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Drill cutting release in Ingøydjupet, SW Barents Sea from a well drilled in 1987, and its impact on benthic foraminifera

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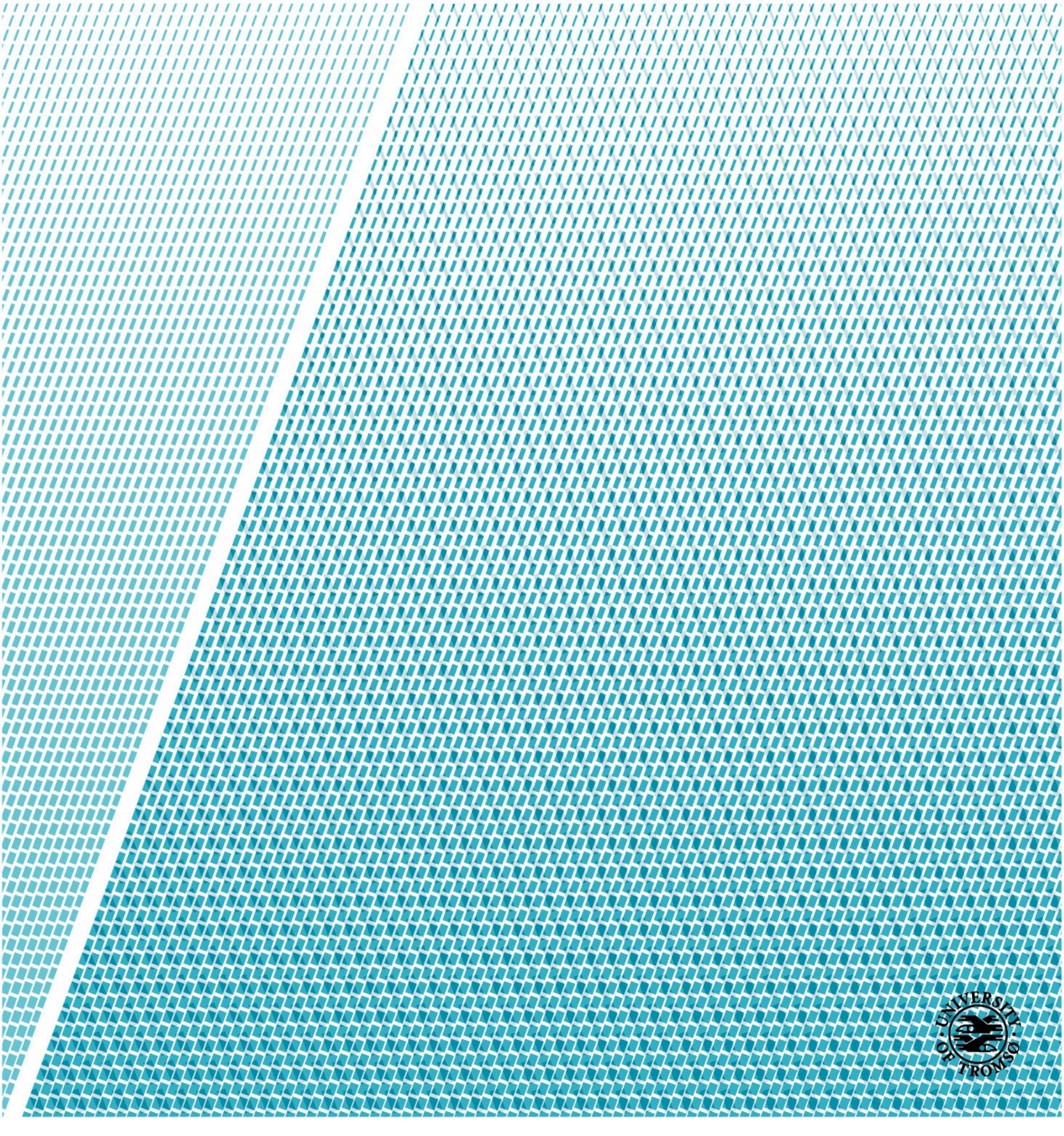

Abstract

In the nearby areas of the SW Barents Sea, large hydrocarbon reserves have been identified. During drilling procedures, drill cuttings are produced and some are released to sea. The disposal of drill cuttings may cause environmental degradation to the marine environment. Increasing petroleum activities, therefore requires further knowledge of ocean current transportation of fine sediment particles (clay and silt) related to cuttings and their effect on the marine environment and fauna including benthic foraminifera. Here, benthic foraminiferal assemblages and heavy metal concentrations in five different cores along a transect away from a well drilled in 1987 in the Ingøydjupet trough are presented.

Elevated metal concentrations of Ba, Pb, Hg and Cu where found in core T 10-4, closest to the pollution source. This core also has a low total number of foraminiferal specimens, which indicates this core is most impacted by drill cutting release. Cores further away reveals heavy metal concentrations that correspond to background levels, and foraminiferal assemblages that correspond to previous studies of pre-impacted foraminiferal assemblages in Ingøydjupet. Patterns in the foraminiferal assemblages in these cores, suggest natural variability related to a stronger inflow of Atlantic water with enhanced food supply. This study provides information about the impact of drill cutting release to the marine environment, and evaluates what can be done to prevent environmental impact of discharges of drill cuttings, alternative solutions for discharges, as well as which approaches can be used for removal of drill cuttings that has already been released to the marine environment.

Abbreviations

As = Arsenic

Ba = Barium

BIC = Bear Island Current

Cd = Cadmium

Co = Cobalt

Cr = Chromium

Cu = Copper

EcoQS = Ecological Quality Status

ESC = East Spitsbergen Current

EWMA = Environmental Waste Management

Hg = Mercury

NAC = North Atlantic Current

NCaC = North Cape Current

NCC = Norwegian Coastal Current

Ni = Nickel

OBM = Oil-Based Drilling Mud

Pb = Lead

PNEC = Predicted No Effect Concentration

QS_r = Quality Standard

ROV = Remotely Operated Underwater Vehicle

SBM = Synthetic-Based Drilling Mud

Ti = Titanium

TROX = Trophic Oxygen

V = Vanadium

WBM = Water-Based Drilling Mud

Zn = Zinc

#/g = Total calcareous/ gram dry sediment

Contents

List of figures

List of tables

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1 Introduction

In this chapter, the objectives of this master thesis will be discussed, and background information based on previous studies in addition to the importance of this work will be provided. Basic information about bio-monitoring indicators and an introduction to drill cuttings, drill cutting release, regulations and monitoring of drill cutting release will be presented.

1.1 Objectives

This master thesis was carried out at the Department of Geosciences, University of Tromsø – The Arctic University of Norway from August 2016 to May 2017. The master thesis is connected to the BARCUT project that aims to identify the environmental impact of drill cuttings released to sea at source and to address relevant societal concerns (EWMA, 2015).

In the nearby areas of the SW Barents Sea, large hydrocarbon reserves have been identified. During drilling procedures, drill cuttings, which are a mixture of fragments of reservoir rocks, chemicals and drilling mud (Hess et al., 2013), are produced and some are released to the sea. Offshore oil drilling activities may therefore cause environmental degradation due to accidental oil spills or the disposal of drill cuttings with oil- or water based drilling mud (Denoyelle et al., 2010). The Norwegian Environment Agency report that the goal is to reach zero discharge of drill cuttings in the Barents Sea (Miljødirektoratet, 2016). Regulations limit the discharges of contaminants to the marine environment, and reinjection has also been used to reduce discharges of drill cuttings and drilling mud (Bakke et al., 2013). Ball et al. (2012) described reinjection as a process where drill cuttings are injected into a subsurface formation, and the material can stay in the future, hence without any harm to the environment. Plans to increase petroleum activity in the SW Barents Sea will lead to an increase in releases of drill cuttings into the ocean. Other elements such as heavy metals, crushed rock fragments and petroleum hydrocarbons are also being released during drilling procedures (Neff, 2005). This increasing discharge provides a need for further knowledge of ocean current transportation of fine sediment particles (clay and silt) related to cuttings and their effect on the marine environment and fauna including benthic foraminifera. The main objective of this thesis is to investigate the environmental impact of drill cutting release from a well drilled in 1987. In order to do this, benthic foraminifera assemblages, the concentration of heavy metals, total organic carbon (TOC) content and the distribution of grain sizes in the area are analyzed.

1.2 Background

1.2.1 Biological proxies

Biological proxies are biological evidence with preserved physical characteristics that can give us information about the environment in the past such as oceanography, climatology and ecology (Harff et al., 2016). They can also give us geochemical information and information about biostratigraphy. Both dead and live biological proxies can be used to provide information about the environment. Examples of biological proxies are microfossils, pollen grains and corals. They are remains of organisms found in marine and terrestrial sediments with skeleton, tests or shells as the preserved part of the organism (Harff et al., 2016). Changes in fauna/floral composition and distribution can help us to detect changes in the environment. These changes can be caused by natural or anthropogenic disturbances such as for example pollution in form of drill cutting release. Therefore, biological proxies can be used to investigate the impact of drill cutting release on the benthic organisms inhabiting the sea floor ecosystem. However, biological proxies do not provide us information on what kind of pollutants are impacting the environment (Denoyelle et al., 2010).

1.2.1.1 Foraminifera

Foraminifera are a group of marine, microscopic single cell organisms. They are 0.05 – 0.5 mm in size and are heterotroph organisms. They are either planktonic, living in the water column, or benthic, living in or on the sediment surface. All foraminifera have reticulopodia, which are fine pseudopodia that can split and rejoin, and have a granular texture when viewed in the microscope (Goldstein, 1999). Foraminifera produce a test which is preserved well in the sedimentary record, and most of these are made of calcite, but organic and agglutinated tests are also present (Hansen, 1999). In this study, benthic foraminifera with calcareous tests will be investigated, due to the well-preserved skeleton of calcareous tests and the dominance of these in the examined sediments.

Within the European Union's Water Framework Directive (WFD), the five bio-indicators listed are phytoplankton, angiosperms, macroalgae, fish and benthic invertebrates (Frontalini and Coccioni, 2011), where benthic foraminifera belong to benthic invertebrates. The use of benthic foraminifera as bio-indicators have increased in recent decades, but they were first used as biological proxies to study effects of pollution in the 1960s (Frontalini et al., 2009; reference therein). Resig (1960) and Watkins (1961) were the ones who first initiated the use of benthic foraminifera as proxy indicators in pollution studies, although pollution effects on benthic foraminifera had been mentioned earlier by other workers (Alve, 1995; reference therein). After that a wide range of studies have focused on the impacts of pollution on benthic foraminifera in various marine environments, and proved that they successfully can be applied as bio-indicators to estimate the impact of drill cutting release (Jorissen et al., 2009). This has been done in various marine environments such as the inner continental shelf exposed to drill cutting disposal, intertidal mudflats impacted by oil spillages, and harbours affected by heavy metal pollution (Mojtahid et al., 2008; reference therein).

Benthic foraminifera are proved to be good bio-indicators because they have specific environmental preferences, react fast to disturbances in the environment and preserve well in the sedimentary record (Murray, 2006; Dijkstra et al., 2015). Changes in the environment have led to changes in faunal composition and species richness (Hess et al., 2013), which means that changes in the environment can be detected by looking at modifications in faunal assemblages of foraminifera. Benthic foraminifera can be investigated in terms of population density and diversity, reproduction capability, morphology, dysfunctional behavior and chemistry of test when using them as bio-indicators of environmental quality (Frontalini et al., 2009). They have a wide environmental distribution, and occur in many different environments ranging from fjords and river estuaries to deep oceanic basins (Polyak et al., 2002). They are usually abundant, which provides a reliable database for statistical analysis (Mojtahid et al., 2006). The distribution of benthic foraminifera is mostly dependent on food availability, substrate type, water temperature, salinity, tidal currents, pollution, depth, competition and predation, and the amount of dissolved oxygen (Murray, 2006). Benthic foraminifera rely on organic matter and the bacterial community living on it as the primary food source.

Monitoring the status of marine environments is traditionally based on macrofauna surveys, for which standardized methods have been established (Schönfeld et al., 2012), which is also the case for the Norwegian continental shelf. However, a new protocol called the FOBIMO protocol has been developed, focusing on including benthic foraminifera in government and international programs regulating surveys in the marine environment (Schönfeld et al., 2012). Based on this protocol, new studies and new method development, the European Union's Water Framework Directive (WFD) realized that foraminifera are also important, and hence now they are under consideration to include the foraminiferal method in the EU legislation (Francescangeli et al., 2016). Additionally, the Norwegian authorities now recommend using foraminifera to reconstruct in situ reference conditions (Veileder02:2013). By including benthic foraminifera in pollution-monitoring programs we will be able to detect changes in the environment caused by anthropogenic pollution. Frontalini and Coccioni (2011) noted that living assemblages of benthic foraminifera should be used when investigating the ecological health of benthic ecosystems living in the marine environment. In other words, by using benthic foraminifera as bio-indicators we can detect information about the ecological health of the marine benthic ecosystem, compared to chemical data that does not provide this sort of information. To obtain comparable results between studies, scientists using benthic foraminifera as bio-indicators should include either the absolute abundance of benthic foraminifera or the relative abundance, with the number of specimens included (Frontalini and Coccioni, 2011).

One aspect to think about when using benthic foraminifera as bio-indicators, is that many polluted areas are often naturally stressed, and disturbances in benthic communities can be caused by natural stress rather than anthropogenic changes. This makes it difficult to interpret which changes in faunal composition and diversity is controlled by natural disturbances or by pollution. Also, it is hard to distinguish between different pollutants that are influencing the benthic community, but it is likely that benthic foraminifera are reacting to a combination of several contaminants related to drill cuttings such as various heavy metals and organic enrichment. A third factor is that different environments can react differently to the same kind of pollution. To be able to get a good understanding of how benthic foraminifera respond to various kinds of pollution, Alve (1995) stated that two different approaches where needed: field based studies both on live and dead foraminifera to investigate abundance and diversity patterns, which is done in this study, and laboratory experiments to investigate the influence of different kind of pollutants, reproduction, growth, abundance etc. Alve (1995) also stated that more efforts should be done to investigate the difference between natural caused test deformation and pollution caused deformation.

Benthic foraminifera are also a reliable tool to assess the recolonization of the affected areas, after cessation of the pollution activities (Denoyelle et al., 2012). To get a good understanding of the recovery of the marine environment after drill cutting releases, it is important to investigate the colonization of new habitats by benthic foraminifera, with focus on the processes involved in the colonization including both environmental and biological processes, as well as focusing on the speed of colonization (Alve, 1999). Colonization can be defined as "*the initial faunal recovery process and subsequent succession following major disturbances*" (Alve, 1999; reference therein). Such disturbances can be related to drill cutting release, depositional events with high sediment load, or the exposure of the sea floor due to for example retreating ice fronts. This is valuable information for paleoenvironmental interpretations, biostratigraphic correlations and for detecting recovery rates after the onset of physical disturbances.

1.2.2 Drill cuttings and drilling mud

To get a precise understanding of drill cutting release and what is being discharged to the marine environment, some basic terminology must be described. "Drill cuttings are particles of crushed rock produced by the grinding action of the drill bit as it penetrates the earth" (Neff, 2005). Drilling mud can be defined as "a suspension of solids (ex. clay, barite, ilmenite) in liquids (ex. water, oil) containing chemical additives as required to modify its properties" (Neff, 2005). Its function is to reduce friction of the drill string, to control pressure inside the drill, to stabilize the well and to lift cuttings to the surface (Trannum et al., 2011). Drilling mud contains fine sediment particles. When the drilling mud with drill cuttings are up on the platform, the drill cuttings and the adhering mud are treated with special devices to separate the cuttings from the surrounding mud, which are recovered and as much as possible used again (Denoyelle et al., 2012). Normally the drill cuttings and drilling mud are successfully separated after mixture before drill cuttings are discharged to sea, but the drill cuttings often still contain considerable amounts of drilling mud after separation. The result is that some amounts of drilling muds are being discharged as well. See figure 1 for an illustration of the drilling process. Drilling mud can be divided into three types: oil-based drilling mud (OBM), synthetic-based drilling mud (SBM) and water-based drilling mud (WBM) (Hess et. al., 2013).

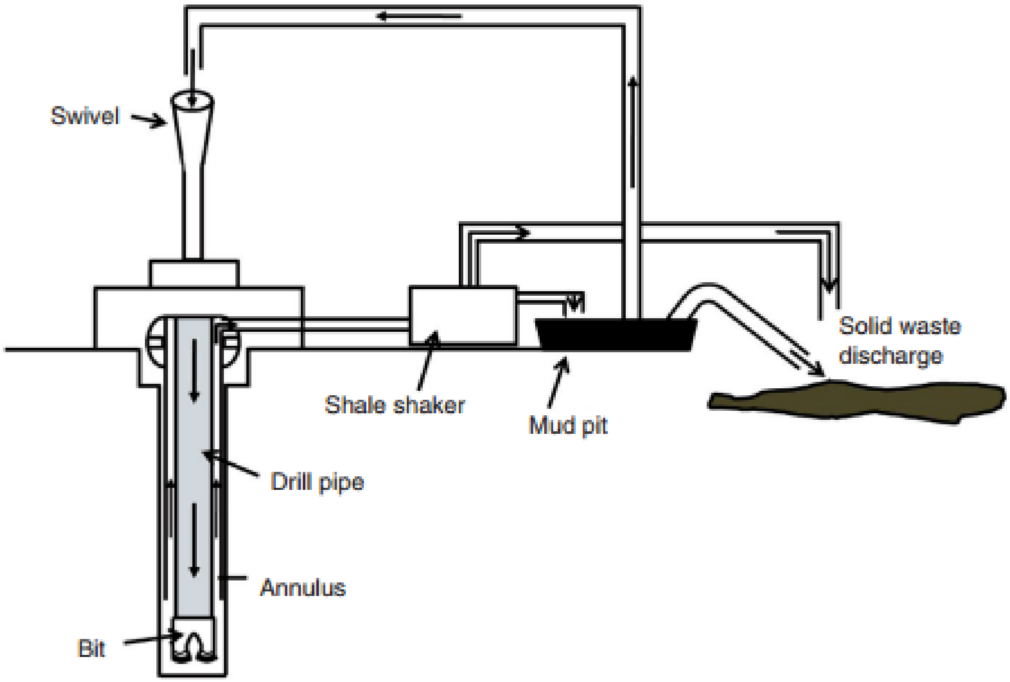

Figure 1: Schematic illustration of the drilling process. After Ball et al. (2012).

WBM is considered less harmful to the marine environment, and is therefore used the most today. It consists of either fresh or salt water, and the water contains a weighting agent (normally barite), clay or organic polymers and inorganic salts, inert solids and organic additives (Neff, 2005). Many of the additives in the WBM are considered to cause little or no risk to the environment (Ball et al., 2012; reference therein). However, recent studies have reported more adverse effects of this type of drilling mud than previously assumed (Trannum et al., 2011; reference therein), and therefore it must be used carefully. The use of WBM has increased the use of barite (Olsgard and Gray, 1995), which is the principal constituent in drilling mud, and it is normally used in high quantities. Around 90% of it is usually discharged after use (Olsgard and Gray, 1995). Barite is insoluble and settles on the seabed, therefore the effect of drill cuttings is likely to be found on bottom-living communities. Although it is considered nontoxic to organisms, it can remain in the water column for a long time, and the fine-grained particles of the mud may therefore lead to the spreading of barite with ocean currents. Barium (Ba) is a component in Barite ($BaSO_4$), and the presence of Ba is therefore a good indicator of drill cutting release. By using WBM, water-based cuttings are produced. In the WBM and cuttings disposed to sea, heavy metals have the greatest toxicological concern (Neff, 2008), and might have harmful environmental impacts on the benthic ecosystem.

1.2.3 Drill cutting release

When drill cuttings and water-based drilling muds are released to the marine environment, the largest particles and solids accumulate and form a plume that settles quickly to the sea floor. The fine-grained particles drift with prevailing currents away from where it was discharged and are diluted in receiving waters (Neff, 2005). For drill cuttings and water-based drilling mud discharged at or near the sea surface, the pollutants are diluted in the water column and settle as thin layers over a wider area of the sea floor. On the other hand, if discharged near the sea floor, they accumulate and form a high pile near the discharge pipe (Neff, 2005). Breuer et al. (1999 with reference therein) stated that up to 75% of the drill cuttings released to the environment accumulates and form the pile, and the rest of the material are dispersed over a wider area of the seafloor. It implies that we can expect to have a thick layer of drill cuttings in the proximity of the well, and a thinning wedge of drill cutting deposits further away from the well. In other words, the distribution of drill cuttings depend on the position of the discharge pipe in the water column.

Water based drill cutting piles on the seafloor are characterized by poorly sorted, impoverished benthic communities with a variable mixture of clay particles (Breuer et al., 2008; reference therein). When the drill cuttings are deposited on the seafloor, they become more consolidated and more resistant to erosion. The size and shape of drill cutting piles depend on the platform construction and position of the well, the rate of discharge, the type of mud used in the drilling operation and the ocean currents influencing the sediments and cuttings deposited in the area (Trannum et al., 2011). Once it is deposited on the sea floor, the drill cuttings can be redistributed or mixed by processes such as bioturbation, ocean currents etc. Areas of stronger ocean currents such as shallow banks have stronger mixing of pollutants, while in areas of weaker currents such as deeper troughs and basins, drill cuttings flocculate and accumulate under and in proximal areas of the platform (Breuer et al., 2008). No two drill cutting piles are alike, and they each represents a combination of contaminants, sediment composition and benthic community, and hence each pile is affected by the local hydrographic regime (Breuer et al., 1999). In general, there is a lack of information on the amounts of drilling muds deposited on the sea floor around drilling platforms. A factor that makes it difficult to measure the amount of disposed material around the discharge pipe is the dilution with natural sediment and transport by bottom currents. However, in Norway this information is either available online (Norwegian Petroleum Directorate, 2012), or compiled in Falk et al. (2013) for older wells.

The pile of drill cuttings accumulated on the sea floor are often characterized by high concentrations of Ba and various heavy metals. The heavy metals that are most often enriched in sediments impacted by drill cuttings are chromium (Cr), lead (Pb) and zinc (Zn) (Neff, 2005). Olsgard and Gray (1995) stated that also copper (Cu) and cadmium (Cd) are related to the discharge of drill cuttings, as well as organic enrichment. Breuer et al. (1999) stated that the heavy metals related to drill cuttings in the North Sea from the first exploratory wells drilled in 1961 was Cr, Cu, nickel (Ni), Pb, and Zn, as well as high concentrations of Ba. This corresponds to a study by Frontalini et al. (2009), which stated that mercury (Hg), Pb and Zn was the heavy metals with the highest concentrations in proximity to the pollution source, and that Cr, Cu and Ni also appeared with elevated concentrations. The metal concentrations in drill cutting piles are influenced by particle size, benthic fauna, content of organic matter and sedimentation rate, and the distribution is influenced by sediment texture, deposition and resuspension. Heavy metals often accumulate in fine sediment particles, due to the ability of clay to bind metals. The transportation of drill cuttings further away from the drill cutting pile, may have a smothering effect on benthic communities far away from the discharge site (Reynier et al., 2015), where benthic communities are impacted by the burial of thick layers of drill cuttings and not the cuttings itself. The spread of cuttings particles is dependent on their particle size and the current regime.

It is important to emphasize that heavy metal concentrations in drill cuttings piles are not only originating from drill cuttings. It is a combination of accumulation and/or migration from natural sediment, from barite and other chemicals related to drilling muds, the platform, other anthropogenic sources and from aeolian input (Breuer et al., 1999). However, high concentrations of many heavy metals in the proximity of the platform may indicate that they are related to drill cuttings. When discussing drill cutting release into the marine environment, it is important to distinguish between two essential terms related to this topic; contamination and pollution. Contamination is described as the raised concentration of chemicals, while pollution is the effects of that contamination on biota (Olsgard and Gray, 1995).

