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Barents Sea Drill cuttings research initiative (BARCUT)-project

End report

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Preface

In the early 2000s, much political and management attention was given to the question of waste management in the Barents Sea and/or northern Norway. At this time, both the industry and environmental regulatory authorities were exploring different options for disposal of drill cuttings – discharge at sea (at seabed or surface) or collect and transport to land by ship.

The memorable hypothesis arose "drill cuttings lie best where they grew up" – quote Liv Nielsen, Eni Norge, approximately 2009/10. Although tinged with typical northern Norwegian satirical humour, the issue in fact was absolutely serious. Because harmful chemicals were no longer in use, most of the material that comprises drill cuttings is derived from the rock formations, the need arose to assess what environmental effects do, in fact, arise from the deposition of waste sediment material on the sea floor. Thus, the ideas for the present project emerged.

Around this time, Eni Norge initiated and financed a large-scale competence cluster – "Environmental Waste Management (EWMA) – managed within the University of Tromsø. This cluster has produced ca. 100 publications, 5 PhD graduates and 11 postdocs between 2010 and 2018. To address specifically the question of drill cuttings, Eni Norge financed a separate programme, within the EWMA concept, and fronted by John Eirik Paulsen, Eni Norge. The Barents Sea Drill Cuttings research initiative (BARCUT) began with a desk study in 2013 (Akvaplan-niva AS Rapport: 5390 – 01), conducted field campaigns in the Goliat-area in 2014 and 2015 and now concludes in 2019.

BARCUT has produced 12 scientific publications, 25 conference/workshop presentations/reports and provided influential information to both the industry and the regulatory authorities. In addition, the project included one postdoc financed by Troms County and educated one PhD, 3 MSc students and one BSc student.

We thank Eni Norge, specifically John Eirik Paulsen for constructive collaboration and guidance during the lifetime of the project and we look forward to continued cooperation with Vår Energi in the future.

Tromsø, 20th December, 2019

1 Overall summary

BARCUT aimed to identify the local long-term environmental impact of drill cuttings released to the marine environment and to address relevant societal concerns. Eight wells drilled between 1987 and 2015 were studied. High quality seafloor sediment samples were collected with a ROV, along transects away from the studied wells at a distance of 5-15m, 30m, 60m, 125m and 250m. This transect was sampled (southeast direction) in line with the reigning average bottom current direction (east to southeast). The sediment samples were studied in a multidisciplinary way. Additionally visual studies were done around the wells.

Based on Ba concentration of seafloor sediments, the spreading of drill cuttings was observed 250 m from the wellheads, varying in thickness from >20 cm (closest to well) to 1 cm (furthest away from the well). The sediment quality is affected ≤ 30 m from the wellheads, apart from well GF where it was affected 60 m from wellhead. The most polluted site in terms of heavy metal concentrations was well T (drilled in 1987), where high Ba concentrations at coincide with the high concentrations of Cd, Cu, Hg, and Pb. Additionally Cu concentrations reach bad levels (level IV) in wells GI, GF and S.

The visual assessments detected deposited drill cuttings to extend to around 150–200 m from the drilling location at recently drilled sites and generally less than 50 m at older locations (3 or more years after drill cutting release). Quantitative underwater hyperspectral imagery (UHI) analyses mostly showed a change-over to conditions resembling undisturbed sediments at approximately similar distances as the visual assessments.

The main environmental impact of released drill cuttings on the foraminiferal fauna is smothering, obstructing bioturbation and resulting in low foraminiferal densities. Smothering of fauna is extended ≤ 30m from the well (apart from well GF).The released drill cuttings do overall not result in changes in foraminiferal species composition. However, at the Goliat field we however observed a different foraminiferal fauna within the drill cutting deposits. These species are interpreted to be part of an old fossil fauna, which was released together with the drill cuttings.
The study of bacterial microbiota at well GI, GF and G2006 showed that deposition of water based drilling waste may cause marked disruption of the indigenous seafloor microbiota. Such changes appear restricted to the most heavily affected locations in the vicinity of the wellheads (≤100 m). No significant changes in microbiota was observable at any sampling distance at well G2000. The present study does not give a basis for concluding if this invariance was the result of a 15 years recovery period or the use of less perturbing drilling mud components in the first place.
Benthic macrofauna only found only minimal disturbance, even at recently drilled stations and stations where there was visible deposition of drill cuttings.

Recovery of sediment quality is observed in some wells, however not in Ba concentrations. On the contrary, increasing Ba concentrations towards present are observed in some wells indicating that Ba rich sediments are still being re-transported by the bottom currents. Current measurements confirmed that resuspension of drill cuttings is likely, due to the intermittently strong currents.
Metal concentrations were not recovered to background values at well T drilled in 1987.
Reduced oxygen penetration into the sediment is still evident up to 9 years after the drilling operation.
Foraminiferal fauna results from well T show that the site remains negatively impacted by drill cuttings even 28 years following their release (i.e. no recovery). The seafloor foraminiferal fauna has recovered,

at least partly, respectively 15 and 8 years after the release of drill cuttings. At well S absence of live fauna implies that no recovery of foraminiferal assemblage 3 years after the release of drill cuttings. This is in contrast with well GF where complete foraminiferal faunal recovery was observed almost immediate (within one year) after the drill cutting release.

Benthic macrofauna showed recovery and/or no detectable impacts of drill cuttings at the locations drilled 3 or more years prior to sampling.

Overall, it can be concluded that the faunal impact of the released drill cuttings at all wells is confined to ≤100m from the wellhead, while the visual and sedimentary impact is biggest ≤150m from the wellhead. In addition, it can be generally concluded that there is a difference in sediment quality and environmental impact before and after the legislations in 1993. However, our findings in well E (drilled in 1992) suggest that not all drill cuttings released before stricter regulations set in place in 1993 have resulted in negative environmental impact. The relatively low amounts of drill cuttings released at this site seem to have limit the environmental impact.

Finally, it should be emphasized that the environmental impact and spreading of the drill cuttings are site specific. The extent of the environmental impact and spreading of drill cuttings might therefore be different at locations outside of or even within Ingøydjupet.

The social and economic study looked at various aspects of the management of drilling waste on the Norwegian continental shelf and waste management in mining industry. Regarding drilling waste it concluded that the controversy over operational discharges is unlikely to cease. It also warned for the danger of regulatory capture, in which the regulatory authorities act on behalf of the industry instead of acting on behalf of the public interest. Finally, it proposed a modification of the discharge regime in which the permission to pollute is specified before the license to drill is announced to better safeguard the sea floor integrity. Regarding waste management in mining industry, it concluded that mining operations take place in a multi-level governance structure. In the north, the topic of indigenous rights also raises issues of legal pluralism.

2 Introduction

Background and overall aim

The Barents Sea is as a sensitive environment with large potential for bio-resources. The Norwegian authorities therefore apply a “zero harmful discharge” policy on petroleum activities in the Barents Sea. However, during the onset of exploration of the Barents Sea, the regulations for marine discharge of drill cuttings was less strict, which resulted in the discharge of several types of drill cuttings and drilling fluids, and their associated contaminants, into the Barents Sea.

Drill cuttings can have a negative effect on the marine environment. Handling of drill cuttings in the Barents Sea is therefore still a topic of debate. Two scenarios include: a) marine discharge or b) transport to and disposal on land. Valid considerations for both options are environmental concerns, health and safety issues and socio-economic cost-benefit assessments. Storage of drill cuttings on land can result in leaking of contaminants into the natural environment. Release of drill cuttings at the seafloor includes other environmental issues that remain poorly understood.

BARCUT is a research and monitoring program for petroleum related activity in the Barents Sea. The project is carried out by Akvaplan-niva, Norut Tromsø and UiT The Arctic University of Norway in Tromsø (UiT). Eni Norway AS, fully finances the program.

The project consists of five different work packages (WP) and has a multidisciplinary approach combining the fields of geology, ecology, biology, oceanography, chemistry and social sciences.
The project will provide knowledge on the long-term environmental impacts of previous- and present sub-marine placement of drill cuttings, contributing to minimization of the environmental footprint of upcoming operations in the High North. The project will contribute to knowledge- based decision making on handling of drill cuttings in the Barents Sea.

A ban on the release of oil-based drill cuttings was introduced in 1993 (NPD, 2018; Bakke et al., 2013; OSPAR, 2000). In the Norwegian part of the Barents Sea, 107 wells were drilled between 1980 and 2012, of which 54 were drilled before 1993 (NPD, 2018). Since 2011, the zero environmental harmful discharge policy applies for the whole Norwegian continental shelf (Ministry of Petroleum and Energy, 2011).The studied wells in BARCUT project were chosen to cover both pre/post-1993 and after 2011 regulations.

3 Aims of the project

BARCUT aims to identify the local long-term environmental impact of drill cuttings released to the marine environment and to address relevant societal concerns.

The project will provide knowledge on environmental impacts of past and present sub-marine discharge of drill cuttings, contributing to minimization of the environmental footprint of upcoming operations in the High North. The project will contribute to knowledge- based decision making on handling of drill cuttings in the Barents Sea

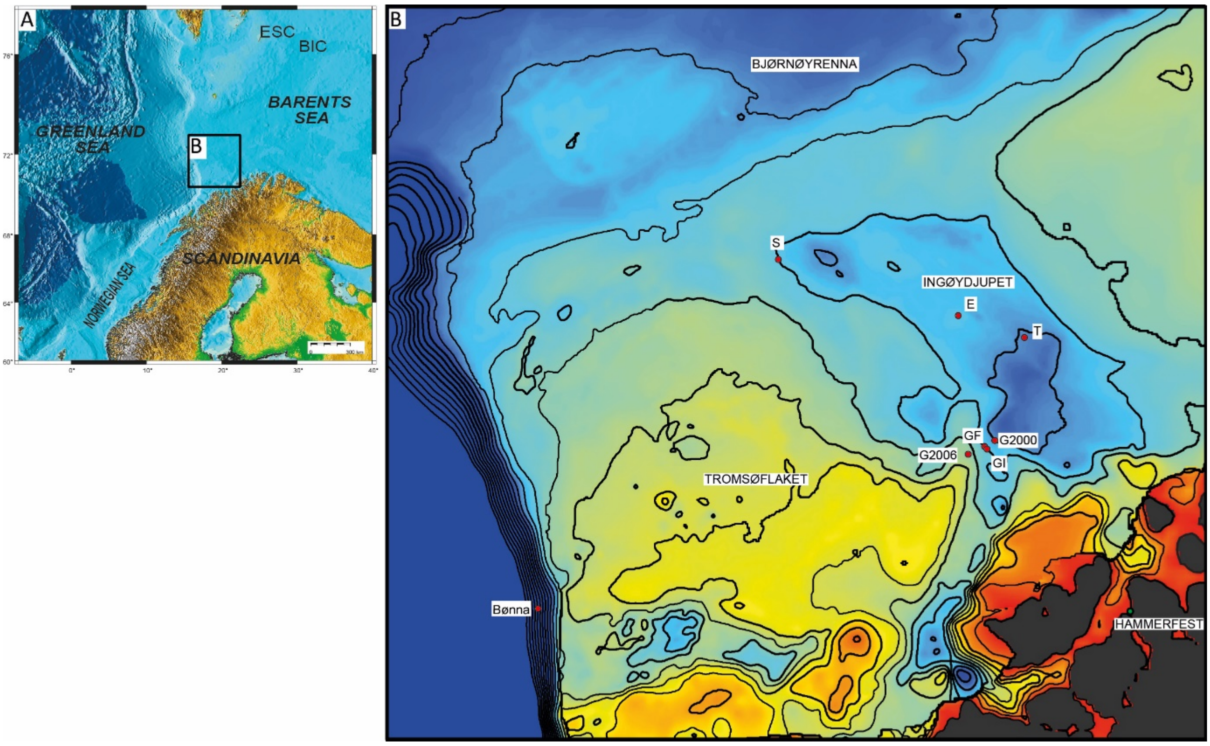
BARCUT aims to improve knowledge concerning the environmental impact from past and current practice for treatment of drill cuttings in the southwestern Barents Sea.

The aim is also to identify knowledge gaps about seabed disturbances and influences, as well as to predict future impacts of emissions versus reinjection or onshore treatment of drilling waste.

BARCUT was officially started in June 2013 by UiT the Arctic University of Norway, Akvaplan niva, Northern Research Institute Tromsø and Eni Norway AS.

Overall sampling concept

Eight wells drilled between 1987 and 2015 were studied (Fig. 1). High quality seafloor sediment samples (push core and grab) were collected with a ROV, along transects away from the studied wells at a distance of 1:5-15m, 2:30m, 3:60m, 4:125m and 5:250m. This transect was sampled in line with the reigning average bottom current direction (See chapter 9 and Appendix 1). The sediment samples were studied in a multidisciplinary way (see description for the relevant WPs). Additionally visual studies were done around the wells to observe sea floor impact of drill cuttings (WP 2).



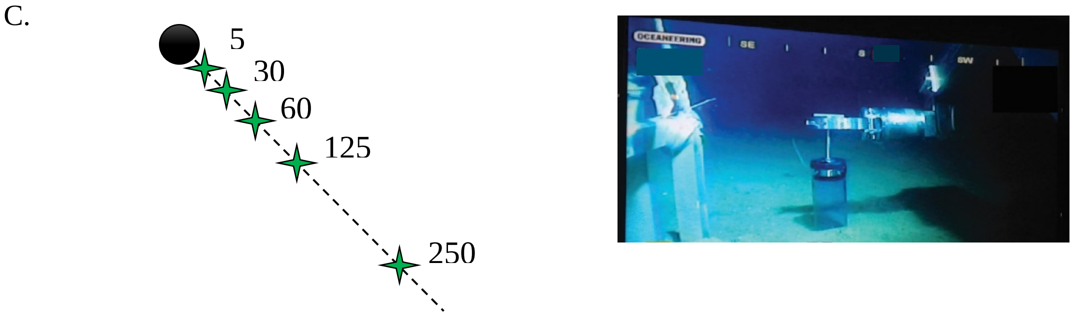


Fig 1. A.) An overview map of Greenland and Barents Seas showing the study area within rectangle. B.) Bathymetric map showing the studied wells (red dots) and C.) transect of sample stations obtain from all of the well stations for baseline studies.

4 WP 1: Management (work package 1)

4.1 Consortium

UiT the Arctic University of Norway, Akvaplan niva, Northern Research Institute Tromsø and Eni Norway AS. The project has a multidisciplinary approach combining the fields of geology, biology, oceanography and social sciences.

4.2 Management and meetings

BARCUT evolved as a spin off project of the already established EWMA (Environmental industrial waste management) consortium and network. The Project leader of EWMA, Stian Røberg, coordinated the process, supported by the EWMA advisory board (listed below), and BARCUT was organised under the same management. The EWMA advisory board had four meetings each year, the BARCUT consortium met twice each semester and when necessary. E.g. preparing for fieldwork or sharing data and writing manuscripts.

BARCUT had three scientific work packages (WP) with a work package leader (WPL).
Each WPL had the responsibility for their WP activity and deliverables and reported to the Project leader.
WP1 Project management and WP5 Application of results and outreach, was managed by the project leader Stian Røberg 2013-2019 and Juho Junttila 2019.
WP2 Applied seafloor research had two sections. Microbiota monitoring, coordinated by Professor Bjarne Landfald, Norwegian College of Fishery Science, UiT the Arctic University of Norway. Macrofoauna coordinated by Sabine Cochrane Akvaplan niva.
WP3 Spreading and deposition of drill cuttings was managed by WPL Juho Junttila, together with Steffen Aagaard Sørensen and Noortje Dijkstra. Department of Geoscience
WP4 Political, economic and societal aspects had two sections. The development of environmental regulations was manages by WPL Peter Arbo together with Maaike Knol, Petter Holm Norwegian College of Fishery Science, UiT the Arctic University of Norway. Cost benefit analysis and waste management in the mining industry was managed by WPL Heidi Rapp Nilsen Northern Research Institute Tromsø.

EWMA Advisory Board all members 2009-2017
Morten Hald UiT Dean Faculty of science and technology
Terje Aspen UiT Director Faculty of biology, fishery and economy
Inger Ann Hansen UiT Subdirector Department for communication
Matthias Forwick UiT Institute leader Department of Geosciences
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Dag Nilsen NOFI R&D manager
Tor Husjord Maritimt forum nord CEO
Salve Dahle Akvaplan niva Director
No show Troms County

5 Initial desk study

The overall goal of BARCUT was to enhance the knowledge on environmental impacts of past and present handling of drill cuttings in the southern Barents Sea. The aim was also to identify major gaps in the knowledge of the status of sea bottom disturbance and impacts as well as to predict future impacts of discharges versus reinjection or onshore handling of drilling waste in the Barents Sea. Phase one-the desk study scrutinised current knowledge on the background of the issues of concern and provided an overview of the following key questions:

- Describe the history of handling of drill cuttings in the SW Barents Sea 1980 - 2010 Review of discharges of cuttings (time, locations, composition)
- Describe drill cuttings discharged in the area based on applications from the operators; particle size, composition and spread. Review of expected/anticipated impacts, derived from discharge permits and targeted/general monitoring
- What components of the Barents Sea benthos are important in determining environmental effects and what is our current knowledge of their status proximal and distal to historic drilling sites?
- What has the monitoring of Barents Sea drilling sites told us so far?
- Assessment of coverage of the monitoring carried out – has the monitoring been targeted to this type of discharges
- Are there previous studies linking effects on the sediment and benthos in other sea areas which may benefit our research purpose
- Identify fieldwork needed for providing in situ data
- Develop research questions and design sampling/analyses for the BARCUT project.

The first of these questions was particularly critical in determining the complete scope of the BARCUT project. It should also be noted that we include the already established baseline survey carried out as part of the Eni-Norge funded ASBD project.

Discharges of drilling waste will gradually become deposited on the seabed. The spreading of the particles will depend on the amount, density, water depth, currents and discharge point (in the drilling devise or on the seabed). On the seabed, the sedimentation of particles will influence the benthic environment physically and chemically, dependent on amount and composition.

The Barents Sea has a varied bottom topography, varying from high current erosion banks and zones, to low energy sedimentation basins where fine-grained particles accumulate. The benthic fauna is adapted to the ambient conditions, meaning that high current sites are inhabited by species intuitively more sensitive to particle sedimentation, compared to soft habitats with animals adapted to particles accumulating from the above water column.

The desk study summarised available knowledge from drilled wells, and monitoring results and was used to outline the extent of the impacts related to drilling in the Barents Sea.

The desk study was carried out by Akvaplan-niva, with input from relevant EWMA partners. The desk study has the following references; Akvaplan-niva AS Rapport: 5390 – 01.

The following information of the studied wells was obtained from the desk study and Norwegian Petroleum Directorate's fact pages (NPD, 2018).

Well T (7122/6-1), Drilling operator: Total Norway AS. Wildcat (exploration) well 7122/6-1 was drilled between 6th of September and 11th of November 1987, to 2707 m depth in the Middle - Late Triassic Snadd Formation. The well was permanently abandoned as a gas and condensate discovery. A water-based drilling fluid was used. Chemicals used include bentonite, mica, gypsum polymer, high viscosity pills, and Norchem-G. In total, 2866 m³ (3353 tons) drilling mud was discharged to the sea bottom.

Well E (7122/4-1), Drilling operator: Esso Exploration and Production Norway A/S. The wildcat (exploration) well was drilled between 13th of November 1991 and 13th of January 1992, to 3015 m in the Late Triassic Snadd Formation. The well was permanently abandoned as a dry hole. Water-based drilling fluid was used with gel and KCl/polymer. The total amount of generated drill cuttings was 688 tons.

Well S (7220/10-1), Drilling operator: Eni Norway AS. The wildcat (exploration) well was drilled between 13th of August and 16th of October 2012, to 2405 m depth in the Upper Triassic Snadd Formation. The well was permanently abandoned as a gas discovery. A water-based drilling fluid was used. No information was found on the amount of released cuttings.

Well G2000 (Well 7122/7-1) the drilling operator was Norsk Agip AS (later known as Eni Norway and Vår Energi). Exploration well on the Goliat prospect was drilled between 16th of September 2000 and 5th of October 2000 to 1524 m depth into the Middle-Late Triassic Snadd Sandstone Formation. The purpose of the well was to test the hydrocarbon potential of the sandstones of the Kapp Toscana Group in the Goliat prospect. The reservoir was oil bearing. The well was permanently abandoned as an oil discovery. The well was drilled with water based drilling fluid containing seawater and bentonite high viscosity pills down to 690 m, and with formate brine/XC-polymer/PAC from 690 m to TD. Total amount of generated cuttings from drilling released to sea was 805 tons. G2000 is located ca. 6 km north-northeast of GI and ca. 4 km north-northeast of GF.

Well G2006/2007 (7122/7-5) includes a sidetrack well (7122/ 7-5A) (71.27° N; 22.28° E) situated within the Goliat exploration area. The exploration well was drilled at a water depth of 370 m during late 2006 and early 2007. From 2000 to the present multiple other exploration and development wells were drilled within a radius of ~3 km to the north, east and south of well 7122/7-5. During drilling procedures 412 tons of drill cuttings, consisting of crushed bedrock, in addition to 711 tons of low risk water based drilling mud, including commonly used drill mud weight materials were released to the sea

Well Bønna (7016/2-1) was drilled on the Bønna prospect in the Harstad Basin in the remote south-west part of the Barents Sea. The objective of the well was to prove petroleum in Eocene and Paleocene reservoir rocks belonging to the Sotbakken Group. Between 3 August and 6 August 2012 a 9 7/8" pilot hole 7016/2-U-1 was drilled from the seabed to 1984 m. There was no indication of shallow gas. The year after, on 14 July 2013, Scarabeo 8 returned to the location and spudded wildcat well 7016/2-1. Due to wellbore stability issues, the well was sidetracked on 31 August 2013. The sidetrack was drilled to TD at 4061 m in Late Paleocene sediments in the Sotbakken Group, Torsk Formation. The well was drilled with seawater and hi-vis sweeps down to 1973 m, with Glydril mud from 1973 m to 2376 m, and with FormPro/brine mud from 2376 m to 2396 m in the primary well. The sidetrack well was drilled with Glydril mud from kick-off to final TD. No Sandstone reservoirs No shows were observed. The well was permanently abandoned on 3 November 2013 as a dry well. Data about drill cuttings was not available.

At well GI (well 7122/10-I-2 H) the drilling operator was Eni Norway AS (Vår Energi). Injection well (development) was drilled between 8th of February 2014 and 16th of March 2014 to 2510 m depth. Data about drill cuttings was not available. GI is located ca. 6 km south-southwest of G2000 and ca. 2 km south of GF.

At well GF (wells 7122/7-F-3 H and 7122/7-F-4 H) drilling operator was Eni Norway AS (Vår Energi). Injection wells (development) were drilled between 4th of July 2014 and 16th of January 2015 to 3820m depth (7122/7-F-3) and between 2nd of August and 28th of September 2014 to 3389 m depth (7122/7-F-4). Data about drill cuttings was not available. GF is located ca. 2 km north of GI and ca. 4 km south-southwest of G2000.

6 WP 2: Sediment macrofauna/ microbiota

Coordinated by Akvaplan niva and UiT
Main objective: Impact of discharges on sediment conditions, macro fauna and microbiota
Participants: Sabine Cochrane (Akvaplan niva) and Bjarne Landfald (UiT)

6.1 Benthic macrofauna

6.1.1 Introduction

Benthic macrofauna are the small animals that live on or in the sea floor. In soft sediments, such as in the south-western part of the Barents Sea, these mostly comprise polychaete worms, bivalves, amphipod crustaceans and echinoderms such as brittle stars and sea-cucumbers. For practical purposes, these are defined as being of a size that are retained on a sieve with 1 mm pore size.

The species composition and functional attributes of the faunal communities are strongly influenced by the surrounding environmental conditions, such as sediment granulometry, food availability, bottom water temperature, salinity and current speeds. Changes in conditions through, for example organic enrichment from human or other sources cause predictable changes in the benthic faunal communities and so analyses of the species composition and diversity have long been used as an indicator of environmental disturbance (Pearson and Rosenberg, 1978; Rosenberg et al., 2001). The annual sediment monitoring surveys conducted at and around sites of petroleum activities on the Norwegian shelf still today are based on benthic faunal analyses, together with contaminant levels.

In the early decades of Norwegian petroleum exploitation, impacts from drilling discharges using oil-based mud were in some cases detected up to or even over 1 km from the sources (Bakke et al., 2013; Olsgard and Gray, 1995). However, since the ban on discharges of oil-based drilling muds, the impacts have declined considerably and currently are limited to a few hundred metres, or less (Akvaplan-niva and DNV-GL monitoring data). The Barents Sea has had a more restrictive policy for releases to sea and generally only top-hole cuttings are released to the sea bed. Sediment monitoring survey data generally have not shown any impacts around exploratory or production sites.

The current monitoring strategy at existing or drilled locations is to place a network of sampling stations in a four-armed cross formation, aligned with the main bottom current direction and at increasing distances from the centre. Currently, the innermost stations are placed 250 m from the centre, the background reason being due to the required safety exclusion zone around production or exploratory drilling structures. With the increase in positioning and navigational precision, this strategy is now under question.

Visual assessment of recently drilled locations have shown that the sediments are fully smothered by drill cuttings to around 50 m around the drill hole (sometimes more or less, depending on the current direction and amount of deposition), but usually the deposition is no longer visible by 150 m in the main current direction, and usually much less upstream. Before the BARCUT project was initiated there were no data available on macrofaunal status after drilling, within 250 m from the drill hole. We therefore do not know how deposition of top-hole drill cuttings affects benthic fauna, and whether faunal analyses can serve as a useful indicator of environmental disturbance from drilling events. Neither do we know how reliable visual assessments by the human eye are – or how much visible sediment smothering causes detectable impacts in the benthic environment.

The sediment macrofauna component of the BARCUT project addressed the following questions and hypotheses:

1. How far do the impacts of drill cuttings deposition on macrofaunal community composition extend from the drilling point?
    - Given that routine monitoring has not revealed impacts at 250 m from the centre, we expected to find statistically significant faunal impacts close to the centre and that these will decline with distance.
2. Is there a pattern of faunal disturbance common to areas influenced by drill cuttings?
    - We expected a marked decline in species and/or abundance in areas heavily influenced by drill cuttings. We further expected that the fauna at disturbed sampling stations would follow a similar pattern in faunal community changes.
3. How accurate are visual assessments of drill cuttings deposition and how do assessments of smothering intensity relate to faunal impacts?
    - We expected that a trained biologist's eye would be able to identify the extent and intensity of drill cuttings deposition, using the biological indicators outlined in Cochrane et al. (2019).
    - We further expected to find statistically significant faunal disturbance within the zone of complete sediment smothering, but decreasing impacts in the zones of incomplete or barely detectible deposition.
4. How long do deposited drill cuttings remain visible on the sea floor and how long do faunal impacts remain detectable?
    - Based on numerous previous field surveys, we expected that the area immediately surrounding the drill hole would remain visibly impacted for an indefinite period, but that within three or more years, the visible deposition area would shrink to 50m or less from the centre. We expected the faunal impacts to follow suit.

6.1.2 Materials and Methods

The following is extracted from Cochrane et al. (2019).

Visual assessment using ROV-mounted video

A visual survey was conducted along a four-armed transect aligned with those used in routine sediment monitoring surveys, but starting at the drilling hole and extending out to 250 m from the centre. In some cases, the transect route was shortened in the "upstream" direction, for practical purposes. Line 2 (south-west) was used as the priority transect, where other methods were deployed.

The planned survey routes and sampling stations were plotted in the main survey system, showing both the position of the ROV and the survey routes. Logging of visual observations was done on a computer connected to the navigation data string to achieve a time-stamped event log. For each observation, the following information was recorded: position (centre of ROV), date/time, heading, depth and altitude. Further, the spatial extent of deposition of drill cuttings was recorded according to criteria described in Table 1. Our categories smothered, visible deposition and no visible deposition correspond with the disturbance categories used in Jones et al. (2006) and continued in Gates and Jones (2012); full: total seabed smothering, partial: disturbance visible on the seabed and none: no visible disturbance to seabed.

We have added the additional transition zone for cases where the change from obvious deposition to undisturbed conditions is very gradual. In advance of the study, an inter-calibration exercise was performed between different operators who carry out visual inspections around drilling locations, to minimise individual bias during recording.

Category	Color code and typical appearance	Description
Smothered		Absence of visible organisms and sediment surface looks unnaturally smooth. Little signs of biological activity but some tracks from scavengers may be seen. Soft, easily suspended sediment. Color of sediments depends on drilling regime, but may vary between reddish brown to olive, often with grey cement remains in the inner parts.
Visible Deposition		Sediment still unnaturally smooth, but some partly-covered organisms such as sponges or boulders can be seen (thickness of deposition can be estimated). Sediments generally more consolidated. The visible sedimentation may also be patchily distributed, depending on the drilling regime.
Transition Zone		In practice, the transition zone is the portion along the transect where it is difficult for the human eye to be sure if there is deposition or not. Mostly this lasts for 2-8 meters along the transect, but it can also be absent if the edge of the deposition is very marked. This is the zone where the environmental footprint shrinks with time, and can be considered as the outward extent of impacts.
No Visible Deposition		Sediment obviously representing natural conditions, with signs of a wider variety of organisms, burrows and, in soft sediments, the typical "fluffy" appearance caused by e.g. agglutinated foraminifera at the sediment-water interface. At this point the conditions will be similar regardless of distance from the drill hole.

Table 1. Classification categories used in visual assessment of sediment condition, with a colour code representing each category

After the survey, the sediment characterisations were quality assured by an additional trained person who had not participated in the survey. For practical purposes, we recorded the length of the four deposition categories along the transect to the nearest metre, according to the positions recorded in the event log. Other biological observations, such as visible organisms and general sediment features also were recorded.

Video camera and visual assessments

High Definition (HD) video cameras were installed on the survey ROVs, with a pan-tilt facility to allow appropriate viewing angles. For the Barents Sea surveys, twin green line lasers for measuring objects were additionally mounted at approximately 45° to the seafloor and adjusted to approximately 10 cm between lines. Four to six LED lights were used on the ROV, at various angles, depending on water conditions such as turbidity and amount of fish following the ROV. The visual surveys started by locating the original drilling location using the positions given either directly by the operating companies and/or the publicly available database on Norwegian drilling operations (www.npd.no/fakta). The flying direction along the survey lines/ transects was selected based on tidal conditions in the field at the time of surveying (flying into the current to minimise interference by resuspended sediment). The survey was conducted according to international standard guidance for visual surveys using remote or towed underwater visual platforms (EN 16260), with a flying speed of around 0.5 knots but allowing the possibility to stop for detailed investigation/ stills photography of objects/conditions of particular interest. The chosen optimal flying height always is a compromise between achieving an overview of the sediment surface and allowing detailed observations. To detect drill cuttings, we generally chose the latter strategy with flying height between 0.5 and 1.0 m above the sediment surface, again, depending on visibility conditions at the time of surveying. Biological organisms were identified in the field to the lowest taxonomic level possible (phylum, family or genus, depending on the group in question) and recorded within the event logging system described above.

Underwater hyperspectral imagery

A major challenge in visual assessments is that both drill cuttings and natural sediments can be very similar in colour. Thus, the human eye with its Red-Blue-Green visual perception may not be able to detect low-level depositions. Hyperspectral imagery (HI), on the other hand, uses the full spectral range of light and thus can distinguish colour nuances that the human eye cannot. We used an underwater hyperspectral imager (UHI), deployed and owned by Ecotone AS.

The UHI was mounted onto the ROV in a vertical orientation, imaging the seafloor from a bird's eye perspective (see Fig. 2). External artificial illumination was provided by means of two 250w halogen lamps flanking the UHI at 35 cm to each side. The UHI interfaced with the ROVs fibre optic network for control and data transfer. The UHI captured frames at 20–30 Hz, while the ROV had a speed of approximately 0.5 m s^{-1}. The flying altitude ranged between 1 and 2 m above the sea floor, with the pilot aiming to maintain 1.5 m. The UHI is a push-broom hyperspectral camera that images the scene by one spatial line at a time. Every spatial pixel contains a full representation of the visible part of the electromagnetic spectrum. The camera acquires the lines perpendicular to the flight direction when mounted on a moving platform. Pre-processing of the hyperspectral datasets included radiometric correction and geo-correction. Navigation data were logged by the surveyor using sonar (ROV-position) and ROV-sensors (altitude, depth, altitude). The navigation logs were filtered to remove outliers and noise. Both radiometric and geocorrection was performed in ENVI 5.3.1 using IDL-extensions specifically developed for UHI. Wavelengths from 400 to 700 nm were used, with a spectral resolution of 5 nm.

Benthic macrofauna

Along Line 2, at each of the seven Barents Sea drilling locations, biological sampling with three replicates was taken for macrofaunal analyses. Sampling stations were 30, 60, 125 and 250 m from the drill hole. Procedures for sampling and sample processing followed international guidelines (ISO 16665). A modified van Veen grab was used, with a 0.1 m2 bite size. Samples were sieved through both a 0.5 mm and 1 mm circular mesh screen, and both size fractions fixed and stored separately for further processing on-land. This procedure was to investigate any gradients in the proportion of small-sized individuals between the stations, while also maintaining comparability with standard offshore sediment monitoring surveys which use a 1 mm mesh screen only. After sorting and identification of the fauna collected, the data were analysed using the PrimerE package (version 7.0.12). A Bray Curtis similarity analysis (Bray and Curtis, 1957) was performed, comparing both root transformed and untransformed data. Untransformed data were used in this study because of the lack of particularly dominant taxa. The results were displayed as a standard cluster diagram.

6.1.3 Results and discussion

Visual assessment of drill cuttings deposition

Obviously, drill cuttings were evident at the immediate vicinity of the drilling hole at all locations (Fig. 2). At the most recently drilled site, GF (2015), the extent of sediment smothering extended out to 290 m in a generally easterly direction. At GI (2014), the extent of smothering along the south-easterly transect did not extend beyond 30 m, but the north-easterly transect was influenced by rock dumps and visible deposition to over 200 m from the centre. The north-western transect had visible deposition out to 250 m from the centre, but this may have been influenced by transported cuttings.

At location S, drilled in 2012, three years prior to sampling, the extent of smothering was less than 50 m, as was the case at location G0, drilled in 2000. Location E, drilled in 1991 showed only minimal impacts (maximum extent 20 m). At the oldest Location T, drilled in 1987, the south-eastern and south-western transect showed smothering up to 50 and 25 m, respectively, but only to 15 m in the other directions. Location G6, not shown on the figure, but drilled in 2006, showed visible impacts less than 50 m from the drilling hole (Fig. 3).

Fig. 2. Example images of seafloor sediments directly impacted by drill cuttings deposition.

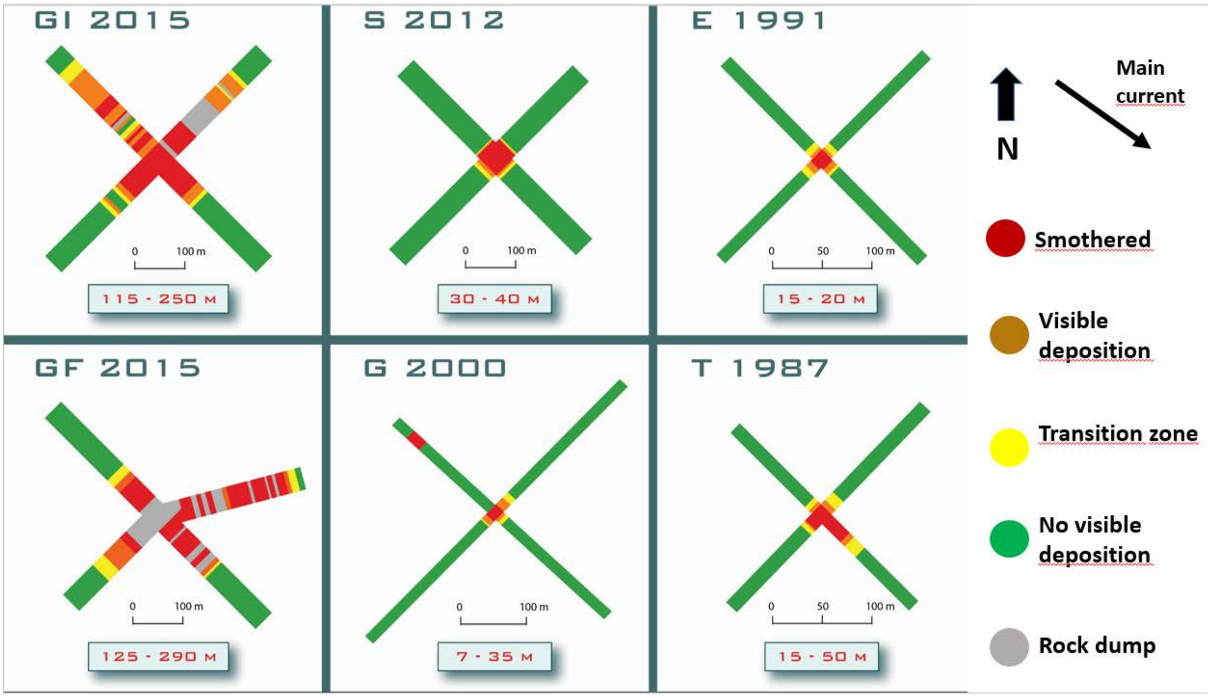

Figure 3. Schematic representation of the extent of smothering at the six locations surveyed in 2015. Location G6, drilled in 2006 and sampled in 2014 is not shown on this figure.

Underwater hyperspectral imagery (UHI)

The results of the UHI surveys at the seven locations are described in detail in Cochrane et al. (2019). The manuscript is presented in the appendix and thus will only be summarised here in brief.

The UHI results in general corresponded with the visual observations, meaning that the technique has a usefulness in detecting the deposition of drill cuttings. This also serves to confirm that a trained biologist's eye is consistently capable of assessing the extent of impacts from drilling operations.

The advantage of the method lies in its objectivity. However, for drill cuttings detection, the disadvantage is that there is no generic spectral signature for drill cuttings, so the only means of determining the spatial extent of deposited drill cuttings is to analyse change along a transect from the drill hole to reference conditions.

The UHI collects spectral data one line at a time, so a "box" of pixels can be compiled at selected points (termed "samples") along the transect. In this case, the spectral samples were taken at the same locations as the biological stations (30, 60, 125 and 250 m). The spectral signature of each of the pixels have to be compared with those at the reference site and the degree of similarity analysed using a specific algorithm. This turned out to be a rather labour intensive process and at present it is not possible to analyse changes along a continuum, as was done using visual assessment.

Further, some anomalies were apparent on the UHI results, which had to be verified using the video material. Examples of anomalies were colonies of encrusting organisms and some metal debris.

We concluded that, while the UHI is an interesting and innovative tool with potential for detecting drill cuttings, some developments are needed before this could be fully automated or time-efficient for commercial purposes.

Benthic macrofauna

Fig. 4 shows a dissimilarity diagram where stations within a cluster are more similar to each other than to any other of the stations.

The first point to note is that stations GF_60 and GI_30 at the most recently drilled locations appear as outlier stations, with approximately 65 and 55% dissimilarity to the other stations, respectively. GF_60 showed some signs of organic enrichment, with a dominance of the indicator species *Capitella capitata* and GI_30 had the lowest numbers of individuals.

Contrary to our starting hypothesis, the stations did not group together according to distance from the drilling point, but according to location. Within the locations, with a few exceptions, the stations generally had less than 30 % dissimilarity, meaning that the differences in faunal composition were relatively minor. Even between the locations (with the exception of GF_60 and GI_30), the differences were between 40 and 50 % which still is relatively minor.

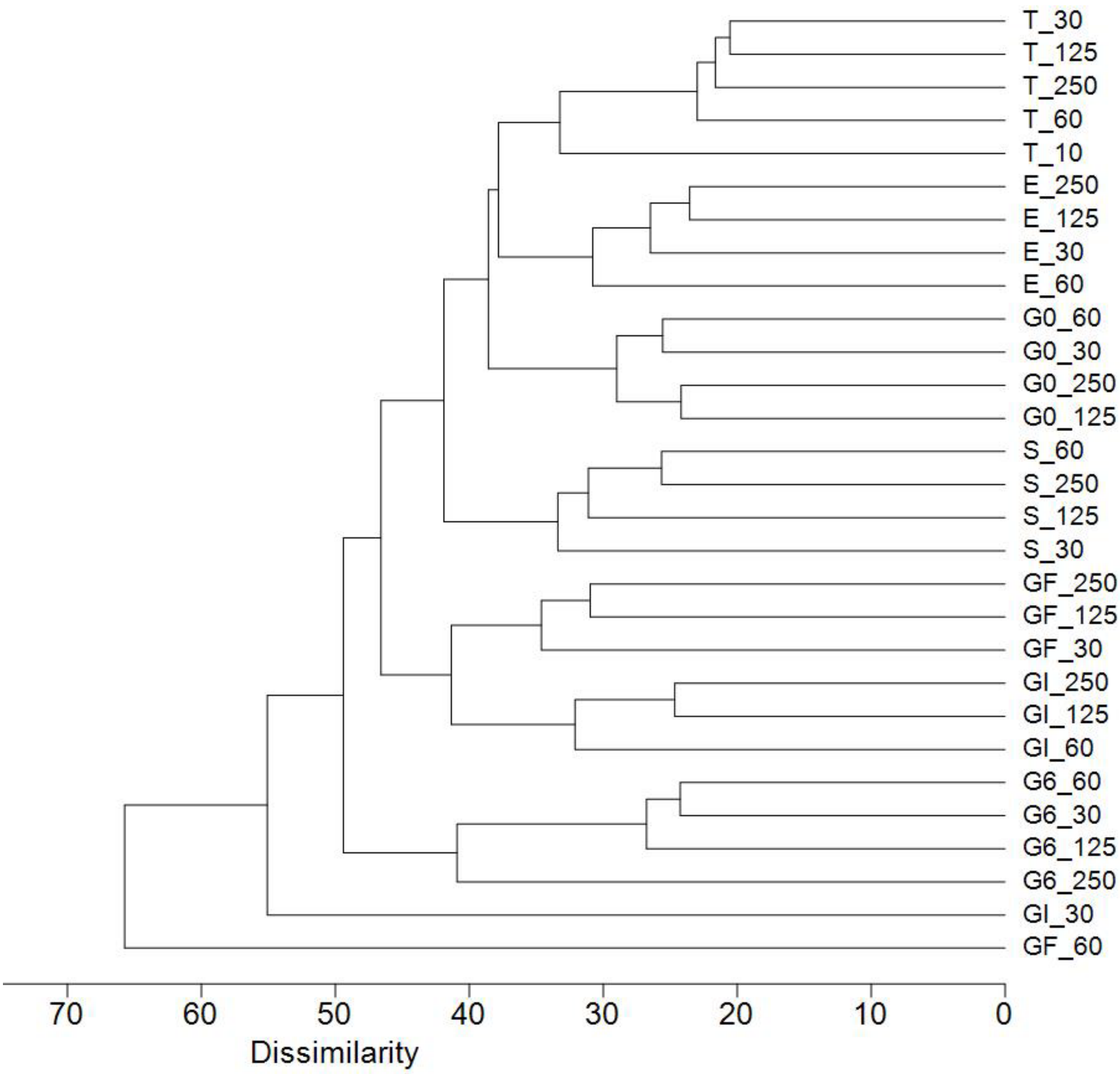

Fig. 4. Cluster diagram showing the degree of dissimilarity between the stations analysed for benthic macrofauna.

A total of 433 individual macrofaunal taxa were recorded from the 21 stations analysed, with the highest number at station G0_125 (157) and the lowest at station GF_60 (61 taxa). The highest numbers of individuals occurred at station G0_250 (2888), but this was largely due to the presence of clumped colonies of the serpulid tubeworm *Salmacina dysteri* and, to a lesser degree, *Filograna implexa*. Without these two taxa, the maximum number of individuals occurred at station T_125 (1316) and the minimum at station GF_60 (61).

Overall, there was a slight tendency for less individuals occurring at the stations located 30 and 60 m from the drilling locations, but only a very marginal (and not statistically significant) reduction in taxa at those distances (Fig. 5).

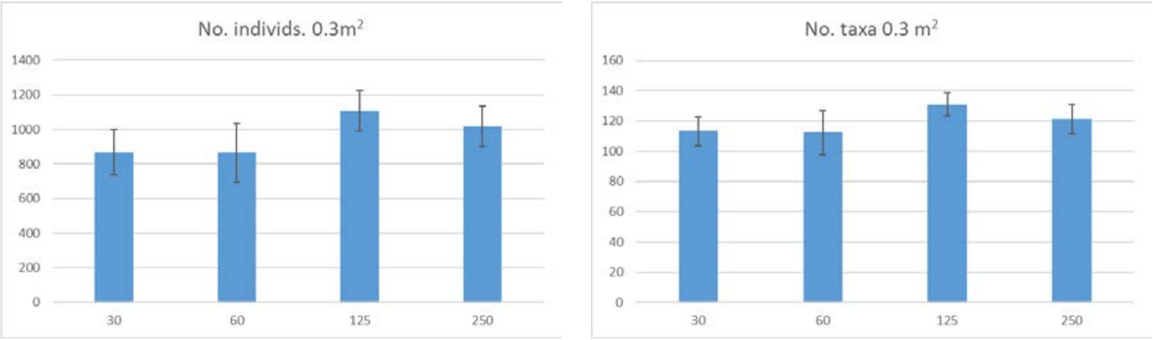

Fig. 5. Overall average numbers of taxa and individuals at all the sampling stations, separated according to distance from the drilling location.

At the most freshly drilled location GI, drilled in 2015 (the same year as sampled), there was a marked reduction in numbers of individuals at distances of 30 and 60 m from the drilling position, with highest numbers at 125 m and somewhat less again at 250 m (Figure 5). Numbers of taxa followed a similar trend. At location GF, drilled in 2014, the absolute number of individuals was less over the entire location, but less difference between the innermost and outermost stations. However, station GF_60 contained the least taxa and individuals of all the stations (likely explanation and discussion given below).

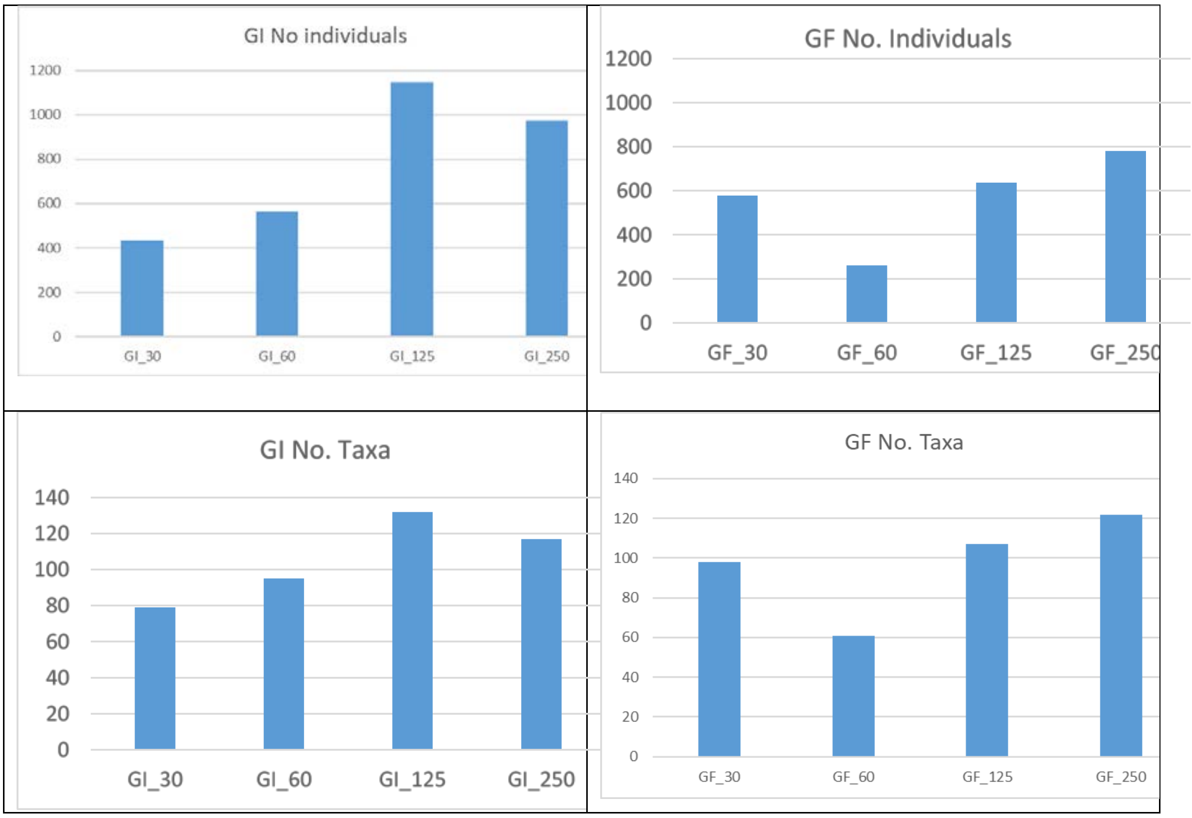

Fig. 6. Bar charts showing numbers of taxa and individuals at the two most recently drilled locations, GI and GF.

At the two oldest drilling locations E and T, drilled in 1991 and 1987, respectively, these trends were either absent or much reduced. At Location E there were no statistically significant differences in numbers of taxa or individuals, but at Location T, the 30 m station (and even more so the additional 10 m station) contained somewhat less individuals, but not less taxa.

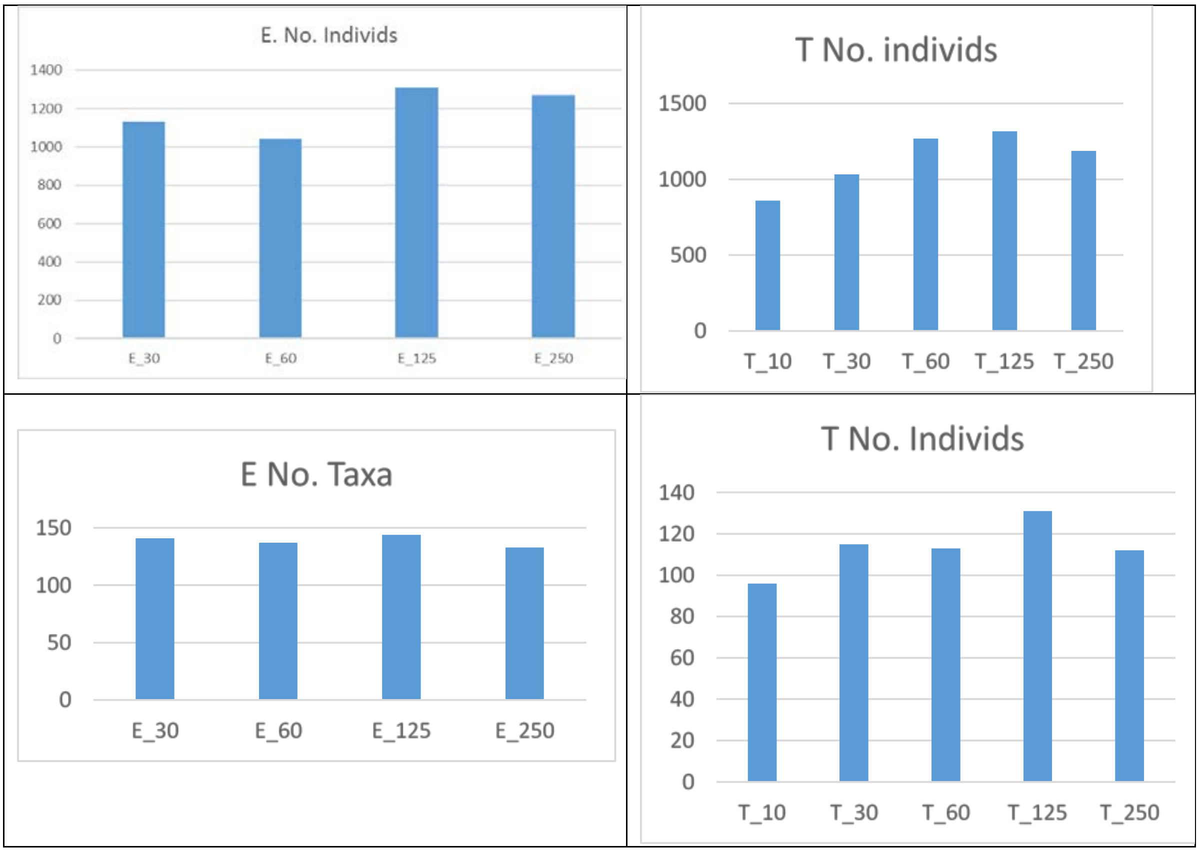

Fig. 7. Bar charts showing numbers of taxa and individuals at the two oldest locations E and T, drilled in 1991 and 1987, respectively.

As a proxy for assessing recovery of the innermost locations over time, Fig. 8shows the numbers of taxa and individuals at 30 m from the drilling positions at all the locations, drilled from 2015 to 1987, i.e. from months to 28 years prior to sampling.

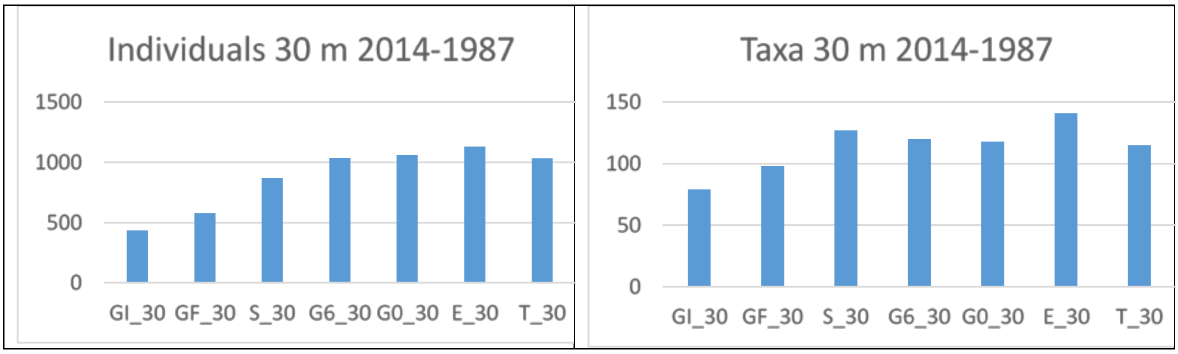

Fig. 8. Bar charts showing numbers of individuals and taxa at the 30 m from the drilling locations, from the "youngest" to the oldest locations (left to right).

There was a notable reduction in numbers of individuals at the inner station at the two most recently-drilled locations, but within 3 years and more (from Location S, G6 etc.) the numbers of individuals showed no differences and can be considered to have returned to normal levels. Interestingly, only few taxa were reduced in representation after the drilling events and these mostly were either taxa that are sessile and cannot resurface after deposition of sediments.

We have drawn the following conclusions:

1. Somewhat surprisingly, we found only minimal faunal disturbance even as close as 30 m from the drilling point, even when the sediments were visibly smothered by drill cuttings.
2. We found no typical faunal indicator of drill cuttings deposition. We found only a reduction in individuals and to a lesser extent also taxa, close to newly-drilled locations, but after three or more years, the communities did not differ between centre and reference conditions.
3. We have confirmed through comparison with spectral imagery that a biologist's eye can detect the presence of deposited drill cuttings on the sea floor. However, faunal communities in the area did not necessarily reflect the deposition status.
4. We have found the visible extent of drill cuttings deposition to be reduced to 50 m or less within a period of three years.

Numerous studies on disturbance to benthic communities by bottom trawling report consistent patterns of change in the benthic fauna, and that the effects may persist over time (see Clark et al., 2019 and references therein). Also Gollner et al. (2017) noted that faunal communities remained changed on decadal scales after deep-sea mining, although much of this could be attributed to permanent alterations in habitat structure (sediment composition).

The fact that we did not find any extensive or even notable changes in benthic community composition even a short time after drilling was surprising.

The dominant species at the stations sampled around Goliat all are typical of the south-western Barents Sea in general (MOD data and Akvaplan-niva unpublished data; Table 2). The overall most dominant species was *Galathowenia fragilis*, which lives in an upright tube and is not mobile. Precisely this species was the one most reduced in number at the innermost stations at the two most recently drilled locations. Most of the other dominant species were free-living, small-bodied polychaetes with a relatively short reproduction cycle and thus a rapid turnover. The bivalve *Adontorhina similis* is a member of the thyasirid family, many of whom are found in physically disturbed habitats, such as in Svalbard glacial fjords (Wlodarska-Kowalczuk et al., 2005).

In contrast, the fauna in the central parts of the Barents Sea is comprised of large-bodied, long-lived sessile taxa such as the polychaetes *Maldane sarsi* and *Spiochaetopterus typicus* (Cochrane et al., 2009). They also identified a region in the northern part of the Barents Sea where the fauna was markedly different, being dominated by small mobile and actively-moving species. Although the actual species represented were more of Arctic origin compared with those we have found in the south-western parts, the functional attributes of the communities were remarkably similar.

Benthic fauna are strongly influenced by the bottom water and sediment characteristics as well as food supply and sedimentation/sediment stability.

The south-western part of the Barents Sea is a dynamic area where the Norwegian coastal current meets Atlantic water, forming a series of gyres and different flow directions at the surface (Loeng, 1991) and Fig. 9. The south-western part of the Barents Sea also is a dynamic area in terms of bottom water, with strong north-flowing Atlantic currentsFig. 10. The northern parts are influenced by ice-rafted sedimentation and the central parts are more stable with more consolidated sediments.

Name	Group	Av.	SD
Galathowenia fragilis	Polychaeta	75	47
Spiophanes kroyeri	Polychaeta	63	35
Heteromastus filiformis	Polychaeta	49	35
Adontorhina similis	Bivalvia	34	25
Paramphinome jeffreysii	Polychaeta	32	21
Abyssoninoe scopa	Polychaeta	30	14
Chone sp.	Polychaeta	24	11
Golfingia sp.	Sipunculida	19	18
Exogone verugera	Polychaeta	22	18
Aricidea catherinae	Polychaeta	18	14
Prionospio cirrifera	Polychaeta	16	13
Myriochele olgae	Polychaeta	19	18

Table 2. Overall dominant species at the sampling stations. AV denotes average numbers per 0.3 m2 sampling station and SD is the standard deviation across the 29 sampling stations.

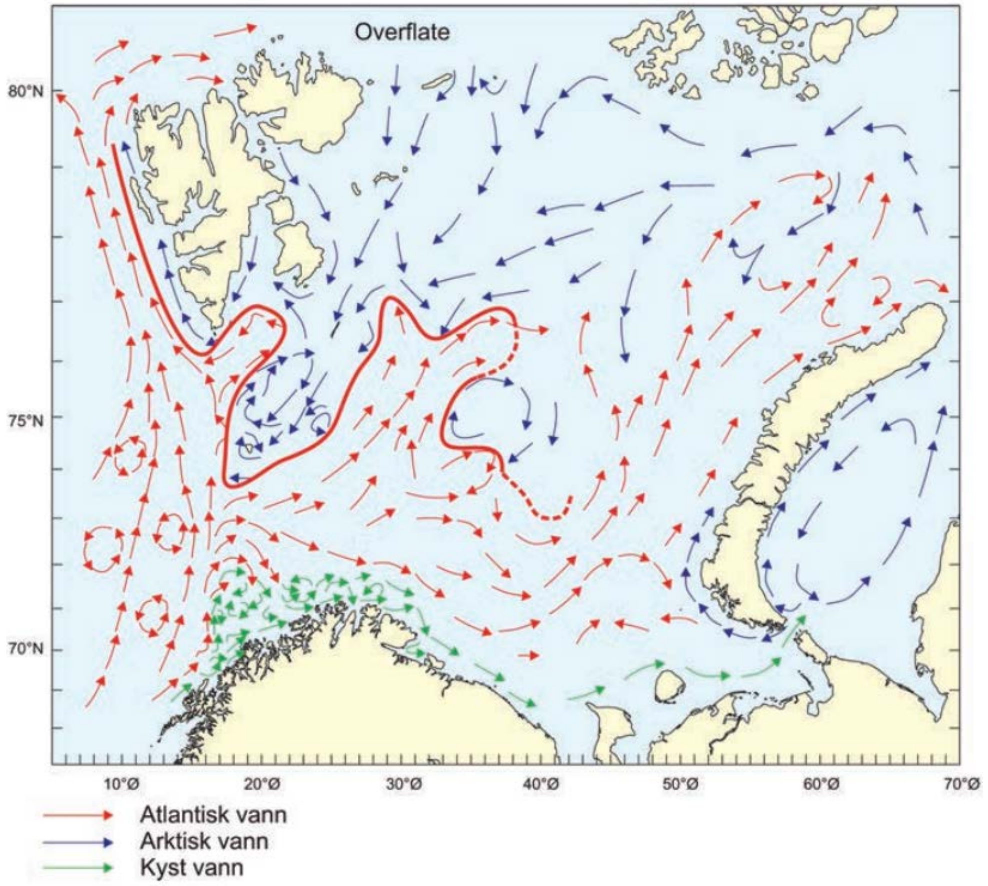

Fig. 9. Schematic representation of surface water masses in the Barents Sea. Red: Atlantic water, blue: Arctic water and green: Norwegian coastal water. Figure modified from the Norwegian Research Institute, after Loeng (1991). Norwegian text retained.

Fig. 10. Simplified sketch of bottom water in the Barents Sea (Norwegian text retained). Red arrows represent Atlantic water and black arrows Arctic water. Line thickness indicates relative strength of flow. The south-western area is a dynamic area with a strong influence of Atlantic currents and the northern area is influenced by Arctic water and ice-rafted sedimentation. The transitional area in the central parts have less water flow and more stable sediments. Figure by Magnus Drivdal, Akvaplan-niva.

We conclude that it is likely that the loose and relatively flocculent sediments in the basins of south-western Barents Sea are naturally "disturbed" by bottom currents (and we have observed that the large fish populations also contribute to sediment re-suspension). The fauna therefore is "adapted" to unstable conditions and thus, with few exceptions, can tolerate the deposition of drill cuttings.
It remains for future research to investigate how the fauna in the more stable, central parts of the Barents Sea will respond to drill cuttings.

6.2 Microbiota

6.2.1 Introduction

The study of effects of DW deposition on the seafloor microbiota has not been part of the environmental monitoring programs imposed on the offshore oil and gas industries in general. However, such microbial effects have been demonstrated, e.g. in the North Sea. There, extensive use of hydrocarbon-based drilling muds has left stable drill cuttings piles characterized by slow degradation of the residual hydrocarbons and enrichment of bacterial groups with capacity for such degradation (Sanders and Tibbetts 1987; Artz et al. 2002; Potts et al. 2019).To our knowledge, BARCUT is the first project where the the microbial impact of water based drill cuttings deposition has been explored. The first study, at the deep water Bønna exploration site on the Barents Sea continental slope (Nguyen et al. 2018), was succeeded by a more comprehensive study at the Goliat field (manuscript in preparation). Here, the focus was both on the spatial extent and the permanence of the bacterial community changes over years. The following three questions were specifically addressed in the study: (i) do changes in the microbiota reflect the same spatial and temporal extent of seafloor perturbation as manifested by established surveying approaches, like visual inspection, geochemical analyses and macrofaunal diversity studies,

(ii) are there statistically robust associations between changes in the bacterial communities and identifiable geochemical factors, and (iii) are there specific bacterial taxa that can be unequivocally associated with the community changes and, thereby, have the potential to serve as indicator organisms for this type of environmental insult.

6.2.2 Materials and Methods

The bacterial community analyses were based on push corer samples collected by ROV operated from M/V Njord Viking in November 2013 (Bønna) and in November 2014 and September 2015 (Goliat). At the Bønna site, the samples were obtained in the range 30 to 210 m from the borehole, while the Goliat samplings were done along 3 approximately straight transects extending from ≤ 15 m to 250 m from three abandoned wells drilled in the years 2000, 2006 and 2015, respectively. After recording the O2 profiles with a needle oxygen electrode, the upper 10 cm of the corer samples were sectioned into the following 4 layers: 0-1 cm, 1-2 cm, 2-5 cm and 5-10 cm. Community-wide molecular-phylogenetic analyses were performed on DNA extracted from these samples. In short, partial 16S ribosomal RNA genes were PCR amplified with universal bacterial primer pairs and the amplicons were subsequently subjected to high-performance DNA sequencing by the Illumina technology. Quality filtering of the sequence data, clustering into operational taxonomic units and subsequent taxonomic annotations were performed within the online QIIME pipeline (www.qiime.org), while different R software packages (https://www.r-project.org) were employed for multivariate ordinations of the data and statistical tests. Geochemical data were provided by approved analytical methods at Akvaplan-niva AS and the Department of Geology, UiT.

6.2.3 Results and discussion

The sediment bacterial analyses at the Bønna site and the Goliat wells drilled in years 2006 and 2015 consolidated the patterns that emerged from geochemical data, visual inspection and macrofaunal and foraminiferal diversity analyses. Demonstrable perturbation of the seafloor microbiota due to water based DW deposition was hardly observable beyond 100 m from the borehole and the most heavily affected sampling locations according to barite deposition and other criteria, i.e. up to 30 m in the 2006 transect and at 60 m in the 2015 transect, were the ones showing distinct deviations from the indigenous sediment microbiotas. The remaining, less affected transect samples were not separable by drilling year or distance from the drilling site (data not shown), but showed an expected, consistent pattern of separation according to sediment depth which corresponded with the transition from oxygenic to anoxygenic conditions. Noticeably, previously collected sediment samples (0-4 cm sediment depth) from remote regions of the southern Barents Sea showed high similarity in community composition with the presumed unperturbed transect samples when included in the multivariate ordination (Fig.11a). The bacterial community changes were manifest both as altered taxonomic composition and reduction in overall diversity. Just a few groups of bacteria were significantly enriched at the heavily affected locations and among them, the two classes *Mollicutes* (mycoplasmas) and *Clostridia* distinguished themselves by hardly being detectable in the the surrounding, native sediments (Fig.11b). Nor are these bacteria pointed out as significant groups in sediments affected by hydrocarbon-based drill cuttings (Potts et al. 2019). On the other hand, we observed highly similar changes of the microbiota at the Bønna site (Nguyen et al. 2018).

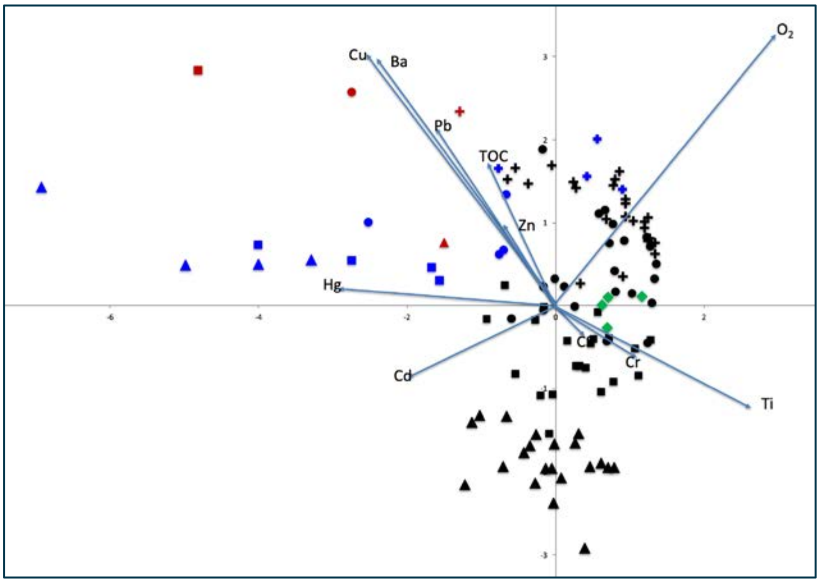

Fig. 11a. Canonical correspondence ordination based on relative abundances of 288 taxa of bacteria. The grouping of the 107 Goliat sediment samples (markers) is constrained by the measured environmental variables (vectors). Marker shapes: crosses, 0-1 cm layer (from surface); circles, 1-2 cm layer; squares, 2-5 cm layer; triangles, 5-10 cm layer. Marker colours: blue, year-2006 ≤30 m distance; red, year-2015 60 m distance; black, all other sampling sites of the Goliat transects; green, control samples from remote, unperturbed regions of the southern Barents Sea.

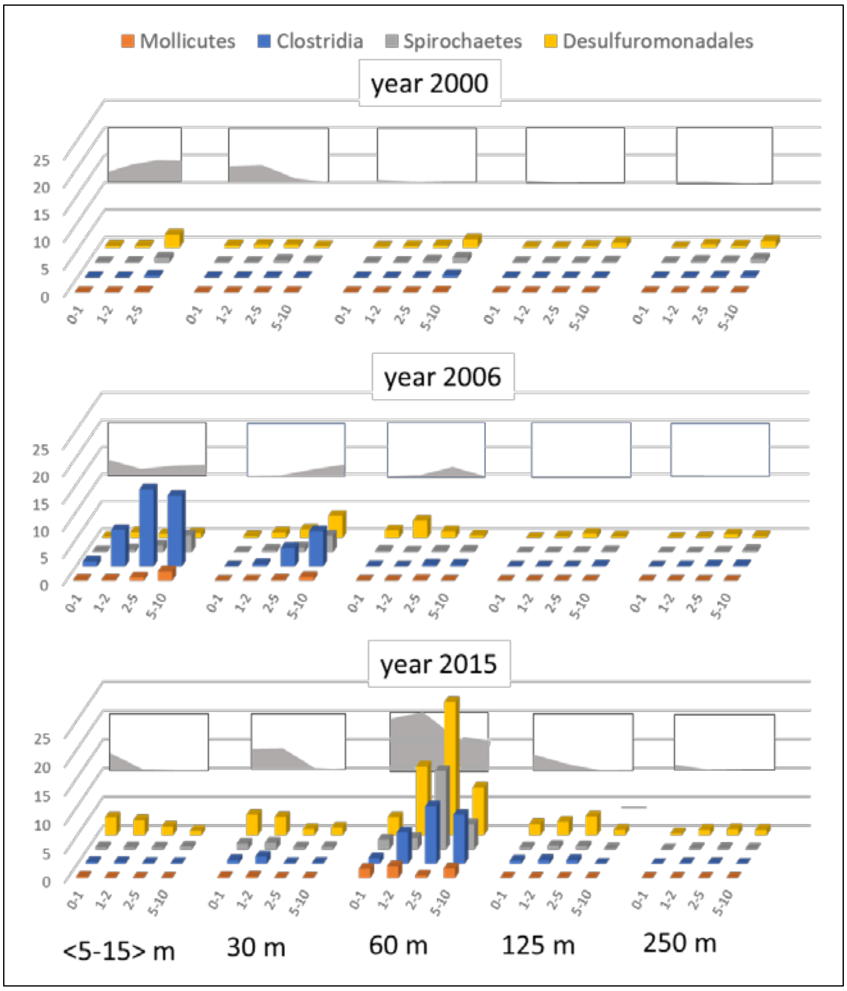

Fig. 11b. Relative abundances of the five bacterial classes that showed marked increases at heavily affected sampling sites at the Goliat locations. Values for each taxon are partitioned by sediment depth (cm) and distance from drilling site (m). Gray area charts: Barium depth profiles at each sampling site with same scale (0-15 mg Ba g^{-1}) in all plots.

The actual environmental driver(s) of the observed bacterial community changes were not fully disclosed by the present work. The perturbed communities were associable with increased levels of barium and other heavy metals (copper, lead and mercury) and reduced levels of oxygen. However, there is no basis in existing literature in the field or in the data from the present study that the observed changes in these inorganic parameters caused the observed community shifts. Rather, we expect one or more of the organic constituents in the drilling fluids to have a vital impact, but well-founded inferences about the nature of these ingredients could not be drawn, as records of the complete composition of the employed drilling fluids were not available. No significant distortion of the microbiota was observed at any sampling distance from the Goliat well drilled in year 2000. We presume this invariance resulted from the use of less perturbing organic drilling mud components in combination with the extended, 15 years recovery period prior to our sampling effort.

6.2.4 Conclusions

In conclusion, the present study confirms that deposition of water based drilling waste may cause marked disruption of the indigenous seafloor microbiota. However, such changes appear restricted to the most heavily affected locations in the vicinity of the boreholes. Significant presence of two taxonomic groups, the *Mollicutes* and *Clostridia*, was uniquely associated with such locations and hence, these taxa seem as promising candidates for rapid and inexpensive DNA-based detection and delimitation of perturbed areas. This can be achieved by polymerase chain reaction with designed taxon-specific primers.

The actual environmental drivers of the observed bacterial community perturbations remain unclarified. On that background, we still cannot conclude with certainty to what extent the observed bacterial community changes have a universal character or are related to specific components of the water based drilling fluids or the environmental conditions in the southern Barents Sea.

7 WP 3: Spreading and deposition of drill cuttings

7.1 Introduction

Coordinated by Department of Geosciences, UiT
Main objective: Site specific spreading of drill cuttings on the sea floor and their influence on marine environment
Participants: Juho Junttila (WP leader), Noortje Dijkstra and Steffen Aagaard Sørensen (UiT)

Task I: Sediment condition
In this task, the following research question was addressed:

> What is the temporal and spatial spreading pattern of drill cuttings and their effect on sediment quality?

The research question is answered by:

a) Investigating sediment conditions of the sea floor before drill cutting discharge (baseline)
b) Investigating the influence of drill cuttings on the sedimentary environment after discharge (impact and spreading)
c) Investigating/predicting of future environmental condition of the sediments (recovery)

Studying the physical sediment properties of the cores taken along the transect (see Chapter 3) provides information on the spreading of the drill cuttings, and on the extent of the long-term environmental effect away from the pollution source. Additionally, studying sediment cores provides us a record back in time (20 cm = ca. 150 years in un-impacted cores), with the upper sample representing present day conditions, while the subsequent samples provide a time line into the past (Fig.12). This provides information on long-term environmental effect and baseline conditions. Baseline conditions reflect the sediment quality under un-impacted environmental conditions (Fig. 12), which can serve as an aim for environmental restoration after impact. The physical sediment properties provide information on the stability of the drill cuttings after deposition and the recovery of the sediments. Heavy metal analyses identify the drill cutting impacted layers, the quality of impacted sediments and also enables to divide the cores in baseline, impacted and post impacted layers. Changes in grain size properties and sortable silt (on un-impacted sediments) can serve as an indicator of natural changes in bottom current strength during time, and hence contain information on the (re-) transportation of drill cuttings. The sediment clay (<2µm particles) and organic matter contents have been linked to the binding of contaminants, and hence changes in these properties, will affect storage and uptake of contaminant concentrations around disposal sites. Sedimentation rates of the sites will provide information on how fast the natural sedimentation has and will cover the impacted sediments.

Task II: Foraminiferal response
In this task, the following research question is addressed:

> What is the response of benthic foraminiferal assemblages to the deposition of drill cuttings?

The research question is answered by analyzing live and fossil foraminiferal assemblages along transects away from the wells. This allows reconstruction of:

a) Environmental baselines in already impacted areas
b) Present and past environmental impact of drill cutting releases

c) Environmental recovery after cessation of drilling wells

The environmental effect of the released drill cuttings is in this task assessed by changes in composition of the benthic foraminiferal assemblage (microorganisms living in the top part of the sea floor; see "Material and Methods" section). Changes in both living and dead foraminiferal assemblages are studied in the same sediment cores as studied in Task I. Dead (fossil) assemblages provide information on long-term environmental changes. This includes past effects of released drill cuttings and potential ecosystem recovery over time, but also natural environmental change. Dead fossil assemblages in the sediment cores also provides in-situ baseline conditions (Fig.12). In-situ baseline conditions reflect the diversity of the ecosystem under un-impacted environmental conditions, which can serve as an aim for environmental restoration after impact.

Living benthic foraminiferal assemblages provide information on the present day effect of the released drill cuttings and potential recovery of the bottom environment since the drill cutting release.

Changes in foraminiferal assemblages down core are compared to the physical sediment properties defined in Task I: i.e. bottom substrate (reflected by grain size), food availability (reflected by TOC) and pollution levels (reflected by heavy metal concentrations). This allows us to distinguish if changes in foraminiferal assemblage have a natural (i.e. changes in oceanography and climate) or anthropogenic (e.g drill cutting discharge) cause.

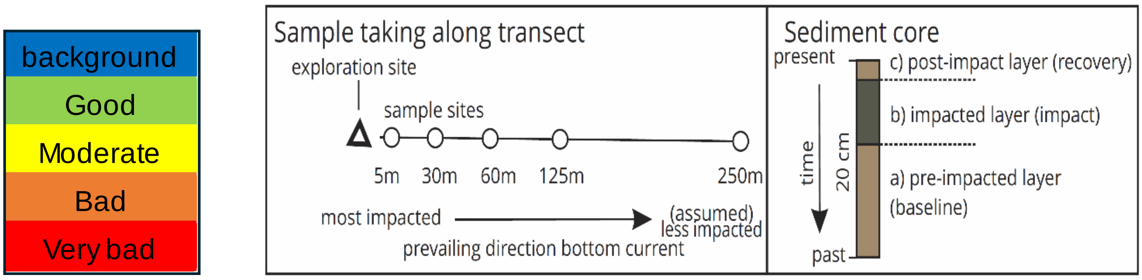

Fig. 12 A: Classification after Bakke et al. (2010) was used in the studied of sediment quality. B: (Left) Typical coring transect with distance from well and (right) generalized sediment type succession in retrieved cores

7.2 Materials and Methods

The push cores and multicores (baseline studies) were sectioned in 1 cm intervals. The samples were analysed for grain-size (including sortable silt for bottom current variation), heavy metal concentration, benthic foraminiferal analyses, total organic carbon (TOC). In addition, some cores (wells, T, G2000 and E) were analysed for 16 EPA-PAH and some cores (G2006, baseline studies) were dated with ^{210}Pb-dating.

Grain-size, benthic foraminifera and TOC analyses were performed at the Department of Geosciences, UiT. Heavy metal and 16 EPA-PAH analyses were performed by accredited Unilab AS (Akvaplan-niva) in Tromsø. ^{210}Pb datings were performed by GEL analyses, USA.

The past and present effect of drill cuttings on the seafloor fauna was quantified by investigating benthic foraminifera. Benthic foraminifera are unicellular organisms (size: 45-1000 µm) living in the upper layers of the seafloor. They are one of the most diverse and widely distributed groups of organisms in the marine realm (e.g. Murray, 2006). Foraminifera are widely used as indicators for climatic and environmental changes. They are considered ideal to assess environmental impact, as they have a high sensitivity to environmental change, and respond quickly to both natural and anthropogenic alterations due to their short reproductive cycle (Murray, 2006). An advantage of benthic foraminifera is that their shells fossilize in the sedimentary record. By studying living and fossilized foraminiferal assemblages in sediment cores, it is possible to go back in time and reconstruct past environments in addition to modern environmental conditions. In pristine environments, such as the Barents Sea, foraminifera are affected by parameters including temperature, salinity, food availability, and bottom substrate (Murray, 2006). Anthropogenic stressors include amongst others elevated heavy metals concentrations, PAH and organic matter enrichment (see review in e.g. Alve, 1995), but also smothering of the species by for example drill cuttings (e.g. Hess et al., 2013). The effect of anthropogenic stressors can be observed by changes in foraminiferal assemblage in the cores, with a shift from so-called “natural assemblages” to “impacted assemblages”. Natural assemblages are dominated by species found under baseline conditions, while impacted assemblages might consist of a higher number of species known to be opportunistic or stress tolerant. In addition, impacted assemblages often consist of lower amounts of foraminiferal species (diversity) and specimens (density) (Murray, 2006).

In 2012, a list of recommendations to standardize the methodology in bio-monitoring studies using benthic foraminifera was formulated by the Foraminiferal Bio-monitoring (FOBIMO) initiative (Schönfeld et al., 2012). This was the first step to implement the foraminiferal method in marine legislations. Additionally, recent studies show that benthic foraminifera are useful indicators of environmental quality status (EcoQS) (e.g. Alve et al., 2016).

We largely followed the methodology proposed by the FOBIMO-protocol. Live foraminiferal assemblages were studied in the top 5cm of the sediment cores. These samples were stained with rose Bengal allowing to distinguish between live (stained) and dead fauna. Dead and live faunas were studied in the 100 µm to 1 mm size fraction.

For a detailed description of used methodology we refer to: Aagaard-Sørensen et al., 2018; Dijkstra et al., in press; Junttila et al., 2018

7.3 Results and discussion

Well T (1987)

Sediment condition (Junttila et al., 2018)

Well T was drilled before the restriction of use of oil-based drilling fluids (1993). Ba concentration is used as a marker for $BaSO_4$ and drill cuttings in this study. At station T10 (10m from the wellhead, number after letter refers to distance from the wellhead) above background Ba concentrations are observed in the entire core (20 cm), indicating that the drill cutting layer is at least 20-cm thick (see Fig. 13, 15 and Appendix 2). Ba concentrations are ca. 100 times higher in the sediments of T10 compared to the baseline concentrations in the area (Dijkstra et al., 2015, 2017b, Aagaard-Sørensen et al., 2018). The high Ba concentrations coincide with the generally high concentrations of Cd, Cu, Hg, and Pb, indicating that these metals can be associated with the drill cuttings. Cu, Hg, and Pb concentrations correspond to a bad (level IV) to very bad (level V) sediment quality, following the classification by Bakke et al. (2010). Cd is of good quality (level II) from the bottom of the core to 3.5 cm depth. The other metals are of background levels (level I) in this core. At station T30, the drill cutting layer is 9 cm thick, while at T60, T125, and T250, the drill cutting layer is 12-, 5-, and 2-cm-thick, respectively. The increase in Hg and Pb concentrations at these sites coincide with the increase in Ba concentrations; this might indicate that they can be associated with the drill cuttings. However, they also coincide with the TOC content. Previous studies (Dijkstra et al., 2015, 2017b) associated these two metals with an increase in fine grain size or TOC content (due to the increased inflow of Atlantic water). The increasing trend (and similarity to the TOC trend) of these two metals is seen in all the cores, except at T10; we argue that this is because the natural variability of the cores is related to the TOC content. Higher metal concentrations are observed in station T10 in well T than those in wells E and the newer well S; this reflects the lack of restricting legislation on drill cutting release in 1987 when well T was drilled. It should also be noted that the released amount of drill cuttings in well T (3353 tons) was almost 5 times higher than that in well E (688 tons). This shows that the lack of restricting legislations has resulted in high heavy metal concentrations in the drill cuttings and their surrounding sediments as seen in well T, whose sediment surface remained exposed at the time of sample collection (2015).The decreased metal concentrations in the top 3-4 cm at T10 (well T) suggest natural sedimentation after the cessation of the well and represent environmental recovery. High Ba concentrations in the top sediment layers of all the T stations show, however, no sign of physical recovery. One explanation could be that the sediments with very high Ba concentrations close to the wellhead (e.g., station T10) could still be re-transported with bottom currents.

16 EPA-PAH were analysed on 4.5 cm sample depth of T30. None of the results indicated higher than good level (Level II, Bakke et al. 2010) concentrations for individual 16 EPA-PAH nor SUM of 16 EPA-PAH. Most of the concentrations were of baseline level (Level I).

