National Oceanography Centre, Southampton

Research & Consultancy Report No. 86

Recovery at Morvin: SERPENT final report

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2010

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DOCUMENT DATA SHEET

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TITLE

Recovery at Morvin: SERPENT final report.

REFERENCE

Southampton, UK: National Oceanography Centre, Southampton, 74pp.
(National Oceanography Centre Southampton Research and Consultancy Report, No. 86)
(Unpublished manuscript)

ABSTRACT

Recovery from disturbance is poorly understood in deep water, but the extent of anthropogenic impacts is becoming increasingly well documented. We used Remotely Operated Vehicles (ROV) to visually assess the change in benthic habitat after exploratory hydrocarbon drilling disturbance around the Morvin well located at 380m depth in the Norwegian Sea.

An ROV, launched directly from the rig drilling the well in 2006 was used to carry out video transects around the well before drilling and immediately after. On a return to the site three years after disturbance a larger survey was conducted with a ship-launched ROV in 2009. Transects were repeated at the disturbed area and random background transects were taken. Visible drill cuttings were mapped for each survey, and positions and counts of epibenthic invertebrate megafauna were determined, revealing a fauna dominated by Cnidaria (45% of total observations) and Porifera (33%).

Immediately after disturbance a visible cuttings pile extended to over 100m from the well and megafaunal density was significantly reduced (0.07 individuals m^{-2}) in comparison to pre-drill data (0.23 ind. m^{-2}). Three years later the visible extent of the cuttings pile had reduced in size, reaching 60m from the well and considerably less in some headings. In comparison to background transects (0.21 ind. m^{-2}), megafaunal density was significantly reduced on the remaining cuttings ($0.04 m^{-2}$), but beyond the visible disturbance there was no significant difference ($0.15 m^{-2}$).

The investigation at this site shows a return to background densities of megafaunal organisms over a large extent of the area previously disturbed. However a central area, where the initial cuttings pile was deepest, demonstrated reduced sessile megafaunal density which persisted three years after disturbance. Elevated Barium concentration and reduced sediment grain size suggests persistence of disturbance beyond the remaining visibly impacted area which may result in changes to the infaunal communities undetectable by ROV video survey.

KEYWORDS

ISSUING ORGANISATION

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Not generally distributed - please refer to author

SERPENT

SCIENTIFIC AND ENVIRONMENTAL ROV PARTNERSHIP USING EXISTING INDUSTRIAL TECHNOLOGY

Morvin Recovery Visit Report

collaboration... education... research... innovation...

RECOVERY AT MORVIN: SERPENT FINAL REPORT

Kophobelemnon stelliferum: the most abundant organism in the Morvin surveys

REPORT PREPARED BY DR. ANDREW GATES

Front cover image: A view of a *Lophelia* reef close to Morvin. As well as the coral (*Lophelia pertusa*), *Molva molva* (ling), *Sebastes* sp. (redfish) and the bivalve *Acesta excavata* are also present

SUMMARY

Recovery from disturbance is poorly understood in deep water, but the extent of anthropogenic impacts is becoming increasingly well documented. We used Remotely Operated Vehicles (ROV) to visually assess the change in benthic habitat after exploratory hydrocarbon drilling disturbance around the Morvin well located at 380 m depth in the Norwegian Sea.

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INTRODUCTION

SERPENT

The SERPENT Project, *Scientific & Environmental ROV Partnership using Existing iNdustrial Technology*, is a collaboration between world leading scientific institutions and companies associated with the oil and gas industry. SERPENT is hosted at the National Oceanography Centre, Southampton (NOCS), one of the world's largest research and teaching organisations specialising in deep-sea science and oceanography. SERPENT encompasses a scientific network of academic partners across the world (UK, Norway, USA, Canada, Venezuela, Angola, Australia), linked to a network of major oil and gas operators and contractors.

The project centres on the opportunistic use of Remotely Operated Vehicles (ROVs) in operational settings during periods of stand-by time, i.e. when the ROVs have no tasked work and would otherwise be effectively idle. The project also aims to maximise the scientific benefit of environmental data collected as part of routine offshore operations and environmental surveys.

This report presents the results of SERPENT investigations in collaboration with Statoil on a return visit to the Morvin site which was drilled in 2006. Through the SERPENT-Statoil collaboration detailed studies have been made of the initial effects of exploration drilling on the seabed accessible by ROV from the rig. This work represents the first opportunity to return to a site several years after the initial disturbance, one of the key aims of this collaboration.

MORVIN RECOVERY

Hydrocarbon drilling is increasing in deeper water (Pinder 2001) and more environmentally sensitive areas and recent research suggests loss of benthic biological diversity results in reduced ecosystem function (Danovaro et al. 2008). Exploration drilling undoubtedly impacts local benthic abundance and diversity (Jones et al. 2006, Jones et al. 2007, Netto et al. 2009, Jones & Gates 2010) because of the physical disturbance to the seabed characterised by deposition of drill cuttings and a potential chemical disturbance from the additives to drill mud used in the process. Recent studies of exploration sites in Norwegian waters using ROVs immediately after drilling have shown that modern, best practice drilling techniques have a visible impact of 100-200 m in diatmeter (Gates & Jones 2010b, a, Jones & Gates 2010). Rates of recovery of megafaunal assemblages from disturbance are poorly studied in deeper water. Directly comparable studies have not been carried out on drilling disturbance but video studies at abyssal sites have shown epibenthic megafaunal densities to remain reduced for seven years following physical disturbance (Bluhm 2001) and older studies of oil drilling in shallower water show altered sediment characteristics and resultant changes to benthic communities over large areas (Olsgard

& Gray 1995), drilling techniques and environmental concerns have advanced since these studies and smaller quantities of less polluting drill fluids are currently used in Norway.

In addition to the importance of understanding anthropogenic impacts from exploration drilling for management purposes this study is valuable to understand processes in the deep sea. Owing to lack of access, deep-sea ecosystems remain to a large extent unstudied. Through collaboration to enable the use of industry offshore infrastructure the science community can progress the understanding of such systems by increased access to the seabed (Jones 2009). With the importance of the megabenthos to the functioning of deep-sea ecosystems (Smith & Hamilton 1983, Bluhm 2001) and the availability of Remotely Operated Vehicles (ROV) to enable their study, a well documented seabed disturbance such as this provides a valuable avenue for scientific investigation of the process of recovery in a deep-sea habitat.

This study focuses on the Statoil operated Morvin well which is located approximately 240km north-northwest of Kristiansund, forming part of the production licence 134b (Figure 1). Water depth at this location is approximately 370 m and previously bottom water temperature was recorded as 7.4°C. The SERPENT project carried out a study of this site in 2006 before and immediately after the drilling of the exploration well (Jones et al. 2008). This report describes the work SERPENT carried during a return visit in 2009.

Aims: The objectives of the SERPENT project work at Morvin were specifically to study recovery of a drilling site. This aims is closely linked to the overall goal of this collaboration that aims to improve the understanding and management of drilling related impacts on the environment. Specifically, the surveys and sample collection attempted to investigate how the following parameters varied in space and time around the drilling location:

- Sediment accumulation around the well head 3 years after disturbance
- Sediment chemistry and particle sizes 3 years after disturbance
- Changes in megafaunal abundance and species composition

PROJECT DETAILS

- Visit dates: 2nd to 6th May 2009
- Industry Partner: Statoil
- Vessel: Acergy Petrel
- ROV Operator: Acergy
- SERPENT scientist: Dr Andrew Gates

LOCATION AND SITE INFORMATION

Figure 1: Location of Morvin in the Norwegian Sea

Morvin is located south of the Vøring Plateau on the continental slope of the Norwegian Sea approximately 240 km northwest of Kristiansund (Figure 1). An exploration well was drilled at the Morvin location in 2006 with follow-up work in 2009/10. At the site the water depth is 370 m and summer seabed water temperature has been recorded as 7.4°C. The site is of importance environmentally because there are many large *Lophelia* coral reefs in region and with drilling activity ongoing Statoil have commissioned many surveys to monitor and preferably avoid potential impacts to these important and diverse deep-water habitats.

EQUIPMENT AND METHODS

The work at Morvin was carried out in two main parts; in 2006 and 2009. Initially two visits were made to the *West Alpha* semisubmersible drilling rig in 2006 during which time three surveys were carried out: before drilling (pre-drill), immediately after drilling (1 month post-drill) and three months after drilling (3 months post-drill). The equipment and methods used to collect data in the field in 2006 are reported elsewhere (Jones et al. 2008). This document reports the results of the 2009 study and makes comparisons with the 2006 data. All of the 2006 data have been reanalyzed for comparison with this work so some description of the analysis of 2006 data is required here.

ACERGY PETREL

The 2009 work was carried out from the survey vessel *Acercy Petrel.* The ship has a fully dynamic positioning system and is equipped to support all major aspects of marine survey/ROV light intervention work. The *Acergy Petrel* is an extremely capable support ship for pipeline inspection, seabed mapping and ROV light intervention activities. The hull design and installation fitment has been undertaken to minimise acoustic emissions through the hull, including the use of all electric thruster drives. The hull design has been optimised to achieve high transit speed.
The vessel is, amongst other things, equipped with special designed survey ROV and vessel mounted multibeam echosounders.

Figure 2: The survey vessel, *Acergy Petrel* (foreground) and the *Skandi Acergy* (background) viewed from the Vestbase at Kristiansund, Norway

ACERGY SOLO MKII SURVEY CLASS ROV

The ROV on board the *Acergy Petrel* is an Acergy Solo MKII. The ROV is deployed via the side of the vessel. It is a survey class ROV specifically equipped for pipeline surveys and has a range of camera systems 1 zoom colour video camera that was used for normal navigation, transects and behavioural documentation and port and starboard booms for additional colour video cameras. A black and white (CCD) camera was also used during periods of low visibility and during observations requiring no light. In addition, an Imenco Z1051 digital stills camera was available although limited time was available for stills photography.

The ROV was equipped with a 5-function and 7-function manipulator arms suitable for the core sampling operations planned for the visit. In addition the ROV team were extremely competent and operated the arms with impressive dexterity. Navigational systems on the ROV were excellent using a long baseline system to provide accurate positional information at all times.

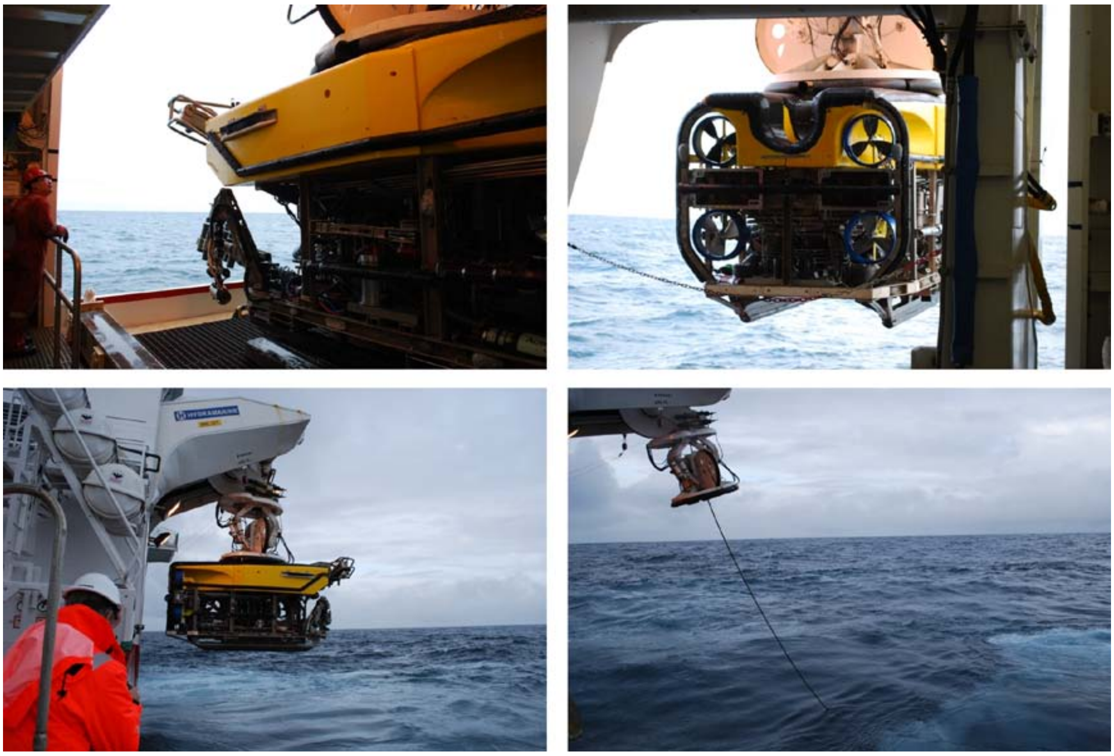


Figure 3: Deployment of the Acergy Solo MK II survey class ROV from the *Acergy Petrel* at Morvin.

SURVEY DESIGN

The video survey was designed to cover the area surrounding the well in order to quantify the visible extent of drill cuttings three years after the initial impact (Figure 4). To assess this four video transects of 1km in length crossed the well at their mid point. For comparison 10 reference transects were also taken. These were of 100 m in length, within a 3km radius but beyond 1km of the well with randomly selected starting locations and headings. If a reference transect covered an area with obvious sea bed features (based on the bathymetry data) that transect was rejected and another random starting point and heading was generated. This was to ensure similar habitats were studied because for operational reasons the drilling took place on flat sediment.

Table 1: the start and end positions of transects carried out at Morvin to assess the megafauna 3 years after drilling at the site.