1.2.3.1 Impacts on benthic fauna and foraminifera

According to Nåmdal (2011), the discharges from offshore petroleum activities to the marine environment has decreased during the last 10-15 years. Indeed, due to increased implementation of regulations and monitoring surveys that is required before drilling operations. Even though the spread of pollutants has decreased, the discharge of drill cuttings to sea still have an impact on the marine environment. As described above it is the area or position in the water column where drill cuttings are being discharged that determine the degree of impact.

Previous work has shown that discharges of contaminated drill cuttings to sea have changed the composition of benthic fauna (Hess et al., 2013), and can affect benthic faunas in three ways; by directly covering organisms, indirectly by toxicity to surrounding organisms, and microbial degradation of organic components in the drill cuttings leading to anoxic conditions (Ball et al., 2012). The most strongly affected areas seems to be characterized by a fauna of lower diversity, and a dominance of opportunistic species (Schaanning et al., 2008). Opportunistic species might be dependent on nutrients in the area that might be related to drill cuttings such as organic substances, nutrient salts, bacteria etc., or the area might be a favourable habitat due to reduced competition and predation, hence they benefit from certain type of pollution (Alve, 1995). However, indicative or opportunistic species are not found in all impacted areas, and there may be several reasons for that. Minor differences in depth and sedimentation rate can influence the natural faunal composition, sensitive species may be specific for one or two types of pollution, and an indicator species may be sensitive to one pollutant and tolerate another (Olsgard and Gray, 1995). Beneath the platform where cuttings are being discharged, the cuttings may consist of no benthic fauna due to burial by drill cuttings on the natural sediments (Davies et al., 1984). Further away from the discharge area the diversity may be the same as for the “reference area”, but there may be a difference in species composition. Davies et al. (1984) stated that the most severe impacts of drill cuttings on the benthic community occurs within 200 m from the discharge pipe, and beyond that zone populations return to background levels. Frontalini et al.

(2009) also stated that the most severe impacts of pollution where found in proximity of the pollution source.

Areas with impacted faunas several years after the cessation of drill cutting release, indicate that drill cuttings have negative environmental impacts on benthic communities (Olsgard and Gray, 1995). If high concentrations of contaminants are present, the sediments may become toxic and will harm the benthic communities living in the sediments (Frontalini and Coccioni, 2011). The impact of drill cutting release on benthic foraminifera is dependent on the amount of toxic material and the distribution of this material in the sediments. Although contaminants are likely to accumulate in fine grained particles and that the sediments capacity to store chemicals, recycle and transforming toxic chemicals through biological and chemical processes are high, the contaminants may not always show direct effects on the benthic communities. Other factors may also change the faunal composition of benthic foraminifera. Olsgard and Gray (1995) stated that there was no correlation between the amount of drill cuttings discharged and the affected fauna, and reported that the area that had the highest concentration of drill cuttings, did not have the largest extent of affected benthic communities. The type of mud used, hydrocarbon conditions, particle size of the drill cuttings and natural variability may influence the distribution of benthic foraminifera (Olsgard and Gray, 1995).

Hess et al. (2013) have tested foraminiferal response in sediment covered with water-based drill cuttings versus foraminifera response in sediments covered with natural test sediment. The study proved that independent on type of material, increasing thickness of added material significantly reduced the benthic foraminiferal abundance and species richness. Most species managed to migrate up to a thickness of 12 mm. Results of the study done by Hess et al. (2013) show that burial had a negative effect on the benthic foraminiferal abundance and species richness when the sediment cover reached a thickness of 24 mm. For some species, the physical disturbance in the environment triggered reproduction, which probably happened following migration up to the sediment surface. This is typical for opportunistic species or stress-tolerant species that might have specific food preferences on the sediment surface. Sexual reproduction increases the genetic variability within a population, which is beneficial under stressed conditions caused by either natural disturbances or anthropogenic changes (Frontalini et al., 2009). This may be the reason why the physical disturbances in the study by Hess et al. (2013) triggered reproduction. Based on this study we know that the use of water-based drill cuttings might affect the marine benthic community also through burial or smothering as referred to in section 1.2.3. Moreover, in the study by Hess et al. (2013), the responses of macrofauna and foraminifera are compared. Both organism groups responded to the addition of water based drill cuttings, with a decrease in abundance and diversity with increased thickness of water based cuttings. However, the macrofauna did not respond to the addition of natural test sediment, which indicates that a triggering mechanism associated to the water based cuttings is affecting the macrofauna. This triggering mechanism could be the toxicity of the water based cuttings. Finally, Hess et al. (2013) emphasized that the foraminiferal response seems to be influenced not only by burial of the water based cuttings, but also by a stress factor related to the water based cuttings.

Studying the impact of drill cutting release on foraminifera is ecologically important, because the reduction of certain foraminiferal species due to pollution, may have consequences for other organisms that feed on these organisms, as for example bottom living fish (Olsgard and Gray, 1995). Even if new stress tolerant or opportunistic species establish the impacted area, they might not be a valuable food source for bottom-living fish populations if they live in the sediment. When investigating drill cutting release and its impact on benthic foraminifera, it is important to keep in mind that various species respond differently to different contaminants, and that the respond of certain species may vary in different marine environments.

1.2.4 Regulations

It is important to prevent large amounts of discharges from offshore petroleum activities to sea to protect the marine environment from environmental degradation. Therefore, discharges are controlled by various regulations and monitoring programs around the world, which put strict limits on levels of contaminants that can be discharged to sea (Bakke et al., 2013). The regulations vary from area to area, and are based on the extent of discharge, and degree of vulnerable species and habitats in the specific area. In this section, the focus will be on regulations in the Barents Sea.

In 1993, Norway introduced a regulation that prohibited discharges of cuttings containing more than 1 % oil (Norwegian Petroleum Directorate, 2012). Before 1993, the limit of oil adhering to the cuttings that were discharged to sea, was 6-17 % (Davies et al., 1984). However, the Oslo

-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) has developed several regulations for the North East Atlantic region (Bakke et al., 2013). The OSPAR convention is the basis for national laws controlling discharges into the North Sea, including drill cutting release (Ball et al., 2012). In 1984, they prohibited the discharge of cuttings contaminated with diesel-based OBM, and in 1996 they prohibited the discharge of cuttings contaminated by any type of OBM (Neff, 2008). SBM is considered less harmful than OBM, but was significantly reduced by the OSPAR convention in 2001 (Neff, 2008). After the regulation took place in 1993 the use of oil-based drilling mud was reduced, and today Norway allows only water-based drilling muds to be used in drilling operations (Bakke et al., 2013). Nevertheless, if cuttings contain more than the accepted 1 % oil by weight, they must either be reinjected or taken to shore for treatment. It implies that the regulations introduced in the mid-1990s, which controls what is being discharged to the marine environment and in which amounts have worked. Drill cuttings on the Norwegian Continental Shelf released before the regulations were introduced, have resulted in large piles of drill cuttings deposited on the seafloor beneath and around the discharge pipes (Norwegian Petroleum Directorate, 2012), including the well drilled in 1987 investigated in this study.

1.2.4.1 Regulations in the Barents Sea

Due to increasing environmental concern the last decades, the petroleum activity started relatively late in the Barents Sea (Knol, 2011). The concerns have been raised based on local issues such as the coexistence with the fisheries, turning into more global issues such as climate change (Knol, 2011). Because of vulnerable habitats in the Barents Sea, and the increasing environmental concerns in this area, it is important with regulations that control the discharges from offshore petroleum activities in the Arctic. The ‘precautionary principle’ is integrated in marine ecosystem governance to reduce the potential harms of offshore petroleum activities. To control the impacts of discharges to the marine environment, Norway introduced a ‘Zero Discharge’ policy on the continental shelf in 1996-97, with stricter requirements in the Barents Sea (Knol, 2011). The main objective with zero discharge is to reduce environmentally hazardous substances discharged from petroleum activities. In practice, this means that during operations no discharges from petroleum activities with any substances with negative impacts on the marine environment are permitted. The most important requirements of this policy are cleansing and replacing added harmful chemicals. The implementation of zero discharge on the Norwegian continental shelf has led to a substantial reduction in discharges of the most environmentally hazardous chemicals (Knol, 2011). The process of reducing discharges started in 2002, and resulted in significantly reduced discharges from 2004 and forward (Knol, 2011). More than 99 % of the chemicals in the red and black categories defined by the Norwegian Environment Agency has been phased out, and now discharges involve nearly only chemicals in the yellow and green categories (Knol, 2011).

When controlling the discharges of hazardous chemicals from petroleum activities, it is important to consider unintended consequences that may be harmful for the environment. When implementing zero discharge, companies must develop technologies to reinject waste into the well and drill cuttings must be taken to shore for treatment (Knol, 2011). This will lead to increased traffic and hence increased emissions of CO_2 to the air, and it will cost. Because of the harmful environmental effect the absolute zero discharge may have on the environment through removal of contaminants, this may not be the optimal environmental solution. Options for the handling of drill cuttings will be further discussed in section 5.3.

1.2.5 Monitoring

Monitoring is essential to prevent large quantities of pollutants to be discharged to the marine environment. To control this, all companies working with oil and gas exploration on the Norwegian continental shelf must monitor field chemistry annually, and do biological surveys every third year for oil production fields (Nåmdal, 2011). The purpose of environmental monitoring is to gather information about actual and potential impacts of offshore petroleum activities, and hence use this to regulate releases of pollutants to the marine environment (Nåmdal, 2011). By doing this, environmental trends over time can be discovered, and we can determine whether discharges are increasing, decreasing or being stable. To get the best results and obtain a useful environmental monitoring, surveys must be conducted in the same way across the continental shelf, and results must be comparable between years. Additional monitoring surveys may be required in some cases, for example in areas where vulnerable species and habitats are likely to occur or have been identified. Monitoring activities must be carried out in a way that makes it possible to verify the risk of impact of offshore petroleum activities on the environment. The extent of the monitoring program must be proportional with the expected risk in the area. Environmental monitoring of benthic habitats will be presented in this section, as well as the processing of monitoring surveys of these habitats.

Monitoring of sediments on the Norwegian continental shelf is divided into 11 regions. Subdivisions into smaller regions may be necessary if large variations in depth or sediment type occur. Monitoring of sediments includes both investigation of the horizontal and vertical extent of impacts from petroleum activities. The horizontal extent gives us information about the extent of the impacted area on the sea floor. The vertical extent emphasizes how deep into the sediment the pollutants are present, and to what extent the sediment and/or organisms are impacted (Nåmdal, 2011).

Monitoring of sediments and bottom fauna consists of two main elements; baseline surveys and field-specific and regional monitoring programs. Baseline surveys must be done before drilling procedures and production in new areas can start. Field specific monitoring programs are part of regional monitoring programs, and they are carried out at the same time, normally after production has started. The regional stations are working as reference stations which provides information on background levels in the area. The field-specific stations provide information about environmental status close to the discharge areas (Nåmdal, 2011). The extent of monitoring programs of sediments and benthic habitats, must be proportional with the extent of petroleum activity in the area. Monitoring of existing offshore petroleum activities is already required, and additional monitoring is required in case of new activities.

During monitoring surveys of benthic habitats, sediment samples are collected and analyzed, based on the observation of drill cutting material or other objects in the sediment, conspicuous fauna and smell (Nåmdal, 2011). This includes analysis of soft-bottom fauna with taxonomic identification and the number of specimens belonging to each species. When using benthic foraminifera as bio-indicators in monitoring programs, it is important to make sure that the same techniques and standard procedures are used when investigating the same type of environment. This is necessary to obtain comparable and reliable results. The same techniques and procedures must be used from the initiation of the sampling until the final treatment of the data. This includes the sampler, sieve size, the minimum quantity of benthic foraminifera to be selected from each sample, the sampling depth, and the total amount of dead and live foraminifera (Frontalini and Coccioni, 2011). Normally a total number of 250-300 dead benthic foraminifera are required from each sample to get an accurate estimation of the faunal composition (Frontalini and Coccioni, 2011). However, newer versions for recommendations during bio-monitoring studies have been developed with the FOBIMO protocol by Schönfeld et al. (2012). These include that the interval from 0-1 cm below the sediment sample should be sampled, that the living benthic foraminiferal fauna on the >125 µm fraction has to be analyzed, that Rose Bengal at a concentration of 2 g per litre is advised for staining with a staining time of at least 14 days, and that analyses of dead assemblages may yield important additional information on pre-impacted conditions (Schönfeld et al., 2012). Grain size distribution, analyses of hydrocarbons, synthetic drilling fluids and the concentrations Ba an various heavy metals such as Cd, Cr, Cu, Pb, Zn and Hg are required for baseline and first monitoring surveys for all regional stations, and minimum two stations closest to the discharge point. If high values are found at these two stations, all metals should be analyzed in the next monitoring survey close to the discharge point.

2 Study area

The study area is located in the SW Barents Sea, just off the coast of Norway (Fig. 2). The area is dominated by the deeper trough Bjørnøyrenna, which extend from Storbanken in the north-east to the shelf break in the south-west (Andreassen et al., 2008). Bjørnøyrenna is surrounded by shallower banks and troughs, such as Tromsøflaket and Nordkappbanken in the south, and Spitsbergenbanken, Storbanken and Sentralbanken in the north. Djuprenna and Ingøydjupet are the troughs dominating in the area. The samples for this study are retrieved from Ingøydjupet, a southeast-northwest trending through located southwest of the deeper Bjørnøyrenna trough. The studied well TOTAL 7122/6-1 are indicated as a red star on figure 2 below, and figure 3 shows a schematic overview of the well, the transect and the cores along the transect directed towards the southeast. The cores are retrieved at different distances from the well in a south-eastward direction. Ingøydjupet is surrounded by the shallower banks Tromsøflaket and Nordkappbanken.

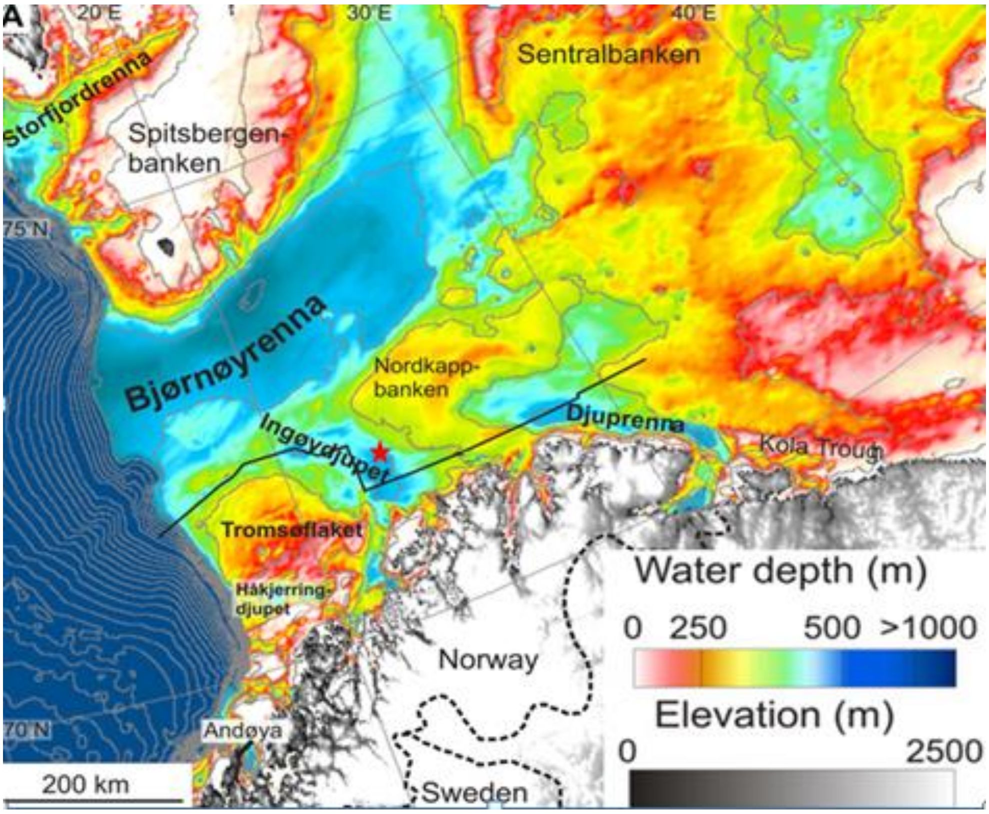

Figure 2: Location of the study area with overview of the SW Barents Sea. Red star indicates location of the studied well TOTAL 7122/6-1. Modified after Winsborrow et al. (2010).

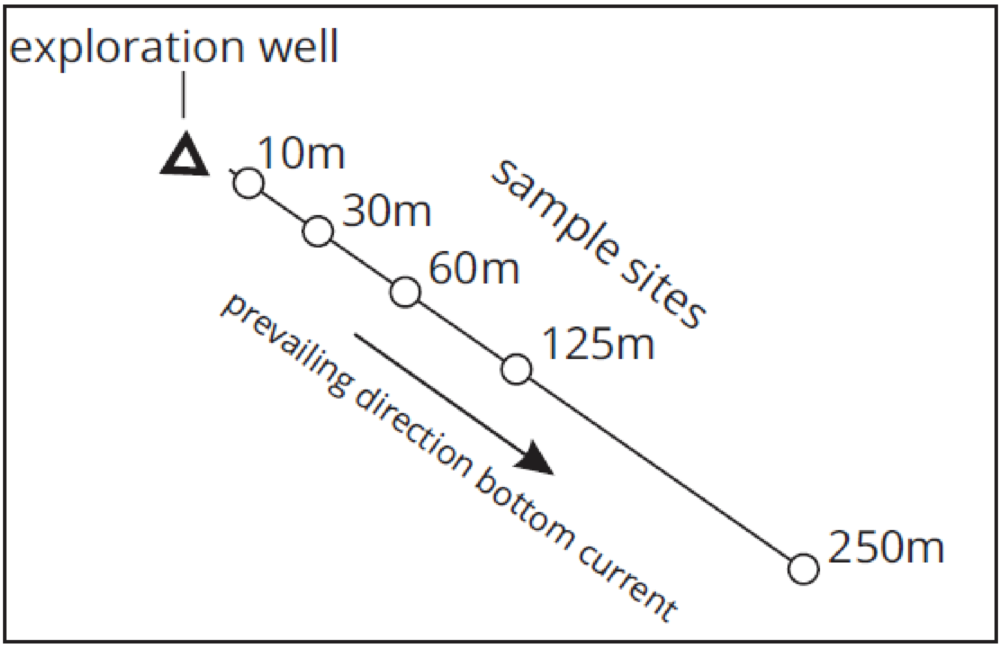

Figure 3: Schematic overview of the well, the transect and the cores taken along the transect.

2.1 Oceanography

The epicontinental Barents Sea covers one of the widest continental shelves in the world (Andreassen et al., 2008). It is a relatively shallow continental shelf with an average water depth of 230 m. Ingøydjupet is characterized by an average water depth of 400 m, while the surrounding shallower banks have an average water depth of 200-300 m (Andreassen et al., 2008). The physical conditions are determined by three main water masses: Coastal water, (North) Atlantic water, and Arctic water (Loeng, 1991). In addition to these three main water masses, locally formed water masses may also be present, as well as mixtures of the water masses (Loeng, 1991). The temperature and salinity varies between the water masses. In general, both temperature and salinity decrease northwards. The Atlantic water is characterized by salinity higher than 35.0, and a temperature variation between 3.5 - 6.5°C (Loeng, 1991). The Coastal water reveals lower salinity, mostly less than 34.7, but approximately the same temperature as Atlantic water. The Arctic water has low salinity, normally between 34.4 and 34.7, but is characterised by its low temperature less than 0°C (Loeng, 1991). The current conditions in the Barents Sea are largely, but not solely dependent on the topography of the sea bottom in the area. For example, the currents in the southern part of the Barents Sea, have an eastward direction, and currents in the northern part of the Barents Sea are directed towards the west or southwest (Loeng, 1991). To understand the distribution of benthic foraminifera on the sea bottom it is important to have knowledge about the physical oceanographic conditions in the area.

The physical conditions in the Barents Sea depend mainly on the inflow of Atlantic water from the Norwegian Sea and the inflow of Arctic water from the Kara Sea and Arctic Ocean (Loeng et al., 1997). The main inflow of Atlantic water takes place at the south-western boundary, and some of the water leaves from the same border, but most of the water passes through the Barents Sea and then enters the Arctic Ocean through the strait between Novaya Zemlaya and Frans Josef land (Loeng, 1991). The outflowing water consist of transformed Atlantic water mainly to the Arctic Ocean, but also partly to the Norwegian Sea. As the Atlantic water passes through the Barents Sea, it changes its characteristics. Loeng et al. (1997) describe this as a result of mixing with surrounding waters and transformation due to cooling and ice formation. The water masses in the Barents Sea also shows seasonal and annual variability. Previous studies show that there is a higher flow of incoming Atlantic water during wintertime. The amount and properties of inflow of Atlantic water influences the climatic variability in the Barents Sea, which again influences the living environment in the water column and on the sea bottom (Loeng et al., 1997).

The SW Barents Sea is characterized by the inflow of the North Cape Current (NCaC) and the Norwegian Coastal Current (NCC) (Fig. 4). The North Atlantic Water (NAC) is a deep-water current that flows along the Norwegian coast up north (Junttila et al., 2014; reference therein), and parallel to the NAC is the NCC. Close to Bjørnøyrenna, the NAC splits into two branches, where one branch continues up north towards Svalbard as the NAC, and one continues into the Barents Sea as the NCaC. The NCC follows the Norwegian Coast towards the northeast all the way into the Barents Sea, and are influenced by some small and larger eddies (Junttila et al., 2014; reference therein). It is a shallow surface current which transports Coastal water that originate from the Baltic, North Sea and some part of it originates from runoff from the Norwegian mainland. The NCaC flows into the Barents Sea and follows Bjørnøyrenna in a north-eastward direction (Loeng, 1991). When the NCaC reaches Tromsøflaket, part of the current (NAC) turns around the bank into Ingøydjupet and passes through Ingøydjupet in a

South-eastward direction, then returns to the coast before leaving it to the east again (Loeng, 1991). Indeed, due to the topography in the area and the Coriolis force that deflects the currents to the right. It illustrates that the ocean currents in Ingøydjupet are directed towards the south-east. When NCC and NCaC meets, they create a front where Coastal water with low salinity meets Atlantic water with higher salinity (Dijkstra et al., 2015). During summer, Coastal water is found in the upper 50-100 m of the water column, and during winter it is normally found at <200 m water depth (Dijkstra et al., 2015; reference therein). Ingøydjupet is characterized by lower salinity Coastal Water in the deeper parts only during periods of intense mixing.

