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Viewpoint

Monitoring strategies for drill cutting discharge in the vicinity of cold-water coral ecosystems

Autun Purser *, Laurenz Thomsen

Jacobs University Bremen, Campus Ring 1, 28759 Bremen, Germany

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ABSTRACT

Cold-water coral reefs represent some of the most biodiverse and biomass rich ecosystems in the marine environment. Despite this, ecosystem functioning is still poorly understood and the susceptibility of key species to anthropogenic activities and pollutants is unknown. In European waters, cold-water corals are often found in greatest abundance on the continental margin, often in regions rich in hydrocarbon reserves.

In this viewpoint paper we discuss some of the current strategies employed in predicting and minimizing exposure of cold-water coral reef ecosystems on the Norwegian margin to waste materials produced during offshore drilling operations by the oil and gas industry. In the light of recent in situ and experimental research conducted with the key reef species *Lophelia pertusa*, we present some possible improvements to these strategies which may be utilized by industry and managers to further reduce the likelihood of exposure. We further highlight important outstanding research questions in this field.

1. Introduction to cold-water coral ecosystems and the offshore oil and gas industry

In European waters cold-water coral (CWC) reef ecosystems are found in highest densities on the European margin. These ecosystems are often in areas of interest or active utilization by the offshore oil and gas industry (Roberts et al., 2009; Fosså et al., 2005; Fosså, 2010). CWC reefs have been described as islands of enhanced local biodiversity by recent European projects such as HERMES (Hotspot Ecosystem Research on the Margins of European Seas) and HERMIONE (Hotspot Ecosystem Research and Mans Impact on European seas) (Weaver and Gunn, 2009). Though few species found at CWC reefs are endemic, the biomass and local density of species is often far higher than found at comparably sized, off reef regions of seafloor (Henry and Roberts, 2007; Buhl-Mortensen et al., 2010). These reefs are commonly located at depths of several hundred meters, and developments in remote sensing and Remote Operated Vehicle (ROV) technologies have allowed progressively more intensive scientific in situ investigations to be conducted over the last 20 years (Fosså et al., 2005; Roberts et al., 2009; Fossa and Skjoldal, 2010).

The complex three dimensional structures of tropical coral reefs are primarily the result of calcareous skeleton deposition by numerous scleractinian (stony) coral species over successive generations (Wilson, 1979). At CWC reefs, scleractinian corals are also the key structure forming fauna, though only one or two azooxanthellate coral species are generally present and responsible for the deposition of the skeletal structure at each individual reef. In European waters, the key structure forming species is *Lophelia pertusa* (Roberts et al., 2009), though elsewhere other species may fulfill this role (Cairns, 2007; Roberts et al., 2009; Tracey et al., 2011).

Species found in association with CWC scleractinian corals vary with location and environmental parameters. A local fauna often includes a array of sessile, filter feeding species using dead coral structure as substrate (Lessard-Pilon et al., 2010), mobile fauna (such as fish and amphipods) utilizing the various hydrodynamic niches provided by the coral structure (Husebø et al., 2002; Costello et al., 2005) and distinct microbial communities (Kellogg et al., 2009).

Aside from representing islands of biodiversity, CWC reefs may potentially be significant agents of medium to long term carbon sequestration. The biodeposited coral skeletons may be slowly in-filled by sediment, with living corals forming a crest on these developing carbon mounds (Dorschel et al., 2007; Titschack et al., 2009).

Fish densities tend to be higher on than off reef, and historically bottom trawl fishing has caused significant impacts on reefs in European waters (Fosså et al., 2002, 2005; Fossa and Skjoldal, 2010), the Western Atlantic (Reed et al. 2007) and the Pacific (Clark and Rowden, 2009). There is the potentiality that CWC ecosystems are utilized by commercially significant fish species at various stages throughout their lifecycle, thus giving CWC reef a commercial as well as scientific significance (Costello et al., 2005).

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* Corresponding author. Tel.: +49 421 200 3576.
E-mail address: a.purser@jacobs-university.de (A. Purser).

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As noted, many CWC reefs in European waters are found in areas of activity by the oil and gas industry, such as along much of the Norwegian margin (Fossa and Skjoldal, 2010). The desire to preserve reefs as valuable in their own right, for scientific and also commercial reasons has led to interest in the development of strategies and protocols for use by the oil and gas industry to best minimize and mitigate any impact their activities may have on these ecosystems (Davies et al., 2007; Baussant et al., 2011). How best to protect CWC ecosystems from oil and gas industry activities is a complex problem to address. Tolerances of many reef species to anthropogenic hazards, such as exposure to waste drilling products or to mechanical disturbance, have not been well investigated. Further, the functioning and tolerances of many species, such as *L. pertusa*, under natural conditions is still poorly understood. These data gaps have resulted in a range of protective legislation aimed at protecting CWC reefs which may vary greatly by nation state (Armstrong and van Den Hove, 2008; Brock et al., 2009).

There are four categories of hazard which may be posed to reefs by the oil and gas industry:

(1) Direct mechanical damage.
(2) Exposure to waste drilling products.
(3) Exposure to waste production products (produced water).
(4) Acute exposure to accidentally released hydrocarbons.

Of these, the first category may be avoided by carefully placing the location of the well hole and drill rig anchors in regions free of coral. Planning for such positioning is a regulatory requirement in Norwegian waters, with a detailed site survey conducted prior to drilling permission being granted (Iversen et al., 2011).

Reducing the risk of the second possible hazard, that of exposure to waste drilling products, is more complex. The drilling of wells is a multi-stage process, consisting of a number of drilling events (Neff, 1987). Throughout the drilling process, 'drilling muds' of various compositions are used to facilitate drilling (Darley and Gray, 1988). These drilling muds are comprised of a selection of (non-toxic) chemicals, seawater and 'weighting agents', which are commonly finely ground dense minerals such as barite, or with increasing frequency, ilmenite (Caenn et al., 2011). This drilling mud is pumped down the well shaft as the well is drilled.

Often in the first stage of drilling, during which the drill passes through the unconsolidated marine sediments and upper rock layers, the material pushed from the well accumulates at the top of the well hole. With increased drill depth, there is a tendency to pump the drill cuttings to the rig via a riser system. These cuttings are then passed across a 'shale shaker' which removes much of the drilling mud from the cuttings for reuse. The drill cuttings are then either released to the ocean or shipped to shore for disposal.

At present, in European waters, only drill cuttings produced with water based drilling fluids can be released into the ocean (Iversen et al., 2011). Historically, and outside of European waters in many regions of the world today, oil based drilling muds can been released to the sea. These oil based cuttings may have hydrocarbon content and their release may have greater ecotoxicological consequences for some ecosystems (Holdway, 2002; Santos et al., 2010). The great variability in water based fluid composition and particularly the weighting agents used (e.g. barite, ilmenite etc.) may influence the amount of heavy metals entering the marine environment, as concentrations of these vary with mineral. In Europe, use of oil based drilling muds is sometimes required to successfully drill through certain types of rock formation, and in such cases the drill cuttings produced are always shipped to shore for on land disposal. According to Norwegian regulations drill cuttings, sand and other solid particles shall not be discharged to sea if the oil content is more than 10 g per kilogram of dry matter (http://www.ptil.no/activities/category399.html). Information provided through the 2009 Environmental report from the Norwegian Oil Association reveal that no cuttings from drilling with synthetic (i.e. oil based) drilling fluids have been discharged to sea since 2005.

Water based drill cuttings may be released at the surface directly from the rig, at some mid-depth below the rig or following return pumping to the seafloor. There are no firm guidelines or procedural protocols in place to determine which of these release strategies is to be used. Dispersal models can be used to predict the dispersal of waste material following release, based on the density and particle size distribution of released material (Rye et al., 1998, 2008). Dispersal models used by industry often do not routinely take into account the possibility of aggregation of components of the waste material (primarily the fine drill cuttings) with phytoplankton or other cell debris suspended within the water column or benthic boundary layer (Curran et al., 2002; Pabortsava et al., 2011). Lepland and Mortensen (2008) observed that small coral reefs in the Traena Deep incorporated barite in the skeletal structure of living coral polyps following drill cutting discharge from roughly 500 m distance. Clear observable effects on many megafauna species as a result of settlement of water based drill cuttings appears to be often limited to distances of less than several hundred meters from point of cuttings release (Jones and Gates, 2010). To date such experimental and in situ impact studies have focused on seabed communities other than those found at cold-water coral reefs, i.e. on typical marine soft bottom communities (Barlow and Kingston, 2001; Schaanning et al., 2008; Smit et al., 2008).

Accurately assessing and mitigating against risks posed to corals by exposure to produced waters, the third key hazard posed to reefs by offshore drilling, is a complex undertaking. Produced waters are made up of waste injected water and other production chemicals associated with the oil and gas extraction phase of a drilling/production operation. Commonly consisting of a range of organic and inorganic chemicals and metals, there is a concern over their potential environmental impacts following release (Neff et al., 2011). As with drill cuttings, the composition and quantities of released produced waters varies greatly between drill sites and during production periods. