand. The predominant colour is different shades of greenish grey. On the X-radiograph there seem to be a denser area between 212-229 cm. In this area (116-220 cm) a sand lens, that is thinning towards the left is located. Some distinct lamination can be seen from approximately 290-303 cm and 338- 447 cm, both start with a dark coarse grain lamination approximately 1 cm. There are two distinct “gravel packages” 325- 336 cm and 366.5- 380 cm with a muddy matrix. Shell fragments are found sporadically in this unit (Figure 28) and shell fragments is found in the gravel package. Drop stones are

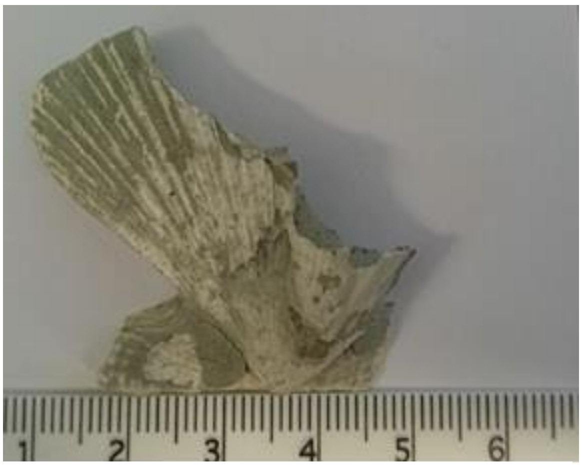

Figure 28: A shell fragment found at 157.5 cm

also found sporadically but the largest quantity is found in the gravel packages.

The wet-bulk density varies between 1.42 g/cm^3 and 2.22 g/cm^3, with the lowest values at 202 cm and the highest value at 331 cm. The magnetic susceptibility varies between 95 SIx10^{-5} and 210 SIx10^{-5}, with the lowest value at 304 cm and the highest value between 374- 374.5 cm. The quantitative iron curve has large fluctuations with four distinct low points. The values vary between 0.38 and 0.59, with the lowest value at 341 cm and the highest value at 145 cm. The sensitivity varies between 2 kPa and 14 kPa, with the lowest values between 300- 320 cm and the highest at 291 cm.

Interpretation: The overall trend in core IG16- 1835 GC is that there are higher values and more fluctuations in unit 2 when it comes to wet-bulk density, magnetic susceptibility, iron, shear strength and grain size distribution. In unit 1, bioturbation and many shell fragments with no internal structure was found. Based on all the observations unit 1 is interpreted to be deposited in an open marine environment. The gradual boundary shows that there are some changes in depositional environment. This can also be seen from the distinct colour change between unit 1 and 2. Unit 2 has a lot of different shades of colour and two “gravel packages” that indicate rapid change in the depositional environment. The sensitivity also shows a lot fluctuation, this can indicate that the material is unstable. The “gravel packages” also show that the environment change drastically. This frequent lithological change and all the other observation indicates that unit 2 is deposited in a proximal glacimarine environment (Forwick & Vorren, 2009).

7.3.3 IG16-1811GC

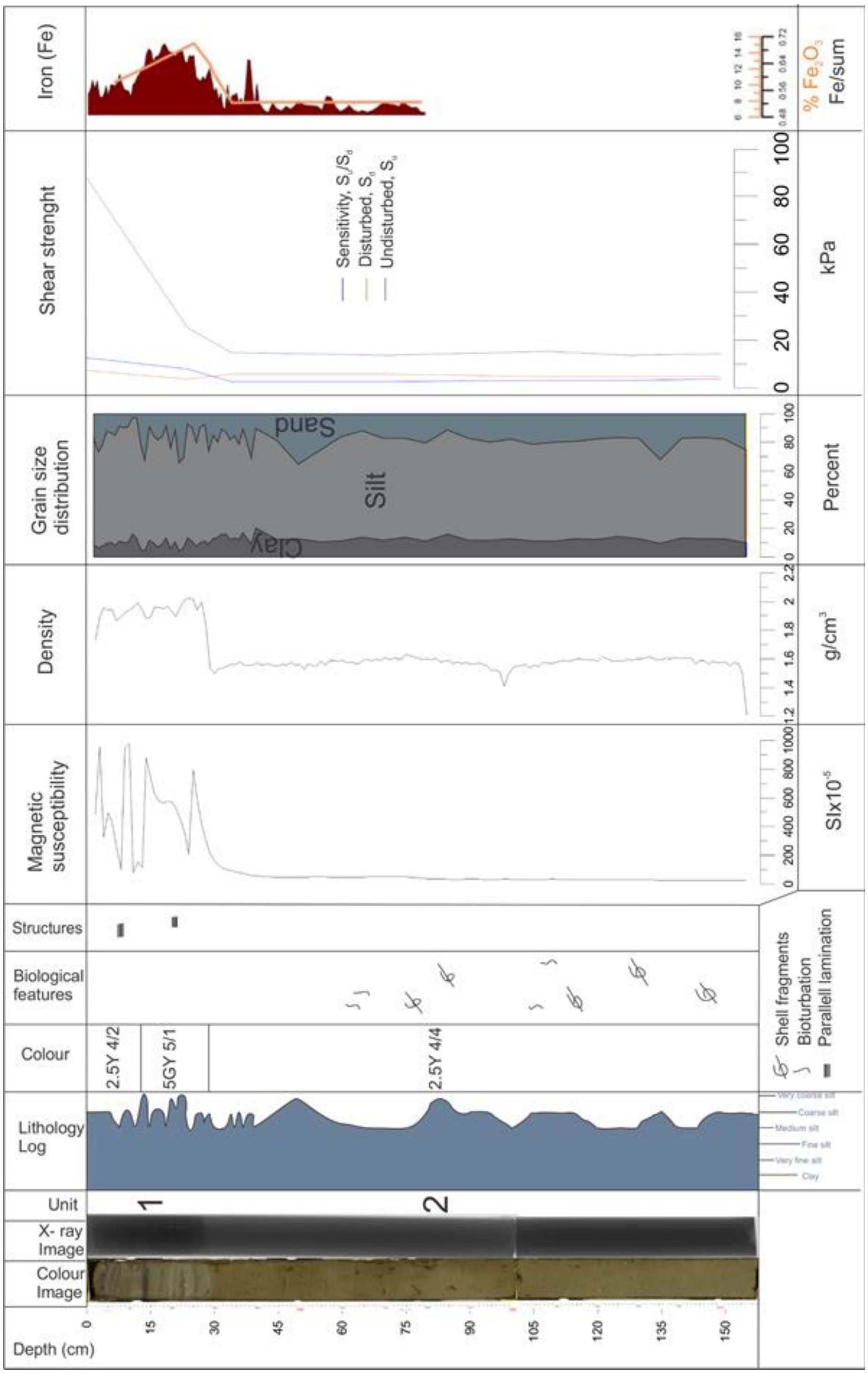

Figure 29: Core IG16-1811GC with all the result from different analyses. The Iron (Fe) was made by Nikolai Figenschau.

Core IG16-1811GC is 159 cm long and divided into two units (Figure 29).

Unit 1 from 0-29 cm mainly composed of unimodal poorly sorted sandy mud with a dominant grainsize of coarse silt. The predominant colour in unit 1 is greenish brown. Some clear lamination can be seen throughout unit 1. The wet-bulk density varies between 1.59 g/cm^3 and 2.02 g/cm^3 with the lowest value at 28.8 cm and the highest values between 23.8- 24.1 cm. There are more fluctuations seen in magnetic susceptibility than in wet-bulk density. The magnetic susceptibility varies between 76 SIx10^{-5} and 982 SIx10^{-5} with the lowest values at 11 cm and highest value at 10 cm. Fe/sum ratio vary between 0.545 at 10.1 cm and 0.695 cm at 17.9 cm. The sensitivity decreases slowly to 23.5 cm. Below 23.5 cm, a more rapid decrease towards the boundary to unit 2 occurs. The sensitivity varies from 7.68 kPa at 29 cm to 12.22 kPa at 6.5 cm. There is a sharp boundary at 29 cm between unit 1 and 2.

Unit 2 from 29- 155 cm is mainly composed of bimodal very poorly sorted sandy mud. The most dominant grain size is medium silt and the predominant colour is olive brown. On the X- radiograph, bioturbation can be seen throughout unit 2. At 54. 4 cm, 63. 5 cm and 64. 5 cm some black long matter was found. Shell fragments are found throughout unit 2. The wet-bulk density and magnetic susceptibility show small fluctuations in unit 2. The wet-bulk density varies between 1.63 g/cm^3 and 1.41 g/cm^3, with the lowest value at 98 cm and highest value at 75 cm. The magnetic susceptibility shows very little fluctuation, and all of the value are around 20 SIx10^{-5}. The iron values vary between 0.495 at 42.2 cm and 0.65 at 37.8 cm. The sensitivity stabilize at 34 cm with a value around 3 kPa.

Interpretation: The clear trend in this core is that magnetic susceptibility, density, iron and grain-size distribution shows large fluctuations in unit 1. There are also laminated layers that can indicate changes in the depositional environment. Unit 1 is interpreted to be mine tailings deposit or at least deposits being influenced by mine tailings. The sharp boundary to unit 2 indicates that there has been a sudden change in depositional environment. Unit 2 consist of a lot of bioturbation and shell fragments, indicating that the unit was deposited in a natural open marine environment.