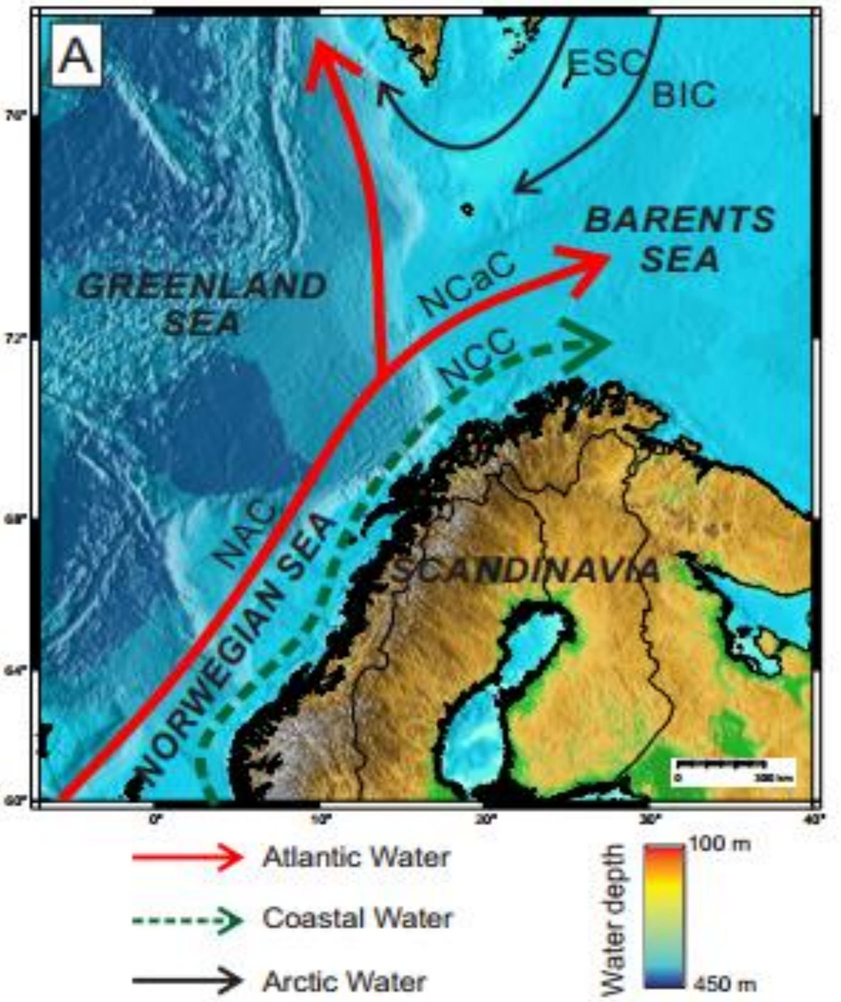

Figure 4: Major ocean currents in the study area. NCaC= North Cape Current; NCC= Norwegian Coastal Current; NAC= North Atlantic Current; ESC=East Spitsbergen Current; BIC= Bear Island Current. Modified after Dijkstra et al. (2015).

2.2 Geological setting

The morphology of the Ingøydjupet trough is characterized by large elongated ridge-groove features. The lineations appear as well-developed depressions, up to 120 km long individually, 0.5-3.5 km wide, 4-5 m deep and with elongation ratios up to 33:1 (Andreassen et al., 2008). These lineations are glacial bedforms produced by a fast-flowing grounded glacier (Andreassen et al., 2008). Some irregularly shaped furrows occur on the bank areas surrounding the Ingøydjupet trough. They occur at water depth less than 450 m, are often 100-300 m wide, and have a relief of 3-10 m. These furrows are iceberg scours, and indicates that Ingøydjupet is formed by an eroding ice sheet which left Tromsøflaket in higher elevation on the west side (Andreassen et al., 2008)

Nordkappbanken is characterized by a prominent sediment accumulation forming a ridge on its northern and eastern side. The ridge is about 60 m high and 13 km wide. Andreassen et al. (2008) interpreted this sediment accumulation to be a morainal bank complex, marking the maximum extent of previous ice advances, which means Nordkappbanken has been mainly formed by sediment deposition in front of an ice sheet. The seafloor geomorphology in the Tromsøflaket area is characterized by a series of ridges and depressions (Andreassen et al., 2008). The smallest ridges are 100-150 m wide, around 5-6 km long and have a relief of 4-6 m, while the largest ridges are 1-5 km wide, around 5-15 km long, and with a relief from 15-25 m to 59 m (Andreassen et al., 2008). The largest ridges are more curved than the smaller ones, and Andreassen et al. (2008) interpreted the ridges at the north-western end of Tromsøflaket to be indicative of grounded ice reaching the area during the last glaciation.

2.2.1 Sediment transport

Sediments can report sources and pathways of pollution (Frontalini et al., 2009), due to the accumulation of material related to drill cuttings in fine sediments, and the transportation of these sediments with ocean currents. Higher concentrations of contaminants in fine sediment particles will have a larger impact on the benthic communities. If the contaminants are transported with ocean currents and hence covering a larger area of the sea floor, they might impact a larger quantity of the benthic community. This might happen if the material is toxic to organisms, or if the sediments containing drill cuttings or other contaminating material are deposited as thick layers. Sediments can be transported as either suspended load or bedload depending on the current strength and particle size. Sediments in suspension can be transported over long distances. Previous studies have shown that the seafloor sedimentary environment in this region is generally influenced by strong currents on the shallow banks, Tromsøflaket and Nordkappbanken, and low-energy currents in the deeper depressions of Ingøydjupet (Junttila et al., 2014; reference therein). This results in coarse grained sediment deposition on the shallow banks, and finer grained deposition at deeper depths (Junttila et al., 2014; reference therein). Junttila et al. (2014) expressed that Ingøydjupet will be a natural accumulation area of drill cuttings due to the current direction in the area, the topography with the surrounding shallow banks and the increasing petroleum activities in the area.

3 Methodology

3.1 Core acquisition

In August 2015, 5 sediment cores where collected on board the support vessel R/V “Njord Viking”. Using a push corer with an inner diameter of 8 cm and a length of 60 cm and a Remotely Operated Underwater Vehicle (ROV), the cores where retrieved at different distances from the well head within a maximum distance of 250 m. The ROV is equipped with a real-time video connection to the control room on the vessel, and a robotic arm that is used to push the core into the sediment, and then pulling the tube with sediment back up and placing the push corer filled with sediment in a holding basket. The holding basket holds in total 12 tubes, and when it is full, the basket with the tubes returns to the ship, and the ROV stays in the water column, waiting for the next basket. The cores where retrieved along a transect 10, 30, 60, 125 and 250 meters from the well head in direction of the prevailing bottom current, at approximately the same water depth (Fig. 3, table 1). It implies that we can expect material from the drill cutting pile to be transported with ocean currents towards the other stations. The total distance of 250 m between the well and the outermost station is based on previous studies investigating the effect of drill cutting release on benthic communities. Numerous studies, including Denoyelle et al. (2010), have reported that the impact of drill cutting release is most severe in the proximity of the disposal site, and decreasing further away, normally reaching background levels around 250 m from the discharge point.

The cores were sampled at 1 cm resolution and the samples were labelled with the core names; T 10-4, T 30-7, T 60-11, T 125-9, and T 250-2, and with its representative depth in the core; 0-1 cm, 1-2 cm, 2-3 cm etc., down to 19-20 cm. At 30, 60, 125, and 250 m from the well, two cores where retrieved, where one was used for benthic foraminiferal analyses, and the other one was used to take out 2 grams from each sample to do analyses of heavy metals, grain sizes and TOC. At 10 m away from the well, only one core was retrieved and it was split in half, so sediment samples was taken from the same core. The upper 5 cm of each core were stained with rose Bengal to colour the live foraminifera in pink. For further laboratory work, all samples except the ones which was stained, where freeze-dried using a Christ Alpha 1-4 LSC plus. The stained samples from the top 5 cm could not be freezed dried due to the rose Bengal that was added to the sediment to colour the living foraminifera in pink. By freeze-drying the samples, water content in each sample could be measured.

As only the water content could be measured for the freeze-dried samples from 5-20 cm core depth, the water % in the top 5 cm had to be estimated. The estimation was performed by calculating the average of the water content down core, and assume this was the water content in the upper 5 cm. To measure the total calcareous/gram dry sediment, which from now on will be referred to as #/g, we need the dry weight of the sediments. Since the upper 5 cm of the sediments were stained, the dry weight was not measured for these samples. To find the #/g for the upper 5 cm, the dry weight had to be estimated. Normally, to find the water percent, the dry weight is subtracted from the wet weight, and this value was then divided by the wet weight and multiplied by hundred. Since the dry weight was missing, the estimated water percent was used and calculated backwards. The value that represented the difference between the wet and the dry weight was calculated, and then subtracted from the wet weight to find the dry weight. When doing this, the freeze dried weight and the water content were assumed to be the same for the dead and live fauna sample.

*Table 1: Location and water depth for the cores T 10-4, T 30-7, T 60-11, T 125-9 and T 250-2. *Data not required.*

Core	**T 10-4**	**T 30-7**	**T 60-11**	**T 125-9**	**T 250-2**
Location	71.38N, 10.48E	71.38N, 4.48E	71.38N, 4.48E	71.38N, 4.48E	*
Water depth (m)	403	402	403	404	*

3.2 Benthic foraminiferal analysis

The distribution of benthic foraminifera was measured by counting and picking 300 dead foraminifera from each selected sample which is normally the required number of specimens to accurately estimate an assemblage (Frontalini and Coccioni, 2011). Forcino et al. (2015)

stated that 58 where the required number of live foraminiferal specimens to get statistically reliable results. Therefore, as only few specimens were observed, ca. 60 live foraminifera specimens where picked from the top 5 cm of the cores, and 300 specimens for the dead fauna. However, other scientists state that 300 is the required total number also for live foraminifera (Schonfeld et al., 2012). A splitter was used to divide the samples into smaller fractions if necessary. The sample was evenly distributed in a picking tray consisting of 45 squares where foraminifera where picked from randomly chosen squares in the picking tray. All the picked foraminifera were identified and the relative abundance and the total concentration of species could be calculated.

3.3 Grain size analysis

Acid treatment of all samples had to be done to remove calcium carbonate ($CaCO_3$), and organic material from the sediments, before they could be analysed in a Beckman Coulter LS 13 320 Particle Size Analyzer. The procedure for acid treatment was to first have > 2 grams of dry sediments in a plastic tube and add 20% HCl to cover the sediment. After 24 hours, the samples where centrifuged 4 min/4000 rpm, liquid was removed, and distilled water was added to the sample. This process was repeated twice. After 20% H_2O_2 was added, the tubes were covered with aluminium and placed in a warming bath at 80 °C for 2 hours. Then, the centrifuging process was repeated 3 times. After centrifuging the samples again, the liquid was removed, and the sediments was transferred to a plastic cup for drying.

Before the grain size analyses could be done, 0.5 grams of the dried sediment was taken out, mixed with 20 ml of water and placed in a shaker for 24 hours. Two drops of calgon (sodium polyphosphate) were added to the sediments to avoid the formation of clay aggregates (Olsen, 2015). Then the sample was placed in an ultrasound bath for 5 minutes before it could be analysed in the Beckman Coulter LS 13 320 Particle Size Analyzer. It is a multifunctional particle characterization tool using laser diffraction, which is based on light scattering (Canzler, 2016). Laser diffraction measures particle size distribution, and the results are presented on the basis of volume, as cumulative volume percentage.

3.4 Analysis of Total Organic Carbon

Total organic carbon (TOC) concentrations was measured at the Department of Geosciences, UiT – The Arctic University of Norway. A LECO CS744 instrument was used to measure the concentration of TOC in the collected sediments. TOC was measured for all samples from each core with a total number of 100 samples. LECO CS744 uses infrared absorption to measure the amount of carbon dioxide and sulphur dioxide generated by the combustion of samples in an induction oven in an environment of clean oxygen. Before the sediments could be analysed with the LECO CS744, the samples were treated with HCl so that all carbonate bound (inorganic) carbon is removed. This illustrates, the carbon which is then determined in the residue is completely organic (UIT, 2017). When the sample is placed in the oven, the combustion chamber is rinsed with clean oxygen to remove atmosphere gases. During combustion, carbon and oxygen are released and reacts with oxygen and produce CO, CO_2 and SO_2. Then, these are measured at the carbon-and sulfur cells. Carbon - and sulfur dioxide absorb infrared energy, so when they pass through the infrared cells, they absorb infrared energy and prevent it to reach the detector. The reduction in energy that are measured by the detector is a measure of the concentration of CO_2 and SO_2.

3.5 Heavy metal concentrations

Heavy metal concentrations were analysed at UniLab AS, Fram centre in Tromsø, Norway. For all 100 samples, 2 gram sediment was taken out for heavy metal analyses. Concentrations of arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), vanadium (V), zinc (Zn), barium (Ba) and titanium (Ti) where analysed using inductively coupled plasma atomic emission spectroscopy (ICP-AES) or inductively coupled plasma sector field spectroscopy (ICP-SFMS) depending on the concentration of the metals in the samples. Standard procedures of the Norwegian standard 4770 were followed, and concentrations of mercury (Hg) were measured with atom fluorescence (AFS) following the procedures of Norwegian Standard 4768.

4 Results

The following chapter will present the various results of this study. First, foraminifera assemblages for all cores will be presented, followed by grain size distribution and TOC-values, and finally heavy metal concentrations. The results will be discussed in the next chapter.

4.1 Benthic foraminifera assemblages

A total number of 75 samples were analysed, and within these samples a total number of 20 different benthic foraminifera species were identified. The distribution of the 7 most dominating species will be presented. Dominance is the tendency of one species to represent a great part of the assemblage (Vilela et al., 2004). The 7 most dominating species are, in alphabetic order: *Cassidulina laevigata, Cibicides lobatulus, Epistominella nipponica, Fissurina marginata Melonis barleaanus, Pullenia bulloides* and *Trifarina angulosa.* The species relative abundance is presented as percentage (%). Continuous plots showing #/g will also be presented. Based on studies which state that 300 is the required number for total foraminiferal specimens, the relative abundances for live foraminifera at all core depths are therefore presented as dotted lines, as this number was never reach for the living fauna. Dotted lines in the fossil fauna also represents statistically uncertain data of samples in which less than 300 specimens were counted. The results will be presented core by core starting with the core closest by the pollution source; T 10-4, followed by cores further away; T 30-7, T 60-11, T 125-9 and T 250-2.

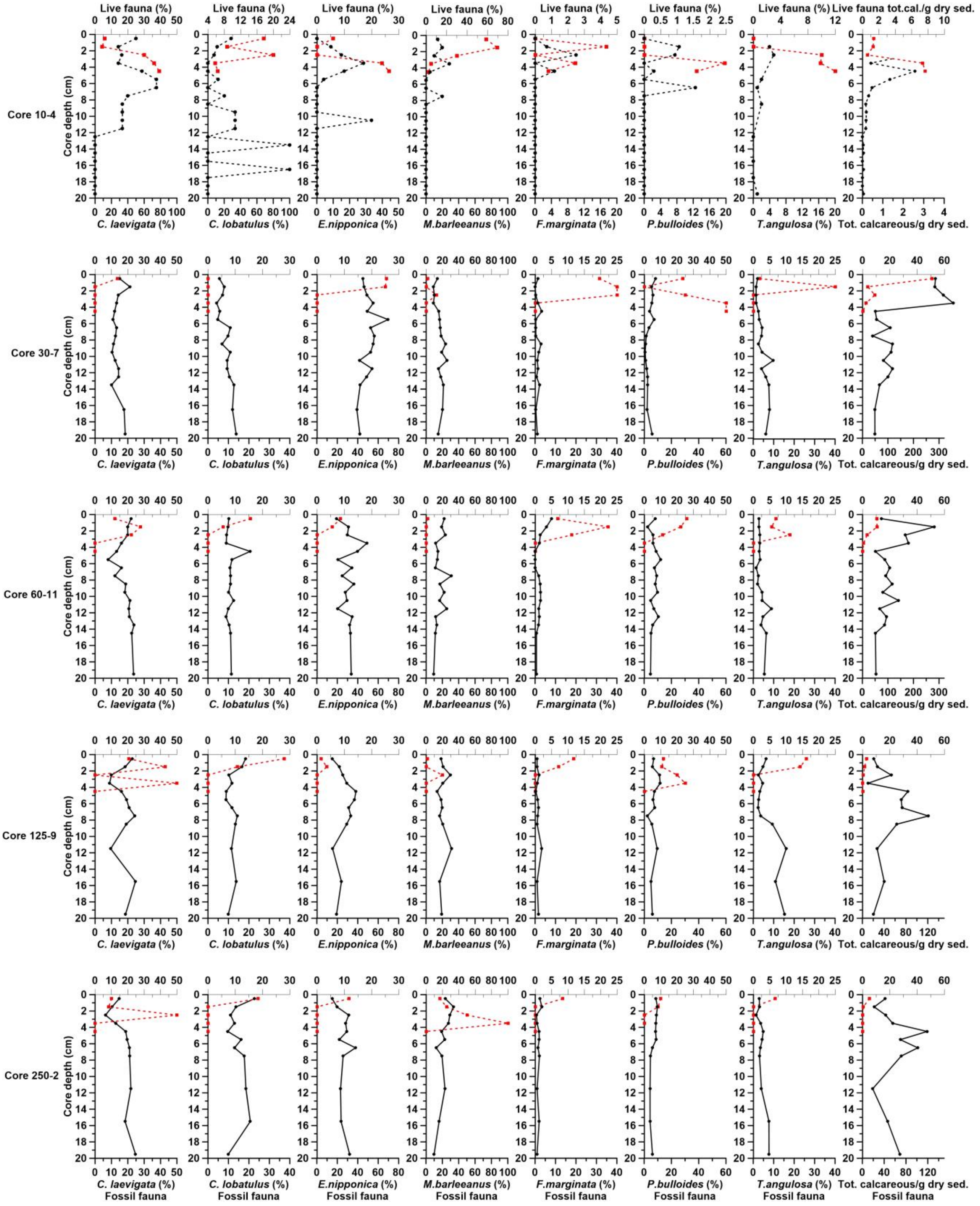

Figure 5: Foraminiferal abundances and total calcareous/g dry sediment. Red line indicates live fauna (upper axis), black line indicates fossil fauna (lower axis). Dotted lines indicate statistically uncertain data.

4.1.1 Core T 10-4

All examined samples in this core contained less than 300 fossil benthic foraminiferal specimens in total, and therefore the relative species abundance in each sample is considered statistically uncertain. For this core, the focus will therefore not be on species distribution, but rather the fact that there are very few specimens present. It is important to emphasize that this core seemingly has more live than fossil benthic foraminiferal specimens present for the upper 5 cm of the core. The concentration of the live benthic foraminifera is decreasing up core from 5 cm core depth, as we can see out from the plot of #/g. This will be further discussed in chapter 5. The core has a much lower #/g than for the dead assemblage than for the other cores (Fig. 5), with an average value of 0.5 specimens. Indeed, due to the low concentration of specimen present in the core.

4.1.2 Core T 30-7

The #/g for the dead foraminiferal assemblage is significantly higher in this core than for core T 10-4, with an average value of 137 specimens, and increasing values up core reaching a value of 286 at the top of the core (Fig. 5). The clearly dominating species for this core is *E. nipponica* with an average relative abundance of 49 %. At 10.5 cm core depth, there is a decrease in the relative abundance of *E. nipponica* with a value of 41%, a small peak in the relative abundance of *M. barleeanus* with a value of 25 %, and a small increase in the relative abundance of *T. angulosa* with a value of 9 %. Further up core at 5.5 cm core depth, there is a peak in the relative abundance of *E. nipponica* with a value of 69.5 %. At this core depth, there is also a small peak of *P. bulloides* with a value of 7 %, and *C. lobatulus* have a small decrease in the relative abundance at this core depth with a value of 4%. The #/g for the live fauna is increasing at 0.5 cm core depth and towards the top of the core, and it is also only the top cm that have enough live specimens to do statistically reliable interpretations according to Forcini et al. (2015), i.e. > 58 specimens. The live fauna is dominated by the species *E. nipponica, P. bulloides and F. marginata* in the top cm with relative abundances of 25 %, 23 % and 19 % respectively.

4.1.3 Core T 60-11

This core is also characterized by an increase in #/g for the dead foraminiferal assemblage from the bottom towards the top of the core, with an average value of 108 specimens (Fig. 5). *E. nipponica* is the dominating species also in this core with an average relative abundance of 30.9 %. At 11.5 cm core depth, there is a decrease in the relative abundance of *E. nipponica* with a value of 20 %. At this core depth, *M. barleeanus* has a small peak of 25 %, and *T. angulosa* has a small peak of 8 %. At 7.5 cm core depth, there is a decrease in the relative abundance of *E. nipponica* with a value of 24 %, an increase in the relative abundance of *M. barleeanus* with a peak value of 30 %, and *C. laevigata* has a decrease in the relative abundance with a value of 12 %. Further up core at 3.5 cm core depth, there is a peak of *E. nipponica* with a value of 48 %. The #/g for the live fauna is increasing towards the top of the core, with the only statistically reliable data in the top cm of the core, i.e. > 58 specimens. The dominating live species in the top cm of the core are *P. bulloides* and *C. lobatulus* with relative abundances of 25 % and 15 % respectively.

4.1.4 Core T 125-9

The #/g for the dead foraminiferal assemblage is increasing up core, with an average value of 50 specimens (Fig. 5). The dominating species of the dead assemblage are *E. nipponica, M. barleeanus* and *C. laevigata* with average relative abundances of 26 %, 20 % and 17 % respectively. At 11.5 cm core depth, *C. laevigata* and *E. nipponica* has decreased relative abundances with values of 9 % and 15 % respectively. At this core depth, *M. barleeanus*, *P. bulloides,* and *T. angulosa* has increased relative abundances with values of 31 %, 9 %, and 16 % respectively. At 4.5 cm core depth, *E. nipponica* has its highest relative abundance with a value of 38 %. At this core depth, *M. barleeanus* has its lowest relative abundance of dead foraminiferal specimens with a value of 13 %. The #/g for the live fauna is increasing up core. Also in this core, only the top cm of the core has enough live specimens to be statistically certain, i.e. > 58 specimens. The dominating live species in the top cm, are *C. lobatulus* and *C. laevigata* with values of 27 % and 20 % respectively.

4.1.5 Core T 250-2

This core also has an overall increasing trend up-core in #/g for the dead foraminiferal assemblage, with an average value of 59 specimens (Fig. 5). The dominating species of the fossil foraminiferal assemblage is *E. nipponica* with an average relative abundance of 26 %. At 6.5 cm core depth, *E. nipponica* has a peak in the relative abundance of dead foraminiferal specimens with a value of 37 %, while *M. barleeanus* has a decrease in the relative abundance with a value of 12 %. At this core depth, the relative abundance of *P. bulloides* is starting to increase up core. The relative abundance of *E. nipponica* is deacreasing up core, while the relative abundance of *M. barleeanus* is increasing up core. The #/g for the live fauna is increasing up core also for this core, where only the top cm has enough specimens to be statistically reliable, i.e. > 58 specimens. The two most dominating live species in the top cm of the sediments are *C. lobatulus* and *M. barleeanus* with relative abundances of 18 % and 16 % respectively.

4.2 Grain size distribution, TOC and water content

The grain size distribution, the amount of TOC and the water content of the sediments are presented in different plots relative to the depth of the cores (Fig. 6). The distribution of grain sizes is presented as the total volume in weight percentage (%) of each grain size fraction; Clay (0-2 µm), Silt (2-63 µm) and Sand (63-2000 µm). The TOC values and the water content of the sediments are also presented as percentage. Due to a source of error with the Beckman Coulter LS 13 320 Particle Size Analyzer, and too little extra sediment available for the sample from core T 60-11 at 7-8 cm core depth, this sample is not analysed. Therefore, grain size distribution results for this sample is not provided. Grain size distribution results are provided for all other samples.

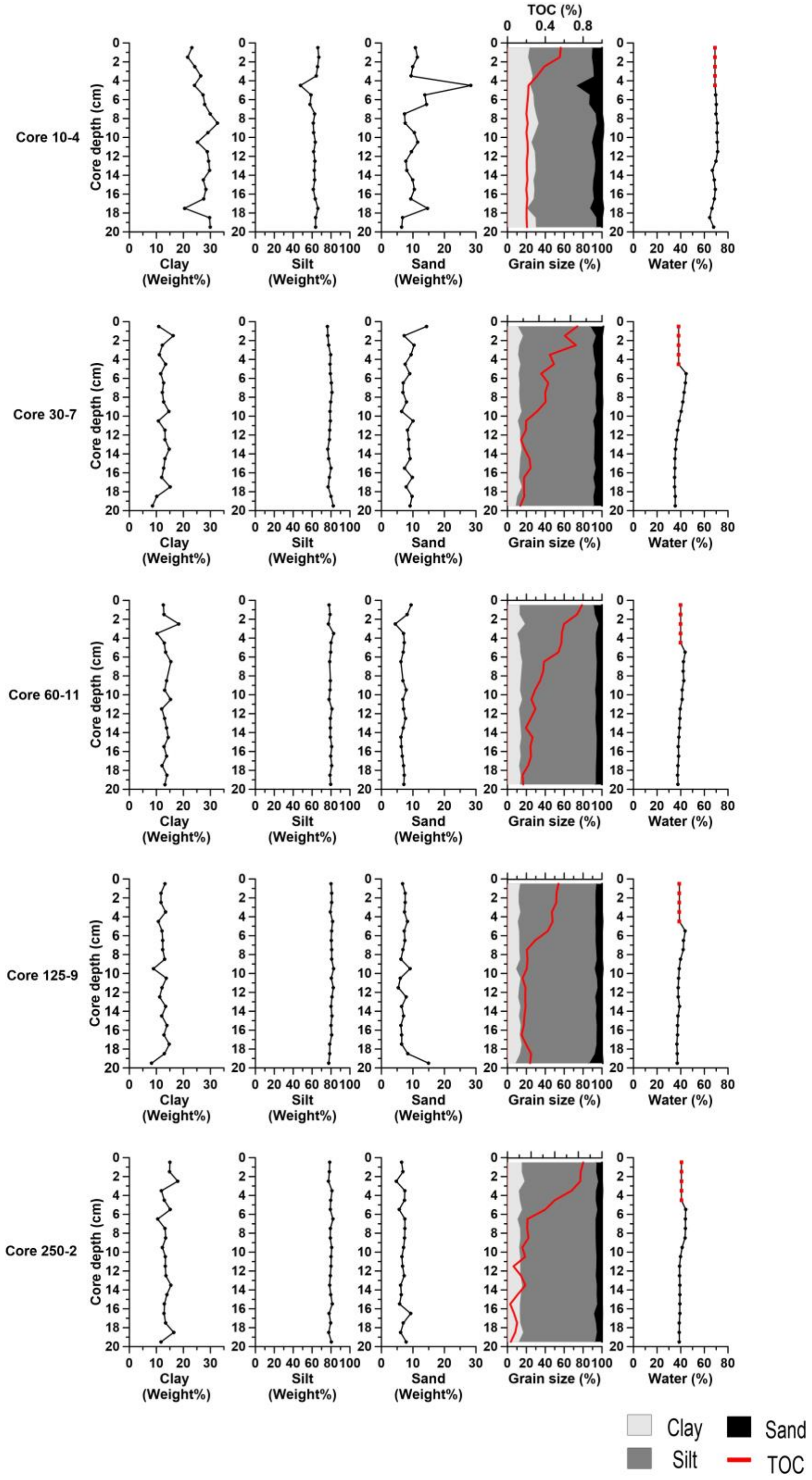

Figure 6: Grain size properties (gray scale; lower x-axis), TOC (red; upper X-axis) and water content. Red upper data in water content indicates estimated values.

All the five cores show a clear dominance of the silt fraction. In core T 10-4 the silt fraction appears with an average concentration of 62 %, while the clay and the sand fraction reveals average values of 27 % and 10 % respectively. Core T 30-7 reveals an average value of 78 % for the silt fraction and average values of clay and the sand fraction of 12 % and 8 % respectively. In core T 60-11, T 125-9 and T 250-2 the silt fraction reveals average values of 79 %, 80 % and 79 % respectively, the clay fraction reveal average values of 13 %, 12 % and 13 % respectively, and the sand fraction reveal average values of 7 %, 7 % and 6 % respectively. In other words, both the silt, sand and clay fraction are relatively constant for all cores, except from the T 10-4 core, and some small peaks of sand and clay in the other cores.

At 4.5 cm core depth in core T 10-4, the silt fraction has reduced concentrations with a mean volume of 47%, while the sand fraction has a peak with mean volume of 28%. The T 30-7 core has a change in the grain size distribution at 10.5 cm core depth, where the mean volume of the sand fraction is increasing, and the mean volume of the clay fraction is decreasing, both reaching a mean volume of 10%. In the T 60-11 core, a small change is occurring at 2.5 cm core depth, where the mean volume of the sand fraction is decreasing down to 4%, and the clay fraction is increasing to 18%. The next core (T 125-9) has a change in the grain size distribution at 9.5 cm core depth, where the sand fraction is increasing and the clay fraction is decreasing, reaching mean volumes of respectively 9% and 8%. For the last core, the sand fraction is decreasing and the clay fraction is increasing at 2.5 cm core depth with values of 4% and 17%.

The TOC are presented as percentage in various plots relative to core depth in the same plots as cumulative grain sizes (Fig. 6). Core T 10-4 appear with an average concentration of 0.25 %, with increased concentrations up-core, reaching a concentration of 0.5 % at the top of the core. Core T 30-7 also have an increasing trend up-core, with an average value of 0.6 %, reaching a value of 0.8 % at the top of the core. Core T 60-11 have an average value of 0.6 %, reaching a value of 0.8 % at the top of the core. T 125-9 also appear with an average concentration of 0.6 %, reaching a value of 0.7 % at the top of the core. Core T 250-2 also has an increasing trend up-core with an average value of 0.7 %, reaching a value of 0.9 % at the top of the core. In other words, Core T 10-4 appears with lower TOC concentrations than for the other cores.

The water content is higher in the core closest by the pollution source (T 10-4) with an average value of 69 % (Fig. 6). For the cores further away from the pollution source, the average water content is 38%, 39%, 38% and 40% respectively. All cores have lower water content at the bottom of the core, and increasing values up-core.

4.3 Heavy metal concentration

The heavy metal concentrations of the samples are presented in different plots relative to the depth of the cores (Fig. 7), and average concentrations for each core are presented (Table 2). They are presented as milligrams per kilograms (mg/kg). The results will be presented on a core to core basis.

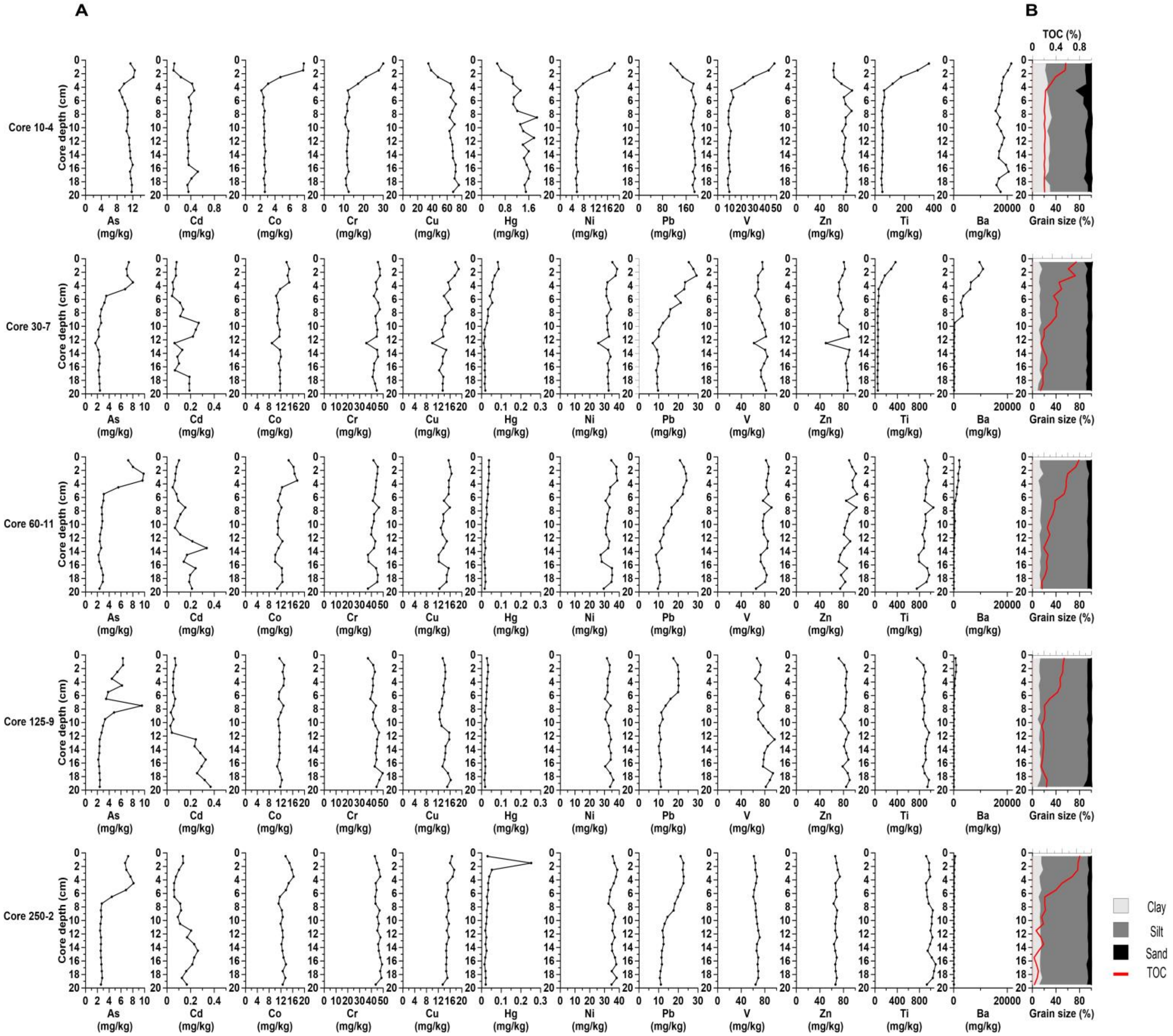

Figure 7: Heavy metal concentrations, grain size and TOC plotted against water depth: (A) heavy metal concentrations throughout the cores expressed in mg/kg. (B) clay (light gray), silt (dark gray), sand (black) and TOC (red line) content expressed in weight percentages.

Table 2: Average heavy metal concentrations expressed in mg/kg.

Core	As (mg/Kg)	Cd (mg/Kg)	Co (mg/Kg)	Cr (mg/Kg)	Cu (mg/Kg)	Hg (mg/Kg)	Ni (mg/Kg)	Pb (mg/Kg)	V (mg/Kg)	Zn (mg/Kg)	Ba (mg/Kg)	Ti (mg/Kg)
10-4	10	0.35	3	14	63	1.3	7	177	15	80	17910	88.4
30-7	3	0.12	11	43	14	0.03	32	15	74	79	2824	925
60-11	4	0.13	12	42	14	0.02	33	15	80	87	674	901
125-9	3	0.14	11	43	14	0.02	32	13	77	83	266	893
250-2	4	0.14	13	45	15	0.03	35	16	65	67	168	989

4.3.1 Core T 10-4

Barium appears with elevated concentrations in this core with values between 15700-21500 mg/kg, and with an average value of 17910 mg/kg (Fig. 7, table 2), with an increasing trend up core. This core is characterized by much higher concentrations of Ba, Pb, Hg and Cu than for the other cores (Table 2). Pb, Hg and Cu have average values of 177 mg/kg, 1.3 mg/kg and 63 mg/kg respectively. Pb has an average value of 185 mg/kg from the bottom of the core up to 3.5 cm core depth, and has then a small decrease in the concentration reaching a value of 107 mg/kg at the top of the core. Hg appears to have an average concentration of 1.5 mg/kg from the bottom of the core up to 8.5 cm core depth with some small peaks up core. At 8.5 cm core depth, the concentration is starting to decrease up core reaching a value of 0.5 mg/kg at the top of the core. Cu has an average value of 68 mg/kg up core to 3.5 cm core depth, where the concentration is decreasing reaching a value of 34 mg/kg at the top of the core. Cd has the lowest concentration with values between 0.1 and 0.5 mg/kg. Zn reveals an average value of 80 mg/kg, and is decreasing from 4.5 cm core depth up core. In other words, the concentrations of Pb, Hg, Cu, Cd and Zn is decreasing in the top 4.5 cm of the core, while the concentrations of Ba, As, Co, Cr, Ni, V and Ti are increasing from 4.5 cm core depth towards the top.

4.3.2 Core T 30-7

This core is also dominated by Ba, with an average value of 2824 mg/kg (Table 2). The values are lowest at the bottom of the core with 110 mg/kg at 19.5 cm core depth and are starting to increase up core at 9.5 cm core depth until it reaches a value of 10900 mg/kg at the top of the core (Fig. 7). Values of Pb, Hg and Cu are also lower for this core than in core T 10-4, with average values of 15 mg/kg, 0.03 mg/kg and 14 mg/kg respectively. Pb has an average concentration of 9 mg/kg from the bottom of the core until 11.5 cm core depth, and is then increasing up core reaching a value of 25 mg/kg at the top of the core. Hg appears with an average concentration of 0.016 mg/kg from the bottom of the core up to 10.5 cm core depth, where there is an increase in the concentration up core reaching a value of 0.08 mg/kg at the top of the core. Cu has an increasing trend up core with an average value of 14 mg/kg up core, reaching a value of 17 mg/kg at the top of the core. In other words, the concentrations of Pb, Hg and Cu are increasing up core, in addition to increased concentrations of As, Co, Cr, Ni, and Ti. On the other hand, concentrations of Cd, V and Zn are decreasing up-core. At 12.5 cm core depth, As, Cd, Co, Cr, Cu, Hg, Ni, Pb, V and Zn, all have decreased concentrations.

4.3.3 Core T 60-11

Ba and Ti appears with the highest concentrations in this core, both with increasing trends up core (Fig. 7), where Ba start to increase at 6.5 cm core depth. The average value of Ba is 674 mg/kg and for Ti 901 mg/kg (Table 2). Ba has lower values than core T 10-4 and T 30-7, with its lowest values in the deepest part of the core with 107 mg/kg, and the highest value of 2250 mg/kg at the top of the core. Ti has relatively constant high values up-core, but is varying between 753-1050mg/kg. All of the heavy metals in this core seems to have overall increased concentrations up-core except Cd that is decreasing up-core. Pb, Hg and Cu has average values of 15 mg/kg, 0.02 mg/kg and 14 mg/kg respectively. Pb has an average value of 9 mg/kg from the bottom of the core until 14.5 cm core depth, and is then increasing up core reaching a value of 20 mg/kg at the top of the core. Hg appears with an average value of 0.018 mg/kg from the bottom of the core up to 9.5 cm core depth, and has a slight increase in the concentration up core reaching a value of 0.038 mg/kg at the top of the core. Cu has an increasing trend up core with an average concentration of 14 mg/kg reaching a concentration of 15 mg/kg at the top of the core. Between 16-14 cm core depth Cd, Co, Cr, Cu, Ni, V, Zn and Ti has decreased concentrations.

4.3.4 Core T 125-9

The heavy metal with highest concentrations in this core is Ti, with a slightly decreasing trend up core with values varying between 974-756 mg/kg up core and an average value of 893 mg/kg (Fig. 7, table 2). Ba has an average value of 266 mg/kg with an increasing trend up core from 2.5 cm core depth, where it reaches a concentration of 697 mg/kg at the top of the core. Pb, Hg and Cu reveal average values of 13 mg/kg, 0.02 mg/kg and 14 mg/kg respectively. Pb also has an increasing trend up core with an average value of 10 mg/kg from the bottom of the core to 8.5 cm core depth, then increasing concentrations until it reaches a value of 17 mg/kg at the top of the core. Hg appears to have an average concentration of 0.018 mg/kg from the bottom of the core up to 8.5 cm core depth, where it has a slight increase in the concentration and reaches a value of 0.027 mg/kg at the top of the core. Cu has a slightly decreasing trend up core with an average concentration of 14 mg/kg, while it reaches a value of 13 mg/kg at the top of the core. The concentrations of Cd, Cr, V and Zn are also decreasing up-core. As and Co are increasing up-core, while Ni has in general a constant concentration up-core except some small peaks at 16.5 cm and 7.5 cm core depth. At 12.5 cm core depth, the concentration of Cd is decreasing from values ranging between 0.25-0.36 mg/kg to values ranging between 0.02-0.07 mg/kg. At 7.5 cm core depth, As has an abrupt increasing peak, where Co, Cr, Ni and V also have small peaks in their concentrations.

4.3.5 Core T 250-2

The concentration of Ti is the highest in this core as well with an average value of 989 mg/kg (Table 2). It has a decreasing trend up core, with values varying between 1060-919 mg/kg up-core (Fig. 7). Ba has its lowest concentrations in this core, with an average value of 168 mg/kg. The concentration of Ba is slightly increasing up-core reaching its maximum value of 561 mg/kg at the top of the core. The average concentrations of Pb, Hg ad Cu are 16 mg/kg, 0.03 mg/kg and 15 mg/kg respectively. Pb has relatively constant values from the bottom of the core up to 11.5 cm core depth with an average value of 11 mg/kg, and is then increasing up core reaching a value of 21 mg/kg at the top of the core. Hg appears with a relatively constant concentration from the bottom of the core up to 11.5 cm core depth with an average concentration of 0-02 mg/kg, and has then a small increase in the concentration up core reaching a value of 0.03 mg/kg at the top of the core. At 1.5 cm core depth, Hg has a peak in the concentration with a value of 0.24 mg/kg. Cu also has a slightly increasing trend up core with an average concentration of 15 mg/kg reaching a value of 16 mg/kg at the top of the core. The concentrations of As, Ni, and Zn also has increasing trends up-core, while Cd, Co, Cr, V has decreasing trends of the concentrations up-core.

5 Discussion

The following discussion is divided into 4 major parts focusing on the environmental characteristics of the study area. The first part is focusing on drill cutting release from the studied well, and evaluates the level of impact of drill cutting release in the area by comparing the heavy metal concentration with background levels. Secondly, changes in faunal assemblages of both dead and live foraminifera as well as grain size distribution are evaluated, where results will be compared and discussed based on previous studies. The third part evaluates what can be done to prevent impacts of discharges of drill cuttings, including the options for the handling of drill cuttings as well as which approaches can be used for removal of drill cuttings that has already been released to the marine environment. An important question is if it is possible to differentiate between the effect of physical disturbances in the environment and impacts caused by drill cutting release?

5.1 Drill cutting release

The purpose of this work is to investigate an area that is impacted by drill cutting release from a well drilled in 1987, and study the level of impact. The method used for this investigation is analyses of benthic foraminifera, where changes in faunal composition can give us information about changes in the environment caused by drill cutting release. The concentration of various heavy metals, TOC and the grain size distribution in the area were investigated. Drill cutting deposits can be identified in the sediments based on elevated concentrations of various heavy metals, grain size properties and TOC content.

5.1.1 Level of impact

During 1993-1994 the first official classification system of environmental state of Norwegian fjords and coastal waters was published by the Pollution Control Authorities (SFT), which was later called KLIF and now they are called the Norwegian Environment Agency (Bakke et al., 2010). After that, the classification system has been revised in 1997 and 2007. The classification system focuses on environmental quality of contaminated marine sediments, and is based on the European Union systems for defining environmental quality standards and performing risk assessment (Bakke et al., 2010). The first revision focuses on the distribution and concentration of contaminants relative to background values and not the biological effects of the compounds, while the revision from 2007 focuses on the ecotoxicity of the contamination, and follows the principles of contaminant risk assessment in the European Community as much as possible (Bakke et al., 2010; reference therein). Toxicity can be described as the degree to which a substance can damage an organism. Common for the revisions is division into five classes based on distribution of levels of the contaminants in sediments along the Norwegian coast (Fig. 8). Class I represents background levels, and class II-V represents increasing degree of damage to ecological communities in the water column and in the sediments. The upper limit of class II represents the upper border of where a certain amount of species is affected by long-term exposure and is damaging community structure and function. The upper limit of class III represents exposure of concentrations with exceedance over short periods of time, while the upper limit of class IV represents short-term exposure, but with more severe effects (Bakke et al., 2010).

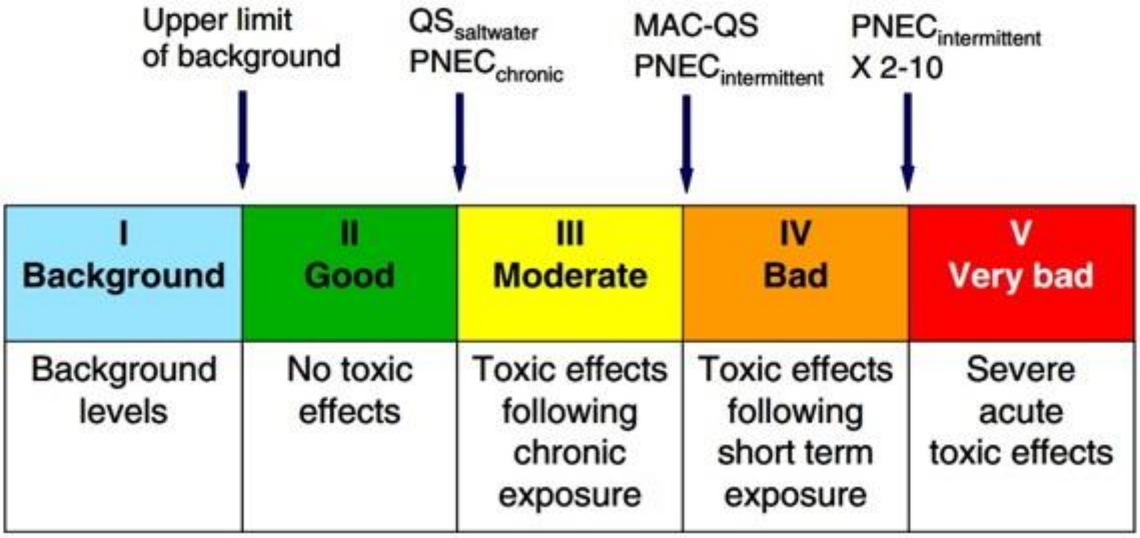

Figure 8: Principles of the Norwegian environmental quality classification system for contaminants in seawater and sediments (Bakke et al., 2010; SFT 2007a). Please see text for abbreviations.

Table 3 shows an overview of the classification of heavy metals in sediments in Norwegian fjords and coastal waters. By using this table, the concentrations of heavy metals obtained in this study can be compared to background levels and the classification system described above.

Bakke et al. (2010) does not provide classification of the heavy metals Ba and Ti, because these heavy metals are considered nontoxic to organisms. However, Ba levels can be used as a marker for drill cuttings and drilling mud, and provides information of the thickness and spreading range of the drill cuttings.

Table 3: Classification of heavy metals in sediments (Bakke et al., 2010).

	I	II	III	IV	V
Metals	Background	Good	Moderate	Bad	Very bad
As (mg/Kg)	<20	20-52	52-76	76-580	>580
Pb (mg/Kg)	<30	30-83	83-100	100-720	>720
Cd (mg/Kg)	<0.25	0.25-2.6	2.6-15	15-140	>140
Cu (mg/Kg)	<35	35-51	51-55	55-220	>220
Cr (mg/Kg)	<70	70-560	560-5,900	5,900-59,000	>59,000
Hg (mg/Kg)	<0.15	0.15-0.63	0.63-0.86	0.86-2	>1.6
Ni (mg/Kg)	<30	30-46	46-120	120-840	>840
Zn (mg/Kg)	<150	150-360	360-590	590-4,500	>4,500

Table 4: Ranges of heavy metal concentrations per core. Bold values indicate values that are above background levels. Non-bold numbers indicate background levels.