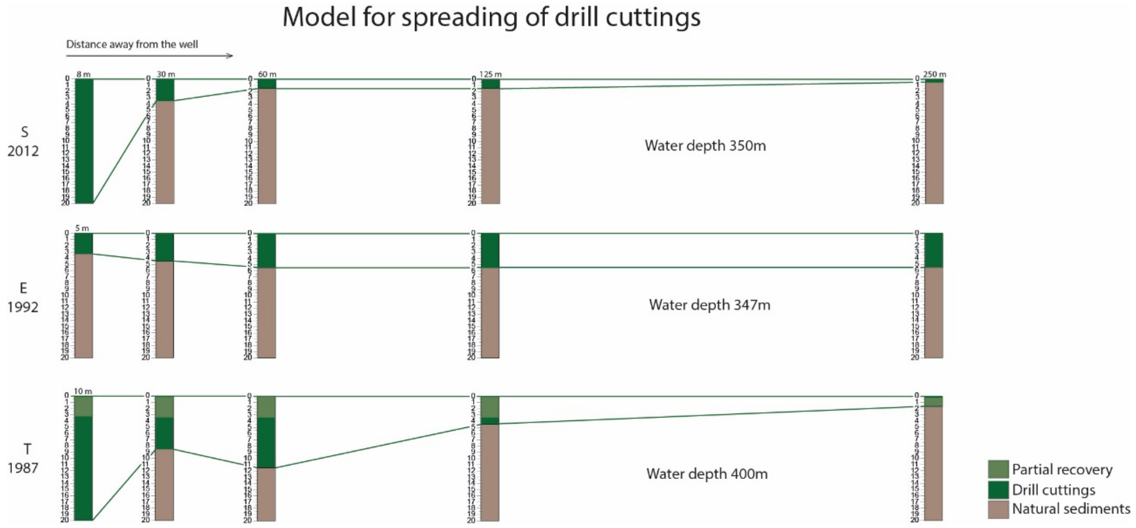

Fig. 13. A model of spreading of drill cuttings in the wells in terms of thickness and distance. The brown bars indicate natural sediments, where the dark green bars indicate elevated Ba concentrations (drilling mud) and light green bars indicate the probable physical recovery of the cores (Junttila et al. 2018).

Foraminiferal response (Aagaard-Sørensen et al. in revision, Berg, 2017 MSc thesis)

A poor live foraminiferal fauna observed in core T10 (10 m from wellhead) was ascribed to elevated sediment Hg and Pb concentrations in combination with low TOC and oxygen contents. These findings show that the site remains negatively impacted by drill cuttings even 28 years following their release. In core T10 the fossil foraminiferal fauna was absent or scarce at ~5-20 cm core depth in sediments interpreted as drill cuttings with high concentrations of Ba, Hg, Cu and Pb and low TOC content. Very low total abundance of fossil foraminifera was observed throughout the upper part (0-5 cm) of core T10 when the sediment quality showed recovery with gradually decreasing yet elevated concentrations of heavy metals (Hg, Pb and Cu). This indicates that site T10 did not support a thriving benthic community at any time during the post-drilling period despite the gradual sediment recovery. The poor condition observed at site T10 is contrasted by the natural fossil foraminiferal fauna compositions and low (background) heavy metal concentrations observed in the cores farther downstream (sites T30, T60, T125 and T250)(Fig 14 and Appendix 2).

Fig 14. Clustering of the samples, from TOTAL core transect, based on non-metric multidimensional scaling (NMDS) performed on the log-transformed total fossil specimen abundance data with Euclidian distance as similarity measure. Light grey, gray and dark gray shading highlights samples assigned by Q-mode HCA to cluster I, cluster IIa and cluster IIb, respectively. Different symbols indicate samples from the different cores (see legend), with mid-point sample depth indicated above. Red vectors represent environmental parameters (Ba, Cu, Pb, Hg and TOC), which are not included in the ordination, reflecting the correlation coefficients between each parameter and the NMDS scores. The length of the vectors are scaled to make a readable biplot, hence only their directions and relative lengths can be considered.

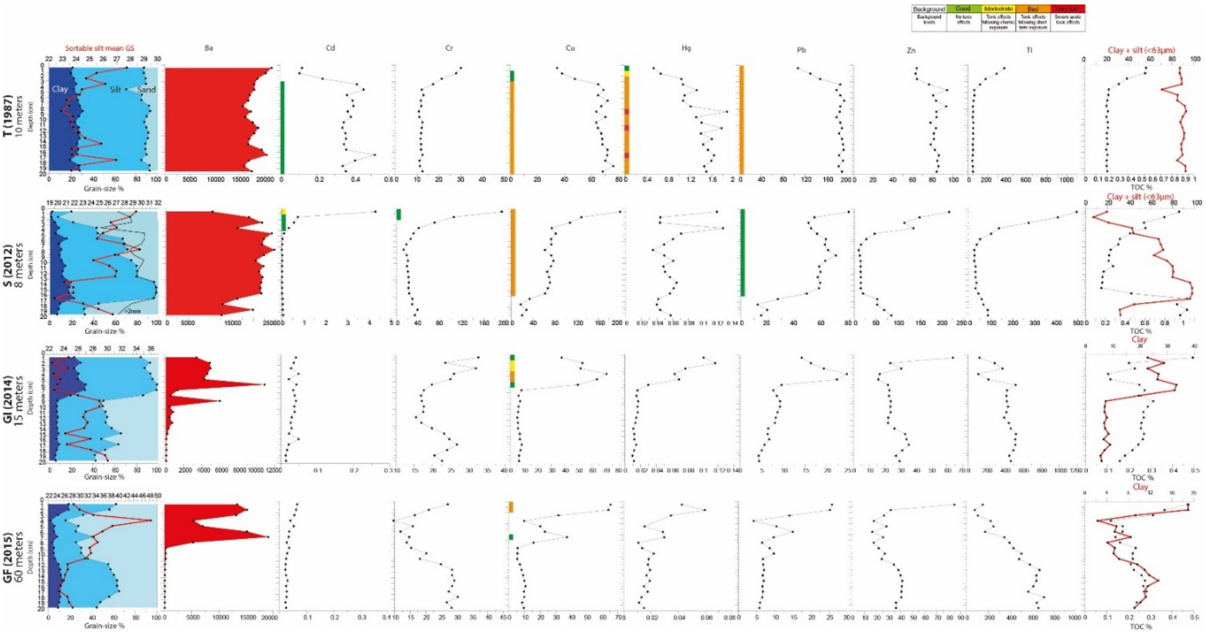

Fig. 15. The figure shows stations with highest heavy metal concentrations in different wells. Results are showing cumulative grain size, sortable silt mean grain size, heavy metal concentrations, and TOC and clay /clay+silt contents. Ba concentrations are shown in red. The color bars indicate sediment quality of the samples according to Bakke et al. (2010). Metal concentrations are in mg/kg and TOC contents in %. The black line in the cumulative grain size in the S8-m plot indicates the amount of>2-mm grain-size fraction in the sand fraction.

Well E (1992)

Sediment condition (Junttila et al., 2018)

The well E was drilled before the regulations in 1993. The Ba concentrations are lower (<500 mg/kg) at the closest station in well E than those at the closest stations in the wells T and S (Figs 15, 16 and Appendix 2). The highest Ba concentrations can be found at station E125, which is unlike the T and S wells, where the highest Ba concentrations are found in the closest core/station. Ba concentrations are 5 times higher than the local baseline concentrations (100-200 mg/kg) in the top 1-6 cm of stations E5, E30, E60, and E125 and 2 times higher at station E250. The increase in the Ba concentrations in the top of the cores at stations E5, E30, and E60 coincides with the increase in sand content in these cores. This similar trend is surprising because usually the transportation of Ba together with fine sediments would be expected. The metal concentrations of the cores, apart from Cd, show background sediment quality levels (level I). The Cd concentrations in the core bottoms (10-20 cm depth) of all the stations, except E125, correspond to good sediment quality (level II). The low Ba concentrations and background sediment quality of the cores in well E are surprising given that the well was drilled before stricter regulations on the release of drill cuttings. Overall, this indicates that wells drilled before 1993 are not necessarily associated with contaminated sediments. As noted above, the amount of released drill cuttings in well E was much lower than that in well T, which might have a positive effect for the environmental impact of drill cutting releases. Ba concentrations at all the stations in well E show no sign of physical recovery but rather increase in Ba concentrations toward the top of the cores. This is similar to that observed in well T; however, the Ba concentrations at the stations in well E are relatively low. The lack of physical recovery during the 23 years after the cessation of well E could also be explained by the re-transportation of Ba.

The 16 EPA-PAH contents were analysed on 7.5 cm sample depth at E5 and 2,5 cm and 7.5 cm sample depth at E30. None of the results indicated higher than good level (Level II, Bakke et al. 2010) concentrations for individual 16 EPA-PAH nor SUM of 16 EPA-PAH. Most of the concentrations were of baseline level (Level I).

Foraminiferal response (Dijkstra et al., in press)

Down core changes in fossil foraminiferal faunal composition and density around well E-1992 were only observed outside the drill cutting influenced sediment layers and could be attributed to natural environmental and climatic changes (Fig 16 and Appendix 2).

Smothering of foraminifera due to burial by e.g. drill cuttings is observed in experimental and field studies when the drill cutting layer exceeds ca. 3 cm (Aagaard-Sørensen et al., 2018, Hess et al., 2013). Un-impacted natural assemblages despite drill cutting influenced layers of >3 cm at the entire transect of well E-1992, implies that the initial amount of drill cutting transported downstream during the drilling activities at the well (late 1991-early 1992) resulted in too thin deposits (i.e. < ca. 3 cm) to influence or smother the foraminiferal fauna (Fig. 16). The prevailing fauna survived and could bioturbate through the drill cutting layer. This implies that drill cutting influenced sediments of 4-6cm around the well more likely represent gradual re-transportation of Ba-rich sediments. Re-transportation of drill cutting influenced sediments from the well head towards the core locations is supported by increased Ba values towards the top of the cores.

Live fauna observed in the top 5cm of the cores in well E-1992 showed no negative impact of released drill cutting. We therefore concluded that the live foraminiferal fauna was not negatively impacted (anymore) by the released drill cuttings during the time of sampling in 2015.

The absence of environmental impact registered by foraminiferal fauna at well E-1992 suggests that not all drill cuttings released before stricter regulations set in place in 1993 have resulted in negative environmental impact. The relatively low amounts of drill cuttings (i.e. 688 tons at well E-1992 versus 3353 tons at well T-1987) released seem to limit the environmental impact.

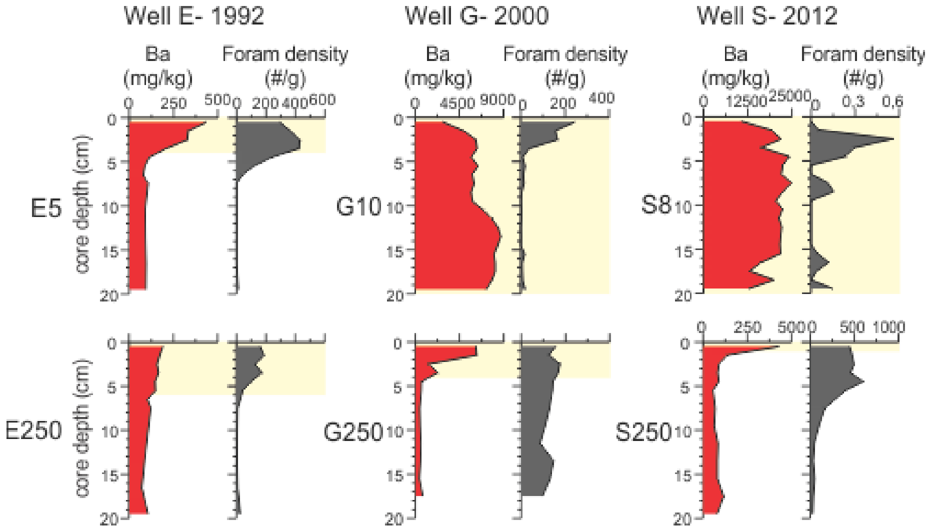

Fig. 16. Down core Ba concentrations (mg/kg) (left) and foraminiferal density (#/g) (right) in each of the wells. Comparison between the station closest to the well head (top) and the station at 250m away from the well head (bottom). Drill cutting (DC) influenced layers are indicated by yellow shading. Smothering, resulting in low foraminiferal density is observed in station G10 and S8

Well S (2012)

Sediment condition (Junttila et al., 2018)

At station S8, high Ba concentrations are observed in the entire core (20-cm long), indicating that the drill cutting layer was at least 20-cm thick. S8 shows up to 100 times higher Ba concentrations than the baseline concentrations (Fig. 15 and Appendix 2). Drill cutting layers based on Ba concentrations are 4 cm thick at S30, 2cm at S60, and S125 and 1 cm thick at S250. At S8, high Ba concentration coincide with higher concentrations of Cd, Cr, Cu, Hg, Pb, and Zn; this suggests that these metals can be associated with drill cuttings. However, only Cu and Pb show high concentrations throughout the entire core, while Cd, Cr, Hg, and Zn show high concentrations only at the top (0- to 4-cm depth). Cu concentrations correspond to bad sediment quality (level IV) from 15.5 cm core depth to the top of the core. Pb concentrations correspond to good sediment quality (level II) in the same depth interval. Cd concentrations show good (level II) to moderate (level III) sediment quality in the top 3.5 cm. Cr and Zn concentrations are of good quality (level II) in the top cm of the core. Hg and Pb concentrations show an increasing trend in the top of cores S30, S60, S125, and S250 similar to Ba concentrations, similar to the observations in wells T and E. However, Hg and Pb concentrations tend to increase earlier than the Ba concentrations and additionally show a similar trend to the TOC content, thus indicating a natural source for these metals for the reasons discussed above.

The majority of the metal concentrations at all the stations of well S are of background level (level I). This indicates that the modern (since 2011) zero harmful discharge regulations (of water-based drill cuttings) has had a positive effect on the sediment quality, compared to the release in well T (before 1993) when no regulations were in place. The stations in well S show no physical recovery, which is not surprising because the well was drilled in 2012, allowing only ca. 3 mm of natural sedimentation on the sites. However, following the observed re-transport and deposition of Ba in the other wells, it is suggested that in 20-30 years, Ba-rich sediment layers might become thicker in the proximity of well S. Re-transportation is likely due to the prevailing high bottom current speeds inferred from the high amounts of sand in well S (compared to those in wells T and E).

Foraminiferal response (Dijkstra et al., in press)

We observed low amounts of fossil fauna in the core collected 8m from the wellhead (Figs 16, 17 and Appendix 2). It can be concluded that the >20 cm drill cutting deposit at core location S8 smothered the in-situ fauna. Smothering of foraminifera due to burial by e.g. drill cuttings is observed in experimental and field studies when the drill cutting layer exceeds ca. 3 cm (Aagaard-Sørensen et al., 2018, Hess et al., 2013). Un-impacted natural assemblages despite drill cutting influenced layers of >3 cm at S-2012 (≥30m from the wellhead), indicates that the initial deposited drill cutting layer was not thick enough (i.e. < 3 cm) to smother the foraminiferal fauna. This implies that drill cutting influenced sediments of > 3cm more likely represent gradual re-transportation of Ba-rich sediments from the original drill cutting deposit towards the core locations. Re-transportation of drill cutting influenced sediments from the well head towards the core locations is supported by increased Ba values towards the top of the cores. Changes in the fossil fauna ≥30 m from the wellhead did not coincide with sediments influenced by drill cuttings, and were attributable to natural environmental change (Figs 16 and Appendix 2).

Additionally we observed no living foraminiferal fauna in the core collected 8m from the wellhead (core S8). Presence of live fauna increases down stream on the sampling transect. The absence of live and fossil fauna, at station S8 of well S-2012, implies that no recovery of foraminiferal assemblage has occurred, 3 years after the release of drill cuttings. This might be explained by the high concentrations of Cu measured at the station. Absence of live fauna in S8 might also be caused by the high sand content and large amounts of particles >2 mm creating unfavorable conditions for foraminifera to re-establish after drill cuttings were released.

All other changes in foraminiferal faunal composition at this well did not coincide with sediments influenced by drill cuttings, and were interpreted to be the result of natural environmental changes (Fig. 17and Appendix 2). We conclude that the impact of drill cutting release on the foraminiferal fauna was confined to less than 30m downstream from the wellhead.

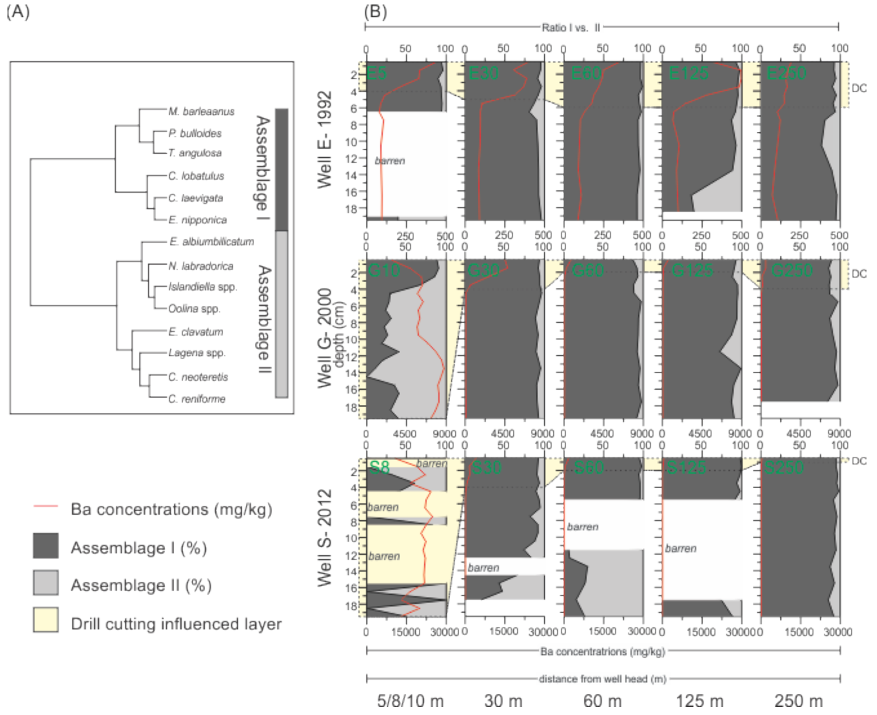

Fig. 17. (A) R-mode clustering of the most common foraminiferal species found in the cores at the studied wells. Two assemblages were found. Assemblages I contains species that are indicative for relatively warm, food rich Atlantic conditions, found in the present-day southern part of the SW Barents Sea. Assemblage II contains of species that are indicative for relatively cooler and fresher Arctic-like conditions, found in the present-day northern part of the SW Barents Sea. See also discussion in paragraph "Baseline foraminiferal assemblages in Bjørnøyrenna" below. In addition, some of the species grouped in Assemblage II have opportunistic characteristics.

(B) Down core distribution of the two assemblages. Downcore Ba concentrations (mg/kg) are shown with red line and drill cutting (DC) influenced layers indicated with yellow shading. High relative abundances of Assemblage II in the drill cutting influenced layers of core G10 are the result of an "old and cold" fauna released together with the drill cuttings. Increased abundances of Assemblage I in the top part of core G10, together with decreasing Ba concentrations, are interpreted to reflect a recovery layer. Relative high abundances of Assemblage II outside drill cutting influenced layers, for example in the bottom of cores S30, S60 and E125 reflect cooler climatic periods and are attributed to natural environmental change.

Goliat Field

Well G2000

Sediment condition (Dijkstra et al., in press)

At G2000 the Ba concentrations are highest (2810-8730 mg/kg) throughout the core G2000-10 at the closest station to the well indicating that the thickness of drill cuttings is at least 20 cm (Figs 16, 19 and Appendix 2). At station G2000-30 elevated Ba concentrations are in the top 4 cm. Elevated Ba concentrations are analysed in the top 2 cm at G2000-60 and in the top 4 cm at both stations G2000-125 and G2000-250 indicating drill cutting layers. Ti has high concentration at station G2000-10. The top 2 cm of G2000-30 also has elevated concentrations of Ti. Ti is the main element of ilmenite, which was also used in the drilling of well G2000. In addition, all the metals except Cd and Pb show a slight increasing trend similarly to Ba concentration in the top 2-3 cm of G2000-30, however their concentrations correspond to background level (Level I) in the classification of sediment quality. The clay and silt contents at G2000-10 is highest of all stations and they (especially clay content) show similar trends together with the Ba and Ti concentrations indicating that Barite and Ilmenite were in the fine-grained sediment fraction discharged. The increase of Ba concentrations in the top of the rest of the stations are not coinciding with a finer grain-size. This indicates that the Ba did not have a uniform but rather wider range in grain-sizes, which resemble the natural grain-size of the sediments. TOC content is lowest at 12-20 cm depth at G2000-10 and it shows an opposite trend to Ba and Ti concentrations throughout the core, which might indicate possible recovery of sediments from 12 cm toward the top of the core. The metal concentrations of the cores, apart from Cr in one sample (Level II), show background sediment quality levels (level I) (Bakke et al. 2010). Further, none of the other metal concentrations, apart from G2000-30, shows similar trends to Ba (or Ti) concentration. Hg concentrations show generally 4 times higher than natural sediments in G2000-10 and 2 times higher in G2000-30 and G2000-250 in the drill cutting layer indicating that it can be associated to discharged drill cutting. Pb concentrations are generally 2 times higher in G2000-10 than in the natural sediments while in other stations it is similar to natural sediments. Despite that Hg and Pb concentrations are higher than in natural sediments they still correspond to background level (Level I) in the classification after Bakke et al. (2010). Decreasing metal concentrations at G2000-10 suggested that the top 2 cm of the core represent physical sediment recovery. However, Ba concentrations of the top sediment layer at all of the stations indicate no physical recovery indicating re-transportation of the Ba rich sediments by bottom current. The increase of the Ba concentrations on the top sediments at these sites (also Cr and Cu at G2000-30) might be caused by the re-transport of drill cuttings after the discharge similarly to the well from 1987 studied by Junttila et al. (2018). The thickness of these Ba layers are from 2 to 4 cm and Ba concentrations considerably lower than at G2000-10 (especially >30 m from the wellhead). Therefore, it would be possible that the sediments would have been transported by bottom current from the wellhead and close by sediments to the stations, while natural sedimentation from above would have been mixed in it simultaneously.

The 16 EPA-PAH contents were analysed on the sample depths of 1.5 cm, 7.5 cm and 12.5 cm at G2000-10. None of the results indicated higher than good level (Level II, Bakke et al. 2010) concentrations for individual 16 EPA-PAH nor SUM of 16 EPA-PAH. Most of the concentrations were of baseline level (Level I).

Foraminiferal response (Dijkstra et al., in press)
Environmental impact of released drill cuttings was only registered by the fossil foraminiferal assemblages in the core taken 10m away from the well head (core G2000-10). This environmental impact was mainly attributable to smothering of the in-situ fauna and resulted in low foraminiferal densities (Fig 16 and Appendix 2). The released drill cuttings did not directly result in changes in foraminiferal species composition. However, in the core (G2000-10) taken at the station 10m from the wellhead, we observe a shift in dominating fauna that coincides with changes in Ba concentrations. The lower part of core G2000-10 (4-20 cm core depth) consisted of an “old” fossil assemblage (Assemblage II) interpreted to be released together with the drill cuttings. The upper part of core G2000-10 (top 4 cm) consisted of a “modern” fauna (Assemblage I), consisting of species normally observed in unimpacted areas of the southern Barents Sea. The increase in abundance of species grouped in Assemblage I corresponds to decreasing Ba concentrations. We therefore interpret the top 4cm of core G2000-10 to reflect a recovery layer that has been deposited after the initial release of drill cuttings at well G-2000 (See figure 16 and figure caption for more details).

Live foraminiferal fauna showed no impact of the drill cuttings released in the year 2000. This indicates that the live fauna was not impacted (anymore) by the released drill cuttings at the time of sampling and thus additionally indicates recovery of the seafloor environment 15 years after the release. Recovery was also confirmed by visual inspection of the samples through a microscope, showing a different sediment composition in the top part of core G2000-10, with natural looking sediments in the top part of the core, and foam like and green particles in the lower part of the core (Fig. 18).

All other changes in foraminiferal faunal composition at this well did not coincide with sediments influenced by drill cuttings, and were interpreted to be the result of natural environmental changes (Fig 19 and Appendix 2). We conclude that the impact of drill cutting release on the foraminiferal fauna was confined to less than 30m downstream from the wellhead.

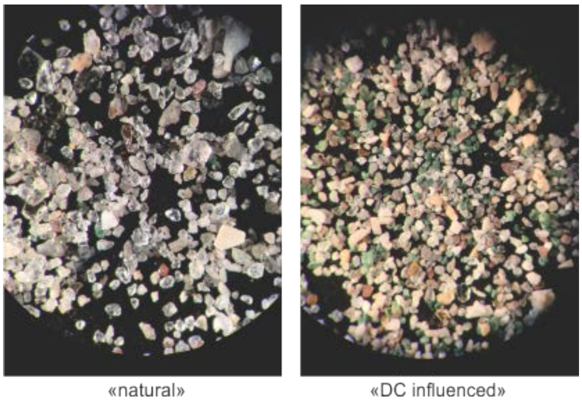

Fig. 18. Left: Picture through microscope of 0.1-1 mm fraction of sample from top of core G2000-10 (0-4 cm) consisting mainly of natural sediments (high amounts of quartz) Right: Picture through microscope of 0.1-1 mm fraction of sample from lower part of core G2000-10 (4-20 cm) consisting mainly of drill cuttings (foam-like yellowish and green particles).

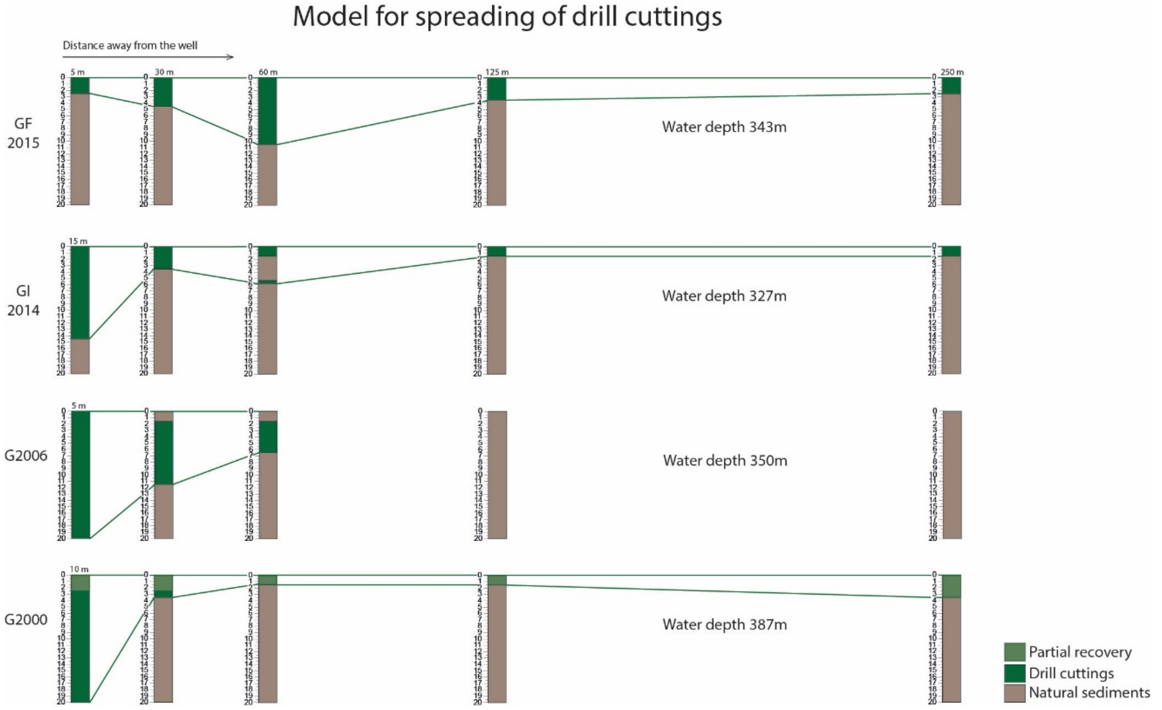

Fig. 19. A model of spreading of drill cuttings in the wells in terms of thickness and distance. Model for G2000 is from Dijkstra et al., in press.

G2006

Sediment condition (Aagaard-Sørensen et al. 2018)

Drill cutting influenced sediments were identified by detection of elevated Ba (and S) concentrations and changes in sediment grain size. DC influenced sediments spread to at least a distance of 60 m from the wellhead with thicknesses decreasing away from the wellhead reaching minimum 20 cm at 5 m (away from the wellhead), ~8 cm at 30 m and 2–3 cm at 60 m (Figs 19, 20 and Appendix 2). At 5 m the DC influenced sediment reaches the surface, while at 30 and 60 m it is covered by ~2 cm almost un-impacted sediment suggesting a post-impact sedimentation rate of ~2.5 mm/yr, while sedimentations rates in non-impacted sediment sections established via 210Pb dating on average were ~0.6–1.7 mm/yr.In both stations 30 and 60 m away from the wellhead the abrupt transition from low to high Ba values indicates the commencement of drill cutting sedimentation which is accompanied by fining of the sediment with an increase of the silt + clay fraction (< 63 μm), indicating settling of finer drill cutting related sediments downstream from the drill hole. The top sediment at 0–2 cm core depth at stations 30 and 60 has low but still slightly elevated Ba levels compared to background values as observed in other cores/core sections and non-impacted local cores (Dijkstra et al., 2015). This slight Ba enrichment likely represent sediments settling after cessation of drilling activity influenced by a combination of bioturbation of the more Ba enriched sediment below in conjunction with reworking of unconsolidated Ba enriched top sediments upstream (e.g. Neff et al., 1989; Junttila et. 2018).

Foraminiferal response (Aagaard-Sørensen et al. 2018)

The foraminiferal fauna composition observed within the strongly DC influenced core 5 (below 5 cm core depth) and in parts of core 30 m from the wellhead (~2–11 cm core depth) shows high relative abundance of arctic species which is markedly different from the live and the fossil fauna composition observed before and after drilling ended (Fig 20 and Appendix 2). The abundance and composition of the fossil fauna observed within the minimally impacted ~2 cm surface sediment in cores 30 m and 60 m from the wellhead furthermore suggest that a natural fauna likely reestablish soon after drilling ended. The immediate impact of DC releases is observed in core 30 m from wellhead where an abrupt and market shift in sediment properties indicates a stop of bioturbation due to delivery of ~8 cm drill cuttings smothering the benthic foraminiferal fauna (Fig. 20). The live foraminiferal fauna observed at all distances from the drill site live fauna distributions from non-impacted local studies. This indicates that a natural foraminiferal fauna had reestablished at the time of coring. The live fauna also resembles the post- and pre-impacted fossil fauna observed in the non-DC influenced sediments of the cores, which shows that the environment in the area was the same prior to and after DC release.

G-I (2014)

Sediment condition (Junttila et al. in prep.)

At station GI-15, high Ba concentrations are observed from 15 cm depth to the top of the core indicating similar thickness to drill cuttings (Fig 19 and Appendix 2). High Ba concentrations were analysed in the top 6 cm of GI-30. At station GI-60 the Ba concentration indicated drill cutting to be 8 cm thick where in station GI-125 it is 2 cm and at GI-250 4 cm thick. At GI-15, the highest Ba concentrations from 6 cm depth to the top of the core coincide with higher concentrations of Cr, Cu, Hg and Pb, which suggests that these metals can be associated with drill cutting release at station GI-15. Cu concentrations correspond to from bad to good sediment quality (level IV-II) from 6 cm core depth to the top of the core at GI-15. The increase of Cu concentrations is gradual starting from good level (level II), followed by bad level (level IV), then moderate (level III) and back to the good level (level II) on the top cm of the core GI-15. The high Cu concentrations could be explained by weakly diluted barite at the core site with little other drill cutting material, for instance sediments from the drill hole or surrounding natural sediments. The increase of drill cutting related metals can also be seen in clay and silt contents, which increases simultaneously with them in core GI-15.This indicates the discharge was drilling mud with fine sediments. These fine sediments (clay and silt) increases the possibility for later re-transport of barite since finer sediments are easier to transport by bottom currents and based on the studies of the well from 1987 (Junttila et al. 2018) this might go on for decades. Although, it should be noted that even though Ba is harmless to the environment the top 5cm of core GI-15 contains Cu concentrations up to (71 mg/kg) bad level (level IV) which means that the Cu might be re-transported as well. However, it could be possible that during possible re-transportation the sediments with high Cu concentration become diluted (reworked with natural sediments) and reach <51 mg/kg concentration, which corresponds to good level (Level II) sediment quality (Bakke et al. 2010). The rest of the metal concentrations at all of the stations of well GI are of background level (level I).

G-F (2015)

Sediment condition (Junttila et al. in prep.)

At the well GF the Ba concentrations are highest in the GF-60 instead of in the core closest to the well like at G2000 and GI wells (Figs 19, 20 and Appendix 2). This is also different compared to a well G2006/2007 (7122/7-5) from the same field studied by Aagaard-Sørensen et al. (2018) and also to wells at other parts of SW Barents studied by Junttila et al. (2018). Ba concentrations at GF-60 are on average 101 times higher in the top 13 cm than in the natural sediments deeper down in the core, which indicates the that thickness of the drill cutting layer is 13 cm. The highest Ba concentrations and thickest drill cutting layer at GF-60 could be caused by the difference in releasing technique for example discharge of cuttings higher up in the water column. However, since we do not possess any information from the cutting release this is only speculative. Ba concentrations are high at GF-10 in the top 3 cm where at GF-30 it is high in the top 6 cm. These depths indicate the thickness of the drill cutting layer for these cores. At GF-125 Ba concentration is high in the top 5 cm where at GF-250 it is highest in the top 3 cm. Cu concentrations at station GF- 60 correspond to bad quality (Level IV) in the top most 2 cm of the core and to good quality (Level II) in 7 cm depth. Both of these depths are within the elevated Ba contents indicating that the sediments are drilling mud/cutting affected. Similarly to GI-15, the high Cu concentrations could be explained by slightly diluted pure barite with little of other drill cutting material. The bad level (Level IV) Cu concentrations at the top 2cm coincides with increase of both clay and silt content which could indicate possibility for future re-transport. However, these sediments with high concentrations of Cu could also be diluted to concentrations corresponding to good level (level II). Rest of the metals in this core and other stations show background quality levels (Level I).

Foraminiferal response (Aagaard-Sørensen et al. in prep.)

The site was samples less than one year after drill cutting release and the foraminiferal fauna at 60 m from the well showed a clear impact from smothering at 10 cm core depth, but also showed a complete recovery within the surface sediments indicating an almost immediate (within one year) re-establishment of a natural fauna despite (Fig. 20) elevated copper values. The other sites in the sample transect showed some impact from drill cuttings in the surface sediments, but no impact on the foraminiferal fauna. Like in GOL2006/07 the most DC influenced sediment section at 60 m from the well held an ancient Arctic fauna related to the drilled sub-bed.

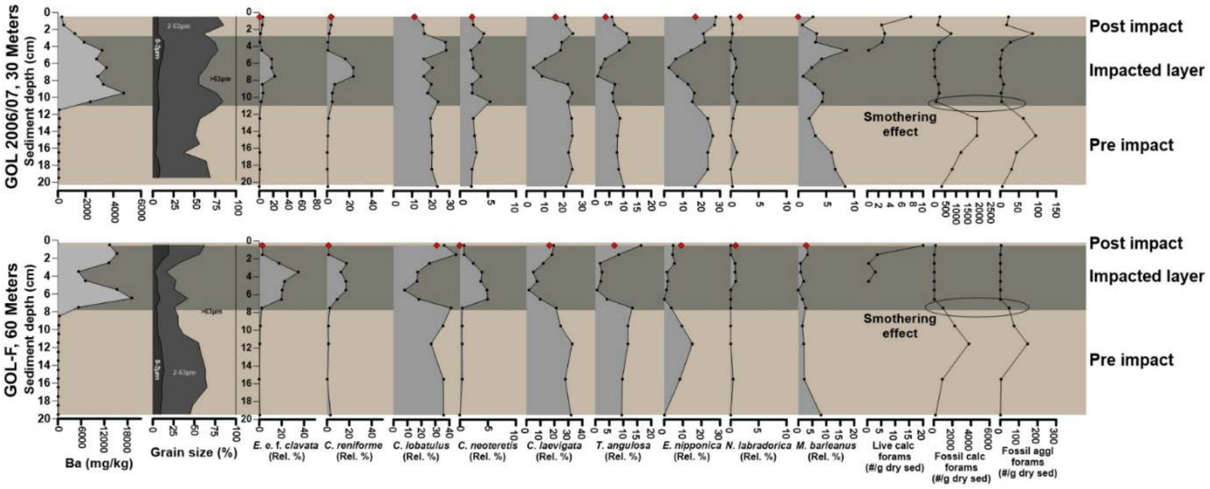

Fig 20. Proxy data from GOL 2006/07 (30 m from wellhead) (Aagaard-Sørensen et al., 2018) and GOL-F (60 m from wellhead) (Aagaard-Sørensen et al., (in prep)) showing pre-impacted (Light brown-gray shade), impacted (Dark brown-gray shade) and post-impacted (Light brown-gray shade) sediments (see also Appendix II) in addition to faunal smothering depth. (From left to right) Barium (Ba) concentrations (mg/kg). Accumulated sediment grain size (Clay (Black, 0-2 µm); Silt (Dark gray, 2-63 µm); Sand (No fill, 63 µm-2 mm)). Relative abundance of fossil (>5 Rel.% in at least one sample) and live calcareous benthic foraminiferal species. Red Diamonds=Live species relative abundance in top sediment (0-5 cm core depth). Total abundance (#/g dry sediment) of fossil and live calcareous and fossil agglutinated foraminifera.

Baseline studies in the SW Barents Sea: Ingøydjupet and Bjørnøyrenna

(published in Dijkstra et al., 2015, 2017; Junttila et al. 2014, Junttila et al., 2015)

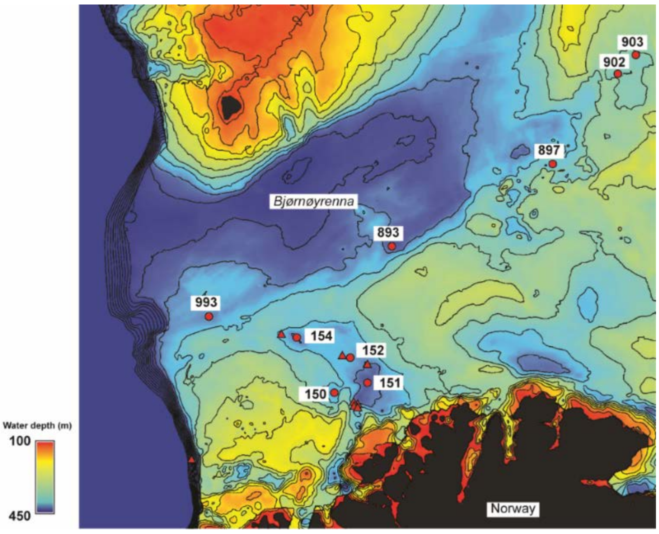

Fig. 21. Map of stations for baseline studies. Red dots are stations for baseline studies (Junttila et al. 2015, Dijkstra et al. 2015; 2017) while red triangles are the studied wells.

Metal concentrations (and PAH concentrations for Ingøydjupet), sediment properties and benthic foraminiferal assemblages were investigated in four sediment cores in Ingøydjupet and five sediment cores along a SW-NE transect in the Bjørnøyrenna trough (Fig. 21). This gained insight into the temporal natural variability of these parameters. The data set serves as an environmental baseline for monitoring potential future environmental impacts associated with petroleum industry activities and other anthropogenic activities in the area. Outcomes of these studies have additionally been used to make an environmental interpretation of the foraminiferal assemblages observed in the transects around the investigated wells in Ingøydjupet. Finally it enabled reconstruction of changes in Atlantic water inflow into the area since ca.1800 CE. Variability in Atlantic water inflow influences both transport of contaminants towards the study area and storage of contaminants into sediments.

Overall, metal concentrations (and PAH concentrations in Ingøydjupet) are considered to be of background/no effect levels (class I and II; Bakke et al., 2010), and are not expected to effect the foraminiferal assemblage. Down core changes in metal concentrations (and PAH concentrations in Ingøydjupet) could be attributed to (natural) variability of the sediment properties (clay and TOC) caused by bottom current changes and natural changes of Atlantic water inflow serving as transport agent of Hg and Pb. An increase in Pb and Hg concentrations after 1960 CE in the SW part of the study area is potentially the only indication of an anthropogenic signal, associated to emission of leaded gasoline. Hence, the reconstructed range in down core metal concentrations and foraminiferal assemblage reflect the (non-impacted) environmental baseline and natural variability of the area.

The most common foraminiferal species could be divided into two groups. Warm associated species (*E.nipponica, M.barleeanus, C.laevigata, C.neoteretis* and *N.auricula*), dominated the assemblages in the SW part of the study area. They reflect the relatively warm conditions and high food flux associated to Atlantic Water inflow in Ingødjupet and Bjørnøyrenna. Cold, Arctic associated species (*E.clavatum, N.labradorica, Buccella* spp.*, C.reniforme* and *Islandiella* spp.,) dominated the assemblages in the NE part of Bjørnøyrenna.

7.4 Conclusions

Drill cutting influenced sediment layers were identified by elevated Ba concentrations (ca. >200 mg/kg), as barite ($BaSO_4$) is used as weighing agent during the drilling process. Based on Ba concentration the spreading of drill cuttings was observed 250 m from the wellheads, varying in thickness from >20 cm (closest to well) to 1 cm (furthest away from the well). Drill cutting impacted layers are generally thickest closest to the wellhead, apart from GF where drill cutting impact was largest at 60 m from wellhead. Drill cutting impacted layers were 1-4 cm thick 250 m from the wellhead. The sediment quality is affected ≤ 30 m from the wellheads, apart from GF where it was affected 60 m from wellhead. The most polluted site in terms of heavy metal concentrations was well T (drilled in 1987), where high Ba concentrations at T10 coincide with the generally high concentrations of Cd, Cu, Hg, and Pb. Additionally Cu concentrations reach bad levels (level IV) in wells GI (15m from wellhead), GF (60m from wellhead) and S (8m from wellhead).

Recovery of sediment quality is observed in some wells, however not in Ba concentrations. On the contrary, increasing Ba concentrations towards present are observed in some wells indicating that Ba rich sediments are still being re-transported by bottom currents. Additionally, metal concentrations were not recovered to background values at well T drilled in 1987.

The main environmental impact of released drill cuttings on the foraminiferal fauna is smothering, obstructing bioturbation and resulting in low foraminiferal densities. ≥8 cm of deposited cuttings resulted in smothering effect. Smothering of fauna is extended ≤ 30m from the well (apart from well GF). The released drill cuttings do overall not result in changes in foraminiferal species composition. In samples from the wells at the Goliat field, we however observe a different foraminiferal fauna within the drill cutting deposits. These species are interpreted to be part of an old fossil fauna, which was released together with the drill cuttings.

Overall, it can be concluded that the effect of the released drill cuttings at all wells is confined to ≤30 m from the wellhead. Exception is well GF where impact was largest at 60 m from wellhead. Traditional monitoring studies around wells mainly focus on samples collected > 250 m from the wellhead, and might thus not capture the real environmental impact of drill cuttings.

Foraminiferal results from well T show that the site remains negatively impacted by drill cuttings even 28 years following their release (i.e. no recovery). Our findings at well G2000 and G2006 indicate that the seafloor environment around the well has recovered, at least partly, respectively 15 and 8 years after the release of drill cuttings. At well S absence of live fauna implies that no recovery of foraminiferal assemblage 3 years after the release of drill cuttings. This is in contrast with well GF where the foraminiferal assemblage showed a complete recovery almost immediate (within one year) after the drill cutting release.

In addition, it can be generally concluded that there is a difference in sediment quality and environmental impact before and after the legislations in 1993. However, our findings in well E (drilled in 1992) suggest that not all drill cuttings released before stricter regulations set in place in 1993 have resulted in negative environmental impact. The relatively low amounts of drill cuttings released at this site seem to have limit the environmental impact.

Finally, it should be emphasized that the environmental impact and spreading of the drill cuttings is site specific. Factors as bottom current strength, water depth, sediment properties influence the spreading of drill cuttings and uptake of contaminants. The type of seafloor fauna and their sensitivity to stressors (i.e. sensitive, indifferent or opportunistic species) will influence the extent of ecosystem impact. The extent of the environmental impact and spreading of drill cuttings might therefore be different at locations outside of or even within Ingøydjupet.

8 Socio-economic issues (work package 4)

Coordinated by UiT and Norut samfunnsforskning
Researchers: Peter Arbo (WP leader), Maaike Knol-Kauffman, Ann-Magnhild Solås (UiT). Heidi Rapp Nilsen, Arild Buanes (Norut)
Task 1: The science-policy-industry interface of waste management (UiT)
Task 2: Comparison with the waste management in the mining industry (Norut)
Task 3: Modifications to the discharge regime (Norut)

Since the 1990s, great efforts have been made to reduce the discharges to sea from ordinary petroleum operations on the Norwegian continental shelf. Zero harmful discharges was first formulated as a political goal in a 1997 report to the Storting, and over the years the work has included prohibition of discharges to sea of oil-based drilling fluids and contaminated cuttings, reduction of the oil content in produced water, and phasing out of environmentally harmful chemicals. Comprehensive monitoring and reporting schemes have also been established.

In 2001, a new government took office, and due to strong political controversy over oil operations in the Lofoten - Barents Sea area the government imposed a moratorium on all new activity until an environmental impact assessment of full-year petroleum operations had been carried out. The government also announced that it would present a comprehensive management plan for the marine environment. The outcome of this process was a tightening of the requirements for oil operations in the northern areas of the Norwegian continental shelf. Instead of zero harmful discharges, the new principle introduced was zero physical discharges. With the exception of the top hole section, there should be no discharges to sea when drilling wells, and drilling waste should be reinjected or brought on land. Nor should there be any discharge of produced water during normal operations.

When the BARCUT project was initiated, the zero physical discharge regime described above still applied. This raised several questions: Was it a rational move to require zero physical discharges during drilling and production? How did these regulations come about? What did they tell about the prevailing risk conceptions and the relationship between science and policy design in this policy field? The extra stringent requirements for the Barents Sea - Lofoten area were lifted when the management plan was updated in 2011. From then on, the rules were harmonized with those applicable to the North Sea and the Norwegian Sea. This, however, raised another question: How could this policy shift occur without any strong political opposition?

Three sub-projects have looked at various social and economic aspects of the management of drilling waste on the Norwegian continental shelf. The first has concentrated on the evolution of the Norwegian discharge regulations and the interaction between science, government, and industry in the management of environmental risks. The second sub-project has studied the waste management regime in the mining industry. The third has looked at possible future changes of the discharge regime.

8.1 The science-policy-industry interface of waste management

8.1.1 Introduction

This sub-project, which has been carried out by the Norwegian College of Fishery Science, has included a survey of the development of environmental regulations on the Norwegian continental shelf and an analysis of the changing governance regimes and what has been achieved in terms of discharge reductions.

8.1.2 Materials and Methods

The work has comprised a comprehensive review of White Papers and reports from various public agencies and industry organizations. It has also included a review of a large number of scientific publications. In addition, 15 semi-structured interviews have been conducted with representatives of the oil industry, the Ministry of Climate and Environment, the Norwegian Environment Agency, the Norwegian Petroleum Directorate, the Petroleum Safety Authority Norway, the Institute of Marine Research, and the environmental organization Bellona.

8.1.3 Results and discussion

The oil business has always been associated with risk. When drilling for oil began on the Norwegian continental shelf, a blow-out or a spill from an oil tanker were regarded as the greatest environmental threats. The potential damages were demonstrated by the Torrey Canyon disaster in 1967, when a supertanker ran aground off the British coast, and the Santa Barbara oil spill in California in 1969. In both cases, the consequences were highly visible in the form of fouled coastlines and dead seabirds. Discharges from regular petroleum operations, however, received little or no attention. Their effects could not be observed without techno-scientific intermediaries, and the environmental consequences thus remained uncertain.

How did operational discharges become a risk object that required public intervention? The environmental movement and the increasing international focus on marine pollution propelled this transformation. Marine pollution was an important issue at the UN Environment Conference in Stockholm in 1972, and the issue was followed up through the Oslo Convention the same year and the Paris Convention two years later, which in 1992 were merged and extended into the OSPAR Convention. In Norway, the Ministry of the Environment was established in 1972 and the Norwegian Pollution Control Authority (SFT) in 1974. The environmental studies carried out around the oil installations in the North Sea in the 1970s showed only minor and highly local effects. However, during the 1980s, more critical studies began to emerge. The research on oil and the marine environment was stepped up sharply after the Bravo accident in 1977. When the Pollution Act was introduced in 1981, the oil companies had to apply for a discharge permit and were required to monitor the marine environment around the installations. After some years, SFT engaged researchers to look into these reports, and the conclusion was that discharges of oil contaminated drill cuttings were a significant source of disturbance and pollution of benthic communities, which could have far-reaching consequences for ecosystems. At the beginning of the 1990s, the discharges of produced water also caused growing concern. The volume of produced water was expected to increase rapidly as the fields in the North Sea became more mature. Since produced water also contains a range of added chemicals and naturally occurring substances with environmentally harmful effects, such as PAH, alkyd phenols, heavy metals, and radioactive isotopes, the focus of the discussion in the 1990s changed to restricting the release of harmful substances. Therefore, it was the environmental movement and the environmental and fisheries authorities, supported by biological and environmental sciences nationally and internationally, that helped define the operational discharges from petroleum operations as an environmental risk. The researchers developed methods for sampling and analysis, and discharges were thus transformed from a type of opaque and diffuse marine pollution to a set of measurable environmental problems.

How was this new set of environmental problems regulated? The Paris Convention covered oil spills from offshore installations. From 1988, it was recommended that discharges of water from all new installations should not exceed an average of more than 40 mg/L of oil-in-water. After 1992, it was also prohibited to release oil-based drilling fluids or cuttings with oil concentrations exceeding 1 percent of the weight. At that time, the management system was prescriptive. The authorities imposed requirements and tried to verify that the companies complied with the regulations. However, the problem with this model was that it did not encourage companies to take active responsibility. Hence, responsibility remained with the controlling authorities, which faced increased institutional risk, because they were in charge of problems beyond their control. The experiences with the Alexander L. Kielland platform, which capsized in 1980, led the authorities to formulate new HSE regulations premised on the principles of internal control, which transferred the main responsibility to the companies. The same principles were adhered to in the Petroleum Act of 1985. Although the oil companies initially believed that there was little reason to take operational discharges seriously, both the Exxon Valdez accident in 1989 and the Brent Spar campaign against Shell in 1995 increased the environmental consciousness throughout the industry.

In 1995, Statoil's CEO took the initiative to establish MILJØSOK, a project that aimed to make the Norwegian shelf a showcase for cost-effective and environmentally friendly petroleum activities. This marked the transition from a prescriptive command-and-control regime to a regime where the oil companies worked closely together with the authorities. The oil companies now recruited their own environmental officers and confirmed their willingness to limit discharges, develop new cleansing technologies, and replace environmentally harmful chemicals. Shortly thereafter, the authorities made zero harmful discharges an important policy goal. This implied that oil and gas activities should be guided by the precautionary principle, and as a rule, no oil or other environmentally hazardous substances should be discharged to sea. In 1998, SFT initiated the zero discharge group. The group, which included representatives from industry, authorities and expert institutions, was commissioned to provide advice and guidelines for the zero discharge work. The industry also actively engaged in the OSPAR Offshore Industry Committee. In 2001, OSPAR set new targets for discharges of produced water and oil content, and the zero discharge group looked specifically at how the targets could be achieved by 2005 for all existing Norwegian fields.

What has been achieved through this collaborative system? Close cooperation between the authorities, industry and research institutions has resulted in three important changes. First, an overall risk-based approach has been established. The operators on the Norwegian continental shelf, together with SINTEF and other research partners, have developed new tools and a new methodology for assessing the individual components of discharges, their dispersion, the recipient conditions, and potential harmful effects for marine life. Through the DREAM (Dose-related risk and effects assessment) and the EIF (Environmental Impact Factor) models, it has become possible to compare alternative remedying measures and to find field-specific solutions based on comprehensive environmental risk calculations. The same approach has been adopted by OSPAR. Secondly, there has been an extensive data collection and build-up of knowledge. This has taken place through research programs such as PROOF and PROOFNY, regular sediment and water column monitoring, verification of dispersal models, testing of biomarkers, studies of effect parameters and other environmental studies. Thirdly, a number of measures has been implemented to reduce harmful discharges and make the petroleum activities more environmentally friendly. There has been a transition to water-based drilling fluid. Oil-contaminated drill cuttings are cleansed or taken ashore for disposal or reuse. Produced water is reinjected for reservoir pressure maintenance, deposited in another structure or purified and discharged. Today, the oil content of produced water is well below the limits set by OSPAR. In the 1990s, SFT classified all chemicals into four categories (black, red, yellow and green) based on their persistence, bioaccumulation and toxicity. Since then, black and red chemicals have been phased out and replaced by more environmentally friendly substances. Other technological advancements in exploration, drilling, well operations and production have also contributed to a reduction of drill cuttings and better treatment of produced water.

Why was a special regime introduced for the Barents Sea - Lofoten area in the period 2006 - 2011, just to disappear again without much fuzz? The extra stringent requirements were part of the compromise needed to open this area for year-round petroleum activity. The shelf areas in the north have long been considered particularly environmentally vulnerable, and fisheries represent another important industry. Hence, to get a social license to operate, the oil industry had to demonstrate a strong environmental commitment. Otherwise, the precautionary principle could have been used as an argument against all oil and gas operations. At the same time, the ambitions of the industry had risen through the zero discharge work. Among the environmental officers, many believed that it would be possible to produce oil and gas without operational discharges. There were different views both across and within the individual companies, but the industry finally committed to avoiding discharges to the sea when drilling wells, with the exception of the top hole section, and there should be no discharges of produced water during normal operations, with only 5 percent disruptions permitted.

Several factors explain why these stricter regulations were withdrawn after a few years. One reason was the progress achieved through the zero discharge work. The good results obtained in the North Sea and the Norwegian Sea made it less obvious why a stricter regime was needed in the Barents Sea. Another reason was a report prepared by SFT, the Norwegian Petroleum Directorate and the Norwegian Radiation Protection Authority in 2008. This report found that it was difficult to see any environmental benefits from storing cuttings and transporting the waste to land for disposal. Transport and treatment on land implied higher energy consumption and increased emissions to air. It also required more personnel, and the many crane lifts entailed risks in the working environment. One type of environmental consideration was thus contradicted by another type of environmental consideration. A third reason was changing political agendas. In the political debate, focus was more and more concentrated on the issue of opening Lofoten and Vesterålen for oil drilling. In addition, the future of oil and gas activity tended to be seen in a climate perspective. Consequently, the operational discharges became a less important issue. A fourth reason was that the risk-based approach made it more difficult to politicize the discharges issue. This had become a matter for experts, revolving around technical details, field-specific solutions and complicated trade-offs. The main conclusion that could be drawn from all the environmental monitoring and research undertaken was that the operational discharges from petroleum activities cause no, or only moderate damage. Drilling waste has a local smothering effect, but the areas are rapidly recolonized when the operations are terminated. The discharges of produced water contain low concentrations of harmful substances, which are quickly dispersed and diluted in the water masses.

8.1.4 Conclusions

Over the past 50 years, operational discharges from the petroleum industry have gone from being a non-issue to becoming a risk object that has been tamed through a risk-based approach. Since the 1990s, the authorities, industry and research institutions have developed a close cooperation. Considerable resources have been spent on environmental research, technology development and replacement of chemical additives. The oil industry's efforts have yielded significant gains. However, the regime also creates its own challenges. One is the danger of regulatory capture. That is, regulatory authorities become too dominated by the industrial interests that they are set to regulate. Instead of acting on behalf of the public interest, they act on behalf of the industry that they are responsible for regulating. Another is the difficulty of taming environmental risks, even within a risk-based framework. The controversy over operational discharges is unlikely to cease. There will still be disputes about neglected substances, measurement methods, the classification of chemicals, their integrated effects, and about how climate change and other stressors amplify the consequences of discharges. Neither the concept of risk nor how much risk is accepted is something constant.

8.2 Task 2: Comparison with the science-policy interface of waste management in mining industry

8.2.1 Introduction

This task centred on four interrelated issues: a) identifying relevant stakeholders at different leveIs, and b) their role in the constitution of mining industry regulations and solutions, to c) assess whether and which economic cost-benefit considerations were involved, and discuss d) how the discourses affect the legitimacy of both mining and the environmental regulations.

8.2.2 Materials and Methods

The task focused on documentary materials concerning hearing responses to the 2009 Minerals Acts and the 2012 "Strategy for the mineral industry" for analysing stakeholder involvement regarding this sectoral policy at national level, and hearing responses to the land use plan for the proposed Nussir copper mine in Kvalsund municipality, Finnmark, for local responses.

8.2.3 Results and discussion

The Mineral Act proposal (Ot.prp. nr. 43 (2008-2009) did not target waste management as such, since this is a topic covered by other legal instruments (a.o. environmental impact assessments pursuant to the Planning and Building Act, the Pollution Act), but focus on mining rights issues. The main active stakeholders were state agencies, industry organisations and land owner organisations. In addition, with special relevance for northern areas, the chapter 14 on mining in Sami areas, mobilised input from the Sami parliament and the reindeer management. The mining municipality of Sør-Varanger articulated a position drawing support from other elected bodies at the regional and local levels, stressing the importance of the balancing of different legitimate concerns (also including waste rock deposits) that occurs through the planning system, in addition to other more topically delimited regulations (e.g. Pollution Act). The Mineral strategy drew responses from a wider range of stakeholders, and here waste management (deposits) was a central concern. Although a strategy for a policy domain is less formalised than a legal act or regulatory mechanisms, the numerous inputs from a wide range of actors signalled that the discussions on future policy direction in the Minerals strategy was given high importance by a wider range of actors: labor and industry organisations, environmental NGOs, seafood industry organisations. Regarding land use at the local level (Nussir), stakeholder composition in the process is even broader and more diverse, and as land use plans are legally binding, it can be argued that they carry a more "hands-on" urgency. In general, cost-benefit considerations at both sectoral policy and local planning levels were not formalized, but more qualitative claims regarding the relative burdens and benefits.

8.2.4 Conclusions

Mining operations take place in a multi-level governance structure where various national policies and instruments, such as the Minerals Act, the governmental mineral strategy, the

Pollution Act, the Nature Diversity Act, the implementation of the EU Water Framework Directive, a.o. meet with local political (majority) priorities given expression through planning decisions pursuant to the Planning and Building Act. In the north, the topic of indigenous rights also raises issues of legal pluralism, i.e. whether national decisions on land use and waste rock deposits are in accord with international law.

8.3 Task 3: Modifications to the discharge regime

8.3.1 Introduction

In the original Barcut project description from 2013 this task 3 was formulated as a cost-benefit analysis, to compare the former physical zero-discharge regime of the Barents Sea to the regime for the rest of the Norwegian Continental Shelf. However, as Barcut started, the former regime was aligned with the latter, hence such a cost-benefit analysis no longer had any purpose. Instead, the chosen approach, modifications to the discharge regime, was decided in a meeting between Norut and Eni's John Erik Paulsen in 2013. Paulsen argued that 'what is the next move' with regard to environmental challenges as posed by different stakeholders, would be interesting to learn about both for Eni and for Barcut.

This task is described in detail in the publication by Heidi Rapp Nilsen and Trond Nilsen (both former Norut): "Licence to pollute: Stakeholders' suggestions for environmental improvements on drilling waste in the Barent Sea", *Barents studies: At the economic, social and political margins,* 2018, vol 5, Issue 1, p. 58 - 80.

In the rest of this subchapter, a short description of this task and paper is included. Still, there is reason to stress that after the publication of this paper, the crucial importance of the integrity of both land- and seascapes are highlighted in the report by The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019). Here IPES stresses the necessity to keep areas free from human activity and stressors, even though each and one of these activities are not deemed harmful to the environment. This is an ecosystem approach, which is a systemic approach, as is guiding the specific task further referred to below.

8.3.2 Materials and Methods

We apply a theory on stakeholders to identify so called definite stakeholders and gather qualitative data on suggestions for environmental improvements to the discharge regime. Both document analysis and interviews of stakeholders are made.

8.3.3 Results and discussion

There were identified 5 different suggestions on modifications to the discharge regime were one of these was supported by all stakeholders, hence this is what is called the most salient proposal. This suggestion is to change the decision-making process and power structure, in granting permission to pollute at the sea floor. In today's regime the public authorities must negotiate with single petroleum firms when granting permission to dump drilling waste. A firm's bargaining position is naturally affected by firm-specific challenges, such as their financial and technical situation. Petroleum firms holding a license to drill is at the same time obliged to use this license to drill. This puts the firms in a very strong position for negotiating the content of the permission to pollute. Part of the trade-off which can be negotiated upon is the sea floor integrity.

The proposed modification is that the permission to pollute is specified before the license to drill is announced. The benefit of such a rearrangement is to better safeguard the sea floor integrity, and it yields a more predictable system for the involved institutions and industries.

8.3.4 Conclusion

The total magnitude of stressors on the marine environment is alarming. The policy sphere has been guided by marginalistic research approaches were the totality of environmental stressors are not easy to grasp. In this research paper we use a systemic methodology which enable the use of the term ‘sea floor integrity’ and hence the proposed modification that the permission to pollute is specified before the license to drill is announced. The purpose is to better safeguarde the sea floor integrity. Such a modification demands broader seafloor investigations by the public, at an earlier stage. A report which goes further into various consequences of such a modification, both positive and negative is called for.

9 Oceanographic recordings

Øyvind Leikvin, Akvaplan-niva

9.1 Summary

For full report, see Appendix 1.

Current measurements with a Teledyne Long Ranger (75 kHz) and a Nortek Aquadopp Point current meter (2 MHz) have been conducted at Bønna (70°50.690' N; 16°33.744' E) and twice at Goliat (71°15.453' N; 22°15.877' E and 71°17.429' N; 22°12.058' E), the two latter about 4 km apart. The depths at Bønna was about 1380 m, while at Goliat the depth was 350 – 370 m.

At both Bønna and Goliat I, a bottom intensified current took place, especially at Bønna. The main current direction at Bønna was along the north-south direction (Fig. 22) with a minor residual current. Goliat had an eastbound main current at both measurement periods and measurement sites (Figs. 23 and 24), that rotated somewhat towards southeast near the seafloor. There was a strong residual current towards east and southeast.

The average current of the deepest measurements 2 – 3 m above the seafloor at Bønna was 10.5 cm/s, while at Goliat it was 17.8 cm/s and 14.1 cm/s.

The residual currents near the seafloor at Bønna was relatively weak, 2.1 cm/s, towards east-northeast. The bottom residual currents at Goliat I and Goliat II were much stronger, with 13.9 and 9.6 cm/s towards east-southeast.

This indicates forth-and-back-currents, not due to the tides, at Bønna. At Goliat, the tidal signal is much more present, but the currents are nearly always flowing towards easterly or southeasterly directions.

The spreading patterns of drill cuttings near the seafloor are likely to roughly correspond to the patterns of the water transport/ water fluxes. Hence, at Bønna the likely spreading is both northwards, but also southwards mainly along the bathymetry contours. At Goliat I, the likely spreading pattern of the drill cuttings is nearly completely in easterly and southeasterly directions. At Goliat II, there would also be some drill cuttings spreading in the western direction.

At all the three sites, resuspension of drill cuttings is likely, due to the intermittently strong currents. Depending on the size and properties of the drill cuttings, there is a likelihood for increased turbidity close to the seafloor in the vicinity of the release point.

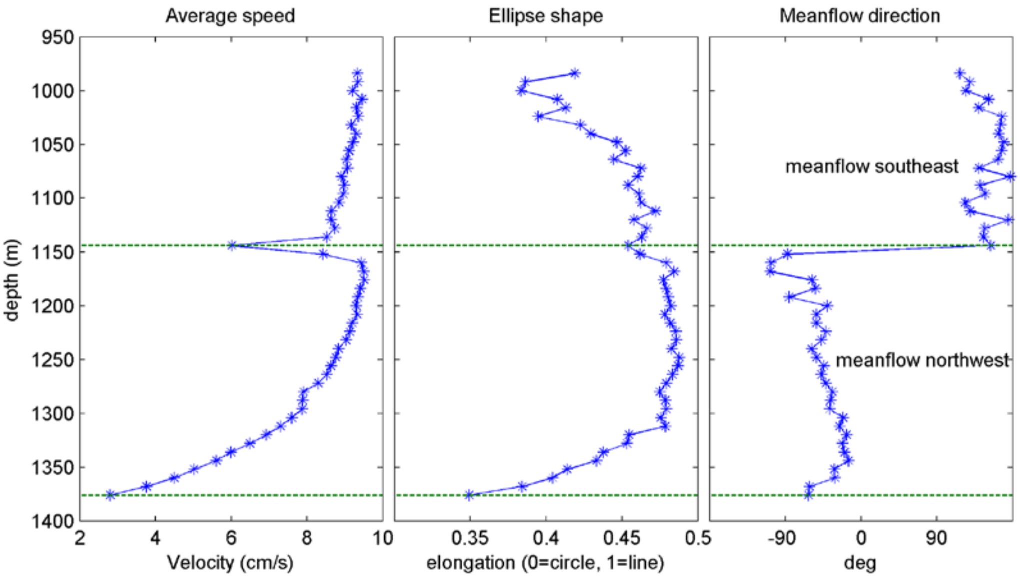

Fig.22. Bønna. Summarised results from the ADCP current profiler, which measured water flow over the lower 450 m of the water column, between 8th August and 15th October 2013. Note the transitional zone at around 1150 m depth, where the mean current flow (right) switches from a northeasterly direction to southwest. The left panel shows the average current. The middle panel shows the elongation of the variance ellipse, where 0 give a perfect circle and 1 give a perfect line. The right panel gives the direction of the residual currents at the various depths.

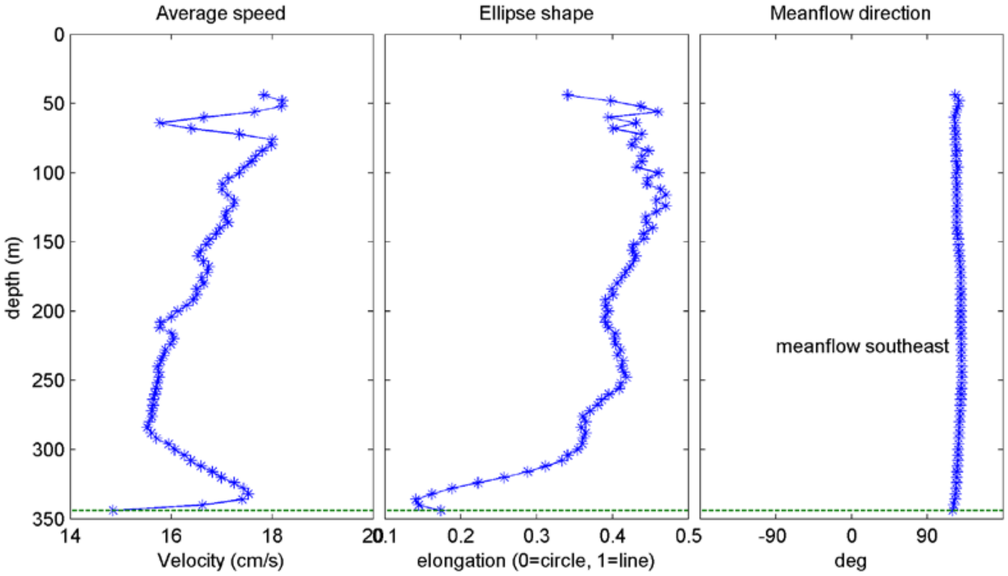

Fig.23. Goliat I. Summarised results from the ADCP current profiler, which measured water flow over the water column, between November 29th 2014 and 6th March 2015. The left panel shows the average current. Note the intensification of the average current speeds from about 290 to 335 m depth, near the sea floor. The middle panel shows the elongation of the variance ellipse, where 0 give a perfect circle and 1 give a perfect line. The right panel gives the direction of the residual currents at the various depths.

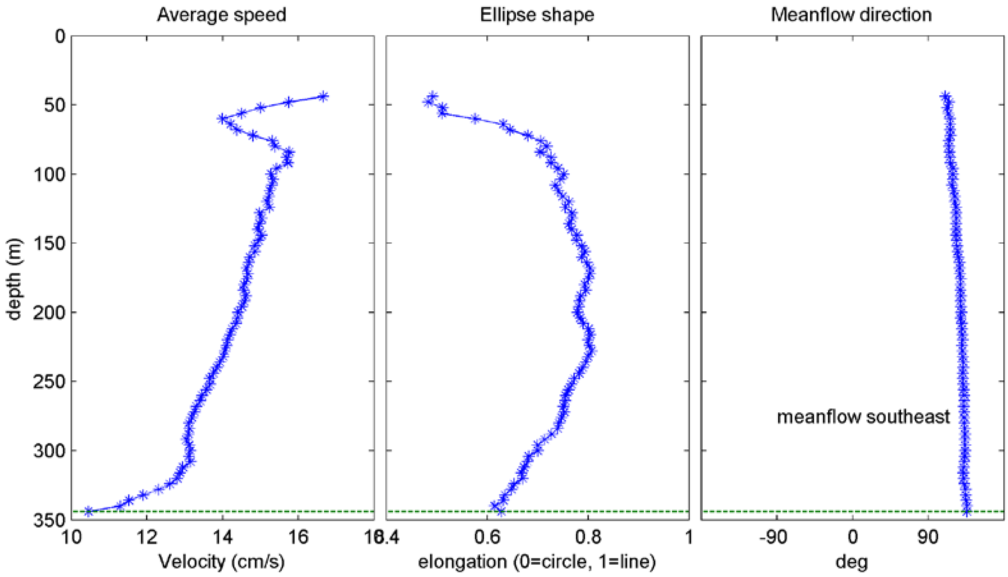

Fig.24. Goliat II. Summarised results from the ADCP current profiler, which measured water flow over the water column, between September 7th 2015 and October 16th 2015. The left panel shows the average current. The middle panel shows the elongation of the variance ellipse, where 0 give a perfect circle and 1 give a perfect line. Note that the elongation is higher than at Goliat I. The right panel gives the direction of the residual currents at the various depths.

10 Outreach

10.1 Scientific publications, PhD, MSc and BSc theses

WP2 Applied seafloor research

Cochrane, S.K.J. Ekehaug, S., Pettersen, R., Refit, E.C., Hansen, I. M., Aas, L.M.S. Detection of deposited drill cuttings on the sea floor - A comparison between underwater hyperspectral imagery and the human eye. Marine Pollution Bulletin, Volume 145, 67-80.

Tan T. Nguyen, Sabine K.J. Cochrane, Bjarne Landfald. Perturbation of seafloor bacterial community structure by drilling waste discharge. Marine Pollution Bulletin Vol. 129, Issue 2, April 2018. pp.615-622

Paulsen, J.E., Cochrane, S.K.J., Leikvin, Ø., Hansen, J., Torbergsen, H., Pierfelici., S. 2014. Assessing Exploratory Drilling Impacts on an Arctic Deepwater Sea-Pen Habitat in Offshore Norway. SPE 168343. Presented at the Society of Petroleum Engineers HSE Conference, California, March 2014.

Cochrane, S.K.J., Junttila, J. and others as appropriate, in prep. Resilience of benthic fauna to deposited drill cuttings in the south-western Barents Sea. Target journal: Marine Ecology Progress Series.

Planned

Synthesis article with more extensive multidisciplinary statistical and oceanographical analyses – aiming to provide a holistic explanation for the apparent resilience of sea-floor systems in the south-western Barents Sea to drill cuttings. Author group as appropriate.

Master, Bachelor and PhD theses

Øverleir, Ida, 2014. Effekter på bakteriesamfunn av boreslamdeponering på havbunnen, Master thesis. UiT the Arctic University of Norway.

Refit, Ea Coralie, 2016. Detection of drill cuttings deposition at the sea floor in the Barents Sea. BSc. Thesis. University of Kassel, Germany.

Than Thi Nguyen, 2017. Microbial community varation in an Arctic seafloor. Biogeograohic and anthropogenic influences. PhD thesis. UiT The Arctic University of Norway

WP3 Spreading and deposition of drill cuttings

Junttila, J., Carroll, J., Dijkstra, N., 2015. Variability of present and past PAH concentrations in sediments of the SW Barents Sea. Norwegian Journal of Geology 95, 191–210.

Dijkstra, N., Junttila, J., Husum, K., Carroll, J., Hald, M., 2015. Natural variability of benthic foraminiferal assemblages and metal concentrations during the last 150 years in the Ingøydjupet trough, SW Barents Sea. Marine Micropaleontology 121, 16-31.

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WP4 Economic and social aspects

Nilsen, Heidi Rapp and Nilsen, Trond (2018): “Licence to pollute: Stakeholders’ suggestions for environmental improvements on drilling waste in the Barent Sea”, *Barents studies: At the economic, social and political margins*, vol 5, Issue 1, p. 58 - 80.

Knol-Kaufman, M., A.-M. Solås and P. Arbo (2019). From complier to accountable partner: The industry's role in the regulation of discharges to sea from petroleum operations in Norway. Paper submitted to Journal of Environmental Planning and Management.

10.2 Presentations and conference contributions

The project web page http://site.uit.no/ewma/ has communicated research description and activity, events and news during the project period. The project participants has also been active presenters in different arenas, communicating through poster, talks and interviews. In all there has been 25 poster presentations, talks, reports and popular science publications. Additionally, project participants have contributed on publications without direct acknowledgement to BARCUT. The project has also communicated results and findings directly to the Norwegian Environment Agency, and contributed to more informed decision-making connected to the marine petroleum industry in northern regions. In addition, results from BARCUT were presented in Offshore miljøforum in Oslo in 2018.

WP2

Cochrane, S.K.J. 2016. Benthic fauna and drill cuttings – can they co-exist? 30 minute invited presentation at the Norwegian Petroleum Association Christmas meeting, 4. December, 2019.

Landfald, B., 2018. Presentation at Arctic frontiers, closing session for EWMA programme.

Cochrane, S., 2018. Presentation at Arctic frontiers, closing session for EWMA programme.

Landfald, B., 2018. WP2. Presentation at Offshore miljøforum 2018.

Cochrane, S., 2018. WP2. Presentation at Offshore miljøforum 2018.

Cochrane, S.K.J., Røberg, S., Dijkstra, N., Junttila, J., Landfald, B., Aagaard-Sørensen, S., Leikvin, Ø., Hveding Bergseth, N., Nielsen, L., Paulsen, J. E., 2016. Environmental footprints of drill cuttings deposition in the southwestern Barents Sea local to ecosystem perspectives. Introduction to the "BARCUT" project. Arctic Frontiers 2016. Presentation.

Cochrane, S.K.J., Numerous presentations of results for various multi-disciplinary presentations, 2015 – 2019. Venues such as the Norwegian Oil and Gas producers association, Akvaplan-niva, NIVA, Eni Norge, Norwegian Research Council and individual petroleum companies.

WP3

Junttila, J., Dijkstra, N., Aagaard-Sørensen, S., 2018. Barents Sea drill cuttings research initiative (BARCUT) – Spreading and deposition of drill cuttings (WP3). Presentation at Offshore miljøforum 2018.

Dijkstra, N., Aagaard-Sørensen, S., Junttila, J., 2018. Foraminiferal responses to drill cutting releases in the SW Barents Sea. Presentation at Forams 2018. Edinburgh, Scotland.

Junttila, J., Dijkstra, N., Aagaard-Sørensen, S., Skirbekk, K., Sternal, B., Forwick, M., Carroll, J., 2018. Deposition of drill cuttings and mine tailings. Presentation at Arctic frontiers, closing session for EWMA programme.

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Dijkstra, N., Junttila, J., Aagaard-Sørensen, S., 2016. Reconstructing pre-impact baseline conditions using benthic foraminifera in an area of increasing petroleum exploration activities. European Geosciences Union (EGU) General Assembly 2016. Poster.

Aagaard-Sørensen, S., Junttila, J., Dijkstra, N., Benthic foraminiferal responses to operational drill cutting discharge in the SW Barents Sea- a case study. European Geosciences Union (EGU) General Assembly 2016. Poster.

Junttila, J., Aagaard-Sørensen, S., Dijkstra, N., 2016. Spreading and deposition of drill cuttings in the Barents Sea – Plans of the Barents Sea drill cuttings research initiative (BARCUT) project. European Geosciences Union (EGU) General Assembly 2016. Poster.

Cochrane, S., Røberg, S., Dijkstra, N., Junttila, J., Landfald, B., Aagaard-Sørensen, S., Leikvin, Ø., Hveding Bergseth, N., Nielsen, L., Paulsen, J. E., 2016. Environmental footprints of drill cuttings deposition in the southwestern Barents Sea local to ecosystem perspectives. Introduction to the "BARCUT" project. Arctic Frontiers 2016. Presentation.

Aagaard-Sørensen, S., Dijkstra, N., Junttila, J., 2016. Pre-impacted baselines and bio-monitoring of the marine environment using benthic foraminiferal assemblages – examples from the SW Barents Sea. Arctic Frontiers 2016. Poster.

Dijkstra, N., Monitoring the environment: the importance of pre-impact baselines. MAREANO conference 2015, Oslo, Norway. Invited speaker.

Dijkstra, N., Junttila, J., Aagaard Sørensen, S., 2015. Bio-monitoring using benthic foraminiferal assemblages – examples from the SW Barents Sea. Arctic Workshop 2015, 10-13 May 2015, Bergen, Norway. Poster.

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WP4

Nilsen, Heidi Rapp, Presentation at internal meeting in Barcut 26 April, 2016. "Status Barcut, WP 4.3. Fra Nytte-kost til Interessent metode.»

Nilsen, Heidi Rapp. Presentation at Arctic Frontier, January 2018, special session for Barcut. "With licence to pollute: Stakeholders' suggestions for environmental improvements on drilling waste in the Barents Sea".

Solås, A.-M., M. Knol and P. Arbo (2015). Involving the industry. Regulation of discharges from the petroleum activity in the Arctic. Presentation at Arctic Frontiers, 22 January 2015.

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10.3 Reports

Solås, A.-M. (2015). Oil and marine environment. About the development of Norwegian petroleum management. Report, Norwegian School of Fisheries, University of Tromsø - Norway's Arctic University.

11 Overall conclusions and implications

11.1 Spatial and temporal impacts of drilling in the SW Barents Sea

Based on Ba concentration the spreading of drill cuttings was observed 250 m from the wellheads, varying in thickness from >20 cm (closest to well) to 1 cm (furthest away from the well). Drill cutting impacted layers are generally thickest closest to the wellhead, apart from well GF where drill cutting impact was largest at 60 m from wellhead. Drill cutting impacted layers were 1-4 cm thick 250 m from the wellhead. The sediment quality is affected ≤ 30 m from the wellheads, apart from well GF where it was affected 60 m from wellhead. The most polluted site in terms of heavy metal concentrations was well T (drilled in 1987), where high Ba concentrations at T10 coincide with the generally high concentrations of Cd, Cu, Hg, and Pb. Additionally Cu concentrations reach bad levels (level IV) in wells GI (15m from wellhead), GF (60m from wellhead) and S (8m from wellhead).

The visual assessments detected deposited drill cuttings to extend to around 150–200 m from the drilling location at recently drilled sites and generally less than 50 m at older locations (3 or more years after drill cutting release). Quantitative underwater hyperspectral imagery (UHI) analyses mostly showed a change-over to conditions resembling undisturbed sediments at approximately similar distances as the visual assessments.

The main environmental impact of released drill cuttings on the foraminiferal fauna is smothering, obstructing bioturbation and resulting in low foraminiferal densities. ≥8 cm of deposited cuttings resulted in smothering effect. Smothering of fauna is extended ≤ 30m from the well (apart from well GF).The released drill cuttings do overall not result in changes in foraminiferal species composition. In samples from the wells at the Goliat field, we however observe a different foraminiferal fauna within the drill cutting deposits. These species are interpreted to be part of an old fossil fauna, which was released together with the drill cuttings.
The study of bacterial microbiota at wells GI, GF and G2006 showed that deposition of water based drilling waste may cause marked disruption of the indigenous seafloor microbiota. Such changes appear restricted to the most heavily affected locations in the vicinity of the wellheads (≤100 m). No significant changes in microbiota was observable at any sampling distance at well G2000. The present study does not give a basis for concluding if this invariance was the result of a 15 years recovery period or the use of less perturbing drilling mud components in the first place.
Benthic macrofauna only found only minimal disturbance, even at recently drilled stations and stations where there was visible deposition of drill cuttings

Recovery of sediment quality is observed in some wells, however not in Ba concentrations. On the contrary, increasing Ba concentrations towards present are observed in some wells indicating that Ba rich sediments are still being re-transported by the bottom currents. Current measurements confirmed that resuspension of drill cuttings is likely, due to the intermittently strong currents. Additionally, metal concentrations were not recovered to background values at well T drilled in 1987. Reduced oxygen penetration into the sediment is still evident up to 9 years after the drilling operation.
Foraminiferal results from well T show that the site remains negatively impacted by drill cuttings even 28 years following their release (i.e. no recovery). Our findings at well G2000 and G2006 indicate that the seafloor environment around the well has recovered, at least partly, respectively 15 and 8 years after the release of drill cuttings. This is in-line with the benthic macrofauna showing recovery and/or no

detectable impacts of drill cuttings at the locations drilled 3 or more years prior to sampling. However, at well S absence of live foraminiferal fauna implies that no recovery of foraminiferal assemblage 3 years after the release of drill cuttings. This is in contrast with well GF where the foraminiferal assemblage showed a complete recovery almost immediate (within one year) after the drill cutting release.

Overall, it can be concluded that the faunal impact of the released drill cuttings at all wells is confined to ≤100 m from the wellhead, while the visual and sedimentary impact is biggest ≤150m from the wellhead. Traditional monitoring studies around wells mainly focus on samples collected > 250 m from the wellhead, and might thus not capture the real environmental impact of drill cuttings. In addition, it can be generally concluded that there is a difference in sediment quality and environmental impact before and after the legislations in 1993. However, our findings in well E (drilled in 1992) suggest that not all drill cuttings released before stricter regulations set in place in 1993 have resulted in negative environmental impact. The relatively low amounts of drill cuttings released at this site seem to have limit the environmental impact.

Finally, it should be emphasized that the environmental impact and spreading of the drill cuttings is site specific. Factors as bottom current strength, water depth, sediment properties influence the spreading of drill cuttings and uptake of contaminants. The type of seafloor fauna and their sensitivity or resilience to stressors (i.e. sensitive, indifferent or opportunistic species) will influence the extent of ecosystem impact. The extent of the environmental impact and spreading of drill cuttings might therefore be different at locations outside of or even within Ingøydjupet.

11.2 Socio-economic issues

The social and economic study looked at various aspects of the management of drilling waste on the Norwegian continental shelf and waste management in mining industry. Regarding drilling waste it concluded that the controversy over operational discharges is unlikely to cease. It also warned for the danger of regulatory capture, in which the regulatory authorities act on behalf of the industry instead of acting on behalf of the public interest. Finally, it proposed a modification of the discharge regime in which the permission to pollute is specified before the license to drill is announced to better safeguard the sea floor integrity. Regarding waste management in mining industry, it concluded that mining operations take place in a multi-level governance structure. In the north, the topic of indigenous rights also raises issues of legal pluralism.

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Appendices

Appx 1. Leikvin, Ø. Current meter measurements. APN

Appx 2. Supplementary figures, WP3

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