7.3.4 P1505011

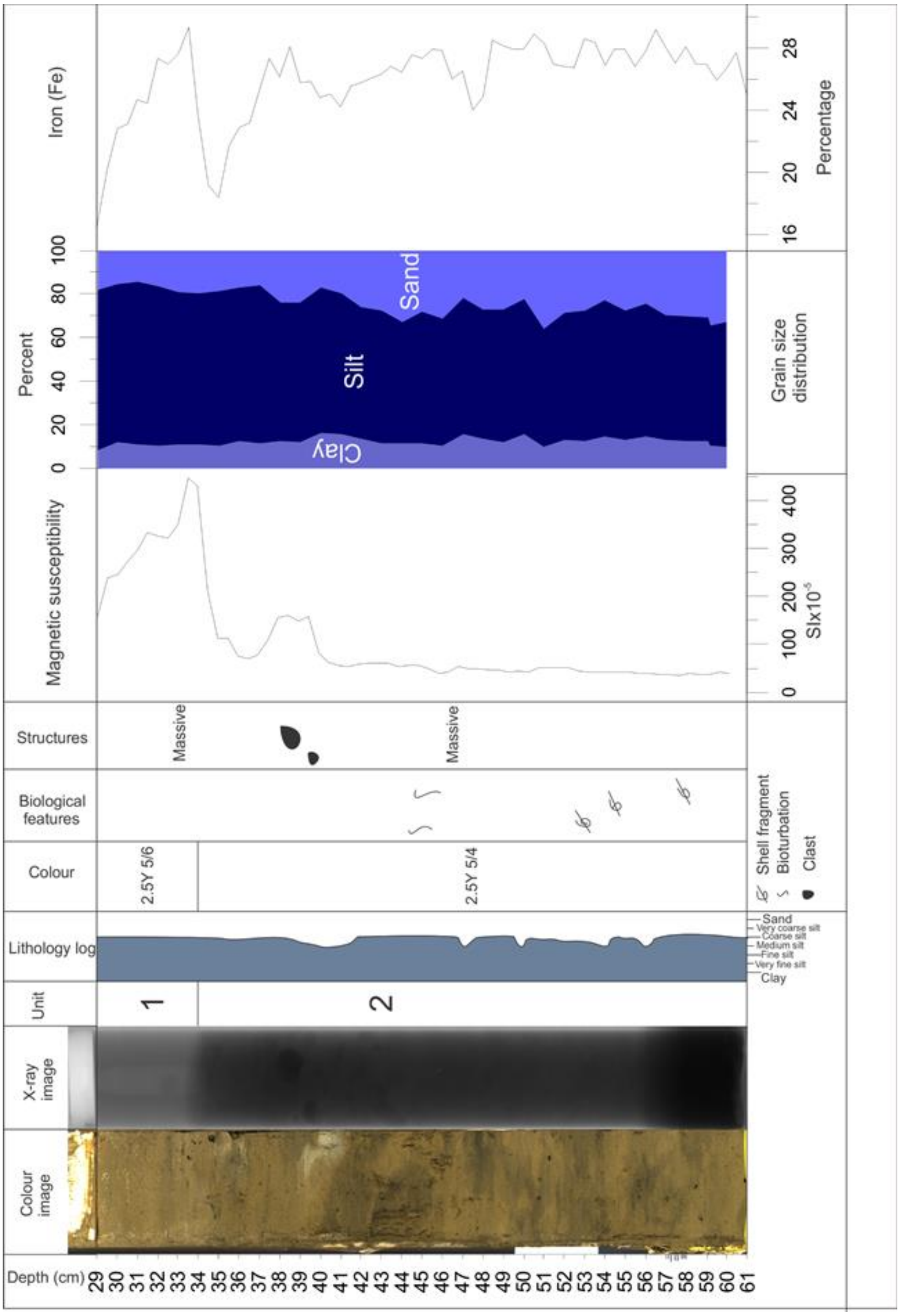

Figure 30: Core P1505011 with the result from the different analyses

Core P1505011 is 61 cm long and divided into two units: unit 1 from 29-34 cm and unit 2 from 34- 61 cm (Figure 30).

Unit 1 is composed of unimodal very poorly sorted sandy mud with the dominant grain size coarse silt. This unit is massive with an olive brown colour. The magnetic susceptibility varies between 155 SIx10^{-5} and 448 SIx10^{-5}, with the lowest value at 29 cm and the highest value at 33.5 cm. Fe/sum ratio vary between 16.5 and 29.5, with the lowest value at 29 cm and the highest value at 33.5 cm.

Unit 2 is composed of unimodal very poorly sorted sandy mud. The dominate grain size is coarse silt, with some areas in between consisting of medium silt. The colour is olive brown the same as unit 1 just a lighter shade. A black clast is found between 34-36 cm. Shinning grains and shells can be found throughout the core, the shinning grains increase slightly downwards. From the colour photo there is possible bioturbation between 41- 46 cm. The magnetic susceptibility varies between 35 SIx10-5 and 155 SIx10-5, lowest values between 57.3-57.7 cm and the highest value at 38.4 cm. Fe/sum varies between 18.2 and 29.2, the lowest value at 35 cm and the highest value at 56.5 cm.

Interpretation: Unit 1 seem to be influence by mine tailings due to the high readings in magnetic susceptibility and iron content. The influence is not large enough to give a clear colour change, hence the unit is probably mixed with natural sedimentation. Unit 2 contains bioturbation and shell fragments that indicate more natural sedimentation.

8 Discussion: The development of sedimentary environment in Bøkfjorden

The overall goal of the project was to characterise and distinguish natural and anthropogenic deposition in Bøkfjorden and to identify the spreading and impact of submarine tailings placements on the seafloor of the fjord. In this chapter the swath bathymetry, high-resolution seismic and lithological data is integrated together to see the development of sedimentary environment in Bøkfjorden.

8.1 The last glacial maximum

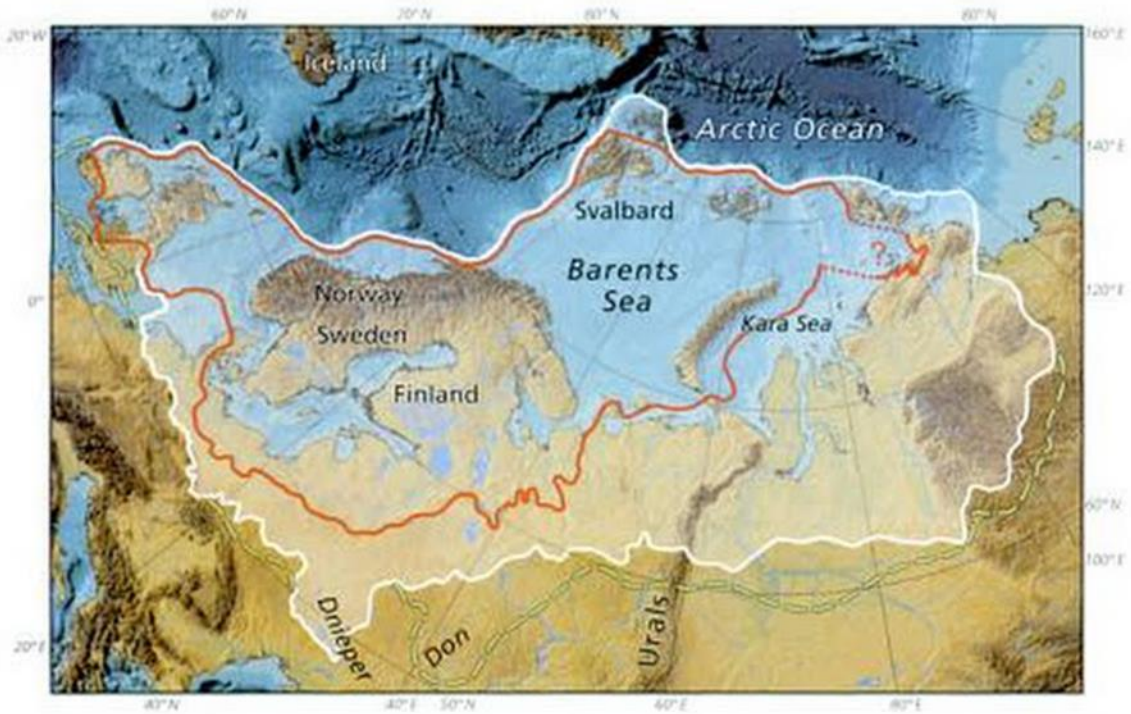

Figure 31: The red line show the max extension of the ice during the Last Glacial Maximum 20 000 years ago. Then the whole of Norway was covered by ice. (Ramberg et al., 2013)

Under the Last Glacial Maximum for approximately 20 000 years ago the entire coast of Finnmark was covered by the Fennoscandinavian ice sheet as represented in Figure 31 (Bakkejord & Lebesbye, 1985). The overall movement of the ice was towards north-north east illustrated in Figure 32 (Marthinussen, 1974; (Bakkejord & Lebesbye, 1985). During the glacial maximum the ice sheet was so thick that it moved independently of the terrain. Consequently, there are not found any evidence of ice in the sediment cores, probably due to high erosion rates from the ice (Hjelstuen et al., 2013) or the sediments in the cores are not old enough to show this event.

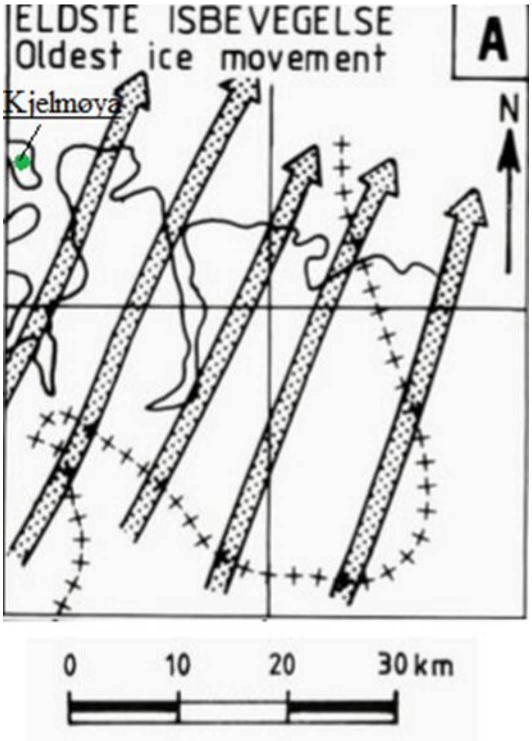

Figure 32: The oldest ice movements in the Sør Varanger area. (Bakkejord & Lebesbye, 1985).

8.2 Deglaciation

The deglaciation in this area was a step ward retreat towards the (Bakkejord & Lebesbye, 1985). There was also large local variation in the ice movement due to reduction in the ice thickness and the ice could be influenced by the local terrain (Marthinussen, 1974). This southwards retreat was divided into three main steps Bøkfjorden, Ropelv and Midtfjell (Bakkejord & Lebesbye, 1985). The first and northernmost step, is the Bøkfjorden step is located just north of Bøkfjorden lighthouse. In 1974, Marthinussen documented this with striations, but in 1985 Bakkejord stated that these striations could be older (Marthinussen 1974, (Bakkejord & Lebesbye, 1985). Large calving activity in Varangerfjorden cause a rapid retreat of the ice sheet in this area. The second step was the Ropelv step located at Kirkenes, revealing that all of Bøkfjorden was ice-free. The ice splits up between the Bøkfjorden step and Ropelv step and in the western part it continue towards the north but in the eastern part the ice movement turned more towards the east with local variations (Figure 33)

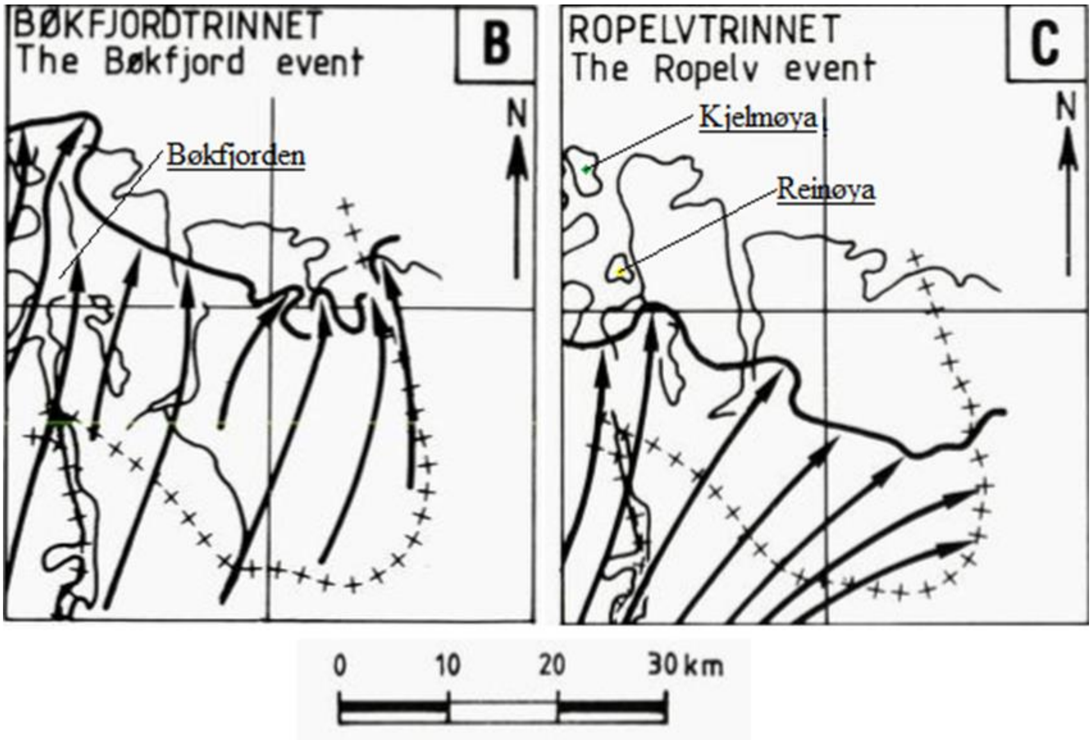

Figure 33: The ice movement in two of the deglaciation steps, Bøkfjord on the left and Ropelv on the right.

The last step was the Midtfjell step during which the center of Kirkenes became ice-free as well; just Langfjorden and the Pasvik river were still covered by ice (Bakkejord & Lebesbye, 1985).

This step ward retreat is most likely documented in one of the gravity cores from UiT. This glacier-proximal sedimentation is located in unit 2 IG16-1835GC. This unit 2 consist of grey laminated sediments with a thickness of 310 cm. The lamination are found in both the TOPAS profiles in unit 1. Unit 1 in the TOPAS data is described to be acoustically well laminate with sub-parallel to parallel reflectors. This lamination is believed to be a result of frequent lithological changes in a proximal glacimarine environment (Forwick & Vorren, 2010). Mass transport activity, temporal and spatial variations in ice rifting and/or sediment supply of one or several sources can be the reason for these changes. In the core IG16-1835 GC there are also two distinct "gravel packages" that are interpreted to be IRD (ice rafted debris).

Ice rafting debris can be deposited by icebergs or sea ice (Forwick & Vorren, 2009). In shore- distal settings the size of the IRD can occasionally be used to determine the most likely deposition source, large particles more likely to be icebergs (Gilbert 1990; Kneis et al., 2001). The grain shape can also give an indication if the IRD was deposited by icebergs or sea ice. Iceberg-rafted debris is more angular- rounded while sea- ice rafted debris is more round (Gilbert, 1990; Goldschmidt et al., 1992; Lisitzin, 2002). However, in polar settings the sea- ice rafted debris can be more angular (Gilbert, 1990). The trend just with look with the naked eye on the "gravel package" in unit 2 in core IG16-1835 GC is that the material is small and look more angular than rounded. The first observation indicates sea-ice debris and since this is in a polar settings sea-ice debris can be angular. More analyses need to be done to draw a conclusion, but the observation indicated that this was sea-ice rafted debris.

8.3 Postglacial

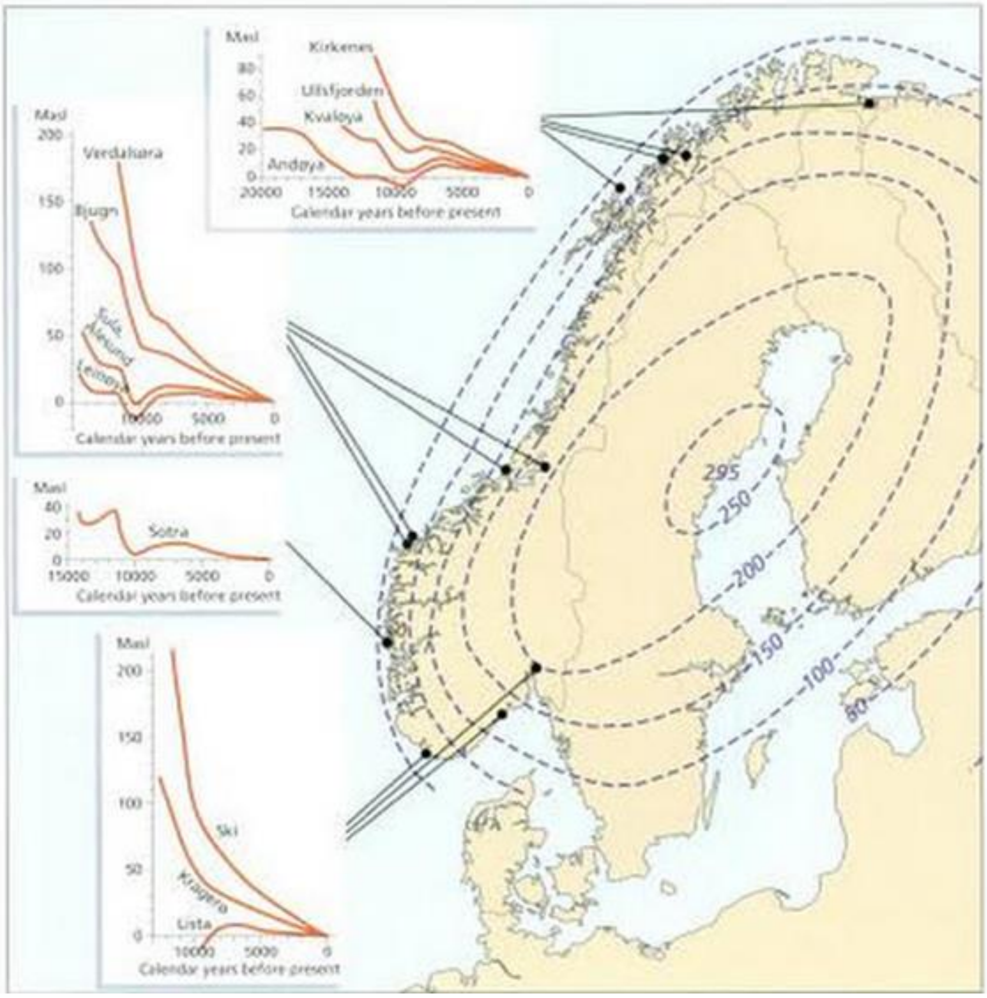

Figure 34: The dotted line on the map show the marine limit (MG). The red line in the graphs show the beach location on different time towards the present, the top graph show this for Kirkenes. (Ramberg et al., 2013).

When the ice retreated southwards during the deglaciation the water followed making the marine limit approximately 80 over the current sea level in Kirkenes (Figure 34) (Ramberg, et al., 2013). The land was also elevated when the ice retreated. This processes is, called isostatic uplift. In the start of the isostatic uplift the processes was slower than the sea level rise, due to viscosity of the asthenosphere (Ramberg, et al., 2013). After a while the isostatic uplift caught up with the sea level rise most places in Norway. The exception was the outermost coast where the isostatic uplift was small and the sea level raised quickly due to melting of the large ice sheets in North America and Antarctica. This happened 9500-6500 years ago and a called the Tapes transgression (Ramberg, et al., 2013).

This change the condition in the fjord to an open marine environment and this is documented in unit 2 in core P1505011, unit 1 in IG16-1835GC, unit 2 in IG16-1798GC and IG16-1811GC. In IG16-1835GC. In IG16-1835GC the transition zone from glacier- proximal sedimentation to postglacial sedimentation is gradually. The sediments in the open marine environment is massive with an olive brown colour with bioturbation and shell fragments. This indicate that the condition become more stable without the large variation in deposition environment. This sedimentation is larges in the outermost part of the fjord basin. However, in core P1505011, IG16-1798GC and IG16-1811GC it is hard to distinguish the full extent of this package due to no lower boundary. Approximately thickness of this package is 130 cm in IG16-1811GC, 94 cm in core IG16-1835GC and around 40 cm in core IG16-1798GC (Figure 25).

In the TOPAS data unit 2 and unit 2* there are found large transparent package. These packages have no internal structure and seem like one whole massive unit. In the N-S profile it seems to be one large event fist (unit 2) and one smaller event (unit 2*) after. Unit 2 is interpreted be massive slide and unit 2* a smaller slide event (Hjelstuen et al., 2013). This slides generally appear when the ice retreat around 9000-10 000 years ago therefor there will be an increase of seismic activity due to the postglacial isostatic uplift (Bøe et al., 2000; Forwick & Vorren, 2002; Hjelstuen et al., 2013). There are no indication of these large slide events in the cores or in the bathymetry. The trench located right south east for Reinøya on the bathymetry map may be a result of a large fault zone that occurred 9300 14C BP (Bøe, 2002). This fault zone, Stuoragurra, follows a two billion years old weakness zone. The Stuoragura fault zone is a part of a bigger system of reverse fault zones that consist of nine fault zones with a maximum vertical offset of 20 m (Bøe, 2002).

8.4 **Tailings placements**

Today, Bøkfjorden is mainly affected by the water and sediment supply from the Pasvik River. There is still large anthropogenic input into Bøkfjorden after Sydvaranger Gruve AS stopped there production in 2015. The largest contribution of anthrophonic input comes from Kimek, the sewage from Kirkenes and the salmon butchery at Jakobsneset (Berge et al., 2012).

Mine tailings deposited during the activity of Sydvaranger Gruve AS are reflected in three of the sediment cores: unit 1 in IG16-1798 GC, IG16-1811 GC and P1505011. The mine tailings are characterized by high magnetic susceptibility and high fluctuations in Fe/sum ratio and also fine grained material. This is found in all off the three cores (note that in P1505011 the Iron values are in percentage). In two of the cores IG16-1798 GC and IG16-1811 GC there are also a distinct colour differences between the natural sediments and the mine tailings. There are no indications of any mine tailings deposited in core IG16-1835 GC that is located on the threshold right south east for Reinøya. The mine tailings is confined by the channel from the depositional site to the threshold. The channel seems to follow the deeper part of the fjord basin represented in Figure 35. This is most likely the reason why there are no indication of mine tailings in core IG16-1835 GC.

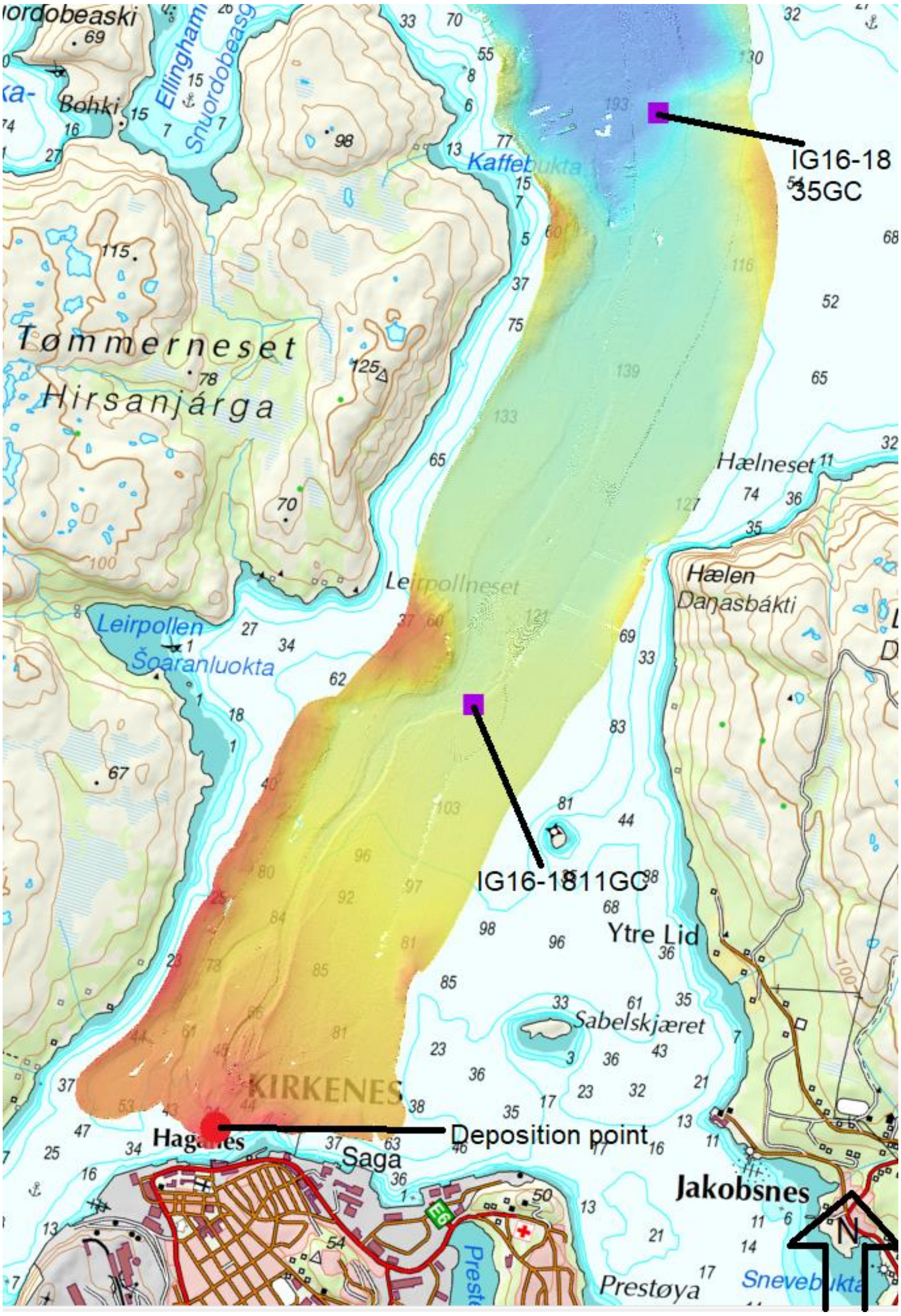

Figure 35: The channel is confined and follows the deep parts of the fjord. The deposition point and two core location is also marked on the map.

When comparing IG16-1798GC and IG16-1811GC the most obvious differences is the succession of mine tailings at 136.5 cm in IG16-1798GC and 29 cm in IG16-1811GC. The magnetic susceptibility values are still large in core IG16-1811GC compared with IG16-1798GC. This can be because of elements with high magnetic susceptibility is small and therefor transported over large distances e.g. spherical iron particles. When the turbidity current comes to the threshold the velocity will increase due to an increase in slope gradient. On bathymetry data, a promontory is located just north-west of Reinøya. This will deflect the turbidity current towards the location of core IG16-1811GC. When the velocity of the turbidity current decrease material will be deposited. The heaviest (coarser) will be deposited first and the lighter (finer) material furthest away. Turbidity currents can transport material several thousands of meters away from the starting point. This may also explain why there are fluctuations in the grain size distribution curve in core IG16-1811GC. When the velocity of the turbidity current is high coarser material is transported all the way to IG16-1811GC and when the velocity is low more fine-grained particles is transported to IG16-1811GC. The magnetic susceptibility signal reflect the same trend, finer material higher values and coarser material lower values. The signal of magnetic susceptibility seems to change prior to the change in grain size distribution. This may indicate that the coarser material is less iron rich and the finer material has a higher iron content. The mine tailings mainly consist for quartz, amphibolite and some magnetite as mentioned earlier. Quartz (SiO_2) consist of no iron and amphibolite consist of some iron. This can indicate that when the turbidity velocity is high a higher amount of quartz is distributed in core IG16-1811GC and therefore lower magnetic susceptibility. When the turbidity velocity is lower more iron (magnetite) is deposed in core IG16-1811GC and therefor higher magnetic susceptibility. Another explanation can be there is a mix of natural sediments and mine tailings deposited in core IG16-1811GC. Large fluctuation in the grain size distribution curve and the laminated layers may indicate that the first explanation is more likely. The high readings and fluctuation especially in magnetic susceptibility in core IG16-1798 GC not unexpected since it is located on the edge of the channel 2.3 km from the depositional site

(Figure 35). This fluctuation can be due to the channel receiving large and relative continuous supply of mine tailings this will lead to overspill, so the core can reflect a levee. (Amundsen, 2015). Levee is also believed to be seen in the TOPAS profile 1505013 represented in Figure 36 (Amundsen, 2015). Channel is also showed in this TOPAS profile and this indicate that the channel is young and erosive.

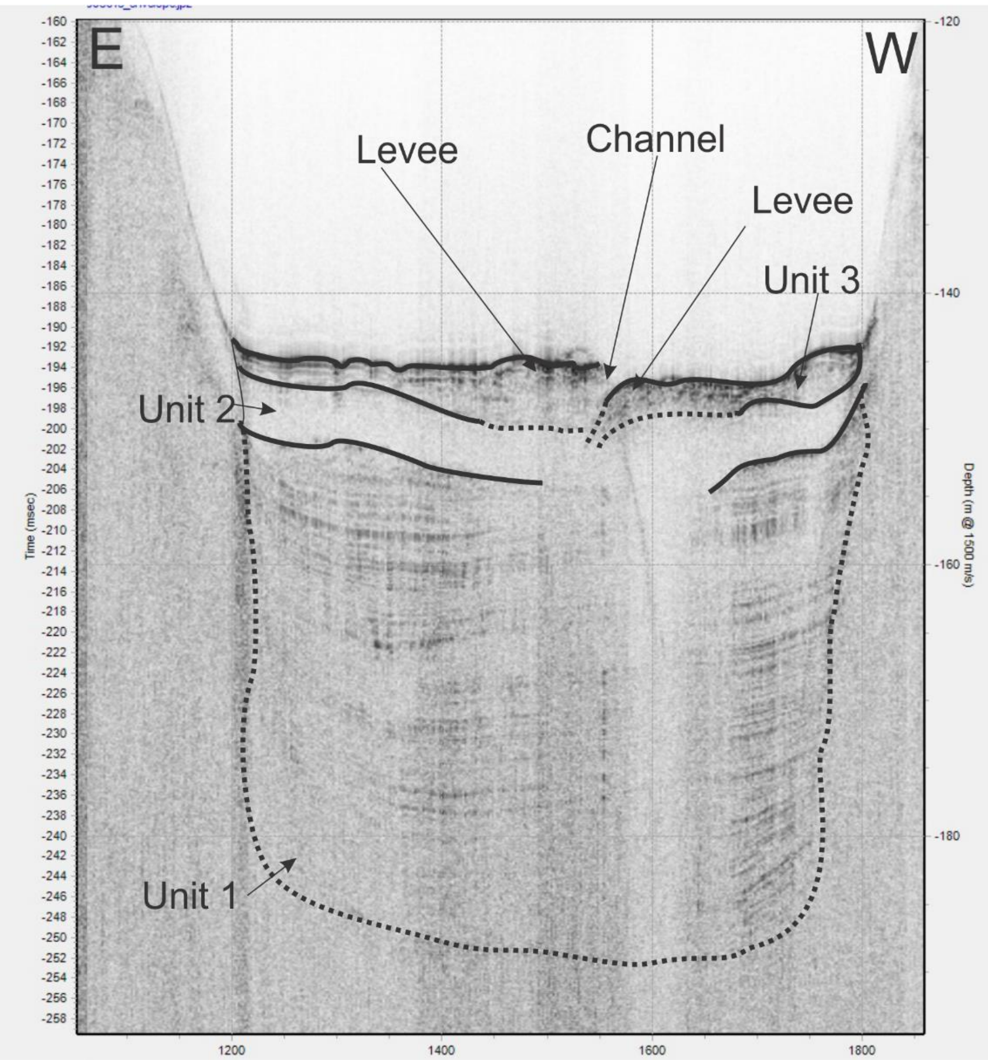

Figure 36: TOPAS profile 1505013, with interpretation of a channel and levees

In P1505011 there are no colour difference separating unit 1 and 2. In unit 1 there are relatively high magnetic susceptibility compared to IG16-1835GC. This indicate potensial mine tailings and since there are no colour change it is most likely deposited together with natural sediment. If this is traces of mine tailings, the mine tailings are effecting the fjord further out then believed before (Berge et al., 2011; Berge et al., 2012). In a previous report has been assumed that the mine tailings effect water depth under 100 m approximately 8-10 km from the depositional site (Berge et al., 2012). However this thesis shows that the mine tailings are at least influencing the sediments 13.2 km from the deposition site and support the findings from 1995 that sediments in the whole fjord system is impacting by mine tailings (Skei et al., 1995). Both P1505011 and IG16-1811GC is located on a depth under 100 m, indicating that the turbidity current is sinking at the threshold SW for Reinøya seen in Figure 12 (Berge et al., 2011). The succession of mine tailings in IG16-1798 GC is larger than in IG16-1811 GC and P1505011, this indicate that main portion od the mine tailings are deposited close to the deposition side. This also support the previous reports that most of the mine tailings is deposited before Reinøya, 7 km from the depositional site (Skei & Rygg, 1989; Skei et al., 1995; Berge et al. 2011 and Berge et al., 2012). The sensitivity also shows a rapid decrease around the transition zone to natural sediments represented Figure 37. This may indicate that the mine tailings are unstable and can cause sliding events in the further. This is unlikely because for sediments to turn quick the sensitivity must be greater than 30 and remoulded undrained shear strength less than 0.5 kPa (Geertsema et al., 2005).

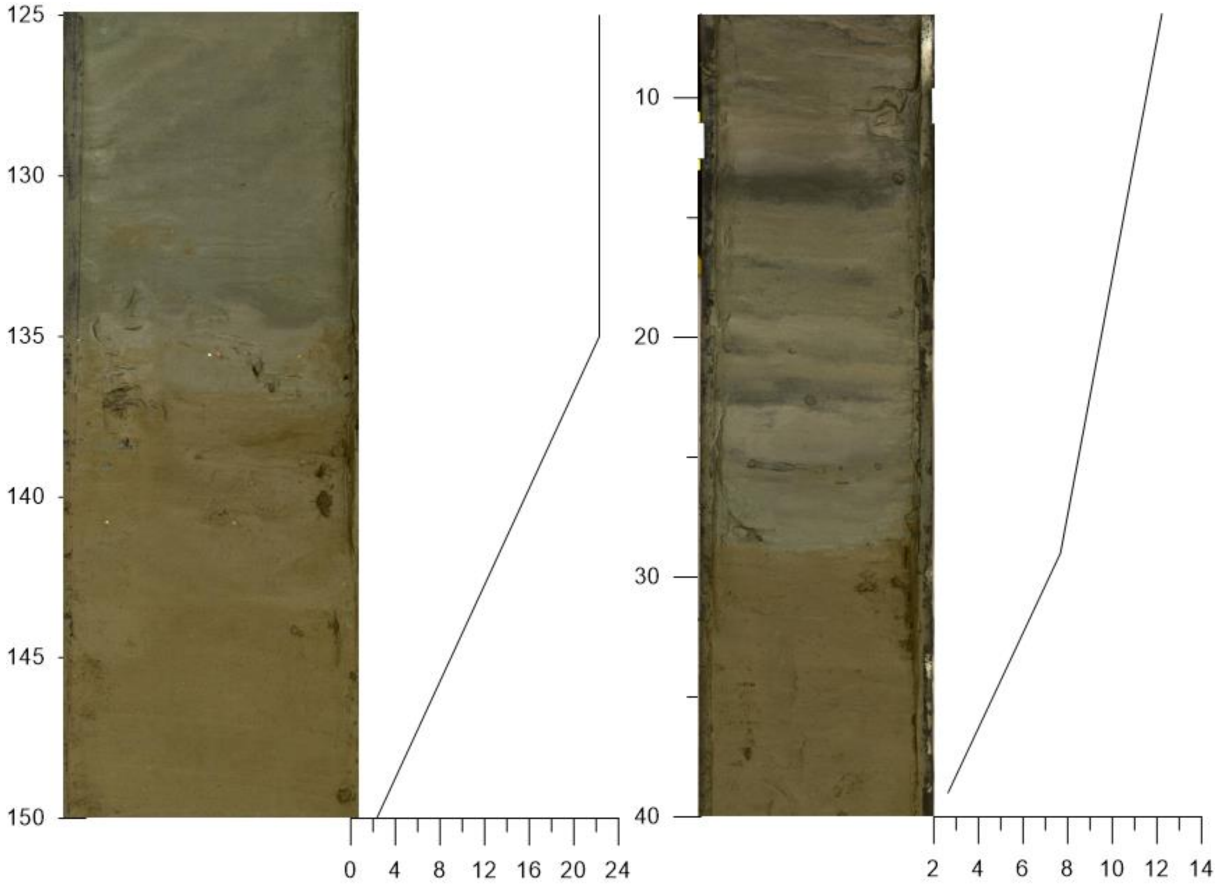

Figure 37: The sensitivity of the sediment shows a rapid decrease around the transition zone, the y axis reflected depth in cm.

9 Conclusion

The overall goal of the project was to characterise and distinguish natural and anthropogenic deposition in Bøkfjorden and to identify the spreading and impact of submarine tailings placements on the seafloor of the fjord. The study was based on the integration of swath bathymetry, high-resolution seismics and multi-proxy analyses of sediments cores. It included mapping of the seafloor morphology, as well as studying sedimentary processes and sediment distribution. The following conclusions can be drawn from this study:

- The bathymetry data in Bøkfjorden shows that the seafloor is generally sloping towards the north with a maximum depth of 254 m and a minimum depth of 9 m. There is a step located right south-west of Reinøya where the water depth increase from around 160 m to 190 m. The most prominent feature on the bathymetry data is a channel that is 5 km long and 270 m wide. This channel can be traced from the innermost part of the fjord-close to depositional side and all the way to the step south-west of Reinøya. This channel follows the deepest part of the basin and the width increase with distance from the depositional side. TOPAS profile 1505013 reveals that the channel erodes into the uppermost seismostratigraphic unit indicating that it is relatively young feature.

- The sediment cores reflect three different sedimentary environments: glacier proximal (deglaciation), open marine (postglacial) and anthropogenic (mine tailings placements). The glacier-proximal sedimentation is reflected in the core as a grey package with internal lamination. On TOPAS profiles it is visible as a massive and acoustically well laminated unit with parallel to sub-parallel reflectors. These laminations indicates repeated change in the depositional environment during the deglaciation. The open marine sedimentation in the cores is archived as a massive units with an olive brown colour, as well as abundant bioturbation and shell fragments. The postglacial isostatic uplift is reflected in the TOPAS profiles as sliding events. These sliding events is reflected as an acoustic transparent layer with no internal structure. The mine tailings placements is archived as a greenish package with some internal lamination. On the TOPAS profile 1505013 this is reflected as acoustically laminated layers with sub-parallel to parallel reflectors. This lamination show repeated change in the deposition of mine tailings.

- The submarine tailings are following the deep part of the fjord basin and is confined by a channel to the step south-west of Reinøya. The most of the submarine tailings (mine tailings) are deposited inside of this area. The findings also show that the submarine tailings are spread over large distances, this support the findings from 1995 (Skei et al., 1995).

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