Core	As (mg/Kg)	Cd (mg/Kg)	Co (mg/Kg)	Cr (mg/Kg)	Cu (mg/Kg)	Hg (mg/Kg)	Ni (mg/Kg)	Pb (mg/Kg)	V (mg/Kg)	Zn (mg/Kg)	Ba (mg/Kg)	Ti (mg/Kg)
10-4	8-12	0.1-**0.5**	2-7	10-30	34-**75**	0.5-**1.8**	5-18	**107-192**	8-48	62-94	15700-21500	43-365
30-7	2-8	0.04-**0.26**	8-14	35-47	9-18	0.01-0.08	25-**38**	6-29	6-29	49-89	106-10900	751-1070
60-11	2-9	0.04-**0.33**	10-17	37-46	12-16	0.01-0.03	27-**38**	8-24	65-91	72-103	107-2250	753-1050
125-9	2-9	0.02-**0.36**	10-13	37-49	12-16	0.01-0.03	30-**36**	10-20	63-96	71-88	114-922	756-974
250-2	2-8	0.05-**0.26**	11-15	42-48	13-17	0.01-0.**25**	32-**38**	10-22	60-71	63-73	92-561	919-1090

By comparing the ranges in metal concentrations per core with the values after Bakke et al. (2010), we can see which of the heavy metals that reveal concentrations above background values (Table 4). Increasing trends of Ba and various heavy metals up core indicate which intervals in each core that are impacted by drill cuttings, and how thick these layers are.

In core T 10-4, concentrations of Pb, Hg and Cu are belonging to class IV (bad), V (very bad) and IV (bad) respectively, and Ba appears with elevated concentrations throughout the whole core. Since Ba is a good indicator of drill cuttings, and that Pb, Hg and Cu are found with elevated concentrations in areas related to drill cuttings in previous studies, it implies that the whole core T 10-4 consist of pure drill cuttings. The sedimentation rate in Ingøydjupet is 1.0-2.4 mm/yr according to Junttila et al. (2014), which indicates that the top 4 cm of the sediments are representing sedimentation during approximately the last 30 years. Hence, the up core decrease of various heavy metals related to drill cuttings, and the increase in heavy metals that normally occur naturally in the sediment such as Co, Ni, V and Ti, at 4.5 cm core depth in this core (Fig. 7), indicates that some natural sedimentation has occurred since the drill cutting release in 1987. However, the much lower concentration of heavy metals related to drill cuttings at deeper depths in cores further away than for core T 10-4, indicates that core T 10-4 consist of pure drill cuttings. Also, the lower concentrations of heavy metals that occur naturally in the sediments at deeper core depths in core T 10-4 than for the cores further away, implies that the heavy metal concentrations below 4.5 cm core depth in core T 10-4 represents the drill cuttings when they were deposited, and the sediments above this core depth is related to natural sedimentation. Also, it implies that the concentration of Pb, Hg and Cu are still higher than background levels in the top cm of the core compared to the other cores, and that Co, Ni, V and Ti still haven’t reached the background levels compared to the other cores. In other words, core T 10-4 is characterized by some natural sedimentation the last 30 years, but it does not represent recovery of the seabed, but rather a step towards recovery. Based on these trends, it will probably take another 30 years until the seabed at this location will be recovered.

Core T 30-7 is characterized by heavy metal concentrations representing background levels, and some samples represents class II (good) for Cd and Ni. However, the up-core increase of Ba from 9.5 cm core depth, and an up-core increase in the concentrations of heavy metals related to drill cuttings, indicates that this core consist of drill cuttings in the top 9.5 cm of the core. The increase of some heavy metals below this core depth, might be related to other sources of anthropogenic pollution. Jensen et al. (2009) stated that increased concentrations of Hg and Pb in Ingøydjupet are associated to atmospheric or oceanic long-range transport and deposition in muddy sediments. Hg is associated to coal combustion, and Pb is associated to leaded gasoline (Jensen et al., 2009).

Most samples in core T 60-11, T 125-9 and T 250-2 are representing background levels. However, the increased concentration of Ba at 6.5 cm core depth and the increase of various heavy metals related to drill cuttings, indicate that this core consist of drill cuttings in the top 6.5 cm. In core T 125-9, the increase of Ba in the top 2.5 cm of the core, indicate that this core only consist of drill cuttings in the top 2.5 cm of the core. Core T 250-2 have very low concentrations of Ba and decreasing trends of several heavy metals (Fig. 7), which indicate that the drill cuttings has not spread all the way out to this location. It implies that a thick layer of drill cuttings are present in core T 10-4, and a thinning wedge of deposits is representing the drill cuttings further away from the well.

The increasing trends up core of various heavy metals and Ba in cores further away, and the elevated concentrations of Ba in the top of the cores, indicates that drill cuttings has been transported approximately 125 m away from the well with ocean currents after the time of discharge. However, values of Ba and various heavy metals are decreasing further away from the well, and we can therefore expect to find less impacted foraminifera faunas further away from the well, due to deposition of thinner layers of drill cuttings at increased distance from well. See section 1.2.3 for more information about the smothering effect of drill cuttings on benthic foraminifera.

5.1.2 Correlation between heavy metal concentrations, TOC and grain sizes

Figure 9 below shows several correlation plots of Ba vs the heavy metals Ti, Pb, Hg, Cu and Ni. There are strong positive correlations between Ba and Pb, Hg and Cu, with $r^2 = 0.89$ for Pb, $r^2 = 0.83$ for Hg, and $r^2 = 0.85$ for Cu, which means that with increased concentrations of Ba, there is also increased concentrations of Pb, Hg, and Cu. The labels in the plots shows the distance from the well, and we can see that there is a clear trend with higher concentrations of Ba, Pb, Hg, and Cu in the core closest by the well.

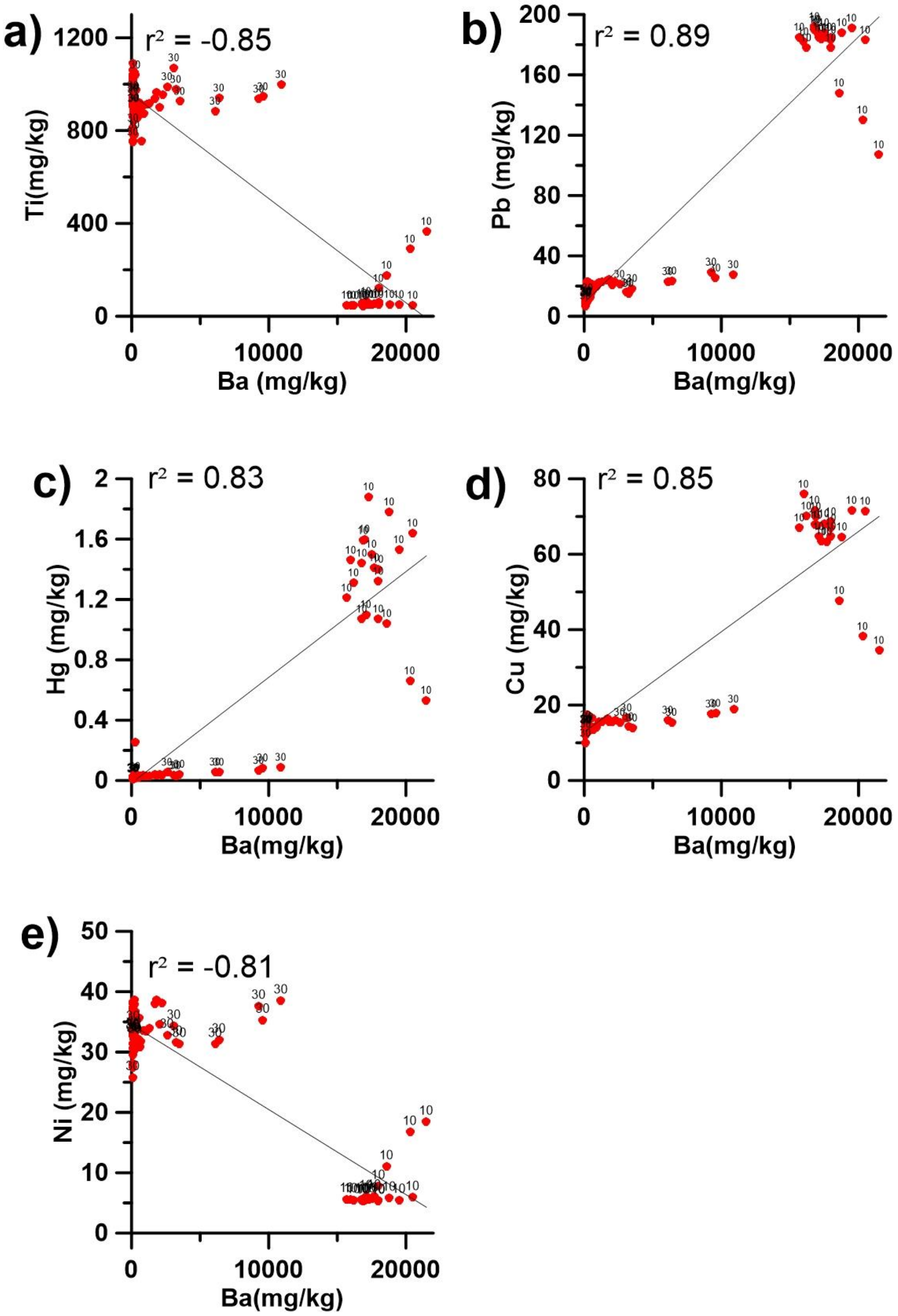

Figure 9: Correlation between Ba and various heavy metals. Ba vs. Ti (a); Ba vs. Pb (b); Ba vs. Hg (c); Ba vs. Cu (d); and Ba vs. Ni (e). Labels indicate distance from well, where only cores 10 and 30 m away are shown.

However, the values of Ba are still high in the core 30 m away from the well, while Pb, Hg, and Cu reveal lower values further away from the well. It indicates that Ba are transported with ocean currents, and that Pb, Hg and Cu mostly stay in the drill cutting pile. This could be due to the accumulation of Pb, Hg, and Cu in clay particles due to the ability of clay to bind metals, and that Ba accumulate and are transported with silt particles. However, it could also be that Pb, Hg and Cu are related to rock fragments, which make them unable to be transported. The plot with Ba vs. Ni shows a strong negative correlation with r^2 = -0.81, where higher concentrations of Ba correlate with lower concentrations of Ni. The strong negative correlation between Ni and Ba, is probably due to the absence of Ni in drill cuttings, and means that Ni most likely occur naturally in the sediment. The same is the case for Ti.

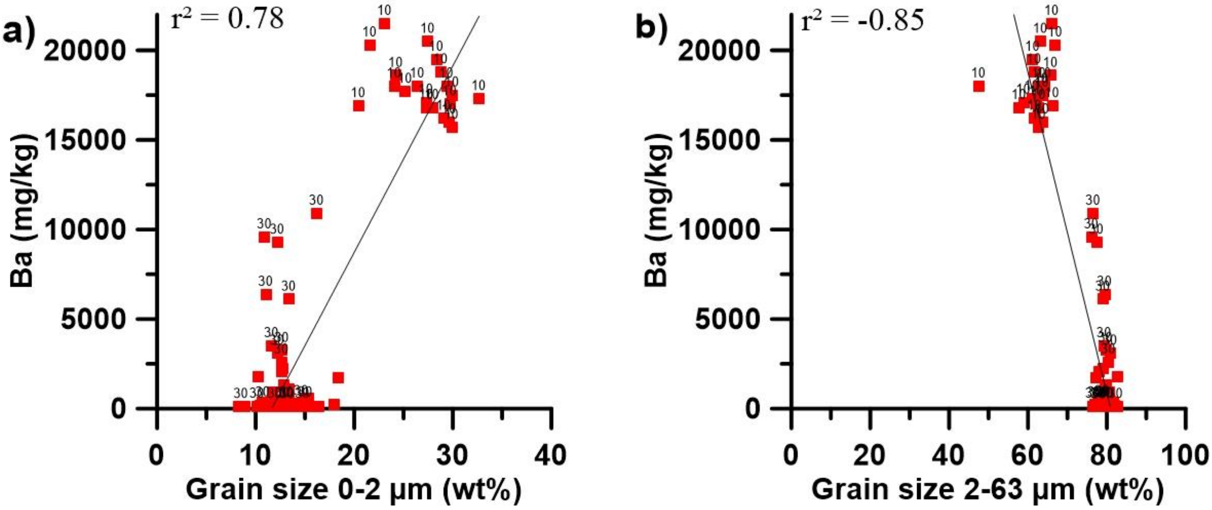

Figure 10: Correlation between Ba and the grain size fractions 0-2 µm (a) and 2-63 µm (b). Labels indicates distance from well, where only cores 10 and 30 m away are shown.

Correlation plots between Ba and the grain size fractions 0-2 µm and 2-63 µm show a strong positive correlation with r^2 = 0.78 for the clay fraction, and a strong negative correlation for the silt fraction with r^2 = -0.85 (Fig. 10). The relatively strong positive correlation between Ba and the clay fraction, correlates with the assumption that Ba accumulate in fine particles. However, it is important to notice that core T 10-4 is outstanding from the other cores, and the strong correlation might be related to the drill cuttings in this core.

To get a better picture of the correlation between Ba and the grain size fractions clay and silt, other plots without the sediments from core T 10-4 are presented (Fig. 11). These plots show much weaker correlations for both grain size fractions with r^2 = -0.0005 for the clay fraction and r^2 = -0.11 for the silt fraction. This means that the cores further away from the drill cutting pile shows weak correlations between Ba and the grain size fractions clay and silt.

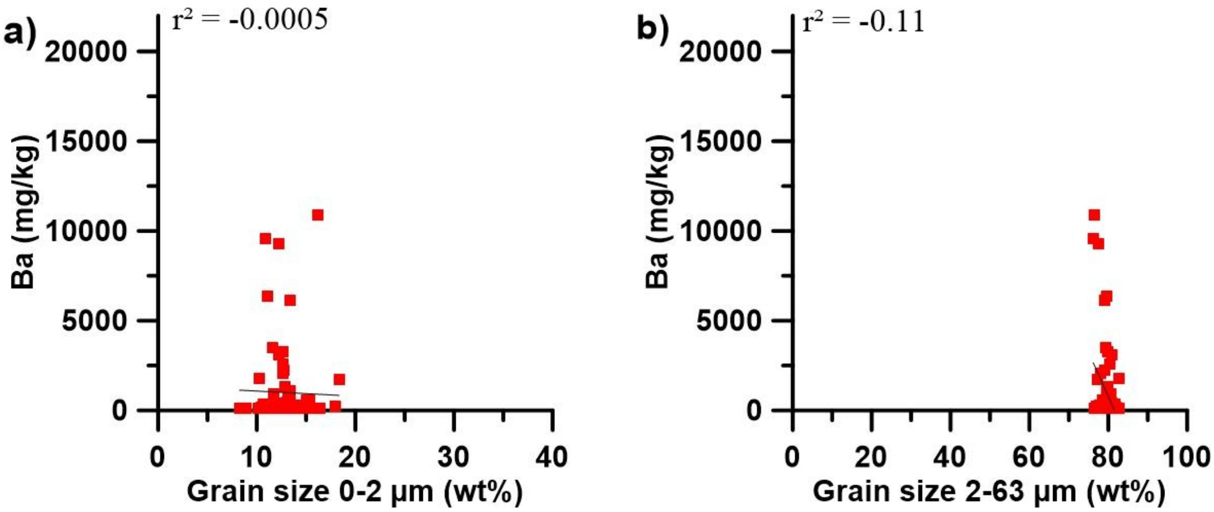

Figure 11: Correlation between Ba and the grain size fractions 0-2 µm (a) and 2-63 µm (b). Data from core T 10-4 are not presented.

However, since Ba correlates well with clay and silt when core T 10-4 is included, and shows weak correlations with these grain size fractions further away, it implies that Ba might be transported away from the well with the strength of the blowout of drill cuttings rather than with ocean currents.

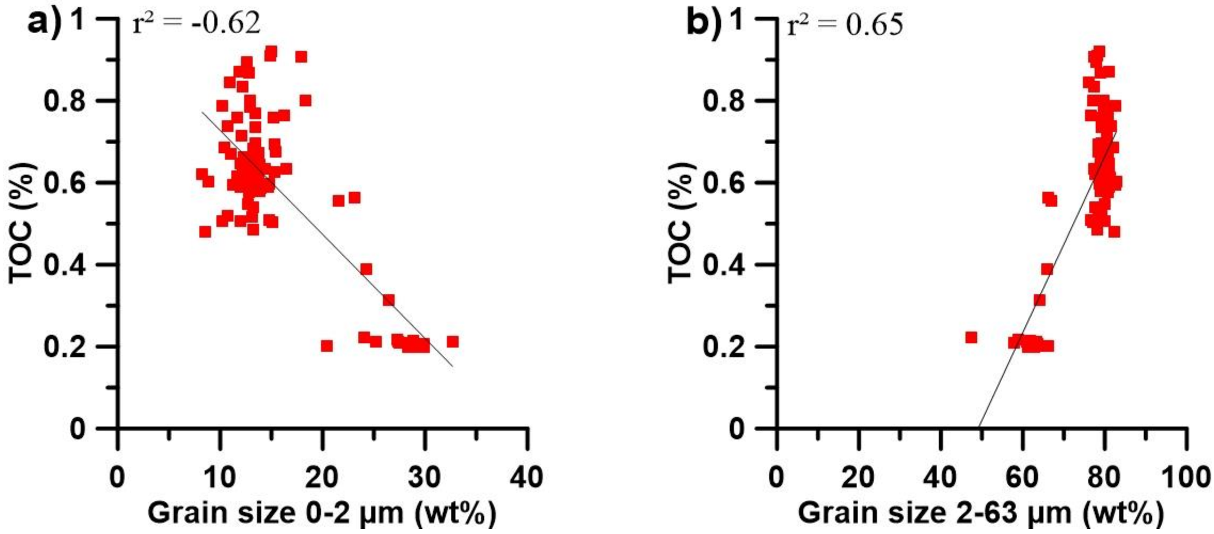

Figure 12: Correlation between TOC and the grain size fractions 0-2 µm (a) and 2-63 µm (b). Labels indicates distance from well, where only 10 and 30 m are shown.

Figure 12 shows plots with correlation between TOC and the grain size fractions 0-2 µm and 2-63 µm. The plots show a strong negative correlation between TOC and the grain size fraction 0-2 µm with r^2 = -0.62, which indicate that with inc^{r}eased concentrations of TOC, we do not have increased concentration of clay. On the other hand, we have a slightly stronger positive correlation between TOC and the silt fraction, with r^2 = 0.65, which means that increased concentrations of TOC are related to higher concentration of silt particles. This corresponds to the results presented in chapter 4, where both the concentration of silt and the TOC concentration is lower in core T 10-4 and increasing further away, as also seen in figure 12.

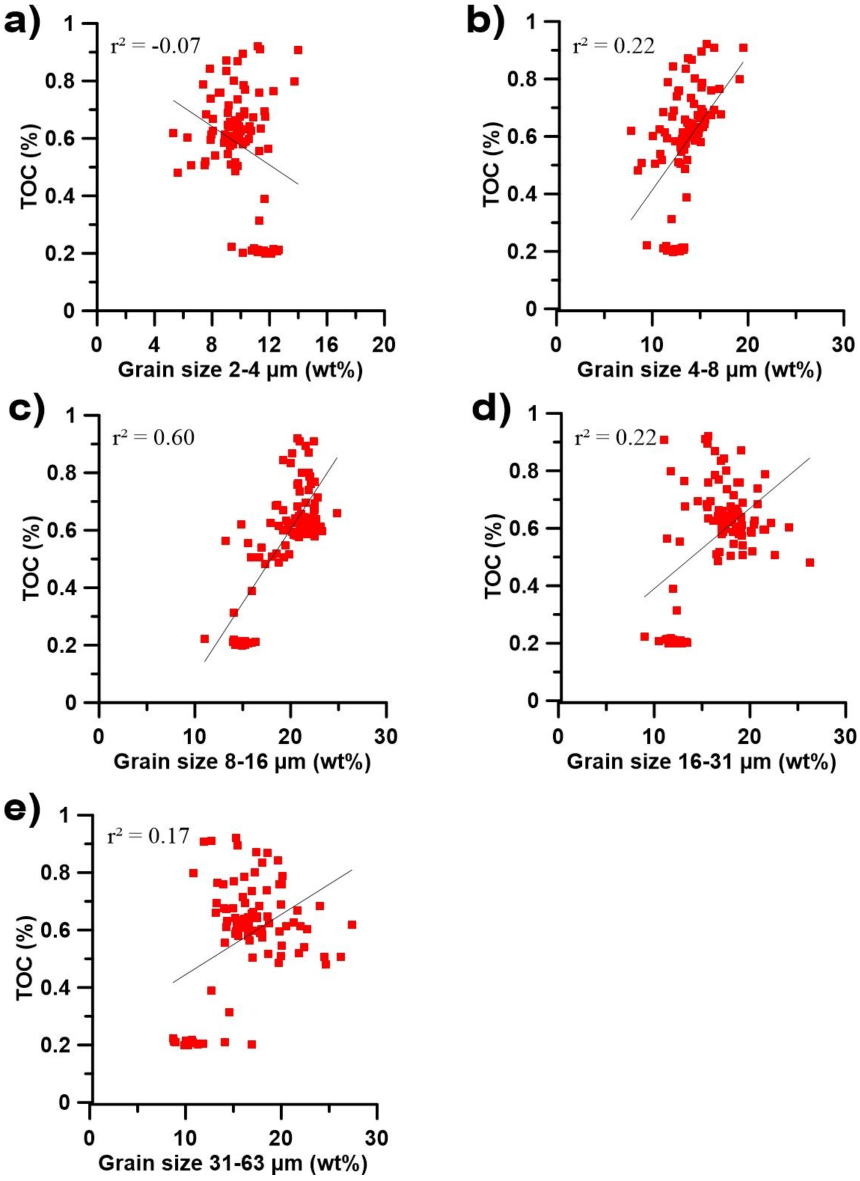

Figure 13: Correlation between TOC and the grain size fractions 2-4 µm (a), 4-8 µm (b), 8-16 µm (c), 16-31 µm (d) and 31-63 µm (e). All cores are presented.

Figure 13 shows plots with correlations between TOC and the grain size fractions 2-4 µm (very fine silt), 4-8 µm (fine silt), 8-16 µm (medium silt), 16-31 µm (coarse silt) and 31-63 µm (very coarse silt). The plots show a stronger correlation between TOC and the medium silt fraction than the other grain size fractions. In other words, the TOC accumulates in sediments with medium silt particles. TOC content represents organic matter, and the low TOC content in core T 10-4 might be related to the natural low TOC content in drill cuttings. However, the TOC content in core T 10-4 seems to be relatively constant up core until it starts to increase at approximately 4.5 cm core depth (Fig. 6). The increased concentrations above this core depth, correspond to increased concentrations of heavy metals occurring naturally in the sediments and decreased concentrations of heavy metals related to drill cuttings. It implies that some natural sedimentation has occurred after the drill cutting release, and that there have been increased concentrations of organic matter during this time. However, the core closest by the well is more outstanding than the other cores and might cause the relatively strong correlation between TOC and the grain size fraction medium silt.

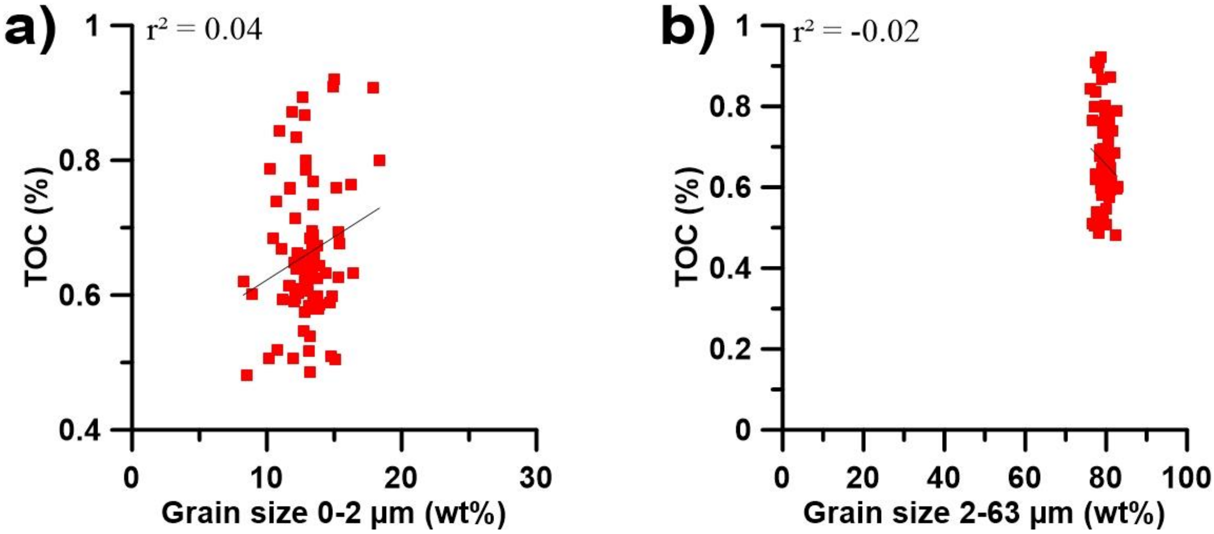

Figure 14: Correlation between TOC and the grain size fractions 0-2 µm (a) and 2-63 µm (b). Data from core T 10-4 are not presented.

Figure 14 shows correlation plots between TOC concentrations and the grain size fractions 0-2 µm and 2-63 µm without samples from core T 10-4. By excluding the core closest by the well, we can see that we have much weaker correlations for both grain size fractions with $r^2 = 0.04$ for the clay fraction, and $r^2 = -0.02$ for the silt fraction. This implies that the TOC content in the cores T 30-7, T 60-11, T 125-9 and T 250-2 does not correlates with fine grained particles as the core closest by the well.

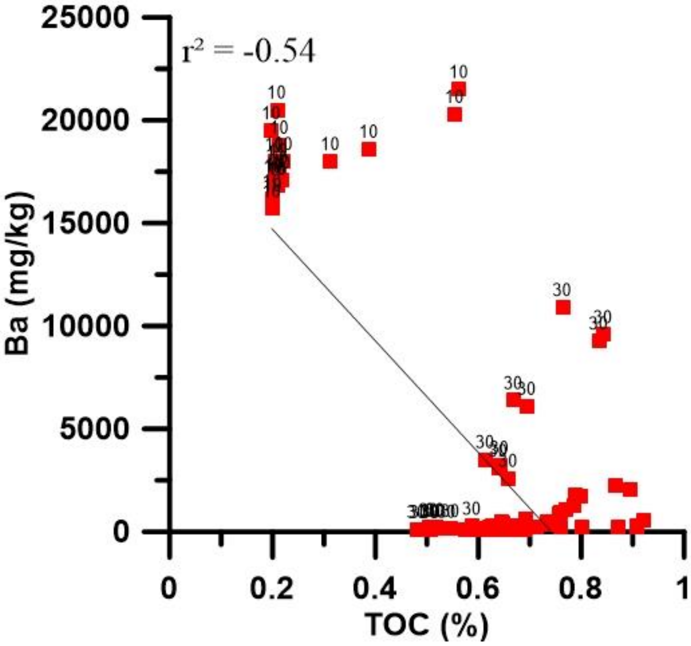

Figure 15: Correlation between Ba and TOC. Labels indicate distance from well, where only 10 and 30 m away are shown.

Figure 15 shows a plot with the correlation between Ba and TOC with $r^2 = -0.54$. The moderate negative correlation tells us that high concentrations of Ba are not related to high content of TOC. It implies that we have increased TOC concentrations further away from the well with decreasing concentrations of Ba. This correlates with the results presented in chapter 4, where TOC concentrations are lower in core T 10-4 where concentrations of Ba are highest (Fig. 7). Reasons for this are described above.

Junttila et al. (2014) with reference therein, stated that the composition of TOC in the SW Barents Sea is dominated by marine organic material from the nutrient rich Atlantic water, which indicates that an increase in TOC might be related to increased inflow of Atlantic water. It implies, that high TOC content is not related to drill cuttings, but rather higher inflow of Atlantic water. We can therefore expect higher influence of the NAC at intervals with high TOC content. Indeed, due to the low velocity of the NAC, we can expect fine grained particles to be related to high TOC content with the influence of the NAC, which correspond with the strong positive correlation between TOC and the medium silt fraction in this study. However, foraminifera data with the presence of Atlantic species at intervals with the influence of the NAC are needed to support this, and will be further discussed in section 5.2.4. In other words, changes in grain size distribution might be caused by the natural variability of ocean currents, or by direct influence of drill cuttings.

5.1.3 Sediment properties

The silt content is relatively constant up core for all cores except core T 10-4 (Fig. 6). The decreased silt content and increased clay content in this core might be related to the clay particles in the water based drilling mud associated with the drill cuttings. The decreased concentration of silt at 4.5 cm core depth in core T 10-4, and the increased concentration of sand at this core depth might be directly related to the deposition of drill cuttings. The cores further away are characterized by relatively constant grain size values up core for all cores, which might indicate that these cores are not as much impacted by drill cuttings as for core T 10-4. However, in core T 60-11 at 3.5 cm core depth, there is a sudden decrease in clay content and increase in silt content that might be related to stronger ocean currents at this interval. The NCC has higher velocity than the NAC, hence intervals with decreased clay content and increased silt content might therefore indicate influence by the stronger NCC at these intervals.

Also, it is worth to mention the water content in the studied sediments (Fig. 6). Breuer et al. (1999) noted that the water content in drill cuttings is normally between 20-60 %. In the core closest by the well the water content is above this value and much higher than the water content in the other cores, which have values within the predicted water content for drill cuttings. This high water content in proximity to the well might be related to the water-based drilling mud deposited in the area, and support the assumption that we have pure drill cuttings in this core, as also testified by the extremely low concentrations of foraminifera, especially at depth, compared to other cores. The lower water content in the bottom of all cores may be related to the compaction of sediments which decreases the porosity, and hence the pore space for water in the sediments.

5.2 Benthic foraminifera assemblages

Dolven et al. (2013) stated that the conventional classification system after Bakke et al. (2010) could be used on benthic foraminifera for defining Ecological Quality Status (EcoQS) back in time. In other words, by applying the foraminiferal method when investigating polluted sediments, we can look at both changes in the environment as a result of pollution back in time and changes that happened in the period just before sampling. The dead fauna, found deeper in the sediment, is a mixture of the original pre-impacted fauna living there before the drill cutting release, and the faunas that colonized during and after the period of drill cutting release (Mojtahid et al., 2006). It represents a period of many years, and can be used to detect changes in the environment back in time. The live fauna represents only the short life cycle when it was alive before sampling, which varies between 3 months to two years (Mojtahid et al., 2006; reference therein). It is therefore important to keep in mind that the release of drill cuttings was in 1987, and the living foraminifera collected in this study represents the environmental conditions in 2015. In this section, both fossil and living foraminiferal assemblages will be discussed. Also the staining techniques used to stain the living foraminifera will be discussed, as well as recolonization of benthic foraminifera and whether the study area seem to have recovered after the drill cutting release in 1987 or not.

5.2.1 Fossil assemblages

Since the number of foraminiferal specimens is so low in core T 10-4 (Fig. 5), interpretations on species relative abundance will not be done for this core. The fact that there is so few specimens present in this core correspond to very high concentrations of various heavy metals related to drill cuttings in this core. The high heavy metal concentrations and the elevated concentrations of Ba throughout the whole core, as well as the low number of foraminifera in the whole core indicate that the whole core T 10-4 consist of pure drill cuttings. However, this low number of foraminifera in core T 10-4 might be realistic, if the drill cuttings contained low number of foraminifera from the drilled layer. Since the drill cuttings where all discharged at the same time, there was no time for foraminifera to live there during deposition of the drill cuttings, and hence no time for an impacted assemblage to form. The foraminiferal assemblage might indicate an old fossil fauna that where dumped with the drill cuttings, hence the drill cuttings contained a low number of foraminifera before discharged to sea.

For all other cores, we have enough fossil specimen for doing statistically certain interpretations. The much higher concentrations of fossil benthic foraminifera further away from the well is related to the lower concentration of toxic heavy metals in these cores, hence the density of foraminifera are not impacted by the drill cuttings. The fossil faunal assemblages in cores T 30-7, T 60-11, T 125-9 and T 250-2 where dominated by *E. nipponica, C. laevigata, C. lobatulus* and *M. barleeanus.* This correspond to assemblages that are normally found in the pre-impacted Ingøydjupet, as described in Dijkstra et al. (2015) which reported dominating species to be *E. nipponica, M. barleeanus* and *C. laevigata.* These species are related to warm, Atlantic water with high food supply, and high sedimentation rates related to fine grained particles (Dijkstra et al., 2015). This corresponds to the grain size properties and the organic rich environment of Ingøydjupet, and the assumption that the NAC is influencing the Ingøydjupet trough.

Downcore trends can be related to layers indicated as drill cuttings described in section 5.1.1. In core T 30-7, decreased relative abundances are observed for the species *M. barleeanus, C. lobatulus, T. angulosa,* and a slight decrease for *C. laevigata.* The relative abundance of all the mentioned species seems to decrease from 9.5 cm core depth, which correspond with the assumption that this core is covered by drill cuttings in the top 9.5 cm. *E. nipponica* has a relatively constant relative abundance up core with some minor changes. Core T 60-11 shows an increase in the relative abundance of *C. laevigata, M. barleeanus, F. marginata* above 6.5 cm core depth where the concentration of Ba is increasing towards the top of the core. Hence since the sediments above this core depth are interpreted to be drill cuttings, the mentioned species doesn’t seem to be impacted by the drill cuttings. Relative abundances of *C. lobatulus* and *T. angulosa* are relatively constant up core from this core depth, while *E. nipponica* and *P. bulloides* is decreasing above this core depth. It implies that *E. nipponica* and *P. bulloides* might be the only impacted species in this core. In core T 125-9, only the top 2.5 cm of the core were impacted by drill cuttings, with increased concentrations of Ba (Fig. 7). At this core depth, the relative abundances of *C. laevigata, C. lobatulus,* and *T. angulosa* seems to increase, while *E. nipponica, M. barleeanus, P. bulloides* and *F. marginata* seems to decrease. In core T 250-2, sediments are not impacted by drill cuttings (see section 5.1.1), and therefore impacted faunas are not expected. In other words, some species have increasing relative abundance, while other species have decreased relative abundances. These intervals are not only related to increased concentrations of Ba and various heavy metals related to drill cuttings, and might indicate that the different species have different environmental preference. Therefore, the downcore changes in fossil faunal assemblages might be related to natural variability in the environment such as ocean currents, rather than the layers of drill cuttings.

An increase in relative abundance of the species *E. nipponica, C. laevigata* and *M. barleeanus* might reflect a higher influence of the NAC and a higher food supply at these intervals due to reasons described above. However, with increased relative abundances of *E. nipponica* there is decreased relative abundances of *M. barleeanus* at several intervals in core T 30-7, T 60-11, T 125-9 and T 250-2 (Fig. 5). Dijkstra et al. (2015) with reference therein interpreted these intervals to be related to the influence by the stronger NCC that transports *E.nipponica*, since *M. barleeanus* is related to fine grained sediments and calm conditions. *E. nipponica* can be easily transported with ocean currents due to the small size and round shape of the species, so it is likely that this species has been transported with stronger ocean currents by the NCC from the Tromsøflaket area to Ingøydjupet (Dijkstra et al., 2015; reference therein). Also, *E. nipponica* is characterized by rapid reproduction which might explain the high relative abundance of this species. Dijktstra et al. (2015) with reference therein, noted that *E. nipponica* where found in areas with low species diversity where few other species where present. This might explain the low total number of benthic foraminifera species found in this study.

In summary, the only impact by the drill cutting release on the dead foraminiferal assemblage seems to be a low number of specimens in core T 10-4, which completely consist of drill cuttings. In the other cores, normal concentrations of the fossil assemblages where found, and changes in relative abundances might be related to natural variability.

5.2.2 Living assemblages

As only the top cm of the cores T 30-7, T 60-11, T 125-9 and T 250-2 had enough foraminiferal specimen to do statistically certain interpretations, only the relative abundances of the top cm in these cores will be discussed. The dominating species in the top cm of the cores T 30-7, T 60-11, T 125-9 and T 250-2 is varying between the cores, and are dominated by *E. nipponica*, *P. bulloides, C. lobatulus, C. laevigata* and *M. barleeanus.* This correspond with the living foraminiferal assemblage in the pre-impacted Ingøydjupet, where *E. nipponica, C. laevigata,* and *M. barleeanus* were dominating (Dijkstra et al., 2013). Dijkstra et al. (2013) stated that *P. bulloides* and *Lobatula lobatula* or *C. lobatulus* as referred to in this study also where abundant in Ingøydjupet. However, Dijkstra et al. (2013) stated that *C. laevigata, C. lobatulus* and *T. angulosa* which were also abundant in the present study are associated with coarse grain sizes. The three species are epifaunal species, and live often attached to branches of kelp or rocks, and are hence not that easily transported. It implies that they indicate stronger bottom currents or coarser grain sizes. *F.marginata* was also present in substantial numbers in the present study, which correspond with the study by Dijkstra et al. (2013). As for the dead foraminiferal assemblages, *E. nipponica* is also abundant in the live foraminiferal assemblage where species diversity is low. This might indicate that *E. nipponica* is either tolerant to the drill cuttings or an opportunistic species (Dijkstra et al., 2013). Previous studies show the same pattern, where low-energy currents are normally characterized by an introduction to smaller taxa with an opportunistic behaviour (Alve, 1999). Jorissen et al. (2009) also reported the same pattern, where the large sized-fraction showed a stronger response to the environmental changes caused by drill cutting release than the small sized-fraction, hence the small sized fraction might represent the opportunistic taxa.

Also, the fact that only the top cm of the cores T 30-7, T 60-11, T 125-9 and T 250-2 had enough living foraminiferal specimens to make statistically certain interpretations, i.e. > 58 specimens, indicates that the sediments below this core depth are still impacted by the drill cuttings. Since the top cm of these cores have enough specimens to do statistically certain interpretations, it implies that the top cm of the living foraminiferal assemblage where not impacted by drill cuttings in 2015. In other words, the top cm of the sediments seems to be recovered since 1987, but the benthic fauna below this core depth are still impacted by drill cuttings, hence the area are moving towards a stage of recovery of the sediments.

An interesting observation in core T 10-4 is the high concentration of the #/g for the live fauna below 2.5 cm core depth (Fig. 5). According to the TROX (TRophic OXygen) model after Jorissen et al. (1995), as described in Koho (2008), foraminiferal assemblages living in eutrophic environments where there is a sufficient food supply and the pore water oxygen conditions are reduced, the benthic foraminifera are normally living in the sediment. The TROX model also shows that no benthic foraminifera can survive in the anoxic zone where there is no oxygen available. TOTAL oxygen profiles (personal communication with Landfald, B., 2017) from the cores investigated in this study, shows that there is no oxygen below 2.5 cm core depth in core T 10-4. It implies that the stained foraminifera observed in the core closest by the well, must have been dead before sampling. Koho (2008) with reference therein explained that increased concentrations of organic carbon leads to a higher consumption of oxygen, which results in reduced oxygen levels deeper in the sediment. In this case, we would expect higher TOC concentrations where we have lack of oxygen. We do have higher TOC content in the top of all cores, which correlates with this statement. Therefore, this may be a possible explanation for the lack of oxygen deeper than 2.5 cm core depth in core T 10-4. However, only few live foraminifera where found below 2.5 cm in the other cores even though the oxygen conditions were slightly better in these cores (personal communication with Landfald, B., 2017), which means that even though oxygen levels had been higher in the core closest by the well, the live foraminiferal assemblage might not be higher. This support the previous assumption that the stained foraminifera below 2.5 cm core depth must have been dead before sampling, and that the low number of living specimens close to the sediment surface indicate that this core is still impacted by drill cuttings.

5.2.2.1 Staining of benthic foraminifera

The high number of stained foraminifera below 2.5 cm core depth might be related to overstaining because of three reasons. Overstaining might be related to either slowly decomposition of the protoplasm (Bernhard, 1988), staining of the organic compounds of the foraminiferal tests or staining of bacteria attached to or living inside the test (Bernhard et al., 2006). It is possible that dead foraminiferal protoplasm will continue to stain in the order of weeks to months (Bernhard, 1988). The decay of dead fauna because of drill cutting release might be associated to bacterial growth on or within the test, which may cause the overstaining of benthic foraminifera. It implies that certain bacteria must be tolerant to material related to drill cuttings. This is shown in a previous study by Duxbury and Bicknell (1983), which reported that one group of bacteria where more tolerant to metal pollution than another, which they explained to be related to the cell of the metal-tolerant bacteria which is characterized by a barrier that does not let metal ions enter the cell. The staining method with Rose Bengal seems now to give problems as seen in literature, and it implies that there is a possibility that the rose Bengal might overstain dead foraminifera with bacteria growing on or within the test below 2.5 cm core depth. However, we do not know which of the various heavy metals related to drill cuttings that might be beneficial for certain bacterial populations. However, various groups of bacterial populations may be tolerant to different types of heavy metals. Since the number of stained foraminifera was only high in core T 10-4, this might indicate that the possible bacteria growing on or within the test are dependent on material related to drill cuttings. This is showed in a previous study by Jordan and Lechevalier (1975), which reported that zinc-tolerant bacteria where found in proximity of a zinc-smelter, where concentrations of zinc where high, and that the zinc-tolerant bacteria where not found in areas with low concentrations of zinc.

The overstaining of dead foraminifera indicate that the foraminifera must have been dead before sampling. This is supported by Bernhard (1988), which proves that rose Bengal will overstain benthic foraminifera that have been dead for as long as four weeks. A later study by Bernhard et al. (2006) reported that Rose Bengal could stain foraminifera that have been dead for months to years prior to sampling. According to these results, the stained foraminifera in the core closest by the well might have been dead several months or years prior to sampling. Another option is that foraminifera can react with Rose Bengal after sediment transportation, which means that the foraminifera did not necessarily live in the area where samples were collected (Bernhard et al., 2006). In other words, the use of vital staining techniques to determine living assemblages of benthic foraminifera are not always reflecting the actual living individuals. It shows that the Rose Bengal include the dead foraminifera in the staining process, and might not be the best staining technique to use in bio-indicator studies. Even though Rose Bengal tend to overstain dead foraminifera and not accurately identify living foraminifera, this is a preferable staining technique, due to its distinctive rose colour.

5.2.2.2 Recovery after drill cutting release in 1987?

As discussed in section 5.2.1 and 5.2.2, the living and the dead foraminiferal assemblage of this study is characterized by similar species as the pre-impacted Ingøydjupet. We know that the living foraminifera in this study are representing the environmental conditions in the area in 2015 before sampling, hence the top cm of the sediments further away from the drill cutting pile seems to have recovered. The result of colonization after drill cutting release is often higher concentrations of certain species in polluted areas, such as *E. nipponica* in this study. In other words, *E. nipponica* seems to have returned to the area in 2015, and indicates that conditions in the top cm of the sediments where good enough for certain species to live there. Normal assemblages above the layers identified as drill cuttings discussed in section 5.1.1 indicate normal sedimentation on top of the drill cuttings, and hence a recovery of the top cm of the sediments. However, the sediments below this core depth does not seem to have recovered, due to the low number of foraminiferal specimens. On the other hand, core T 10-4 is still impacted by drill cutting release in the whole core. Based on the elevated heavy metal concentrations of Pb, Hg, and Cu in core T 10-4, and the low number of living foraminifera in the top cm of this core still 30 years after the cessation of drill cutting release, we can expect recovery of the sediment in proximity to the disposal site to take another 30 years from today.

5.2.3 Correlation between foraminiferal assemblages, heavy metals, grain sizes and TOC

Since Ba is a good indication of drill cuttings, and it is transported by ocean currents further away from the well, plots with correlation between Ba and foraminifera are made to illustrate the correlation between drill cuttings and foraminifera. Since *E. nipponica* and *M. barleeanus* is among the most dominating foraminiferal species, correlation plots are made for them vs. Ba. Since the total number of foraminiferal specimens is so low in core T 10-4 and hence statistically uncertain, these data are not presented in the correlation plots.

Figure 16 below shows plots with the correlation between Ba and the foraminiferal species *E. nipponica* and *M. barleeanus. E. nipponica* shows a weak positive correlation with Ba with $r^2 = 0.22$, and *M. barleeanus* shows a weak negative correlation with Ba with $r^2 = -0.14$. This shows that neither of the species are related to high concentrations of Ba. However, the slightly stronger correlation between *E. nipponica* and Ba, might indicate that *E. nipponica* is less impacted by the smothering effect of the drill cuttings described in section 1.2.3, and might support the assumption that *E. nipponica* has an opportunistic behaviour.

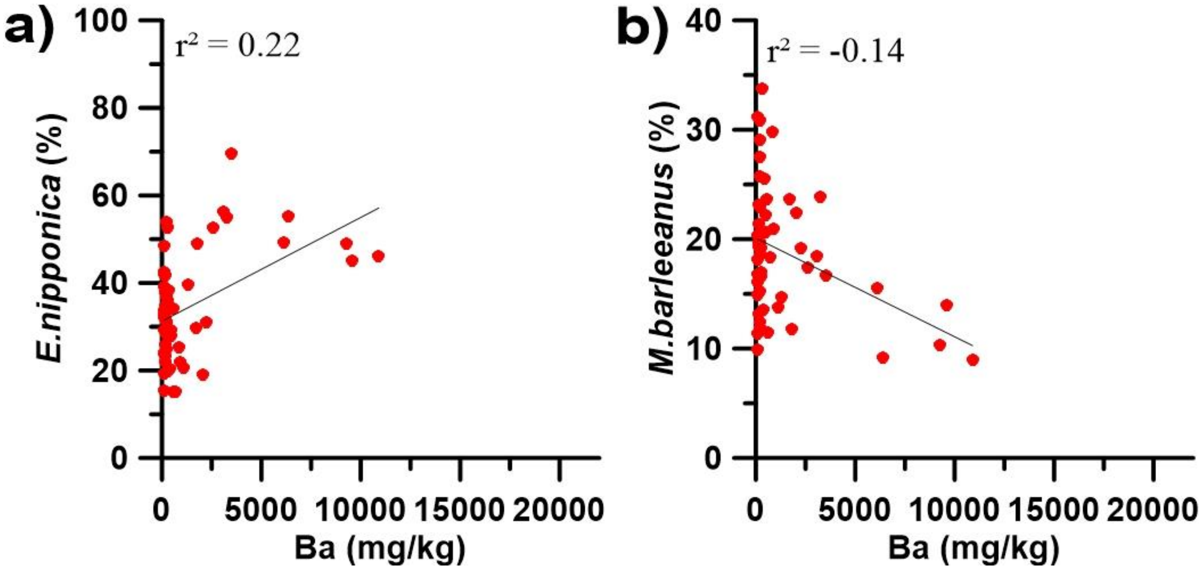

Figure 16: Correlation between Ba and a) E. nipponica and b) M. barleeanus. Data from core T 10-4 is not presented.

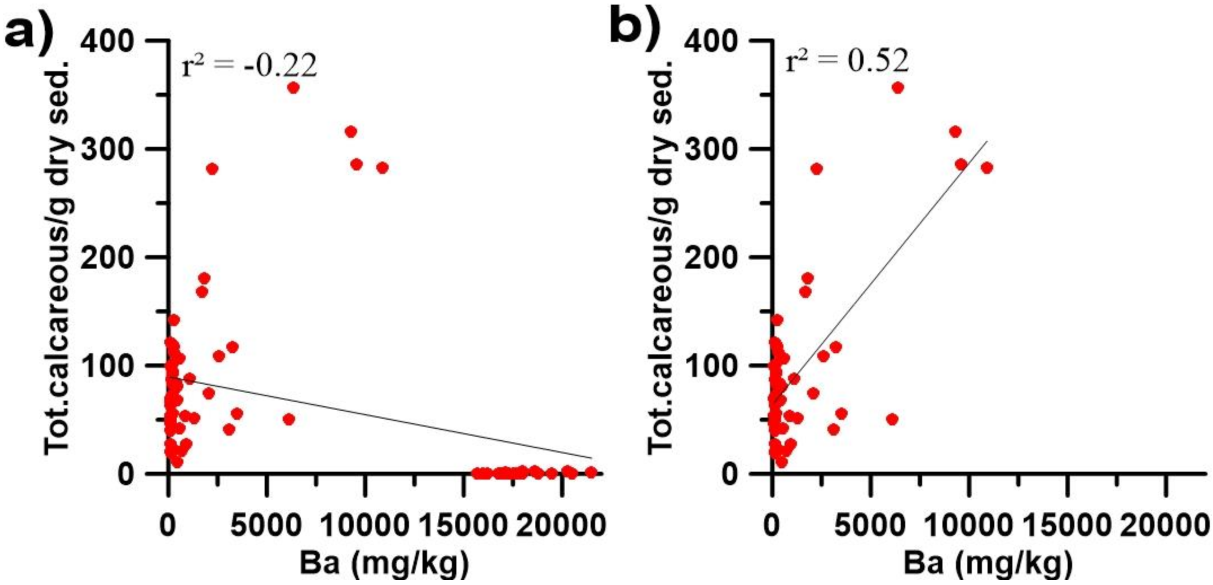

Figure 17: Correlation between Ba and total calcareous/g dry sediment with data from core T 10-4 included (a) and without data from core T 10-4 included (b).

Figure 17 shows correlation plots between Ba and the #/g where a) shows the correlation with data from core T 10-4 included, and b) shows data where T 10-4 is not included. Plot a) shows a weak negative correlation with $r^2 = -0.22$, which indicates that high densities of foraminifera are not correlated to high concentrations of Ba. This correspond to the low densities of benthic foraminifera found in core T 10-4 where concentrations of Ba are high. Plot b) shows a moderate positive correlation with $r^2 = 0.52$, which indicate that high concentrations of Ba correlates with higher density of benthic foraminifera, which was observed in cores T 30-7, T 60-11, T 125-9 and T 250-2. It also supports the assumption that only core T 10-4 seems to be largely impacted by drill cuttings, while the cores further away from the well seems to have less impacted faunas showed by higher densities. This correlates with previous studies, where benthic foraminifera have showed maximum densities at some distance from disposal site, and decreasing densitites closer to disposal site (Denoyelle et al., 2010).

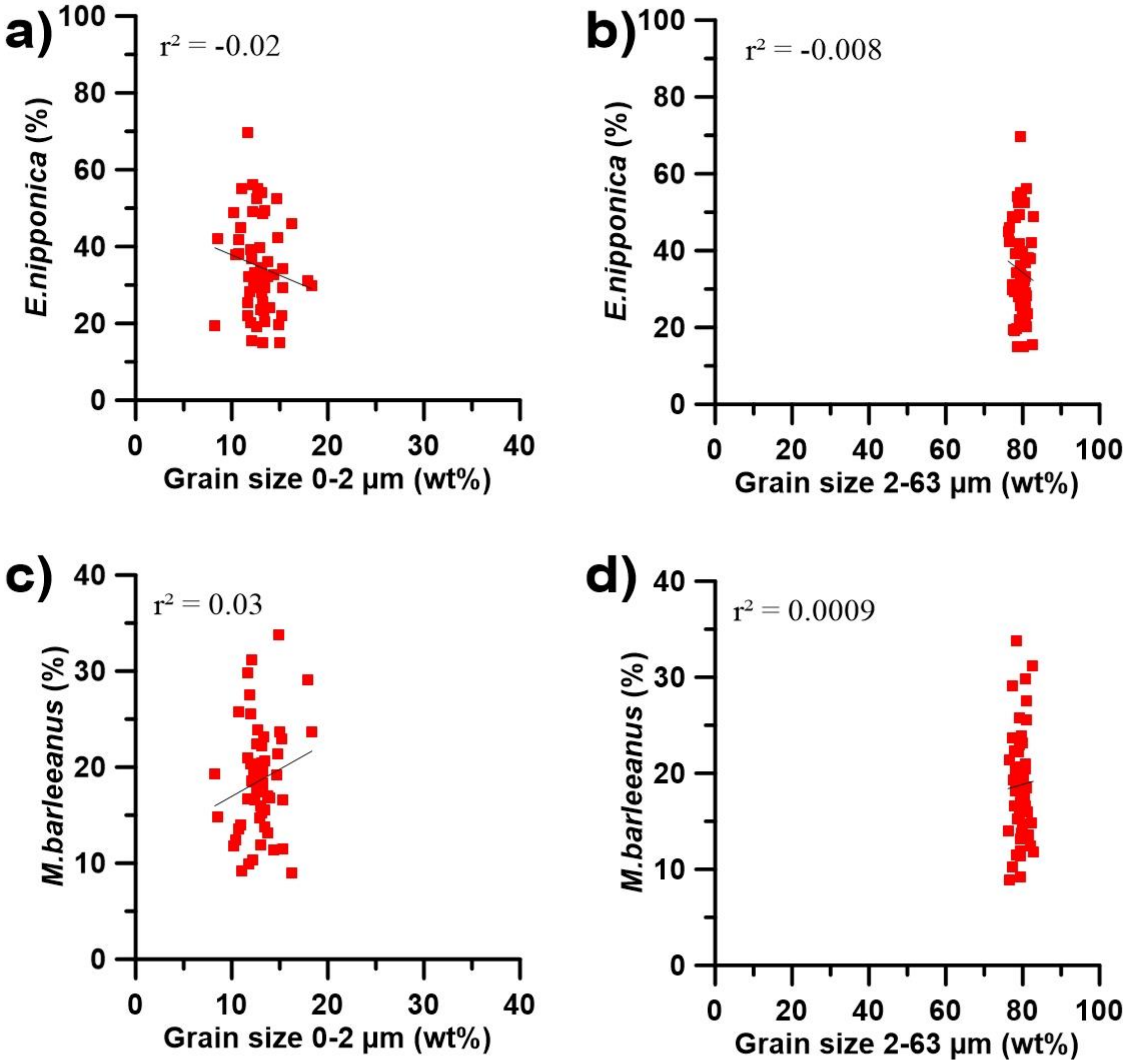

Figure 18: Correlation between E. nipponica and the grain size fraction 0-2 µm (a) and 2-63 µm (b), and between M. barleeanus and the grain size fraction 0-2 µm (c) and 2-63 µm (d). Core T 10-4 is not presented.

Figure 18 shows correlation plots between *E. nipponica* and the grain size fractions 0-2 µm and 2-63 µm and between *M. barleeanus* and the grain size fractions 0-2 µm and 2-63 µm, where core T 10-4 is not included in the data. All plots show very weak correlations. This means that these foraminiferal species are not related to fine grained sediment particles. However, this is somehow surprising, because it is well known that *M. barleeanus* is associated to and often limited to fine grain sizes. It implies that there must be another reason for this species to live in the area. It is also well known that this species is associated and often limited to high food availability, which is reflected in TOC. Hence, the TOC content might be the possible reason why this species live in the area.

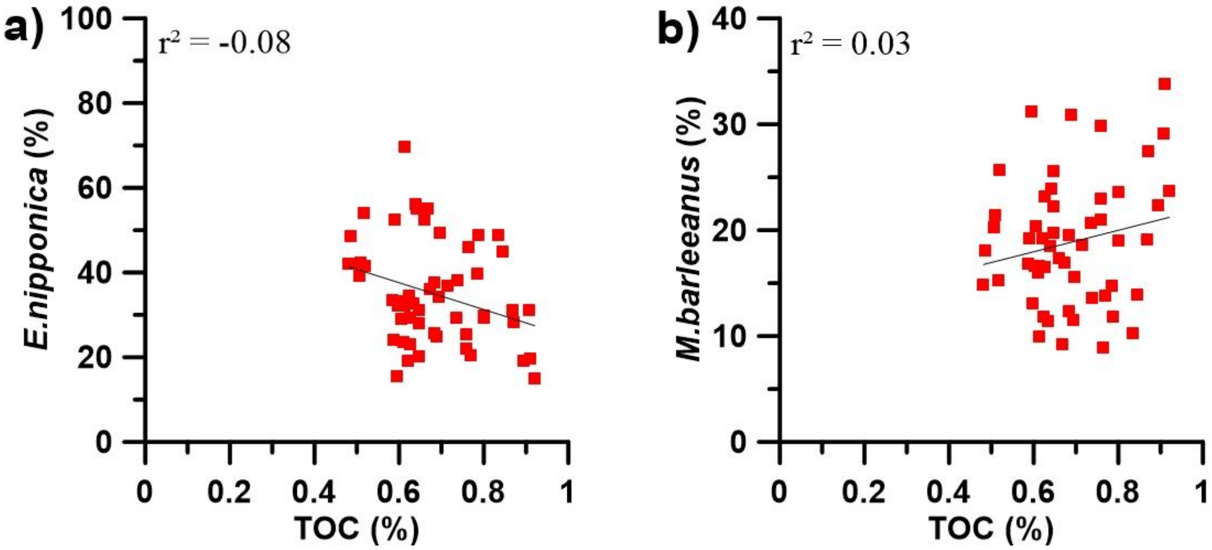

Figure 19: Correlation between TOC concentrations and a) E. nipponica and b) M. barleeanus. Core T 10-4 are not presented.

Figure 19 shows plots with correlations between TOC and the species *E. nipponica* and *M. barleeanus*, where data from core T 10-4 are not included in the data. *E. nipponica* illustrate a weak negative correlation with $r^2 = -0.08$, and *M. barleeanus* shows a weak positive correlation with $r^2 = 0.03$. This means that neither of the two species correlates with higher concentrations of TOC. This is does not correlate with previous results where *M. barleeanus* are related to high food availability, reflected in the TOC.

Figure 20 below show a summary figure with the layers interpreted as drill cuttings in this study. It illustrates that core T 10-4 consist purely of drill cuttings, and that a thinning wedge of deposits are present further away from the well.

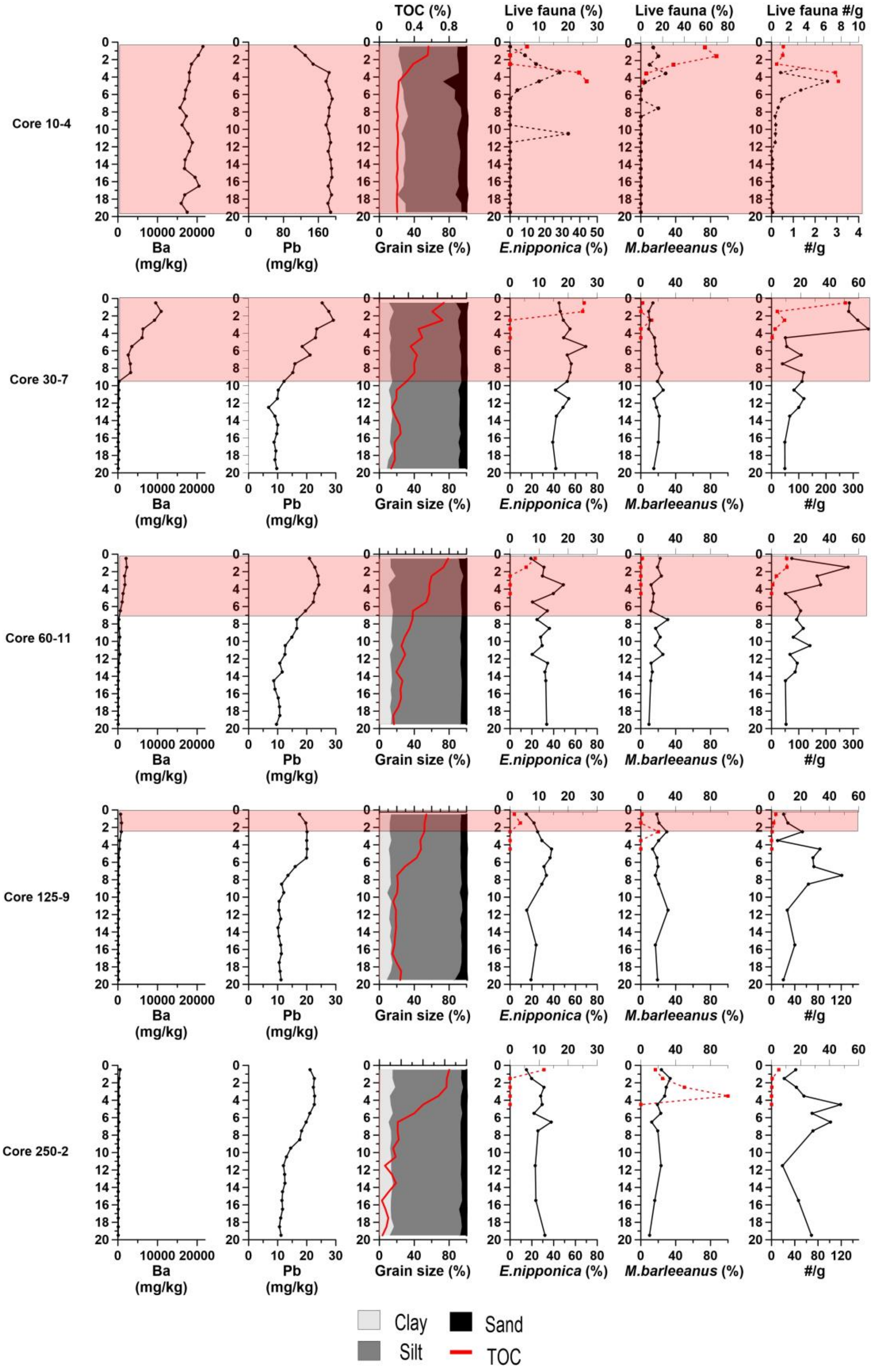

Figure 20: *Summary figure with layers indicated as drill cutting deposits (red bars). #/g= total calcareous/gram dry sediment.*

5.3 Options to prevent impacts of drill cutting release

As addressed in this thesis and in previous studies, drill cutting release is a problem for the marine environment. The handling of these drill cuttings is a topic of debate today. The question is what to do with the drill cuttings. What we know is that guidelines through regulations and monitoring programmes are needed to prevent further degradation of the marine environment. The US Pollution Prevention Act (1990) stated that disposal of drill cuttings into the marine environment should only be used as a last option, and that pollution that could be prevented should be rather recycled in an environmentally safe manner (Ball et al., 2012). In this section, different methods used for disposal of drill cuttings will be presented, as well as the factors needed to be considered when choosing the best method for drill cutting disposal, including the environmental risks associated with drill cutting disposal.

The methods used for drill cutting disposal include a) discharging at sea, at the drilling site, b) underground injection or c) transporting elsewhere for disposal (Ball et al., 2012). The first method was used in the present study, where we have seen that the area is heavily impacted by drill cuttings, still 30 years after disposal. The core closest by the well has not recovered yet, but is moving towards a stage of recovery. As discussed previously in this thesis, recovery in proximity of the well will probably take another 30 years from today. This might have consequences for the food web in the marine environment due to the absence of certain species in the impacted area which might be a valuable food source for other species. It implies that leaving the drill cuttings at the drilling site is not a good option for handling of drill cuttings. The cores further away show impacted faunas for the live assemblage below the top cm of the cores, and recovered sediments in the top cm.

When re-injecting drill cuttings, a mixture of cuttings, waste mud and water are sent to a tank before being injected downhole to the subsurface formation (Ball et al., 2012). This is an appropriate solution for the handling of drill cuttings, due to its low impacts on the marine environment. However, when drill cuttings are already left on site, they might be diluted in the surrounding sediments and spread out covering a wider area of the sea floor. Hence injection of the drill cuttings released in 1987 in this study might not be the best option for the handling of these drill cuttings.

The last option is removing drill cuttings to landfill. The landfill is covered by a bottom layer that prevent contamination of the soil. This method is beneficial for water based cuttings, it requires limited surface area, and requires low costs. The disadvantages of this method are possible contamination of groundwater, and required monitoring and stabilization (Ball et al., 2012). Also, if choosing to remove the drill cuttings that are already discharged to sea, to landfill for disposal, high toxicity of sediments might be a problem during pile removal due to resuspension of contaminated fine sediments (Grant and Briggs, 2002). When deciding to bury drill cuttings, several factors must be considered. Depth of the pit is important, which should be located at least 1.5 m above groundwater to reduce contamination, and the top of the pit should be located 1 m from potential rooting zones of plants. The type of bottom layer used at the burial site is important to consider, to reduce runoff and leakage. For example, a clay layer will prevent contamination to groundwaters. Monitoring is also recommended to reduce the risk of potential environmental damage (Ball et al., 2012). This method is a good option for the handling of drill cuttings, not regarding the negative consequences related to this method.

When considering the best method for disposal of drill cuttings several factors need to be considered. The disadvantages of these three methods indicate that the handling of drill cuttings that are already released to the marine environment is difficult. All the methods described above have environmental concerns, health and safety issues and socio-economic concerns (EWMA, 2015). Which of the methods that should be used for the handling of drill cuttings in the future, will be up to the authorities and ultimately the people to decide. If discharged at sea, it will harm the marine environment. If transported somewhere else, this will cost and it may be harmful for the environment where it is disposed. Other factors that need to be evaluated are safety factors, CO_2 emissions and accidental spills during transportation, regulations in the area and the local environment.

Although most drill cuttings are disposed in one of the ways described above, some drill cuttings can be reused after treatment. Before reusing drill cuttings, it is important to check the quality so that the cuttings are feasible for the intended use. Hydrocarbon content, clay content, moisture content and salinity must be checked before use (Ball et al., 2012). Reused drill cuttings can be used to several applications after treatment. They can be used as fill material in landfills, concrete, bricks, asphalt and cement, as well as to stabilize surfaces that are subject to erosion, as for example in road spreading. Restoration of wetland is another application of reused drill cuttings, where cuttings are used as a substrate for restoring wetlands because well treated cuttings support growth of wetland vegetation (Ball et al., 2012). In the UK, cuttings have been used as fuel for power plants. In this case, the power plant should be in proximity to the drilling platform or in proximity to where cuttings are disposed on land to reduce costs and accidental spills during transportation.

6 Conclusion

This master thesis provides an insight into drill cutting release in the Ingøydjupet trough and its impacts on benthic foraminifera at different distances from a well drilled in 1987. The method used for this study was analyses of benthic foraminifera, analyses of heavy metal concentrations, total organic carbon (TOC) and grain size distribution in the area.

Ba is nontoxic to organisms, but is a good marker for drill cuttings because it is related to Barite which is a component in water based drilling mud. The strong correlation between Ba and Pb, Hg and Cu indicates that these heavy metals are also related to drill cuttings. The elevated concentrations of Ba and the heavy metals Pb, Hg and Cu in core T 10-4, and the low number of foraminiferal specimens in this core, indicates that core T 10-4 consist purely of drill cuttings. Increasing concentrations up core of Ba and the heavy metals Pb, Hg and Cu are found in core T 30-7 at 9.5 cm core depth, in core T 60-11 at 6.5 cm core depth, and in core T 125-9 at 2.5 cm core depth. These increased concentrations represent layers of drill cutting deposits, and indicate that the drill cuttings has been transported with ocean currents further away from the well. They are representing a thinning wedge of deposits at increased distances from the well. Core T 10-4 shows decreased concentrations of Pb, Hg and Cu in the top 4.5 cm of the core, and increased concentrations of various heavy metals that normally occur naturally in the sediments, which is indicating some natural sedimentation the last 30 years. However, concentrations of the heavy metals are still higher than in the bottom of the other cores, indicating that the core is moving towards a stage of recovery, but has not recovered yet.

The distribution of benthic foraminifera is characterized by lower densities of benthic foraminifera in proximity to the well and increased densities at further distance from the well. The lack of oxygen below 2.5 cm core depth in core T 10-4 implies that the stained foraminifera below this core depth must be related to overstaining of dead foraminifera. The overstaining is related to either 1) slowly decomposing of dead protoplasm, 2) staining of organic compounds of the test, or 3) staining of bacteria living on or within the test. Both the dead and the live foraminiferal assemblage in core T 10-4 have too few specimens present to do statistically certain interpretations. The foraminifera assemblages for cores T 30-7, T 60-11, T 125-9 and T 250-2 are dominated by *E. nipponica, C. laevigata, C. lobatulus* and *M. barleeanus,* which correspond to assemblages that are normally found in the pre-impacted Ingøydjupet. The living foraminiferal assemblages are dominated by *E. nipponica, P. bulloides, C. lobatulus, C.*

laevigata and *M. barleeanus*, which also correspond to the living assemblages *in* the pre-impacted Ingøydjupet. However, both the live and dead foraminiferal assemblage is characterized by lower diversity, which may indicate that the fauna is affected by smothering of drill cuttings. Also, the high abundance of *E. nipponica*, where species diversity is low might indicate that this species has an opportunistic behaviour.

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Appendix 1

Species list:

Cassidulina laevigata

Cassidulina neoteretis

Cassidulina reniforme

Cibicides lobatulus

Cibicinoides species

Elphidium albiumbilicatum

Elphidium excavatum

Elphidium incertum

Epistominella nipponica

Fissurina marginata

Melonis barleeanus

Nonionellina labradorica

Polymorphinidae species

Pullenia bulloides

Pullenia osloensis

Quinqloculina seminulum

Sphaeroidina bulloides

Spirillina vivipara

Stainforthia species

Trifarina angulosa

Unidentified species

Appendix 2

Table 5: Table showing the analysed benthic foraminiferal samples for each core.

Depth/Core	T 10-4	T 30-7	T 60-11	T 125-9	T 250-2
0-1 cm	x	x	x	x	x
1-2 cm	x	x	x	x	x
2-3 cm	x	x	x	x	x
3-4 cm	x	x	x	x	x
4-5 cm	x	x	x	x	x
5-6 cm	x	x	x	x	x
6-7 cm	x	x	x	x	x
7-8 cm	x	x	x	x	x
8-9 cm	x	x	x	x	
9-10 cm	x	x	x		
10-11 cm	x	x	x		
11-12 cm	x	x	x	x	x
12-13 cm	x	x	x		
13-14 cm	x	x	x		
14-15 cm	x		x		
15-16 cm	x			x	x
16-17 cm	x	x			
17-18 cm	x				
18-19 cm	x				
19-20 cm	x	x	x	x	x

Appenix 3

Table 6: Table showing the counted squares/total squares for the analyzed foraminifera samples.

Depth/Core	T 10-4	T 30-7	T 60-11	T 125-9	T 250-2
0-1 cm	45/45	6/180	12/90	26/45	34/180
1-2 cm	45/45	7/180	5/180	14/45	17/45
2-3 cm	45/45	5/180	4/90	15/90	16/90
3-4 cm	45/45	8/360	7/180	28/45	15/90
4-5 cm	45/45	7/45	6/180	15/180	6/90
5-6 cm	45/45	7/45	12/180	9/90	10/90
6-7 cm	45/45	13/180	12/180	9/90	7/90
7-8 cm	45/45	8/45	12/180	5/90	10/90
8-9 cm	45/45	11/180	10/180	9/90	
9-10 cm	45/45	12/180	15/180		
10-11 cm	45/45	14/180	8/180		

11-12 cm	45/45	9/180	16/180	19/90	16/45
12-13 cm	45/45	10/180	12/180		
13-14 cm	45/45	15/180	12/180		
14-15 cm	45/45		21/180		
15-16 cm	45/45			13/90	12/90
16-17 cm	45/45	21/180			
17-18 cm	45/45				
18-19 cm	45/45				
19-20 cm	45/45	21/180	10/90	24/90	8/90

Appendix 4

Table 7: Water content in percentage (%) for each sample.

Depth/Core	T 10-4	T 30-7	T 60-11	T 125-9	T 250-2
0-1 cm	69,00	38,16	39,87	38,86	40,54
1-2 cm	69,00	38,16	39,87	38,86	40,54
2-3 cm	69,00	38,16	39,87	38,86	40,54
3-4 cm	69,00	38,16	39,87	38,86	40,54
4-5 cm	69,00	38,16	39,87	38,86	40,54
5-6 cm	69,69	44,63	43,86	43,87	44,27
6-7 cm	70,12	43,97	42,27	42,46	43,98
7-8 cm	69,93	42,86	42,14	42,18	44,04
8-9 cm	70,90	41,87	42,55	39,74	43,65
9-10 cm	70,70	40,33	41,13	38,64	41,15
10-11 cm	71,00	38,69	41,15	38,24	39,79
11-12 cm	71,16	37,40	39,49	37,79	38,94
12-13 cm	69,75	36,30	39,16	37,84	39,05
13-14 cm	66,82	35,55	38,89	38,96	39,15
14-15 cm	68,32	32,21	38,38	37,74	39,23
15-16 cm	69,16	35,03	39,01	37,38	39,19
16-17 cm	68,54	34,96	38,21	37,22	39,18
17-18 cm	66,40	34,95	37,73	36,68	38,81
18-19 cm	64,54	35,38	37,40	37,14	38,73
19-20 cm	67,94	35,32	37,69	37,09	38,87

Appendix 5

Table 8: Heavy metal concentrations expressed in mg/kg.

Core Depth	ELEMENT	As (Arsen)	Cd (Kadmium)	Co (Kobolt)	Cr (Krom)	Cu (Kopper)	Hg (Kvikksølv)	Ni (Nikkel)	Pb (Bly)	V (Vanadium)	Zn (Sink)	Ba (Barium)	Ti (Titan)
cm	SAMPLE	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS
0,5	T-10-4	11,4	0,119	7,9	30	34,5	0,532	18,4	107	48,1	63,9	21500	365
1,5	T-10-4	12,5	0,105	7,82	27,8	38,2	0,66	16,7	130	43,2	62,8	20300	289
2,5	T-10-4	12,2	0,233	4,74	21,2	47,7	1,04	11	148	30	64,1	18600	177
3,5	T-10-4	9,82	0,421	3,06	17,2	64,8	1,07	7,77	185	22,7	76,3	18000	120
4,5	T-10-4	8,58	0,458	2,14	12	68,6	1,32	5,28	178	11,6	94,6	18000	61,9
5,5	T-10-4	9,32	0,367	2,47	12,8	64,7	1,1	6,05	185	13,3	80,5	17100	64,4
6,5	T-10-4	10	0,398	2,35	11,6	71,7	1,07	5,57	192	10,8	83,4	16800	55,5
7,5	T-10-4	10,7	0,403	2,61	11,8	67	1,21	5,6	185	9,43	93,7	15700	48,1
8,5	T-10-4	10,7	0,371	2,45	10,7	63,4	1,88	5,55	184	9,17	83,8	17300	51,2
9,5	T-10-4	10,7	0,388	2,5	10,9	70,1	1,31	5,42	178	9,23	83,9	16200	46,1
10,5	T-10-4	10,4	0,349	2,59	12,3	63,3	1,41	6,13	185	11,2	77,8	17700	52,4
11,5	T-10-4	11,1	0,342	2,51	12	64,6	1,78	5,81	188	10,5	83,3	18800	51,6
12,5	T-10-4	11,1	0,358	2,56	11,7	67	1,4	5,4	183	9,63	81,1	18000	50,6
13,5	T-10-4	11,3	0,362	2,7	11,5	67,7	1,6	5,44	188	9,33	81,3	17000	51,8
14,5	T-10-4	11,4	0,35	2,54	11,7	67,9	1,44	5,4	190	9,3	78	16800	46,9
15,5	T-10-4	12	0,363	2,56	11,7	71,6	1,53	5,46	191	9,85	82,1	19500	50,2
16,5	T-10-4	11,3	0,52	2,72	12,4	71,4	1,64	5,9	183	10,5	86,3	20500	47,4
17,5	T-10-4	11,5	0,411	2,48	11	70	1,59	5,31	190	8,65	84,7	16900	43,2
18,5	T-10-4	11,8	0,343	2,62	11,2	75,9	1,46	5,55	182	8,9	85,9	16000	46,7
19,5	T-10-4	11,7	0,361	2,62	12,4	68,1	1,5	5,64	188	10	84	17500	49,6
0,5	T-30-10	7,34	0,0813	13,9	45,6	17,8	0,0831	35,3	25,3	75,5	80,5	9580	946
1,5	T-30-10	6,95	0,0735	14,8	47,1	18,9	0,0869	38,5	27,6	76,2	82,3	10900	998
2,5	T-30-10	7,07	0,0753	14,3	47,3	17,6	0,0666	37,6	29,2	68,2	78,1	9280	936
3,5	T-30-10	8,04	0,0474	14,8	43,8	15,4	0,0549	32	23,4	68,1	72	6380	940
4,5	T-30-10	6,69	0,0553	11,7	44,7	16	0,0562	31,3	23	68,6	73,3	6110	883

5,5	T-30-10	3,5	0,0433	10,4	42,1	13,9	0,0423	31,3	18,4	63,5	70,7	3510	926
6,5	T-30-10	3,21	0,111	10,9	45,8	15,4	0,0547	32,8	21,2	70,1	75,6	2600	989
7,5	T-30-10	2,67	0,137	11,3	47,1	16,6	0,033	34,3	15,9	73,4	78,8	3100	1070
8,5	T-30-10	2,48	0,112	10,8	43,5	14,3	0,0324	31,6	15,2	70	72	3240	977
9,5	T-30-10	2,63	0,269	10,9	44	14,3	0,0271	31,9	12,2	75,4	72,6	281	1040
10,5	T-30-10	2,17	0,244	11,6	45,1	13,3	0,0163	32,1	10,2	80	87,1	199	899
11,5	T-30-10	2,26	0,219	11,5	44,5	13,7	0,0175	33,1	9,93	81,9	88,8	206	945
12,5	T-30-10	1,66	0,063	8,94	35,7	9,93	0,0104	25,8	6,92	61,4	49,9	106	751
13,5	T-30-10	2,17	0,13	11,7	44,8	14,7	0,0164	32,5	9,09	80,3	89,7	132	934
14,5	T-30-10	2,38	0,0881	12	45,6	13,6	0,0165	34,1	9,98	84,1	87,6	134	952
15,5	T-30-10	2,36	0,101	11,3	42,4	13,4	0,0167	32,1	9,69	78,6	83,4	162	896
16,5	T-30-10	2,18	0,067	11,8	41,9	12,3	0,0164	32,8	8,75	73,3	84,9	120	811
17,5	T-30-10	2,32	0,191	11,6	41,1	13,7	0,0186	32,2	9,36	73,5	84,8	208	781
18,5	T-30-10	2,36	0,189	11,8	43,1	13,5	0,0156	32,6	9,08	78,6	86,9	124	895
19,5	T-30-10	2,44	0,19	11,7	44,5	13,5	0,0189	32,8	9,66	81,8	86,7	110	941

0,5	T-60-12	7,22	0,102	14,6	41,8	15,5	0,0383	34,6	20,9	82	89,5	2060	899
1,5	T-60-12	8,04	0,0817	16,3	45,3	16	0,0366	38,1	22,8	86,7	94,4	2250	954
2,5	T-60-12	9,84	0,0726	16,6	45	16,5	0,0379	38	23,9	85,8	101	1710	937
3,5	T-60-12	9,66	0,0673	17,5	44,1	15,6	0,0358	38,7	24,2	83,4	95,3	1800	964
4,5	T-60-12	5,55	0,0487	12,4	43,6	15,6	0,0316	33,9	22,7	82,5	96	1290	917
5,5	T-60-12	3,08	0,0802	11,7	42,9	15,5	0,0324	33,4	22,3	86,3	103	1100	913
6,5	T-60-12	3,02	0,0941	11	41,2	13,9	0,0286	30,8	19,6	76,9	84,5	592	893
7,5	T-60-12	2,75	0,155	12,2	46,4	15,9	0,0249	33,5	16,6	91,5	102	209	1050
8,5	T-60-12	2,79	0,114	11,3	42,2	13,7	0,0279	32	16,6	78,9	89,7	280	905
9,5	T-60-12	2,85	0,0891	10,9	42,1	13,8	0,0219	31,8	14,9	76,7	86,2	480	912
10,5	T-60-12	2,71	0,067	11,1	40,4	12,9	0,021	30,8	12,6	76,9	82,4	263	893
11,5	T-60-12	2,48	0,113	10,9	39,9	13,4	0,0224	31,2	12,5	78,7	80,7	426	855
12,5	T-60-12	2,39	0,214	12,5	43,3	14,9	0,0156	33,3	10,7	85	91,4	198	893
13,5	T-60-12	2,65	0,337	11,2	42,3	13,7	0,0203	32,6	11,6	84	81,3	165	875
14,5	T-60-12	2,18	0,17	10,1	37,1	12,1	0,0147	27,4	8,67	73	74,3	116	786
15,5	T-60-12	2,32	0,142	10	37,5	12,2	0,0146	28,1	9,09	72,9	72,1	117	792
16,5	T-60-12	2,69	0,242	12,3	44	15,5	0,0178	35,1	10,2	78,8	85,9	110	938

17,5	T-60-12	2,97	0,196	12,4	45,4	14,9	0,018	35,2	10,6	83,2	75,7	108	972
18,5	T-60-12	2,91	0,188	12,5	45,1	14,8	0,0198	34,8	10,7	80,4	82,9	108	927
19,5	T-60-12	2,35	0,212	10,7	37,1	12,4	0,0158	29,5	9,63	65	74,3	107	753
0,5	T-125-6	6,32	0,0671	11,5	37,1	13,5	0,0274	31,7	17,5	66,6	71,8	697	756
1,5	T-125-6	6,34	0,074	13,1	41,6	14,2	0,0322	33,5	19,7	73,1	81,4	922	873
2,5	T-125-6	5,39	0,0558	12,6	42,9	14,4	0,0325	33,5	20,1	71,4	85,6	859	906
3,5	T-125-6	4,45	0,0526	13,1	41,2	14,3	0,0287	32,1	20	63,7	84,3	477	868
4,5	T-125-6	6,17	0,0519	12,9	41,4	13,8	0,028	32,2	20,1	73,9	83,1	369	887
5,5	T-125-6	3,82	0,0511	11,4	40,7	14	0,0254	32,1	19,9	73,3	85	210	891
6,5	T-125-6	3,49	0,0683	11,3	39,2	13,3	0,0241	30,3	16,1	70,8	83,6	207	847
7,5	T-125-6	9,55	0,0569	12,9	43,9	13,3	0,0222	34,2	13,6	77,9	83,7	123	884
8,5	T-125-6	4,82	0,0322	12	41,6	12,4	0,0186	31,4	11,4	68,6	81,8	131	886
9,5	T-125-6	3,31	0,0544	11,1	41,2	12,5	0,024	30,6	12,1	68,7	74,7	138	867
10,5	T-125-6	2,96	0,0281	11,3	43,5	13,1	0,0169	32,9	10,5	77	82,2	117	905
11,5	T-125-6	2,72	0,0406	11,6	46,5	15,7	0,019	33,3	10,4	85,8	88,7	121	974
12,5	T-125-6	2,39	0,245	11,5	44,8	15,7	0,0192	34,4	11,1	96,6	84,1	123	933
13,5	T-125-6	2,35	0,233	11,4	44,7	14,5	0,0173	33	10,1	84,7	81	114	905
14,5	T-125-6	2,32	0,282	11,6	43,6	14,4	0,0164	34,3	10,4	79,3	84,8	118	906
15,5	T-125-6	2,17	0,328	11,4	44,3	14,1	0,0176	34,2	11,1	78	88,4	114	915
16,5	T-125-6	2,31	0,292	10,7	42,8	13,4	0,0193	30,5	11,3	76,8	78,6	120	861
17,5	T-125-6	2,38	0,254	11,7	49,6	15,3	0,0179	33,9	10,5	93,8	87,3	125	892
18,5	T-125-6	2,42	0,318	12,3	46,7	16,2	0,0151	36	10,8	88,7	90,5	128	967
19,5	T-125-6	2,41	0,369	11,8	44,4	15	0,0184	33,8	11,2	81,5	84,5	126	944
0,5	T-250-1	7,21	0,135	13,6	42,9	16,6	0,0302	35,6	21,2	61,4	66,1	561	922
1,5	T-250-1	6,7	0,137	14,9	44,6	16	0,253	36,7	22,6	63,9	68,2	300	974
2,5	T-250-1	6,91	0,101	15,7	46,5	17,4	0,0529	38,6	22,3	64	70,2	217	971
3,5	T-250-1	7,62	0,0763	16,3	47,4	16,9	0,0394	37,8	22,7	66,7	73,8	211	991
4,5	T-250-1	8,12	0,0607	14,6	43,6	15,1	0,0334	36,3	22,6	64,9	66,3	204	919
5,5	T-250-1	6,85	0,0596	13,7	44,3	15,3	0,0341	34,1	21,1	62	67	192	928
6,5	T-250-1	4,43	0,0616	11,6	43,3	14,7	0,0278	33,4	19,8	60,6	68	198	940
7,5	T-250-1	2,74	0,112	11,2	43,4	15,3	0,0312	32,7	18,2	63,9	63,3	147	966

8,5	T-250-1	2,59	0,119	12,3	47	15,5	0,0266	36,2	17,6	64,8	69,3	120	1040
9,5	T-250-1	2,69	0,0913	12,6	45	14,8	0,0268	37,3	14,5	65,7	67,7	119	1020
10,5	T-250-1	2,53	0,11	11,9	46,3	15,6	0,0236	35,6	13	67,1	66,2	106	1020
11,5	T-250-1	2,46	0,205	12,5	45	14,9	0,0196	35,3	12	68,9	66,2	154	997
12,5	T-250-1	2,61	0,17	12,7	47,7	15,6	0,0244	37	12,4	71,1	68,8	116	1030
13,5	T-250-1	2,62	0,23	12,2	45,8	14,8	0,02	35	12,5	66,6	64,1	110	992
14,5	T-250-1	2,56	0,261	12,5	46,3	14,7	0,0251	35,2	11,7	66	66	106	945
15,5	T-250-1	2,62	0,23	12,9	47,4	14,8	0,0194	37,1	11,5	68,8	68,5	102	1020
16,5	T-250-1	2,68	0,215	13,7	49	14,7	0,0149	38	11,7	67,7	66	102	1090
17,5	T-250-1	2,74	0,163	12,6	47,4	14,7	0,0198	34,9	11	68,7	66,7	107	1060
18,5	T-250-1	2,83	0,126	13,5	48,5	15,1	0,0212	38,3	10,6	68,8	68,6	99,9	1040
19,5	T-250-1	2,59	0,168	12,6	43,6	13,5	0,021	34,8	11,2	64,4	66,3	92,7	931

background	Good	Moderate	Bad	Very bad

Appendix 6

Table 9: TOC concentrations expressed in percentage (%).

Core depth	T 10-4	T 30-10	T 60-12	T 125-6	T 250-1
0,5	0,5632	0,8434	0,8942	0,7696	0,9207
1,5	0,5546	0,764	0,8673	0,7591	0,9096
2,5	0,3881	0,8345	0,7992	0,758	0,9079
3,5	0,3131	0,6689	0,7873	0,7348	0,8711
4,5	0,222	0,695	0,7857	0,7389	0,8004
5,5	0,2177	0,6142	0,7692	0,7138	0,7597
6,5	0,2083	0,659	0,693	0,6464	0,6845
7,5	0,1996	0,6393	0,689	0,6023	0,6835
8,5	0,2128	0,6422	0,6728	0,6058	0,6886
9,5	0,1999	0,5883	0,6455	0,602	0,6629
10,5	0,2119	0,5186	0,6265	0,5796	0,6747
11,5	0,2143	0,5167	0,6479	0,5953	0,6254
12,5	0,2045	0,4863	0,6231	0,594	0,6573
13,5	0,2045	0,5093	0,5975	0,5955	0,6759
14,5	0,2105	0,5395	0,6325	0,5898	0,6427
15,5	0,1985	0,5465	0,6211	0,5862	0,6116
16,5	0,2092	0,5054	0,6246	0,5751	0,628
17,5	0,2018	0,5046	0,609	0,5981	0,6409
18,5	0,2012	0,5067	0,5797	0,6251	0,6328
19,5	0,2062	0,4812	0,5834	0,6195	0,6141

Appendix 7

Table 10: Grain size distribution of the grain size fraction 0-2 µm, 2-63 µm and 63-2000 µm expressed in percentage (%).

		0-2 µm	2-63 µm	63-2000 µm
Core depth	Core	Clay	Silt	Sand
0,5	T 10-4	23,10834	66,08844	10,80322926
1,5	T 10-4	21,59052	66,9815	11,42809832
2,5	T 10-4	24,23235	65,81631	9,9513276
3,5	T 10-4	26,42459	64,19098	9,384407925
4,5	T 10-4	24,07302	47,54289	28,38409123
5,5	T 10-4	27,30666	58,92178	13,7715694
6,5	T 10-4	27,91907	57,80917	14,27178572
7,5	T 10-4	29,9024	62,79001	7,307681935
8,5	T 10-4	32,66194	61,06638	7,534468183
9,5	T 10-4	29,10293	61,69951	10,41951301
10,5	T 10-4	25,18791	63,4224	11,51994288
11,5	T 10-4	28,80071	61,64565	9,557601062
12,5	T 10-4	29,37675	62,84415	7,779088589
13,5	T 10-4	29,70882	62,23659	8,054555995
14,5	T 10-4	27,34212	62,75809	9,899773698
15,5	T 10-4	28,34297	61,23926	10,42367493
16,5	T 10-4	27,47823	63,21773	9,309326812
17,5	T 10-4	20,43937	66,20689	14,62025033
18,5	T 10-4	29,65998	63,65755	6,682451017
19,5	T 10-4	29,93973	63,6195	6,440754338
0,5	T 30-7	10,92322	76,17528	14,3650805
1,5	T 30-7	16,2127	76,59501	7,19230016
2,5	T 30-7	12,21727	77,46372	10,31900255
3,5	T 30-7	11,05418	79,53532	9,410507287
4,5	T 30-7	13,3896	79,09758	7,512815355
5,5	T 30-7	11,64974	79,39151	8,958763241
6,5	T 30-7	12,64774	80,42629	6,925970627
7,5	T 30-7	12,19856	80,9431	6,85833784
8,5	T 30-7	12,69016	79,77141	7,950543388
9,5	T 30-7	14,64895	78,9203	6,430756564
10,5	T 30-7	10,75806	79,23842	10,00353183
11,5	T 30-7	13,16009	78,55587	8,284033954
12,5	T 30-7	13,23011	78,12202	8,64785616
13,5	T 30-7	14,7694	76,51847	8,712132734
14,5	T 30-7	13,18034	77,66205	9,157606312

15,5	T 30-7	12,72299	79,94118	7,335824724
16,5	T 30-7	11,98633	78,21386	9,799883445
17,5	T 30-7	15,0876	77,02377	7,888618107
18,5	T 30-7	10,17763	80,09214	9,730228216
19,5	T 30-7	8,549975	82,33749	9,112568284
0,5	T 60-11	12,61813	77,9362	9,445645609
1,5	T 60-11	12,77727	79,04826	8,174486
2,5	T 60-11	18,33901	77,25244	4,408573586
3,5	T 60-11	10,2273	82,71581	7,05663972
4,5	T 60-11	12,88847	79,84879	7,262735894
5,5	T 60-11	13,40051	79,70883	6,890715691
6,5	T 60-11	15,3489	78,49304	6,158072725
7,5	T 60-11			
8,5	T 60-11	13,77623	79,38173	6,84203351
9,5	T 60-11	13,08432	79,01831	7,897424462
10,5	T 60-11	15,30001	77,86997	6,83002298
11,5	T 60-11	12,02074	80,98632	6,992950531
12,5	T 60-11	13,0174	79,35974	7,622886344
13,5	T 60-11	13,75618	79,34021	6,903604209
14,5	T 60-11	14,39456	79,37889	6,226556
15,5	T 60-11	12,84775	80,80817	6,344111434
16,5	T 60-11	13,77258	79,58604	6,641381295
17,5	T 60-11	12,12611	80,85492	7,018995852
18,5	T 60-11	13,86194	78,8878	7,250229774
19,5	T 60-11	13,15207	79,74629	7,101624262
0,5	T 125-9	13,19252	80,13092	6,676575337
1,5	T 125-9	11,68841	80,76347	7,548139578
2,5	T 125-9	11,70288	80,78252	7,51462611
3,5	T 125-9	13,40795	79,29333	7,298709022
4,5	T 125-9	10,71235	81,60229	8,232193521
5,5	T 125-9	12,11059	80,6324	7,257006143
6,5	T 125-9	12,3236	80,20635	7,470071975
7,5	T 125-9	12,36687	80,7931	6,840042938
8,5	T 125-9	13,08419	80,73182	6,183972034
9,5	T 125-9	8,894137	82,75722	9,096959767
10,5	T 125-9	13,68751	80,31292	5,999579136
11,5	T 125-9	12,08106	82,54183	5,377104789
12,5	T 125-9	11,20324	80,93292	7,864134101
13,5	T 125-9	13,4583	80,10743	6,434263765
14,5	T 125-9	12,02253	80,91452	7,062958543
15,5	T 125-9	13,91451	79,91208	6,173477184
16,5	T 125-9	12,779	80,78604	6,434981479
17,5	T 125-9	14,81035	78,76214	6,427506689

18,5	T 125-9	12,98994	78,6177	8,39235715
19,5	T 125-9	8,242102	77,5277	14,98455532
0,5	T 250-2	15,00344	78,59021	6,406359717
1,5	T 250-2	14,91471	78,25515	6,83031891
2,5	T 250-2	17,91801	77,35486	4,727213235
3,5	T 250-2	11,86957	81,1018	7,425079258
4,5	T 250-2	12,8996	79,78851	7,311913917
5,5	T 250-2	15,16193	79,2067	5,631365988
6,5	T 250-2	10,46141	82,08243	7,456153432
7,5	T 250-2	13,20545	79,35958	7,435073147
8,5	T 250-2	13,45345	79,18243	7,364286825
9,5	T 250-2	12,23913	80,71361	7,047264435
10,5	T 250-2	13,35025	80,16042	6,489338221
11,5	T 250-2	13,29328	80,00412	6,702605855
12,5	T 250-2	13,48705	79,29865	7,214425719
13,5	T 250-2	15,42303	78,46564	6,111380743
14,5	T 250-2	13,86738	79,8205	6,312154827
15,5	T 250-2	12,99183	81,25813	5,750095369
16,5	T 250-2	12,85868	77,99735	9,306959816
17,5	T 250-2	13,37608	79,65629	6,967656161
18,5	T 250-2	16,41882	77,48365	6,097647286
19,5	T 250-2	11,72855	80,39885	7,872589138