Transect	**Reference**	**Details**	**Distance**	**start position**	**end position**	**Area surveyed**
T1	AP/030509/007	N to S over well	1000 m	380173 E 7223986 N	3801712 E 7224980 N	2386
T2	AP/030509/008	E to W over well	1000 m	380669 E 7224482 N	379671 E 7224480 N	2162
T3	AP/030509/009	NE to SW over well	2000 m	379683 E 7224377 N	380663 E 7224590 N	2203
T4	AP/030509/010	NW to SE over well	1000 m	379819 E 7224833 N	380526 E 7224120 N	2488
R1	AP/030509/011	Random (see survey plan)	100 m	380155 E 7225658 N	380239 E 7225604 N	296
R3	AP/030509/013	Random (see survey plan)	100 m	381060 E 7224828 N	381122 E 7224746 N	469
R6	AP/030509/016	Random (see survey plan)	100 m	380416 E 7225676 N	380511 E 7225633 N	347
R7	AP/030509/017	Random (see survey plan)	100 m	380688 E 7226244 N	380773 E 7226184 N	309
R8	AP/030509/018	Random (see survey plan)	100 m	381854 E 7223502 N	381905 E 7223418 N	318
R9	AP/030509/019	Random (see survey plan)	100 m	381156 E 7224655 N	381100 E 7224574 N	400
R10	AP/030509/020	Random (see survey plan)	100 m	3787665 E 7224059 N	378566 E 7224079 N	398
R11	AP/030509/021	Random (see survey plan)	100 m	378454 E 7224999 N	378507 E 7225083 N	316
R13	AP/030509/022	Replacement for R12	100 m	379243 E 7225473 N	379312 E 7225415 N	339
R14	AP/030509/012	Replacement for R-2	100 m	379621 E 7223450 N	379580 E 7223580 N	369

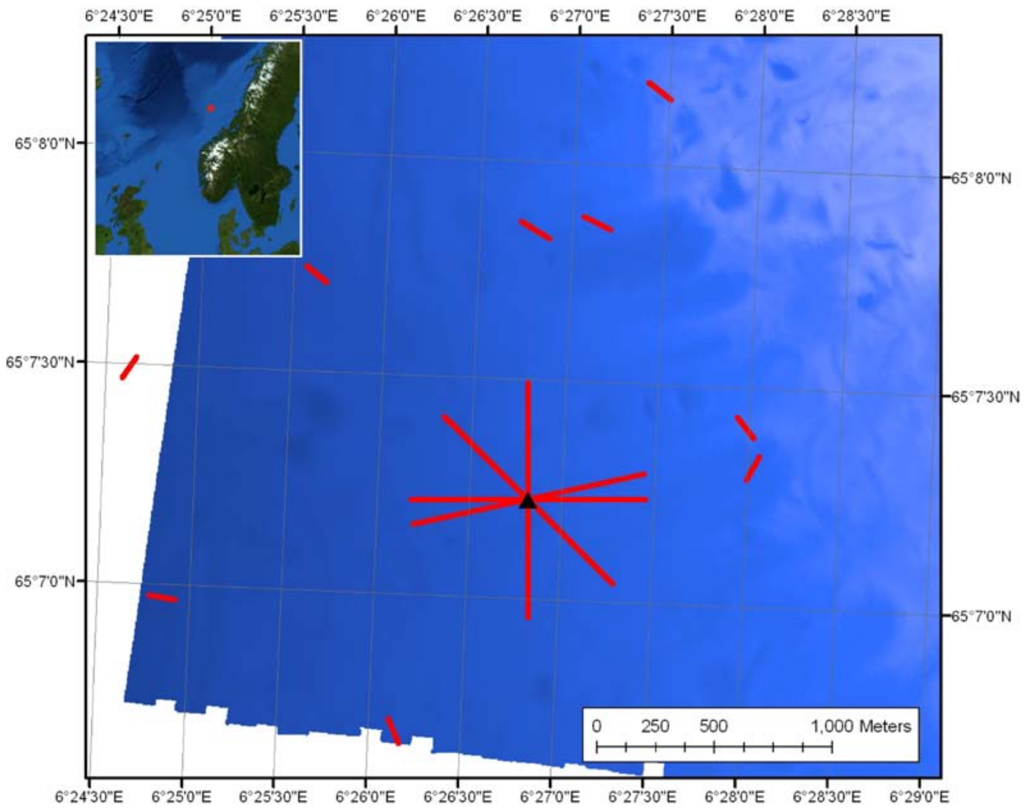


Figure 4: The survey design during the Morvin return visit in 2009 with Morvin location in the Norwegian Sea as an inset. The well is shown as a black triangle and the video transects are shown as red lines. Bathymetry is shown in blue with paler blue representing shallower areas.

VIDEO TRANSECTS

Each video transect was carried out to the same protocol. The starting transect began an at least 20 m ahead of the pre-planned starting point in order to ensure that the correct altitude and speed were attained before the intended starting point. At the end of each transect the same procedure was applied. The ROV was flown consistently at approximately 0.3 m s^{-1} with the camera height of approximately 2.5 m above the seabed. The camera was as close to vertical as possible with the zoom on maximum wide angle. UTM positional data were continually recorded.

VIDEO ANALYSIS

Video footage was replayed and all organisms, *lebensspuren* (burrows, tracks and traces) and seabed features were recorded. Where possible, distinctive features were referenced between the 2009 footage and the post drilling surveys because navigation was superior on the later visit. Where discrepancies arose the older video footage was georeferenced with the new data. This was not done with the pre-drill data because the well hadn't yet been drilled so the exact starting point was not evident. Videos were replayed at half speed, only features passing through the bottom of the screen were counted based on the following criteria:

- Individual, whole, live animals
- Only those that passed out of shot via the bottom of the frame
- Sponges or other colonies were counted as single individuals

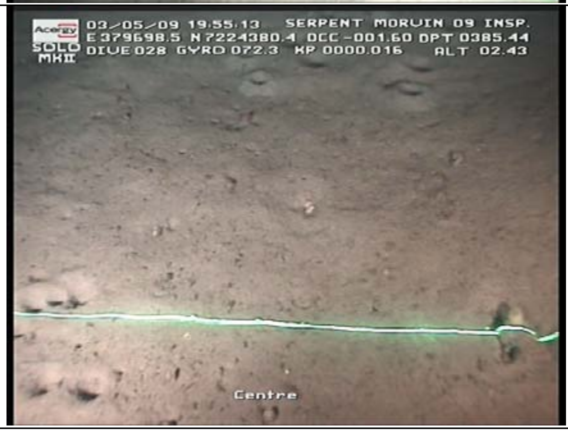
Following the transect analysis some organisms were excluded from further quantitative analysis and only organisms that typically live on the seabed (benthic organisms) and those of over 5 cm in size were included. All fish were excluded. However these organisms are recorded in species lists to augment the descriptions of the biodiversity in the area.

DISTURBANCE ASSESSMENT

Disturbance was visually assessed from the video footage. Examples of disturbed and undisturbed sediment are shown in Table 2. Disturbed sediment was more difficult to classify for the 2009 survey but typically disturbed sediment was identified based on the appearance of its surface. It was typically more homogeneous than undisturbed sediment from pre-drill and Reference transects and it had areas of very pale material (barite in the drill mud), particularly visible where bioturbation had occurred.

The boundaries of the disturbed area were identified and mapped on GIS. Megafaunal datasets were extracted from these zones in the ArcGIS for comparison of the disturbance zone with other sites.

Table 2: Examples sediment classified as disturbed and undisturbed at Morvin in 2009.

Disturbed	Undisturbed
	
	
	

ECOLOGICAL HIGHLIGHTS

Ecological highlights data are the photographs and video footage used to assist identification of the organisms observed in the main video surveys. During the Morvin work in 2009 it was not possible to spend time collecting such data but material was available from the work carried out in 2006 during which time the ROV was flown in different directions from the BOP gather close up video footage and stills photographs of megafaunal organisms. In addition “screen capture” images were collected of each organism observed in the 2009 video surveys to ensure consistency in identification.

STATISTICAL ANALYSIS OF BIOLOGICAL DATA

SAMPLING UNITS

For analysis the data were grouped into samples based on 100 m distance zones which were compared with the 100 m Reference sites. The visibly disturbed zone was less than 100 m in each heading and not consistent in length so the 100 m sample unit closest to the well was split into “Disturbed” and “Beyond disturbance”. Comparison was made with the transects from 2006, which were re-analysed and also split into sampling units based on “Disturbed” and “Beyond Disturbance”. In this case the “Disturbed” zone included only the area classified as Complete Coverage”. Therefore the disturbed zones are of differing size.

UNIVARIANT ANALYSIS

A One Way ANOVA design was used for comparisons of Density and Diversity between sample groups. Data were further explored using *post hoc* pairwise comparisons (Holm Sidak method). Where data failed Normality of Equality of Variance tests the non parametric Kruskal-Wallis One Way ANOVA on Ranks was used with *post hoc* pairwise comparisons using Dunn’s method. The statistics package Sigmaplot v.11 was used for these analyses.

MULTIVARIANT ANALYSIS

PRIMER software (Plymouth Routines In Multivariate Ecological Research) was employed for the analysis of the biological/ecological datasets. This package includes univariate and multivariate routines for analysing ‘species-by-samples’ data for community ecology (Clarke & Gorley, 2006).

Multivariate analysis is based on comparing the similarity of two or more samples. Similarity can be defined as the extent to which the samples share their components. Multivariate techniques are thus based on similarity coefficients calculated between pairs of samples. These can then be used to either classify the samples into similar groups (clustering) or to "map" them on an ordination plot so that the distances between the different samples reflect the differences in their composition.

A commonly used measure of similarity between two samples is the Bray-Curtis coefficient of similarity. The measurement of similarities can be biased by a small number of highly abundant components. To account for this, and to obtain a better reflection of the overall community composition, the data can be transformed so that less emphasis is given to the highly abundant components. The data transformation techniques range from square root to logarithmic to presence/absence transformations with fourth root (or double square root) transformation being the most commonly used method.

Cluster analysis is based on the principle that samples within a group (or a cluster) are more similar to each other than samples outside the group. Hierarchical methods group together samples that are most similar in terms of their community composition forming further clusters at increasingly lower level of similarity until all samples are connected. The results can be displayed as a dendrogram with one axis representing the samples and the other defining the similarity levels.

Non-metric multi dimensional scaling (MDS) produces a map of the samples based on their dissimilarity so that samples that are most dissimilar are plotted furthest apart. These MDS plots are produced by an iterative procedure that constructs MDS plots from successive runs until an optimal solution is reached. After each run the dissimilarity between each sample is plotted against their distance on the MDS plot and a regression line is fitted to these points. The goodness of fit of this line is referred to as "stress" with low stress values corresponding to a closer fit. The procedure is repeated until the lowest stress value is obtained. Hence the stress value effectively reflects how the multi-dimensional relationships among the samples are represented on a two dimensional plot. Stress values of less than 0.05 give an excellent representation whilst values exceeding 0.3 indicate a fit little better than randomly placed data.

Stress <0.05: excellent representation of data with no prospect of misinterpretation

Stress <0.1: good and reliable ordination with no real prospect of misinterpretation

Stress <0.2: potentially useful ordination

Stress >0.3: ordination is close to arbitrary and is potentially completely random.

SEDIMENT SAMPLING

Sediment samples were taken for Chemical (heavy metals), Paticle Size Distribution (PSD) and Total Organic Matter (TOM) analyses in four headings (N, E, NW & SW). Three replicate samples were taken at 25 and 50 m from the well on each heading. On all headings except to the east of the well the samples were divided into 0-20, 20-40 and 40-60 mm sections and preserved by freezing. The samples from the east heading were not divided for operational reasons and the top 60 mm were preserved by freezing. The location of the samples is shown on Figure 11.

Figure 5: Andrew Gates and Martin Hovland removing cores and preparing samples for sectioning and preservation in the ROV hanger on board the *Acergy Petrel*

SEDIMENT ANALYSIS

Sediment analysis was not carried out at NOC. In this report the chemical disturbance is discussed in relation to Barite, the weighting agent used in the drilling mud, which is useful to assess the extent the cuttings spread on the seabed. Full details of all the chemicals analysed and TOC data are given in a separate StatoilHydro report (Aas 2010).

The chemical analysis was performed by Norges Geologiske Undersøkelse (NGU) according to accredited in-house analysis procedures. The heavy metals analysis (Cd, Pb, As, Se, Sn) was carried out using atomic absorption spectroscopy (Perkin Elmer SIMAA 6000). The method applied was in accordance with Norwegian standard NS4770 and consisted of a partial acidic extraction using 7 NHNO3 in an autoclave. Hg was analysed according to the same standard but using a different instrument (CETAC M-6000A Hg Analyzer). 30 other elements were analysed according to the same standard using ICP-AES (Perkin Elmer Optima 4300 Dual View). The particle size distribution was determined using a Coulter LS200 instrument in the range 0.4-2000 µm.

The electron microscopy investigation was carried out at StatoilHydro's research centre in Trondheim using the FEI Quanta 400 scanning electron microscope equipped with a Bruker XFlash 4010 EDS detector for elemental analysis. The microscope was operated in the low vacuum mode with nitrogen inlet gas (0.3 torr) in order to compensate for any charging of the surface during electron bombardment. The accelerating voltage was 15 kV and the working distance 10 mm. The detector used was a back-scattered electron detector (BSE). The samples were investigated in the wet state, as received.

RESULTS AND DISCUSSION

The results section of this report is subdivided into sections:

- The natural, background environment at the Morvin site is described based on data collected in 2006 and new data collected at the Reference sites in the 2009 survey.
- The physical disturbance evident in 2009 and how it has changed since 2006 is described based on visual observations and sediment samples collected during the visit.
- The recovery and remaining effects on the invertebrate megafaunal communities are described by comparison of 2009 data with data collected in 2006.

BACKGROUND ENVIRONMENT

BATHYMETRY

The depth at well location was 378 m. Depth varied between 362 m and 402 m across the whole survey area. There were areas of greater slope which were likely the areas of hard substrate. These areas produce different habitats from the background sediment and are highlighted in Figure 8.

OCEANOGRAPHY

Data from a single dive commencing at 19:23 03/05/2009 from the ROV mounted CTD showed seabed temperature to be 7.4ºC. Surface water temperature was 8.6ºC and in the upper 100 m the temperature was variable. Below 100 m the temperature reduced relatively consistently from 8.5ºC to 7.4ºC (Figure 6a). In comparison the seabed temperature measured during the pre-drill survey from the *West Alpha* on 20/04/2006 was also 7.4ºC. Water column data are not available for the 2006 surveys. Salinity was consistently 35.35 below a halocline at 80 m and was as low as 35.15 at the surface (Figure 6b). Again there are no data available for the salinity during the 2006 surveys.

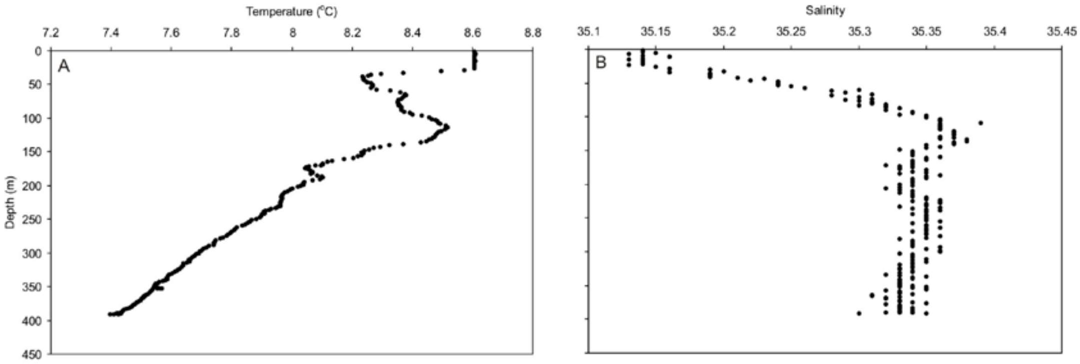


Figure 6: The temperature (A) and salinity (B) profiles from the first dive at the Morvin site in May 2009.

BENTHIC ECOLOGY

The high quality cameras on the ROV enabled identification of megafauna from the video footage, however time restraints during the ROV survey prevented detailed ecological highlights data collection. All the distinct taxa observed during the video surveys are listed in Table 3 and video grabs from the survey are shown in the Ecological Observations in Appendix 1. In addition, the high resolution digital still photographs collected during the 2006 visits were valuable identification aids. Observations are also shown on the SERPENT archive database: http://archive.serpentproject.com/view/sites/Morvin.html.

In total, across the 4 disturbance assessment transects and 10 reference transects 2546 organisms were counted from 44 distinct taxa representing nine phyla. Of the megafauna the Cnidaria was the most common Phylum comprising 45% of all the observations. The Porifera (33%) and Echinodermata (15%) were the other important phyla. The important species are described below in taxonomic order (percentages quoted are the proportion of all observations across all Phyla):

Porifera: Sponges are notoriously difficult to identify from photographs, requiring microscopic examination of the spicules for certainty. There were many very small sponges visible attached to rocks and on the sediment. These may be juveniles of other species or separate species in their own right but because of their size and the difficulty to make accurate counts they were excluded from analysis. There were 10 distinct sponge groups evident in the survey. Where similar colours and morphs were encountered they were grouped and categorized by a letter (Sponge A and B). Those sponges that were distinctly different were numbered. Sponges missing from the sequential numbering have been grouped into letter groups. The most common were described as Sponge 4. This was distinctly fan shaped similar to and probably *Phakellia* sp. (11% of observations). These were invariably seen on rocks and areas of hard substratum. Those that were apparently on sediment were likely attached to a small rock inconspicuous in the sediment. Sponges A (cream in colour and erect/branching) and B (cream colour and rounded in appearance similar to *Mycale* sp.) comprised 9% and 5% of organisms respectively. The sponges were typically associated with hard substrata (Figure 8).

Cnidaria: of the Cnidaria the Pennatulid octocorals (seapens) were the dominant organisms with a species of *Kophobelemnon* (likely *K. stelliferum*) the most abundant organism observed during the survey with mean density of 0.06 m^{-2} at the background sites (26%). *Kophobelemnon stelliferum* occurs on either side of the Atlantic with a bathymetric from 40 m to 2000 m. It has been suggested that it reaches high densities in canyon systems (12 m^{-2}) (Rowe 1971) and in the Porcupine Seabight its maximum density was 2.6 m^{-2} at 400 m, reducing with depth (Rice et al. 1992). *Kophobelemnon* sp. lives in the sediment through which it can slowly move vertically. Other important pennatulids were the large whip-like seapen likely *Funiculina* sp. or *Halipteris* sp. (0.03 m^{-2}, 12%) and to a lesser extent *Pennatula phosphorea* (1%). Pennatulids are clearly important components of the continental shelf soft sediment ecosystems such as Morvin and previous work has highlighted the need to understand their responses to anthropogenic disturbance (Edwards & Moore 2009). Large anemones similar to *Bolocera* sp. were regularly observed on the sediment (likely attached to rocks under the sediment surface) and faced into the current (enabling them to catch food particles) providing a useful indicator of current direction. The burrowing cerianthid anemones were present at Morvin but at far lower densities than in the deeper waters of the Norwegian Sea (Gates & Jones 2008, Gates et al. 2008, Gates & Jones 2009). Perhaps the most important members of the Cnidaria in the area of the survey (although deliberately avoided in the area around the drilling) were the deep water reef forming coral *Lophelia pertusa*. These reefs support diverse communities including other corals such as *Paragorgia arborea* as well as a many other hard substrate organisms (Hovland 2008, Roberts et al. 2009). As reefs were avoided in the drilling process these reefs are beyond the scope of this study, however they were encountered during other survey and sampling work in the area.

Arthropoda: In the sea arthropods are predominantly represented by the Crustacea. While the density of crustaceans determined from the video at Morvin was not particularly high they were clearly an important group at the site. Burrows were extremely abundant and shaped the seafloor in the soft sediment areas. The organisms which make the burrows were generally not visible but some photographic evidence shows *Geryon* sp. crabs in these holes. Previous work has suggested similar burrows to be formed by *Geryon* but pointed out that, like this site, the evidence is circumstantial (Attrill et al. 1991). Other possibilities for the creators of the burrows include *Nephrops norvegicus* which were occasionally observed at the site. Of note in the 2006 post drill study was the presence of large lithodid crabs apparently feeding on organic material under the drill cuttings. Other smaller scavenging decapod crustaceans (shrimps, likely *Pandalus* sp.) were present in all surveys. As with other studies of disturbed sites the numbers of scavengers (of which crustaceans are an important component) were increased following disturbance to benthic habitats (Ramsay et al. 1998, Jones et al. 2006). Excluded from the surveys because of their size, pelagic habit, high motility and well documented diurnal migration Krill (*Meganyctiphanes norvegica*) must be mentioned because of their ecological importance. At times they were extremely common at the Morvin site; these provide an important food source in the Norwegian Sea and provide a direct link between the surface waters and the seabed. At Morvin there were observations of fish feeding on krill highlighting this important role (Melle et al. 2004).

Mollusca: The only megafaunal molluscs observed during the video surveys were large gastropods, likely *Colus sp.* or *Buccinum* sp. Analysis of Ekman grab samples from the initial visits to Morvin showed an abundance of infaunal molluscs including bivalves and gastropods invisible to the ROV's cameras.

Echinodermata: The holothurian (sea cucumber) *Stichopus tremulus* was third most abundant megafaunal organism at Morvin (11% of all organisms) and the most abundant motile species. Easily recognisable from the video *Stichopus* lives on soft sediment feeding on phytodetritus and was seen on most video transects, however it was notably absent from the surveys immediately after drilling. Other important echinoderms were the asteroids, of which 3 species accounted for 3% of organisms at Morvin.

Chordata: The most common fish were redfish. Two species were observed, the most common of which was likely *Sebastes viviparous*. *S. viviparous* was observed throughout the survey area. They were most common where there were structures that provided shelter including the well site, rocks and coral reefs further afield. The smaller, *Helicolenus dactylopterus* was also seen at the site but in lower abundance. Commercially important fish including *Lophius piscatorius* (monkfish), *Gadus morhua* (cod) and *Pollachius virens* (Saithe/coalfish) were present at Morvin but abundance was low.

Other Phyla: There were also representatives from the Bryzoa, Echiura and Nemertina although these were relatively minor contributors to megafaunal biodiversity.

Table 3: All the species observed in video survey work at Morvin in 2006 and 2009.

Working species name	Phylum	Class	Order	Family	Species
Sponge 1	Porifera				
Sponge complex A	Porifera				
Sponge 4	Porifera	Demospongiae	Halichondrida	Axinellidae	*Phakellia*
Sponge complex B	Porifera	Demospongiae	Poecilosclerida	Mycalidae	*Mycale*
Sponge 7	Porifera	Demospongiae	Poecilosclerida	Hymedesmiidae	*Hymedesmia*
Sponge 8	Porifera				
sponge 9	Porifera				
Sponge 10	Porifera				
sponge 12	Porifera	Demospongiae	Halichondrida	Axinellidae	*Phakellia*
sponge 13	Porifera	Demospongiae	Halichondrida	Axinellidae	*Axinella*
Bolocera	Cnidaria	Anthozoa	Actiniaria	Actiniidae	*Bolocera*
Funiculina	Cnidaria	Anthozoa	Pennatulacea	Funiculinidae	*Funiculina*
Kophobelemnon	Cnidaria	Anthozoa	Pennatulacea	Kophobelemnidae	*Kophobelemnon* (*stelliferum*)
Pennatula phosphorea	Cnidaria	Anthozoa	Pennatulacea	Pennatulidae	*Pennatula phosphorea*
Lophelia	Cnidaria	Anthozoa	Scleractinia	Caryophylliidae	*Lophelia*
Alcyonium digtatum	Cnidaria	Anthozoa	Alcyonacea	Alcyoniidae	*Alcyonium digitatum*
Cerianthidae	Cnidaria	Anthozoa	Ceriantharia	Cerianthidae	
Cidaris cidaris	Echinodermata	Echinoidea	Cidaroida	Cidaridae	*Cidaris cidaris*
Echinoid 1	Echinodermata	Echinoidea	Echinoida	Echinidae	*Echinus esculentus*
Crossaster	Echinodermata	Asteroidea	Velatida	Solasteridae	*Crossaster*
Asterias rubens	Echinodermata	Asteroidea	Forcipulatida	Asteriidae	*Asterias rubens*
Asteroid 1	Echinodermata				
Asteroid 2	Echinodermata				
Asteroid 3	Echinodermata	Asteroidea	Valvatida	Poraniidae	*Porania pulvillus*
Stichopus	Echinodermata	Holothuroidea	Aspidochirotida	Stichopodidae	*Parastichopus tremulus*
Echiuran	Echiura				
Gastropod 1	Mollusca	Gastropoda			
Geryon	Arthropoda	Malacostraca	Decapoda	Geryonidae	*Geryon*
Nephrops	Arthropoda	Malacostraca	Decapoda	Nephropidae	*Nephrops*
Pandalidae	Arthropoda	Malacostraca	Decapoda	Pandalidae	
Lithodes	Arthropoda	Malacostraca	Decapoda	Lithodidae	*Lithodes*
Munida	Arthropoda	Malacostraca	Decapoda	Galatheidae	*Munida*
Nemertea	Nemertina				
Chimaera	Chordata	Holocephali	Chimaeriformes	Chimaeridae	*Chimera monstrosa*
Flatfish	Chordata	Actinopterygii			
Lophius piscatorius	Chordata	Actinopterygii	Lophiiformes	Lophiidae	*Lophius piscatorius*
Sebastes	Chordata	Actinopterygii	Scorpaeniformes	Sebastidae	*Sebastes viviparus*

Helicolenus	Chordata	Actinopterygii	Scorpaeniformes	Sebastidae	*Helicolenus dactylopterus*
Ling	Chordata	Actinopterygii	Gadiformes	Lotidae	*Molva molva*
Saithe	Chordata	Actinopterygii	Gadiformes	Gadidae	*Polachius virens*
Cod	Chordata	Actinopterygii	Gadiformes	Gadidae	*Gadus morhua*
fish 1	Chordata	Actinopterygii			
fish 2	Chordata	Actinopterygii			

BENTHIC HABITAT OBSERVATIONS AND REFERENCE SITES

The seabed at Morvin was characterised by large expanses of flat seabed mud, punctuated by the occasional glacial drop-stone. These areas were characterised by soft sediment megafauna including pennatulids, holothurians and sabellids. *Lebensspuren* (life traces) were an important feature of the soft sediment at Morvin (Figure 7), with a notable abundance of burrows in the sediment thought to be caused by the burrowing activities of decapods such as *Geryon* sp.

Figure 7: the burrows made by the decapod crustaceans in the soft sediment at Morvin

In the wider vicinity Morvin is located in an area important for deep-water *Lophelia pertusa* coral reefs. While these were deliberately avoided in the drilling programme former areas of this type of reef were encountered on some of the reference transects and other operations in the area. These provided hard substrate for the attachment of organisms such as sponges and anemones, providing important areas of biological diversity.

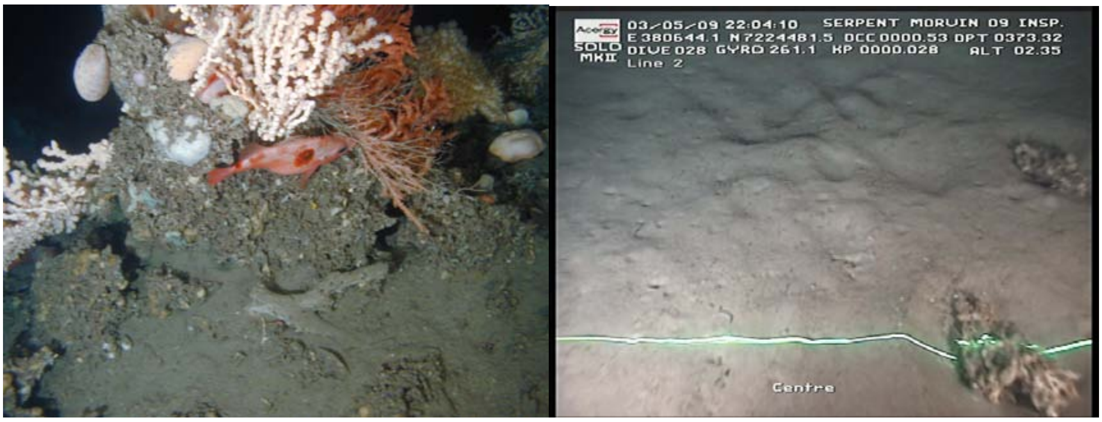


Figure 8: Coral reefs were not present in the immediate vicinity of the well but provided a hard substratum for the attachment of sessile organisms such as sponges and anemones (left). There was evidence of former reefs in the survey area (right) which also provided attachment sites for sessile organisms.

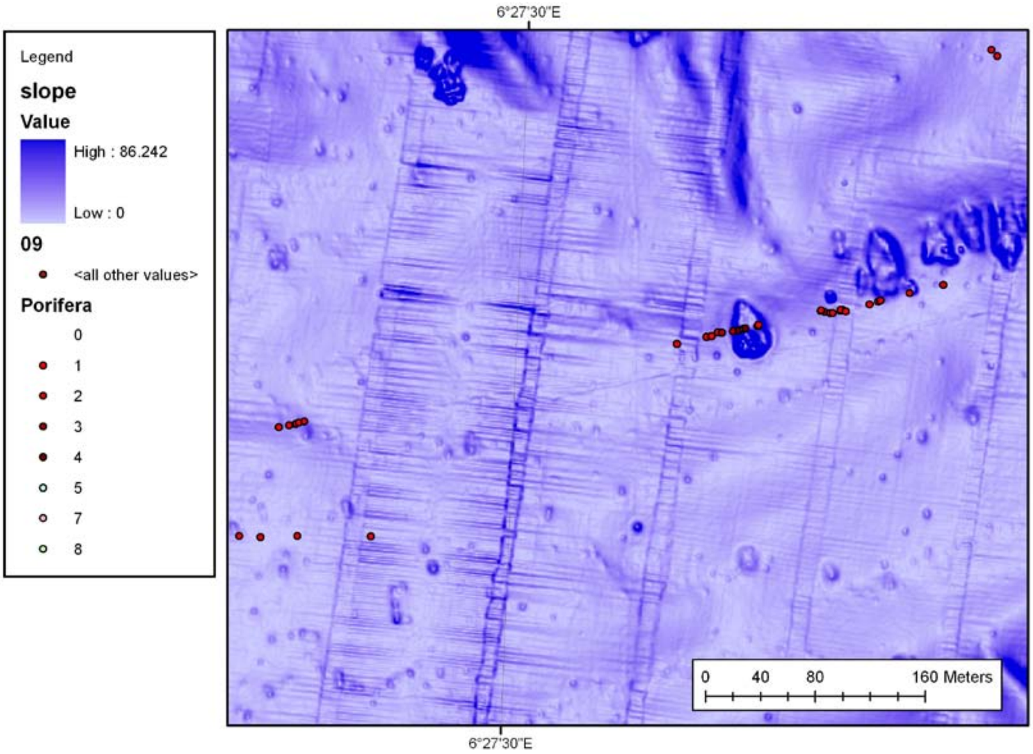


Figure 8: An example of the relative slope of the seabed and distribution of Porifera at Morvin on a section of the north west transect at Morvin. Darker blue on the seabed represents greater slope. The coloured points represent observations of sponges. The vertical lines on the map are artefacts of the survey process.

There was a significant relationship between the number of rocks observed in the background transects and rarefied species richness (*$ES_{(50)}$*) (R^2 = 0.76, ANOVA, $F_{(1,8)}$ = 25.43, P = <0.001) and Shannon Weiner (*H'*)species diversity (R^2 = 0.72, ANOVA, $F_{(1,8)}$ = 20.17, P = 0.002).

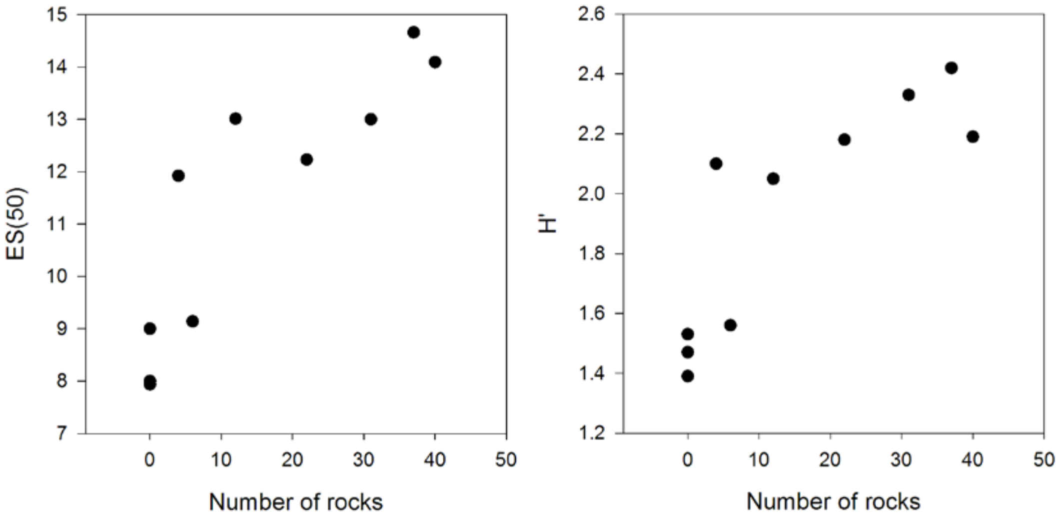


Figure 8: The relationship between the number of rocks observed in a video transect and megafaunal invertebrate species diversity for the R sites (randomly selected background 2009) (left; rarefied species richness, right; Shannon-Weiner Index)

Table 4: Species diversity indices for the whole survey and the individual transects. S = total number of species in area studied. N = total number of individuals in area studied; J' = Pielou's eveness (1 = maximal eveness, 0 = minimal eveness or maximum dominance); H'(loge) = Shannon Weiner diversity index to log base e (high values = high heterogeneity diversity).

Transect	S	N	J'	ES(50)	H'(loge)
R1	14	74	0.83	12.23	2.18
R3	14	60	0.88	13.00	2.33
R6	23	136	0.70	14.09	2.19
R7	18	94	0.84	14.66	2.42
R8	9	36	0.70	9.00	1.53
R9	8	36	0.67	8.00	1.39
R10	12	128	0.59	7.94	1.47
R11	15	75	0.76	13.01	2.05
R12	12	52	0.84	11.92	2.10
R13	12	115	0.63	9.14	1.56
T1	30	394	0.78	15.66	2.66
T2	28	364	0.76	14.96	2.53
T3	30	567	0.74	14.43	2.53
T4	26	385	0.79	13.89	2.56

Table 5: Comparison species diversity of drilling sites at a range of depths in the North East Atlantic.

Site	Depth (m)	Area surveyed (m^2)	N	S	Density (ind. m^{-2})	J'	ES(70)
Lancaster	155	653	190	30	0.27	0.73	20.14
Cashel	175	818	256	33	0.31	0.70	18.55
Morvin 2009 R sites	380	3561	546	25	0.21	0.73	14.79
Schiehallion	420	2715	1133	18	0.42	XX	9.3-10.7
Foinaven	510	1519	1075	33	0.71	XX	10.8-15.1
Midnattsol	930	XX	1765	23	XX	0.33	6.55
Haklang	1250	1023	411	20	0.40	0.54	11.68
Asterix	1350	1106	407	22	0.37	0.55	10.32

DISTURBANCE

The Morvin well was drilled in April 2006. 192 t barite were discharged to the seabed from drilling the top hole and 77 t discharged from the rig (to the sea surface) from the 17.5” section (Aas 2008, *personal communication*).

The well was easily located and was visible as a hole in the seabed at the exact position provided for the survey plan (Table 5). Pale sediment was evident in the visible cross section. The cuttings pile was still evident on the seafloor extending out from the well. The sediment waves, characteristic of cuttings piles immediately after disturbance were no longer present. As explained in the methods section the sediment remained homogeneous in large areas and on occasions there were larger pieces of unidentified material, perhaps larger cuttings. Close to the well there was limited evidence of animal activity (*lebensspuren*). Where the sediment surface was broken by bioturbators or ROV activities pale white sediment was evident, likely the barite from the drill cuttings. Table 5 shows a comparison of the sediment from the first post-drilling survey with the 2009 survey.

Table 5: A comparison of 100 m of video transect from the first post-drill visit in 2006 and the recovery visit in 2009.

Position	Approx. Distance to well	Post-drill 1	Post-drill 2009
380172 7224481	Well location	n/a	
380172 7224477	4		

380172 7224471	10		
380172 7224468	13		
380172 7224463	18		
380172 7224457	23		

380172 7224450	31		
380172 7224441	40		
380172 7224431	50		
380172 7224423	58		

380172 7224418	63		
+380172 7224409	72		
380172 7224400	81		
380172 7224391	90		

380172 7224381	100		

DEVELOPMENT OF THE CUTTINGS PILE

In 2006 the cuttings pile extended to approximately 100 m from the centre of the well in most headings and in some cases beyond the extent of the survey (Figure 9). The depth of the cuttings pile, measured using marker buoys deployed before drilling was 400-500 mm above the seabed at 8 m from the well in three headings (N, E, W). Further afield at 50 m to the SE of the well an additional marker buoy showed much reduced depth of cuttings (50 mm) (Jones et al. 2008).

In the three years since the Morvin surveys in 2006 the cuttings pile reduced in size considerably. Figure 9 shows the estimated extent of the cuttings pile in 2006 and 2009. The visible extent of disturbance extended furthest to the north of the well, comparable with the surveys carried out in 2006. Combination of the Morvin 1 and Morvin 2 surveys (taken within a short time period of each other) gives a better estimate of the actual area disturbed immediately after drilling (because the navigation equipment was inferior to that used in 2009 although visual observations did suggest some change to the sediment around the well between April and June 2006. The area visibly impacted from drilling reduced from 26,601 m^2 (including partial and complete coverage of the seabed with cuttings) 2006 to 3536 m^2 in 2009. There was evidence of living organisms and *lebensspuren* throughout the visibly disturbed area, although density was low (see later sections).

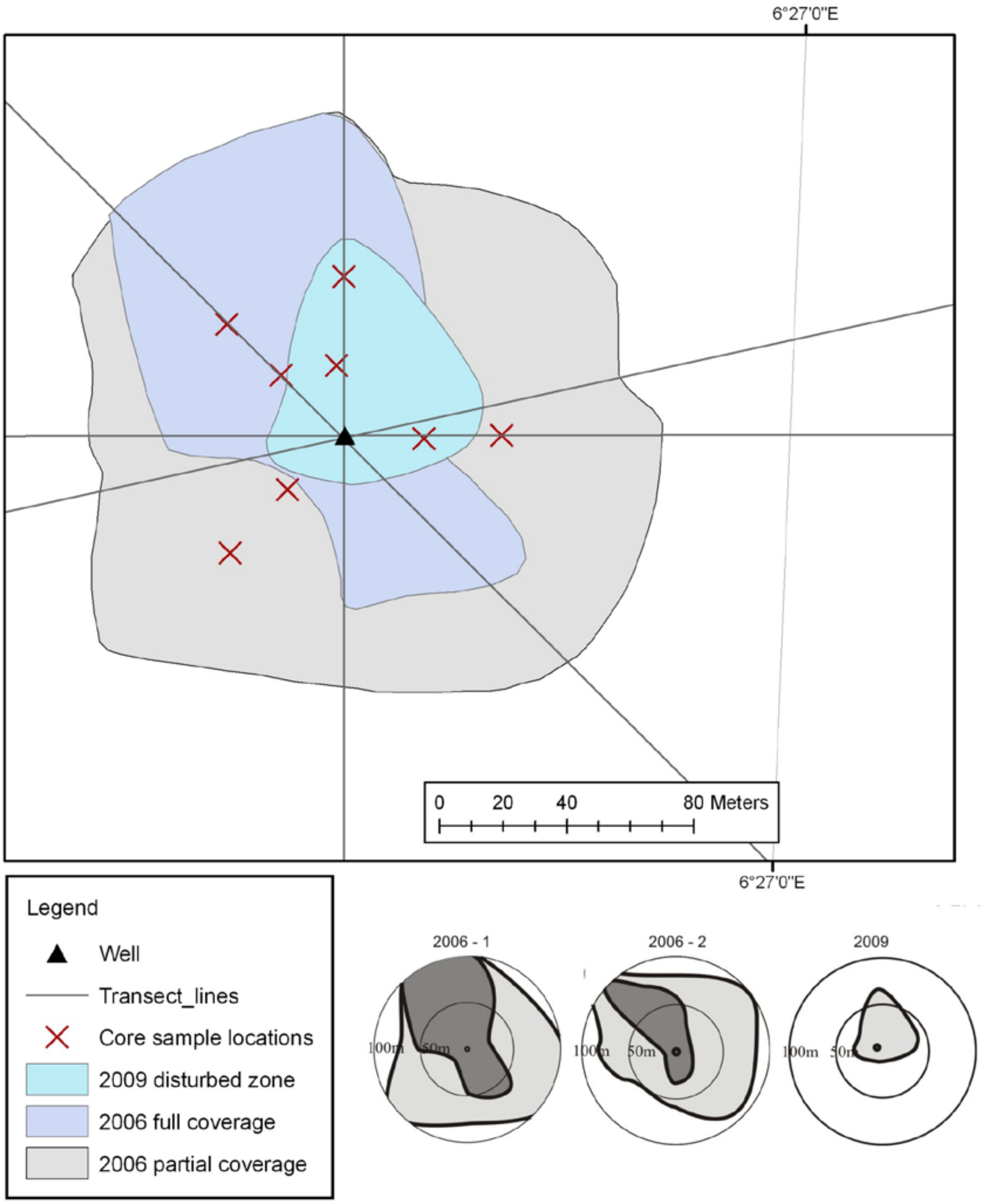


Figure 9: The horizontal drill spoil map showing the well, the transect lines and the estimated extent of visible disturbance during the 2009 survey (green), the area of complete coverage of the seabed in 2006 (blue) and area partially covered in 2006 (grey). The locations of core samples are shown as red crosses. The impact maps produced after the 3 post drilling surveys are also shown. In these the dark grey represents complete coverage of the sea bed and light grey shows partial coverage.

SEDIMTENT CHEMISTRY

In the surface layers of the sediment the mean Barium concentration across the 3 sample sites (the east sample was excluded from this analysis because it was not sectioned) was consistent and not significantly different between 25 m and 50 m (Figure 10). In the lower sections the Ba concentration reduced but it was only at 40-60 mm in the 50 m site that sediment Ba concentration was at similar levels to the Norwegian Coastal Shelf background levels and the Pre-Drill (150 mg kg^{-1}) concentrations recorded during the 2006 SERPENT visits (Appendix 2). However, there was variability between the sample headings, which is shown in Figure 11. At all headings the mean Barium concentration reduced with depth in the sediment at the 50 m sites, however on the N and SW headings Barium concentration was consistently high through the depth sections at 25 m. Mean Barium concentration was lowest in the samples taken on the NW heading with significant differences between the sections at both the 25 m and 50 m site.

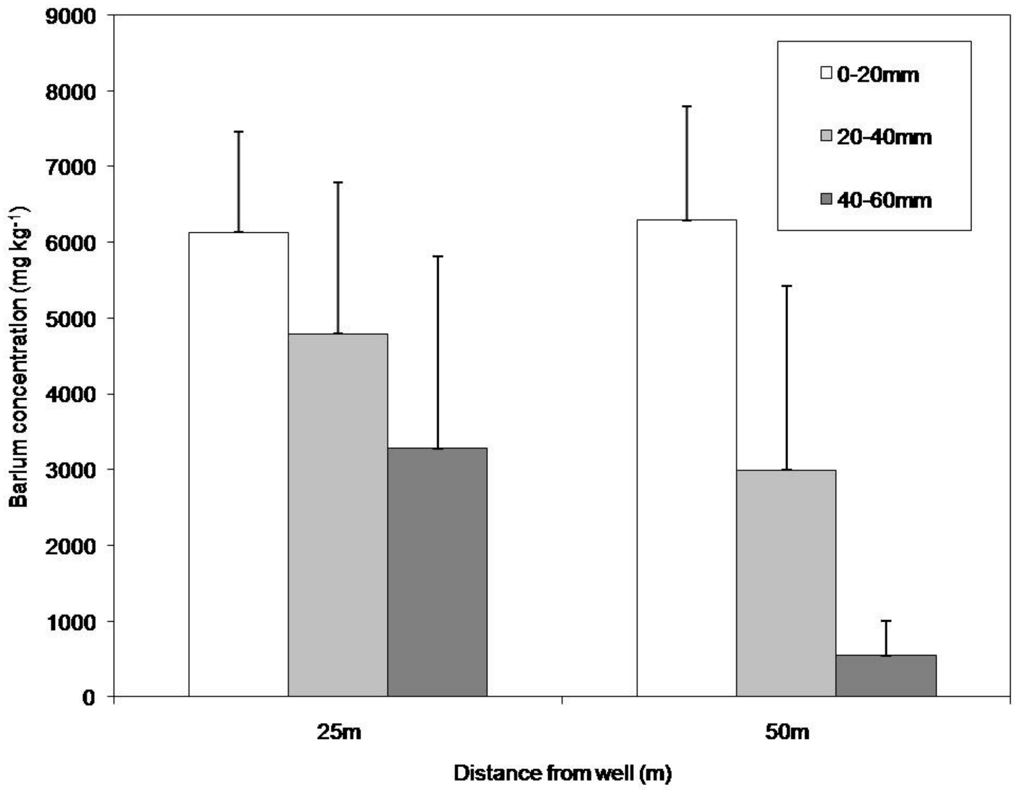


Figure 10: Mean Barium concentration (mg kg^{-1}) at increasing depth in the sediment at the two sampling rings.

Table 6: The mean barium concentration (mg kg^{-1}) at the three headings where sectioned samples were possible.

Year (survey)	Heading	Distance	Section	Number of replicates	Ba concentration (mg kg^{-1})
2006 (pre)	Well centre	0	0-50 mm	1	150
2006 (post)	N	10	0-50 mm	1	6300
2006 (post)	S	10	0-50 mm	1	4600
2006 (post)	N	110	0-50 mm	1	230
2009 (recovery)	N	25	0-20 mm 20-40 mm 40-60 mm	3	4750 6267 4580
2009 (recovery)	SW	25	0-20 mm 20-40 mm 40-60 mm	3	6930 4985 5155
2009 (recovery)	NW	25	0-20 mm 20-40 mm 40-60 mm	3	6987 3288 738
2009 (recovery)	E	25	0-50 mm	3	8233
2009 (recovery)	N	50	0-20 mm 20-40 mm 40-60 mm	3	6440 3261 385
2009 (recovery)	SW	50	0-20 mm 20-40 mm 40-60 mm	3	7503 4183 970
2009 (recovery)	NW	50	0-20 mm 20-40 mm 40-60 mm	3	4250 800 157
2009 (recovery)	E	50	0-50 mm	3	5727

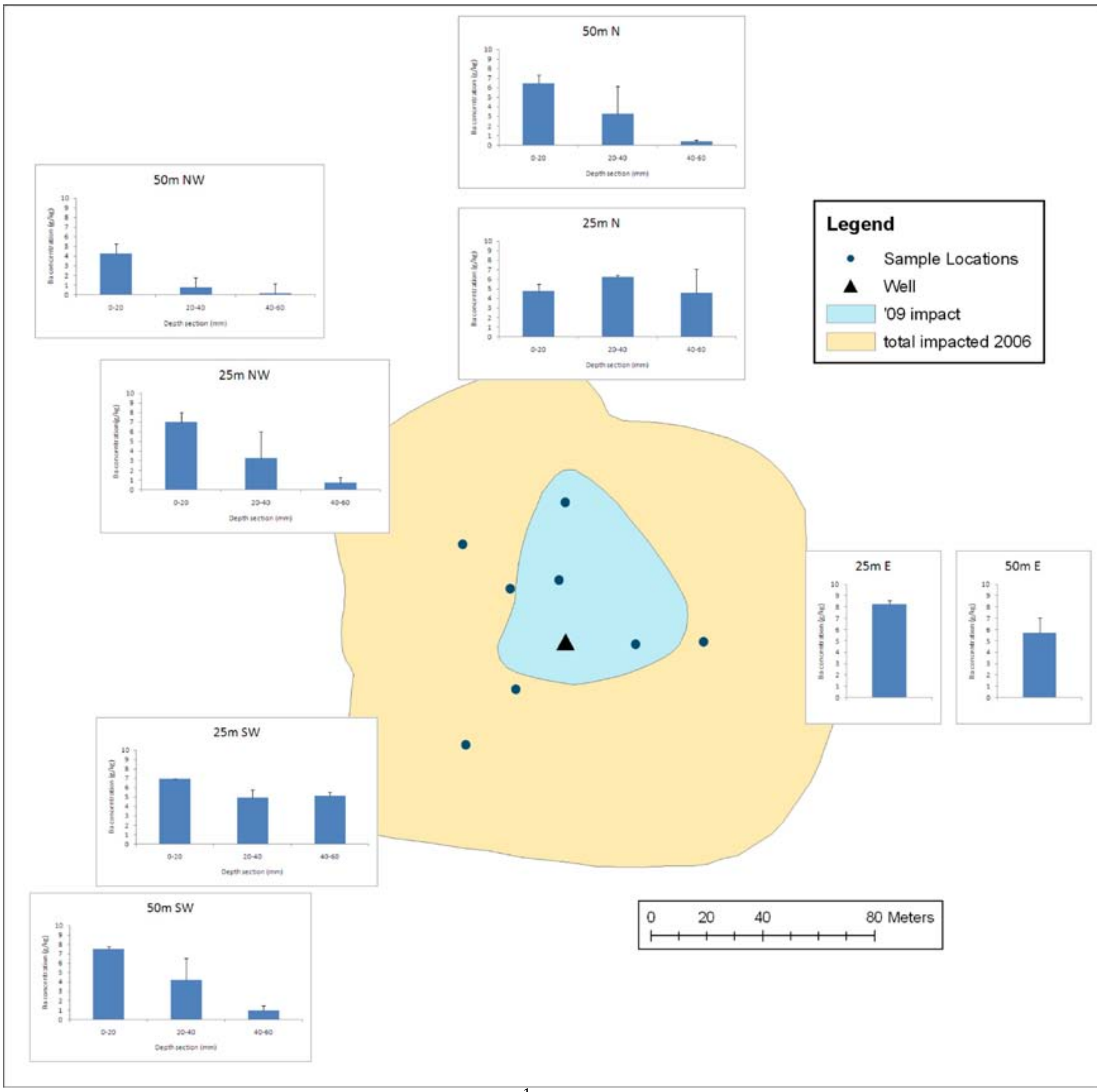


Figure 11: The mean barium concentration (g kg^{-1}) at the 25 m and 50 m sampling sites around the well at Morvin during the 2009 survey. Three samples were taken at each site, each of the N, NW and SW samples were sliced into 0-20, 20-40 and 40-60 mm depth sections. The yellow area shows the total area impacted in 2006 (both partial and complete coverage with cuttings in both post-drill surveys). The light blue shows the area identified as visibly disturbed in 2009.

At Morvin the sediment characteristics were influenced by the deposition of drill cuttings. If the 50 m samples are considered to be more representative of the background environment than the 25 m samples then there was a shift towards smaller grain size here. This is suggested by the shift towards the left with the red curves in Figure 12. Typically there was a smaller grain size in the surface layers of sediment at Morvin as shown by both the solid red and black lines, evidence of the cuttings at the surface of the sediment.

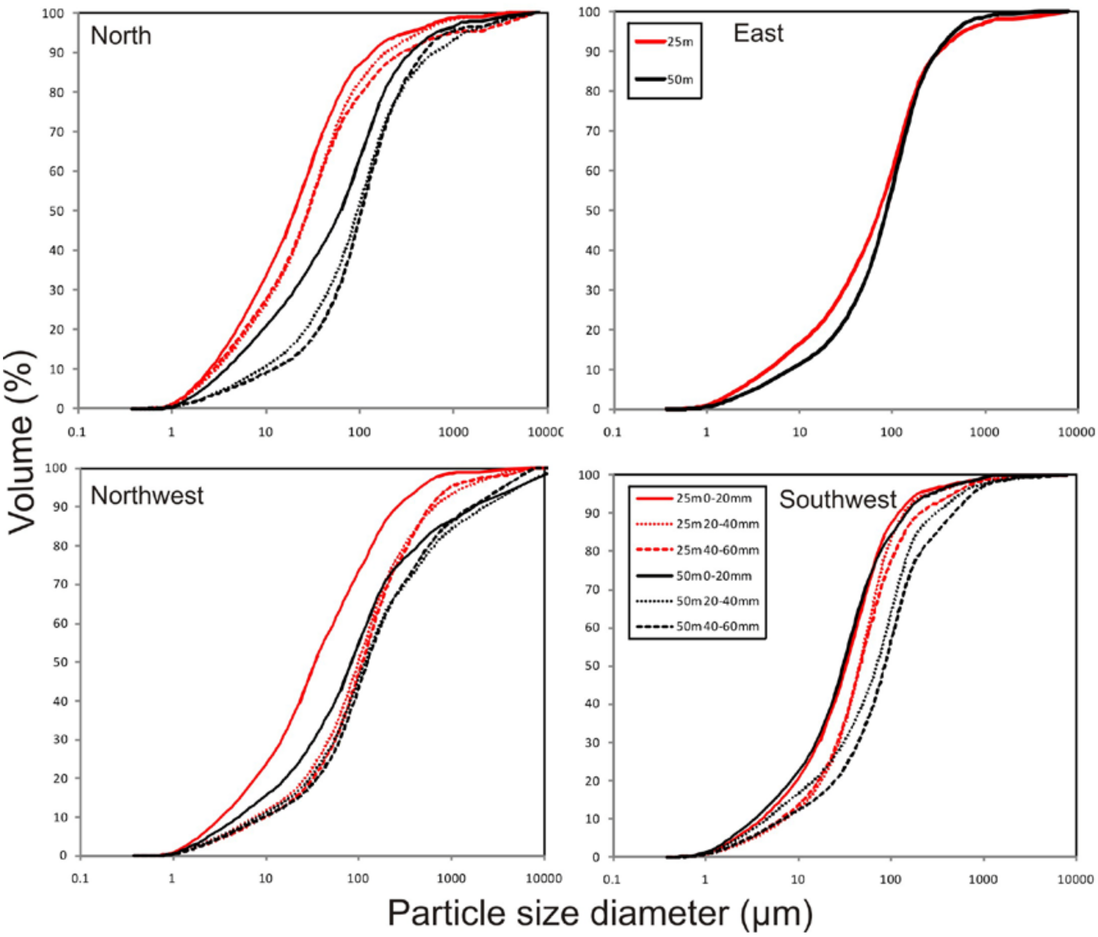


Figure 12: Mean particle size distribution at the four sampling sites around the well at Morvin. Red lines represent samples taken at 25 m from the well and black lines are the 50 m sites. The solid lines are the top 20 mm of the sediment samples and the dotted lines represent the lower sections (see figure legend).

THE EFFECTS OF THE DISTURBANCE EVENT

The initial disturbance that occurred at Morvin following the drilling can be characterised as a physical burying or smothering event with the addition of a large quantity of finer sediment. In addition there was the potential chemical disturbance of the constituents of the drill mud. Initially, this resulted in a reduction in megafaunal density close to the well, with very few megafaunal organisms in the immediate vicinity of the well. This is now a well documented effect of modern drilling practices (Jones et al. 2006, Gates & Jones 2009, Jones & Gates 2010) but there are no data available about the longer term effects of drilling disturbances in deeper water. Table 7 shows the mean density of each taxon across the different disturbance/background groups. This will be referred to when individual species are discussed in the remainder of this report.

TOTAL DENSITY

2009 SURVEY

Consideration of the 2009 survey alone showed that there were significant differences in total invertebrate megafaunal density between the transects (Figure 13; Kruskal-Wallis H= 21.32, d.f. = 6, p = 0.002). Density was lowest in the disturbed zone (median 0.04 individuals m^{-2}) and highest in the R sites (median 0.176). Pairwise comparisons (Dunn's method) showed significant differences between the disturbed zone and R and 2009 100-200 m and the 200-300 m zones. There was no significant difference between the sites beyond the disturbed zone and the background "R" sites suggesting a return to background density in these areas.

COMPARISON WITH 2006

There were significant differences in total invertebrate megafaunal density between the sample groups when analysis included the 2006 and 20009 data (Figure 13; Kruskall-Wallis, H = 38.92, d.f. = 11, p = <0.001). Further investigation (pairwise comparison, Dunn's method) showed the "Post drill 2009 Disturbed Zone" and "Post Drill 1 2006 Disturbed Zone" to differ significantly from the "2009 R" sites and "Post Drill 2006 Beyond Disturbance" sites and that "Post drill 2009 Disturbed Zone" differed from the "Pre Drill" sites. There was no significant difference between the sites beyond the disturbed zone and the background 2006 "Pre Drill" or 2009 "R".

Table 7: The mean density of invertebrate megafauna (ind. 100 m^{-2})

	Pre	Post drill 1		Post drill 2		2009						
		Dist	Beyond	Dist	Beyond	R	Dist	Beyond	100-200	200-300	300-400	400-500
Sponge A	0.4	0.1	0.1	0.1	0.8	2.5	0.3	0.6	1.0	1.6	0.9	0.9
Sponge B	1.1	0.1	0.3	0.7	0.4	0.9	0.2	0.7	0.7	1.0	0.8	0.9
Sponge 4 (*Phakellia*)	3.0	0.3	0.0	3.1	1.7	2.9	0.2	1.1	1.3	1.3	0.7	0.7
Sponge 7	0.4	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.2	0.2	0.0	0.0
Sponge 8	0.5	0.0	0.0	0.0	0.1	0.5	0.0	0.4	1.1	0.9	0.7	0.8
Sponge 9	1.4	0.2	0.0	0.1	0.2	0.6	0.5	0.4	0.5	0.5	0.1	0.2
Sponge 12	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Sponge 13	0.2	0.0	0.0	0.1	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Indet red cnidarian	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0
Cerianthid 1	0.0	0.3	0.2	0.2	0.4	0.4	0.0	0.5	0.2	0.1	0.3	0.5
Bolocera	0.5	0.2	0.4	0.2	0.4	0.3	0.0	0.1	0.0	0.2	0.2	0.2
Kophobelemnon sp.	4.5	3.4	5.9	1.6	7.3	6.0	0.9	4.9	4.4	4.2	3.3	3.3
Funiculina sp.	0.8	0.2	0.7	1.3	2.1	3.1	0.2	1.7	1.8	1.8	2.1	1.9
Pennatula sp.	0.4	0.1	0.4	0.1	0.4	0.4	0.0	0.1	0.2	0.2	0.2	0.0
Lophelia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Nemertean	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0
echiuran?	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gastropod 1	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.1	0.0	0.0	0.0
Indet 1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.2	0.1	0.1	0.2
Nephrops sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Munida sp.	0.1	0.0	0.0	0.0	0.2	0.0	0.7	0.1	0.0	0.0	0.0	0.0
Geryon sp.	0.2	1.1	1.8	0.0	1.1	0.1	0.0	0.3	0.1	0.1	0.1	0.0
Lithodes sp.	0.0	0.0	0.0	1.0	0.3	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Pandalid	0.4	0.0	0.0	0.3	0.8	0.1	0.1	0.4	0.4	0.2	0.1	0.1
Echinoid 1	0.1	0.0	0.0	0.1	0.3	0.1	0.0	0.1	0.1	0.2	0.3	0.2
Cidaris sp.	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0
Ceramaster sp.	0.2	0.0	0.0	0.0	0.2	0.2	0.0	0.1	0.2	0.2	0.3	0.4
Crossaster sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Asteria rubens	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Asteroid 1	0.0	0.3	0.0	0.1	0.5	0.2	0.2	0.1	0.2	0.1	0.1	0.1
Asteroid 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Asteroid 3	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.2	0.0	0.1	0.1
Stichopus tremulus	2.3	0.0	0.4	0.0	0.4	1.7	0.8	1.2	2.1	1.4	1.5	2.0
Indet 2	0.0	0.0	0.0	0.1	0.2	0.4	0.2	0.1	0.0	0.1	0.1	0.0

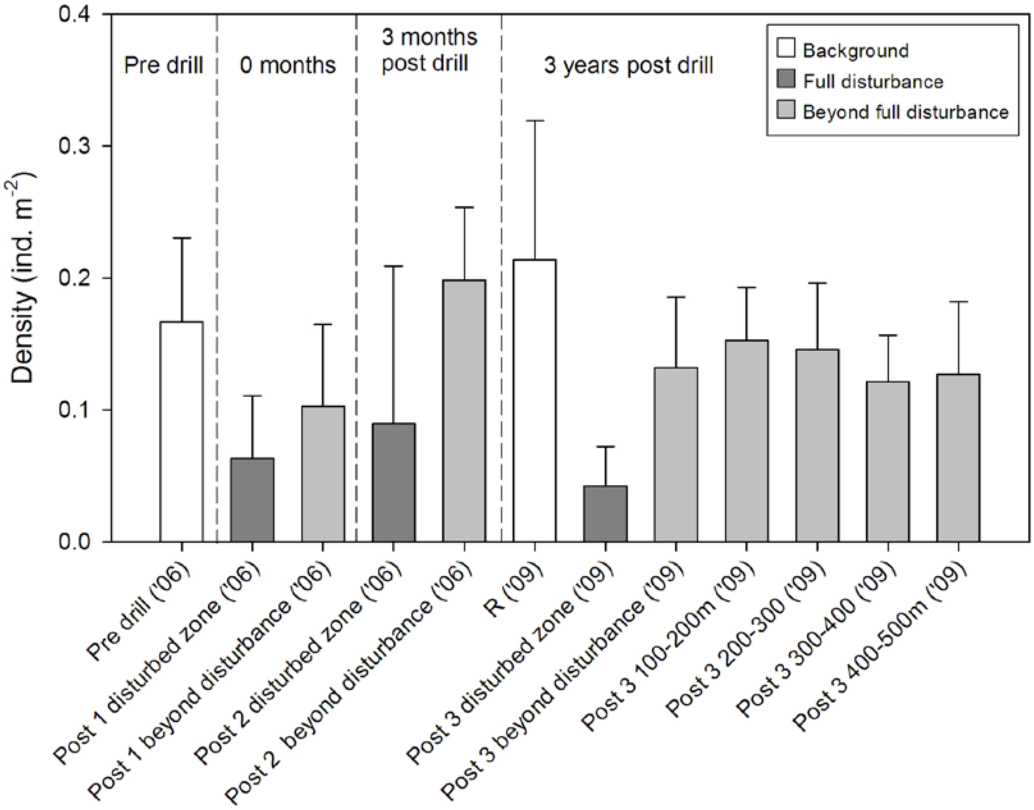


Figure 13: Mean (±sd) total density of benthic invertebrate megafauna from the 2006 and 2009 surveys at Morvin.

PHYLA DENSITY

In the 2009 survey, at undisturbed sites and at greater distance from well the proportional representation of Phyla was relatively consistent, however at the disturbed location the density of Porifera (Sponges – generally sessile hard substrate organisms) and Cnidaria (dominated by sessile soft sediment organisms) were dramatically reduced. The 2006 Post-drilling surveys also showed reduced Porifera density but Cnidarian density was seemingly initially unaffected with reduced density only apparent by 2009.

Mean echinoderm density was relatively consistent in 2009 but significantly reduced in 2006 (ANOVA, $F_{(11,97)}$=5.08, P<0.001). Pairwise comparison (Holm-Sidak) showed the 2006 Post-Drill surveys to differ significantly from background and later studies. This reduction was driven by a notable absence of the most abundant echinoderm, *Stichopus tremulus* on the cuttings pile in 2006 (Table 7).

Arthropod density was apparently higher in the 2006 post-drill surveys although differences were not significant. Variation in arthropod density was high because of the nature of their distribution, in places they were found in aggregations (possibly feeding) and on other transects they were not present.

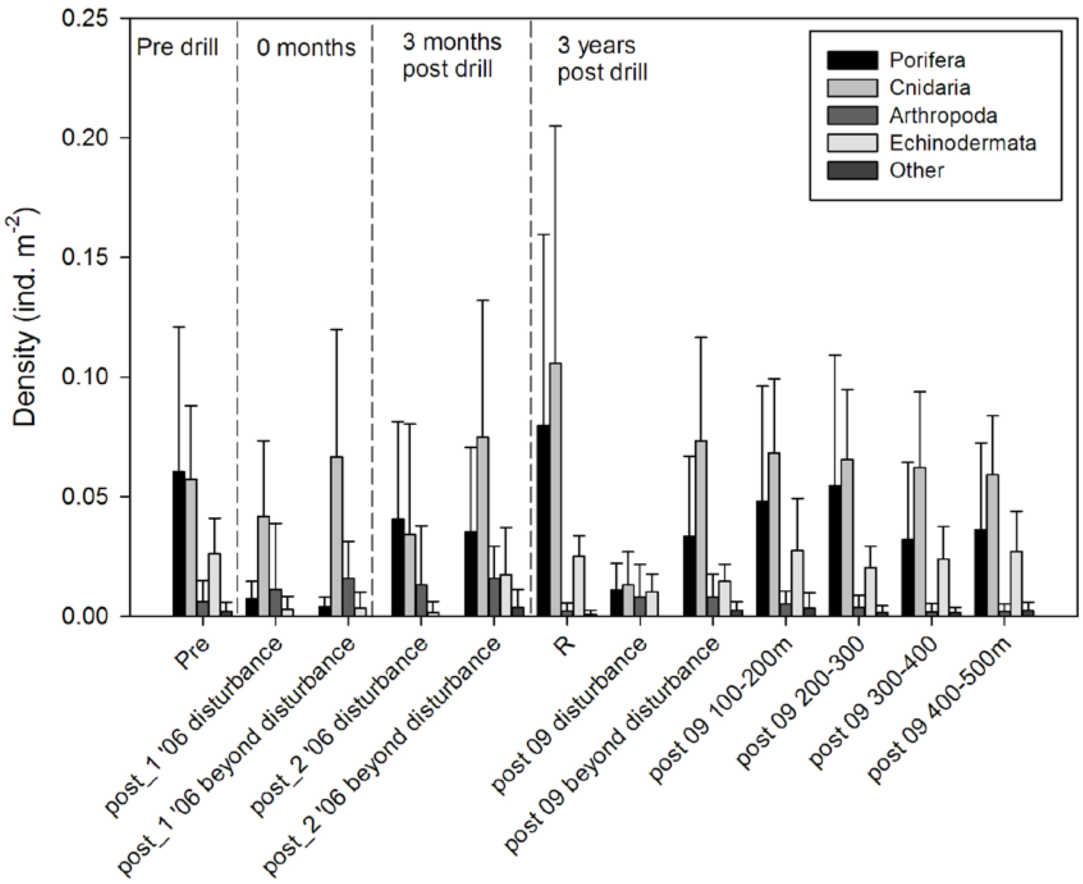


Figure 14:Mean density (individuals m^{-2}) of each of the major phyla during the different surveys and at increasing distance zones for the 2009 survey at Morvin.

SESSILE/MOTILE DENSITY

Motile and sessile – there was a significant difference between the sessile organism densities at Morvin (Figure 15; Kruskall Wallis 28.95, d.f. = 11, p=0.002). Pairwise comparisons (Dunn's method) showed that the "2009 Disturbed Zone" and the "2006 Post drill 1 Disturbed Zone" differed significantly from the from the 2009 "R" sites. There was no significant difference between the density of motile organisms.

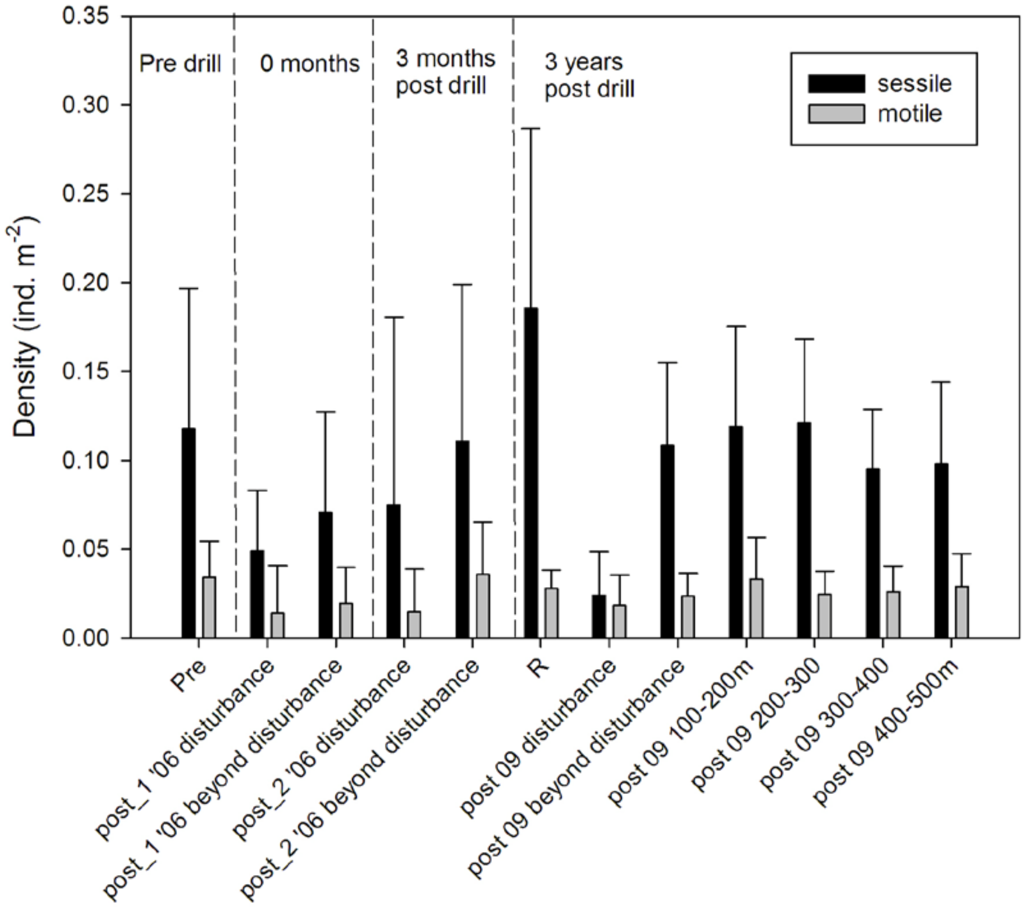


Figure 15: Mean density (individuals m^{-2}) of motile and sessile invertebrate megafaunaat the sampling locations at Morvin.

DIVERSITY

Species diversity indices are presented for comparison of pooled distance zones in Table 8. Species richness (S) was variable between the samples because of different sample sizes between the 2006 and 2009 surveys so rarefied species richness ($ES_{(X)}$) is a more useful index. Rarefied species richness ($ES_{(50)}$), Evenness (J') and Shannon-Weiner Diversity (H' log e) were similar at the background sites (Pre-Drill, Reference) and the 2009 locations beyond disturbance). In the 2009 disturbed zone evenness was higher and rarefied species richness and Shannon-Weiner diversity were reduced. The diversity indices for the 2006 post-drilling surveys were variable between zones.

Table 8: Diversity indices for the combined transects for each distance zone . S = total number of species in area studied. N = total number of individuals in area studied; J' = Pielou's evenness (1 = maximal eveness, 0 = minimal eveness or maximum dominance); ES(x) = Rarefied species richness; H'(loge) = Shannon Weiner diversity index to log base e (high values = high heterogeneity diversity).

Sample	S	N	J'	ES(50)	H'(loge)
Pre	19	140	0.79	13.75	2.33
Post 1 Disturbed zone	11	35	0.78	11.00	1.88
Post 1 Beyond disturbance	9	52	0.66	8.92	1.46
Post 2 Disturbed zone	15	43	0.78	15.00	2.12
Post 2 Beyond disturbance	26	136	0.78	18.05	2.54
Post 09 Disturbed zone	11	30	0.91	11.00	2.18
Post 09 Beyond disturbance	21	152	0.77	14.09	2.34
R 2009	25	546	0.73	12.95	2.33
POST 09 100-200	23	278	0.76	13.52	2.39
POST 09 200-300	25	271	0.76	13.78	2.44
POST 09 300-400	24	218	0.75	13.59	2.37
POST 09 400-500	19	234	0.80	12.78	2.34

MULTIVARIATE ANALYSIS

Further investigation of the density data using multivariant analysis to consider the contirbution of individual species highlighted differences between the disturbance zones. There were significant differences in invertebrate megafaunal community composition between the zones (One way ANOSIM R = 0.27, p = 0.001). Pairwise comparisons showed that the disturbed zones (Post 1 disturbed zone, Post 2 disturbed zone and Post drill 2009 dsiturbed zone) differed significantly from the 2006 pre drill and 2009 reference sites and the 2009 zones beyond the disturbance. Bray-Curtis similarity plotted as a multidimensional scaling plot (Figure 16) showed similarity amongst the Background (Reference and Pre-drill) and Beyond Disturbance (Post-drill 2 and 2009) sites (60% similarity). The disturbed sites and the Post-drill 1 disturbed zone were plotted separately. There was 80% similarity between the all of the 2009 sites beyond the disturbance.

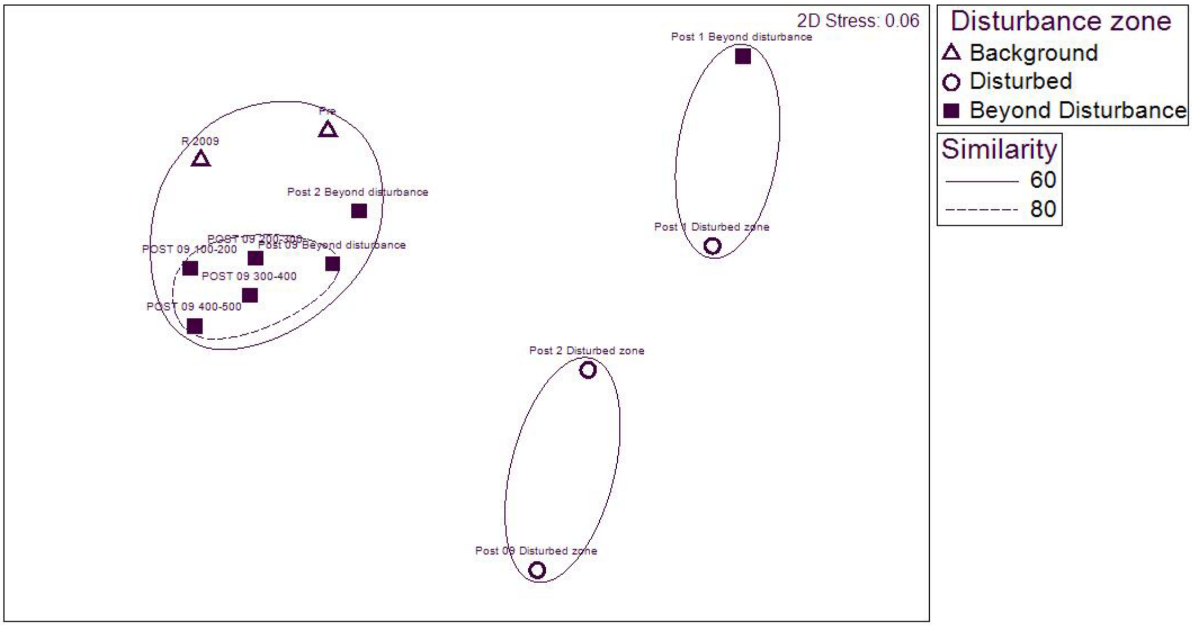


Figure 16: Mutidimensional scaling plot based on Bray Curtis similarity of pooled invertebrate megafauna data for the disturbance zones at Morvin in 2006 and 2009.

BIOLOGICAL ACTIVITY

There was a significant difference in mean density of decapod burrows in the 2009 surveys (Figure 17; ANOVA F = 4.77, d.f. = 57, P<0.001). Pairwise comparisons (Holm-Sidak method) showed significant differences between the "Disturbed Zone" and all the other zones with the exception of the area beyond disturbance within 100 m from the well.

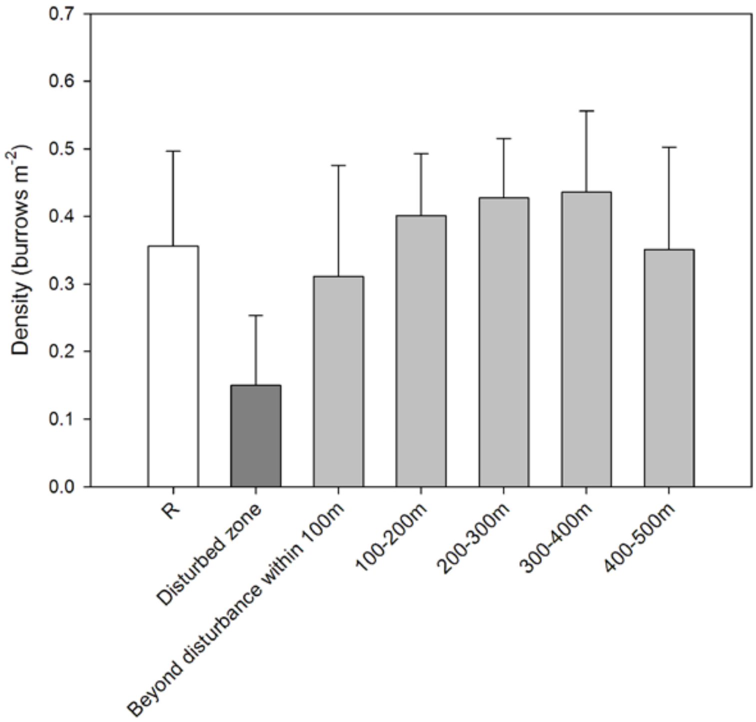


Figure 17: Biological activity (decapod burrows) in the 2009 survey at Morvin.

DISCUSSION

There are limited published studies of the megafauna of this area of the Norwegian Sea, however at similar depth in the Porcupine Seabight, southwest of Ireland the soft sediment habitat and dominant megafaunal species and species densities were similar (Rice et al. 1982, Attrill et al. 1991, Billett 1991, Rice et al. 1992). The areas of hard substrate, mainly outcrops of rock but also some former coral reefs, increased habitat heterogeneity at Morvin with a resultant increase in density and species richness, most notably the Porifera. There are direct similaritues between Morvin and a study of megafauna from the Le Danois Bank at equivalent depth in the Cantabrian Sea in which areas of mixed substrate of sand and exposed rock form a distinct habitat, notably with high abundances of *Phakellia ventilabrum* (Sánchez et al. 2009), the same species as tentatively identified as the most abundant sponge at Morvin. The importance of habitat heterogeneity to benthic diversity has recently been highlighted on global (Vanreusel et al. 2010) and local scales (Buhl-Mortensen et al. 2010).

Several studies are available that show the immediate extent of drill cuttings from modern, best practice hydrocarbon drilling and the effects on benthic invertebrate megafauna in the Norwegian Sea (Jones et al. 2006, Jones et al. 2007, Jones & Gates 2010) but the persistance of these disturbance events and their effects on the benthos after several years are unknown. This study showed that after three years, there was still visible evidence of disturbance surrounding the well, however the area had reduced considerably since the surveys after drilling in 2006. Data from Morvin in 2006 showed the depth of the cuttings pile to be over 400 mm at 10 m distance from the well while at 50 m there was only a thin covering of drill cuttings, estimated at less than 50 mm and this was unevenly distributed (Jones et al. 2008). It was this shallower coverage that appeared reduced in 2009. Since 2006 the cuttings pile has been subject to a number of environmental factors leading to this change in its visible extent. Rate of dispersal of the cuttings (directly related to the current regime), the nature of the cuttings themselves, bioturbation rate and the rate of rate of vertical flux of organic matter from the surface are likely the most important cosiderations. Closest to the well the cuttings were deepest so clearly a greater time period is required for its erosion or the cuttings becoming obscurred by settelment of material from above. The larger cuttings deposited in the immediate vicintiy of the well may also contribute to the persistance of the pile. It must be noted that in 2006 much larger particles were noted in the cuttings pile to the north and north west of the well, the same heading as the furthest extent of disturbance in 2009. Cement is used to secure the structure of the well and in the plug and abandon phase and may consolodate the cuttings pile in the immediate vicinity of the well, although it must be noted that cement was not observed in the cuttings. It is likely that the visibly disturbed area in 2009 is the remains of the deeper areas of cuttings identified in 2006.

Visible disturbance was limited to a relatively small area but sediment sampling showed elevated Barium levels beyond the visible extent of disturbance. Barium can be used as a tracer to indicate presence of drill cuttings because barite ($BaSO_4$) is a dominant component of the lubricants and weighting agents (drilling mud) used in to drill a well (Hartley 1996, Breuer et al. 2004) so its presence above the pre-drilling value and the Norwegian Continental Shelf background levels suggests persistance of the drill cuttings beyond the visible extent. Alongside the persistence of Barium in the sediment there was also a change in the sediment characteristics with a shift towards smaller particle size closer to the well. Despite the apparently persistent change to the benthic habitat, because of the particle size and chemical contamination of the sediment beyond the visible disturbance there was no significant difference in megafaunal density or or species diversity beyond the visibly disturbed zone (in some instances the reduced megafaunal abundance extended beyond the visible cuttings but this was not by a great distance).

Within the remaining visibly disturbed zone there was significant change in the megafaunal community. Density was significantly lower, species richness reduced and evenness increased in comparison to the Pre-drill and Reference sites as well as the further reaches of the 2009 disturabance assessment transects. The notable difference in the community structure between the 2009 disturbed zone and the reference sites was the reduction in abundance and therefore proportional representation of sessile organisms. After disturbance, on the hard substrates the sponges were rare and on soft sediment the pennatulids were uncommon. Close to the well sponges were absent where the rocks they inhabited were buried by the cuttings. Where the rocks were still exposed sponges appeared reduced in abundance although differences were not significant. With the burial of the rocks they inhabit, recovery of these organisms is not possible. It remains unclear how the sponges respond to intermediate disturbance, i.e. sedimentation but not complete burial and further research is required here. Of the soft sediment fauna the pennatulids were most common but their numbers were also reduced in 2009. Figure 18 shows how the megafaunal assemblage in the specific area still visibly impacted in 2009 changed in the 3 years of this work. It is clear that the Porifera and Cnidaria (predominantly the pennatulid *Kophobelemnon* sp.) actually reduced in abundance between the 2006 post disturbance survey and the 2009 recovery survey. The same is true of the Porifera. It seems that in this highly impacted area recovery does not occur in a three year period but numbers in fact continue to reduce. The presence of decapods burrows indicates biological activity and therefore the commencement of bioturbation, likely aiding in the recovery of the soft sediment environment.

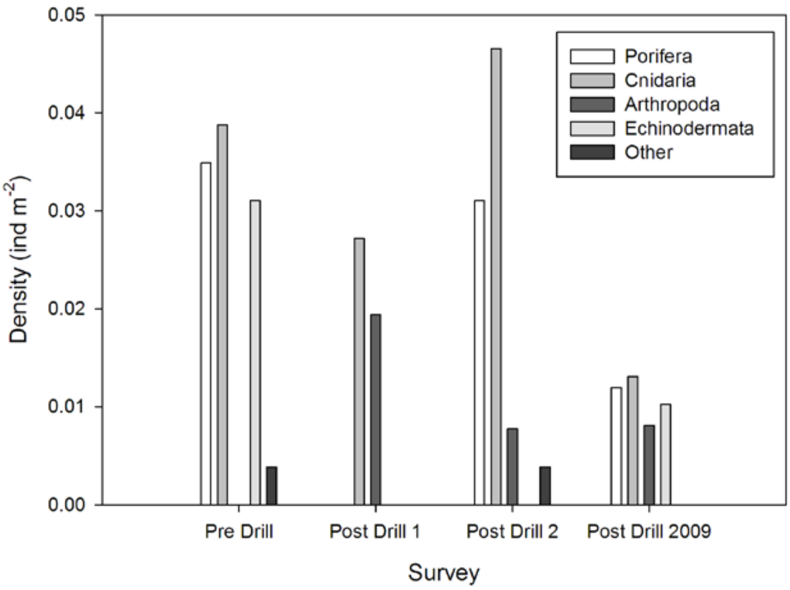


Figure 18: The change in the megafaunal assemblage on the area identified from visual observations as remaining disturbed in 2009

With the changed sediment characteristics persistent in the visibly disturbed zone and apparently persistent beyond that (evident from the sediment samples) it probably presents a different habitat for the infauna. In particular the composition of meiofaunal assemblages are well documented to be varaiable between sediments of differing grain size (Schratzberger & Warwick 1999, Gray 2002). In addition, selective deposit feeders such as the holothurian *Stichopus tremulus*, numerically important at this site, physically manipulate and select the sediment particles they ingest (Hudson et al. 2004). Scanning electron micrographs of drill cuttings within sediment reveal notable differences in shape at this site (Aas 2010) and other sites in the Norwegian Sea (Aas 2009) could perhaps explain the near absence of *Stichopus tremulus* close to the well during all post-drilling surveys. *Stichopus tremulus* was completely absent from the two surveys immediately post drilling. Although it has been noted that there are seasonal variations in *S. tremulus* density (Sanchez et al. 2008) in this case, owing to the relatively short time period between the pre-drill survey and the first Post-drill survey and consistent abundances at the same time of year in 2009 outside the disturbed zone it is likely that the organisms were absent because of the drill cuttings, either because of reduced food particle availability on the newly deposited cuttings (Billett 1991) or because they are selective in their consumption of particles (Hudson et al. 2004).

Bioturbation rates are poorly understood in deep water but the process is important in the recovery of sediment after physical disturbance. It was visibly evident at Morvin in the form of *lebensspuren* (burrows, tracks and traces) which were common even on the disturbed sediment. Of the animals common at Morvin it is likely that the burrowing decapods (*Geryon* sp.) were responsibl for these sediment features. They were not observed frequently during the surveys becuase of their burrowing habit but evidence of their activity was common. Notably they were more commonly observed on the sediment surface immediately after drilling in 2006. Their activity was still reduced on the remaining cuttings pile in 2009 but beyond this extent their activity was similar to Reference sites and may explain a large proportion of the apparent recovery of the sediment through redistribution of the surface layers. The infaunal macrofauna are also important bioturbators which are not included in this study and require further consideration in future studies of recovery. Of the more abundant epibenthic megafauna observed in this study the holothurian *Stichopus tremulus* must be considered important in dispersal of cuttings. Although vertically the holothurian is unlikely to play an important role in sediment mixing their feeding mode enables the transport of material over relatively large distances horizontally (Billett 1991).

RECOVERY

Studies of recovery from disturbance in the deep sea are rare because repeated access to such sites is expensive. Examples that have been carried out include studies relating to trawling disturbance (Engel & Kvitek 1998, Hannah et al. 2010), experimental disturbances to predict the effects of abyssal nodule mining (Bluhm 2001) and some shallower water studies of oil and gas activities (Neff et al. 1989). Until more studies have been carried out on deep water drilling sites it is only possible to comment on individual sites, because between locations there is important variation in the physical and biological environments and the individual nature of each cuttings pile. However this study is valuable to understand the process at this particular site under these conditions and may indicate areas of future concern when assessing recovery from drilling operations.

In this study recovery was defined as the return of the megafaunal community structure to similar conditions to the Pre-drill and Reference sites. A number of methods were used to assess recovery and megafaunal abundance, measures of diversity and multivariant analysis suggested a return to the background condition in the areas beyond the visible disturbance and therefore a reduced disturbed area, in terms of the megafauna. Recovery is suggested, although mean megafaunal density was actually lower throughout the disturbance assessment transects than at the Reference and pre-drill sites, it was not significantly different from the control sites under the design of this experiment. It is suggested that because the Morvin well was drilled away from rocky outcrops for operational reasons the disturbance assessment transects did not encounter so many areas of increased habitat heterogeneity, and therefore (as already explained) increased diversity.

An important observation from this work is that, aside from the changes in density and the influx of scavengers immediately after drilling, the megafaunal communities did not change greatly and was limited to the relatively small area around the well. The same organisms were dominant during each survey, with the few exceptions already discussed. In this respect it can be considered that the impact of drilling this exploration oil well on epibenthic soft sediment megafauna is relatively small when using the techniques employed here (water based mud, only discharged to the seabed from the top hole). However the significant reduction in megafaunal density which appears to persist for some time (at least 3 years in this case) is important becuase it is likely that this will occur at all deepwater sites, with the size of the impact related to the amount of material deposited on the seabed. It anticipated that the effect is likely to be greater in deeper, colder areas of the Norwegian Sea where background sediment particle size is smaller {Gates, 2010 #3807;Gates, 2010 #4058} which has been associated with lower recovery rates of soft sediments (Dernie et al. 2003), and the rate of metabolism and growth are expected to be considerably lower (Gage & Tyler 1991). To ensure limited impact on the benthic environment it seems that the most important factor is the quantity of material deposited on the seabed.

This study is a comprehensive assessment of the recovery of megafauna around an exploration oil well drilled using best practice techniques. Further research is required to determine the recovery of the smaller fractions of the benthic community including the meiofauna and macrofauna but the use of ROVs is valuable as a rapid assessment technique and readily available as survey vessels are regularly working in the areas surrounding active hydrocarbon exploration. It is encouraged that such surveys are carried out during operations in the vicinity of old or abandoned wells because for a relatively small investment in time valuable data about the recovery of deep water habitats can be aquired.

CONCLUSIONS

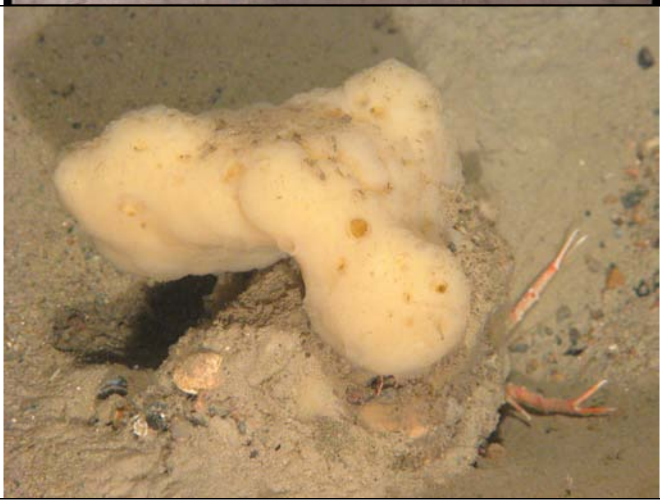
In the three years since the Morvin well was drilled the area visibly affected by the cuttings reduced dramatically from the total area disturbed in 2006, reaching a maximum extent of only 60 m in comparison to over 100 m previously. Although the extent of the visible disturbance was limited, elevated levels chemicals associated with drilling (including Barium) persisted both within and outside this area. At 50 m distance this was concentrated in the surface layers of sediment but at 25 m from the well Barium concentration was high throughout the 60 mm analyzed.

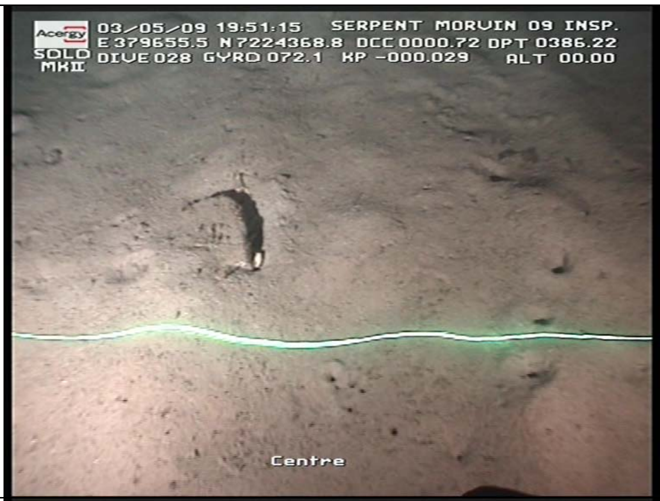
The visible disturbance in 2009 was likely the remains of the deeper part of the cuttings pile identified in 2006. Megafaunal density was significantly reduced in this area with sessile organisms most impacted. Epibenthic megafaunal abundance had reduced in this area since the 2006 surveys so there was no evidence of recovery in this area. Beyond this area megafaunal density had recovered to pre-drill and reference site densities. It remains unclear how the other components of the benthic community, particularly the infauna, respond to and recover from drilling disturbance.

The persistence of the relatively small disturbed area with low megafaunal density suggests that the quantity of drill cuttings discharged on the seabed should remain as low as possible because where disturbance is greater, megafaunal recovery is low. In deeper sites where dispersal of the cuttings may be slower this may be even more important.

APPENDIX 1: MORVIN IDENTIFICATION GUIDE

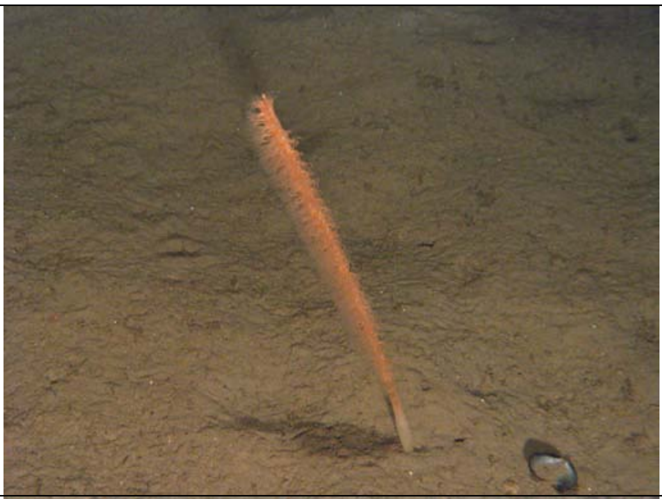
Observations of all the organisms observed during the SERPENT visits to Morvin in 2006 and 2009 and the additional video material provided by the ROV team on board the *West Alpha* are shown in the table below. Please note that large motile organisms and the very small sponges were excluded from analyses. Detailed tables of the organisms included in analysis are given in the Results section.

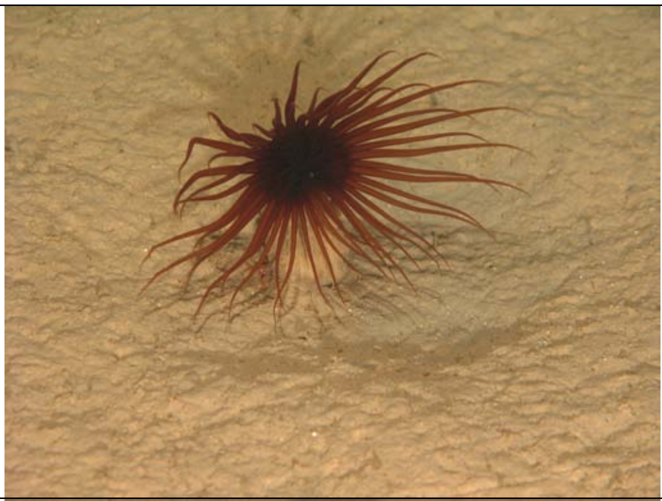
Working title	Species name Description and notes	video grab from first observation
Sponge A	Sponge A (cream in colour and erect/branching) and comprised 9% Typically associated with hard substrata *Haliclona* sp. or similar	
Sponge B	Sponge B (cream colour and rounded in appearance similar to *Mycale* sp.) 5% of organisms. Typically associated with hard substrata	

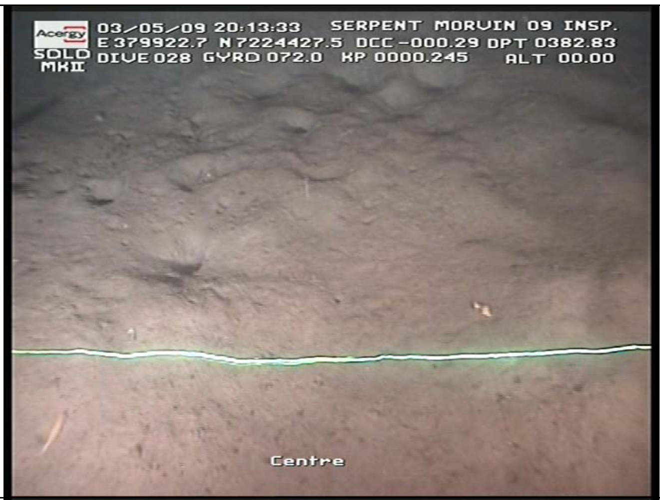
Sponge 1	Small spherical white sponge seen on rocks (excluded from megafaunal analysis because of small size)	
Sponge 4	*Phakellia* sp. (possibly *P. ventilabrum* or *P.robusta*) The most common sponge at Morvin. This was distinctly fan shaped similar to and probably *Phakellia* sp. (11% of observations). These were invariably seen on rocks and areas of hard substratum. Those that were apparently on sediment were likely attached to a small rock inconspicuous in the sediment	
Sponge 7	*Hymedesmia* sp. Distinctive encrusting blue sponge	

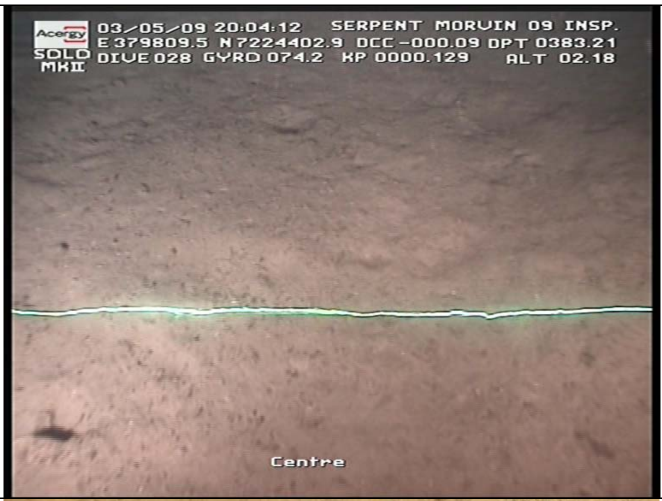
Sponge 8	Resembles the stalked sponge *Stylocordila borealis*	
Sponge 9	Encrusting white sponge seen on hard substrates	
Sponge 10	Very small white sponge observed on the sediment. Excluded from analysis because of its size	N/A
Sponge 13	White funnel shaped sponge – Similar in shape but distinctly different from Sponge 4. Probably *Axinella* sp. Apparently not always on rocks but likely attached to small rocks or those covered with sediment.	

Sponge 12	Many layered sponge similar to sponge 4. Possibly *Phakellia rugosa/*	
Kophobelemnon	The large polyps are characteristic of *Kophobelemnon* (likely *K. stelliferum*) the most abundant organism observed during the survey mean density of 6 m^{-2} at the background sites (26%). *Kophobelemnon stelliferum* occurs on either side of the Atlantic with a bathymetric from 40 m to 2000 m. It has been suggested that it reaches high densities in canyon systems (12 m^{-2}) (Rowe 1971) and in the Porcupine Seabight its maximum density was 2.6 m^{-2} at 400 m reducing with depth (Rice et al. 1992) *Kophobelemnon* sp. lives in the sediment through which it can slowly move vertically	

Funiculina	Large whip-like seapen, likely *Funiculina* sp. or possibly *Halipteris* sp. (3 m^{-2}, 12%)	
Pennatula (*phosphorea*)	This species of *Pennatula* may be *P. phosphorea*, which is generally from shallower water or *P. aculeata* which is typically known from deep water (2000 m) although has been identified from 500 m. (1% of observations)	
Bolocera	Large sediment dwelling anemone but seems to also live on rocks see below	

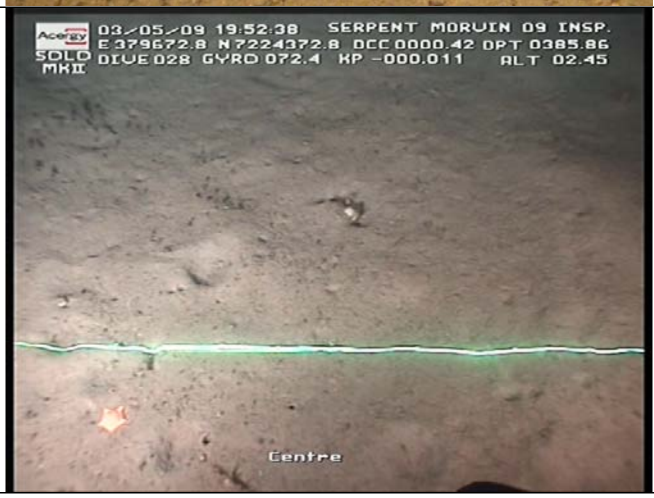
Cerianthid 1	dark coloured cerianthid anemone	
indet 1	*Alcyonium digitatum*	
Lophelia?	The reef forming coral *Lophelia pertusa*. The reefs support diverse communities. As reefs were avoided in the drilling process these reefs were beyond the scope of this study, however small pieces were occasionally encountered and at other times during the visit they were the subject of study.	

Nermertean – possibly *Nipponemertes pulchra*	smooth, worm-like organism on sediment surface	
Pandalid	These decapods crustaceans are small and impossible to identify from the video footage.	
Munida sp	*Munida sarsi* This squat lobster is most likely *M. sarsi* Species identification requires examination of maxillipeds so is not possible from photograph	

Nephrops norvegicus			
Geryon sp.	Burrows were extremely abundant and shaped the seafloor in the soft sediment areas. The organisms which make the burrows were generally not apparent but some photographic evidence shows *Geryon* sp. crabs apparently in these holes.		
Lithodes	Large lithodid crabs, apparently feeding on organic material under the drill cuttings, were only seen in the surveys immediately after drilling in 2006.		

indet coral or bryozoan	Small epifauna were difficult to identify from the video footage	
Echiuran??	Echiuran worms were occasionally observed at Morvin. They are important bioturbators. Identification is impossible from the video	
Gastopod 1	This gastropod is probably *Colus* or *Buccinum*	

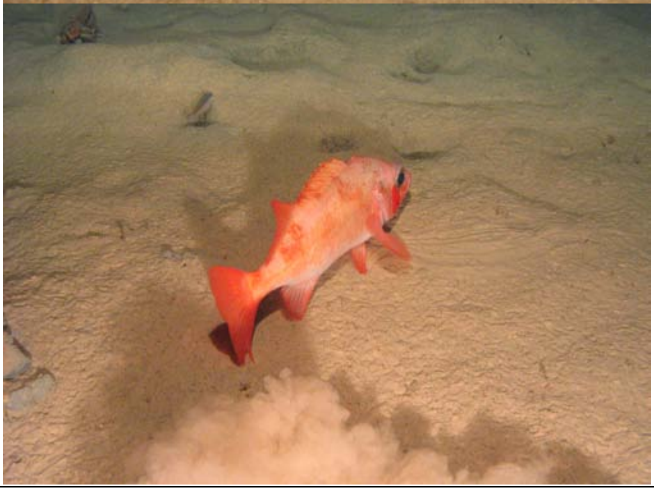
Echinoid 1	Likely *Echinus* sp.	
Cidaris cidaris	The “pencil-spine urchin”	
Asteroid 1	Orange starfish similar to *Stichastrella*	

Asteroid 2	*Hippasteria*?	
Asteroid 3	A poraniid starfish	
Ceramaster sp.	A cushion star possibly *Ceramaster granularis*	

Crossaster	A sunstar. Uncommon at the site	
Asterias rubens	*Asterias rubens*, the common starfish was present at Morvin in low numbers. It is distinctive and can be identified from photographs.	
Stichopus	The holothurian (sea cucumber) *Stichopus tremulus* was third most abundant megafaunal organism at Morvin (11% of all organisms) and the most abundant motile species. Easily recognisable from the video *Stichopus* lives on soft sediment feeding on phytodetritus and was seen on most video transects.	

Chimaera	*Chimaera monstrosa*	
Lophius	The monkfish *Lophius piscatorius*. This was rare at Morvin	
Cod	*Gadus morhua* was observed during the 2006 visits	

Pollachius virens	Coalfish/Saithe were commonly observed during the work at Morvin	
Molva molva (Fish 2)	Ling were occasionally seen making use of shelter on the seabed. They were more commonly seen in areas of hard substrate, particularly the coral reefs.	
Fish 1	A single observation, from this image it is difficult to identify but swimming mode resembles the dogfish *Scyliorhinus canicula*	

Flatfish	only one species observed at this site	
Redfish *Helicolenus dactylopterus/ Sebastes viviparus*	Redfish were common at Morvin, particularly around the abandoned well and near hard substrates. There were probably two species present.	 

APPENDIX 2: GLOSSARY

ABUNDANCE – Number (usually of organisms) in a defined population, community or habitat

BENTHIC – Pertaining to the seabed

BIOTURBATION – sediment particle reworking by organisms inhabiting the seabed environment.

BOP – Blow Out Preventer: the large seabed safety valve at the top of the well, that can be closed if the crew lose control of subsurface fluids.

BRYOZOA – small, sessile and mesh-like colonies that are composed of tiny individual zooids. Sometimes called sea mats or moss animals.

CHORDATA – those animals having a backbone/spinal cord.

CNIDARIA – the jellyfish, sea anemones and the corals; radially symmetrical and often brightly coloured.

DEEP-SEA – Marine environments with a water depth greater than 200 m

DEMOSPONGIAE - class of the phylum Porifera (sponges) containing 90% of sponge species and including most of the common and familiar forms.

DENSITY – Number (usually of organisms) per unit area

DEPOSIT FEEDER - An animal that feeds by eating sediment and digesting the organic material within the sediment

DISTURBANCE - A discrete event or process, either natural or human induced, that causes a change in the existing conditions of an ecological system.

DRILL CUTTINGS - Chips and small fragments of drilled rock that are brought to the surface by the flow of the drilling mud as it is circulated.

DRILLING MUD - A mixture of clay, water, chemical additives, and weighting materials that flushes rock cuttings from a well, lubricates and cools the drill bit, maintains the required pressure at the bottom of the well, prevents the wall of the borehole from crumbing or collapsing, and prevents other fluids from entering the well bore.

DRILL SPOIL - A heterogeneous mix of drill cuttings and residual drilling mud discharged from drilling directly onto the seafloor.

ECHINOID - An echinoderm of the class Echinoidea, which includes the sea urchins.

EKMAN GRAB – a sampler designed for sampling soft sediments by scooping, or grabbing, a given volume.

EPIFAUNA – organisms living on the sediment surface, with or without attachment.

FILTER FEEDER - An aquatic animal that feeds by actively filtering particulate organic material from water.

GASTROPOD – the largest class of molluscs; generally with spiral and conical shells.

GIS – Geographical Information System

HABITAT - The area or environment where an organism or ecological community normally lives or occurs.

HOLOTHURIAN - Any of various echinoderms of the class Holothuroidea, which includes the sea cucumbers.

INFAUNA – organisms living within the sediment (below the sediment surface).

LARGE FRAGMENTS –sediment fragments greater than 50 mm diameter, deposited on the seabed as a result of drilling activity.

LEBENSSPUREN – Traces of organisms found in sediment surface, for example tracks and holes.

MACROFAUNA – Animals retained on a 0.5 millimetre mesh sieve.

MEGAFAUNA – Animals visible in seabed photography, typically greater than 10 mm.

MEIOFAUNA - Animals retained on a 0.06 millimetre mesh sieve.

MOON POOL – the opening in the hull of a drilling vessel, through which drilling equipment passes and ROVs are deployed.

MOTILE – organisms capable of spontaneous movement.

PELAGIC – pertaining to water-column organisms living away from the bottom.

PILOT HOLE – an exploratory well

POCKMARK ACTIVITY – sub-seafloor degassing processes forming carbonate structures at the seabed.

PORIFERA – the sponges.

PRE-SPUD – pertaining to conditions prior to installation of sub-sea structures.

PRIMER SOFTWARE - Plymouth Routines in Multivariate Ecological Research computer software for analysis of ecological/biological datasets (From Plymouth Marine Lab).

ROV – Remotely Operated Vehicle

SABELLID – Tube dwelling polychaete worm

SESSILE - an attached or stationary organism; one unable to move.

SESTONIVORE – Filter or suspension feeding organism

SPECIES DIVERSITY – A measure of the variety of life present in a particular habitat, composed of both the number of species present and their relative dominance.

SUSPENSION FEEDER - An aquatic animal that feeds by passively filtering particulate organic material from water.

VESTIMENTIFERA - (phylum) sessile deep-sea worms that live in chitin tubes fixed in bottom sediments/structures, and which harbour symbiotic chemoautotrophic sulphide-oxidising bacteria (CHEMOAUTOTROPHIC – any organism using an inorganic chemical energy source).

APPENDIX 3: 2006 SEDIMENT DATA

Heavy metal concentrations (mg/kg) at Morvin in 2006.

	Pre-drilling	***Post-drilling***		
	Well centre	*N 10 m*	*S 10 m*	*N 110 m*
Barium	150	6300	4600	230
Lead	8.7	130	15	6.8
Cadmium	0.06	0.79	0.14	0.11
Chromium	19	15	28	14
Copper	8.4	81	21	5.8
Zinc	38	280	70	26

PSA and TOC for sediment samples at the Morvin site in 2006.

	Distance	***Heading***	***Mean (µm)***	***Mode (µm)***	***%Fines (<69µm)***	***TOC (%)***
Pre-drilling	Well centre	n/a	116.7	89.9	53.6	1.14
	50	n/a	133.0	107.5	37.9	0.93
	100	n/a	134.2	108.0	38.4	1.03
Post-drilling	10	N	38.8	40.4	83.2	1.11
	10	S	43.9	61.7	76.5	1.06
	110	N	107.7	108.5	50.2	1.52
	100	W	127.2	105.2	44.0	1.14
	8	E	39.5	54.7	80.8	1.37
	90	E	126.1	106.2	41.9	1.45

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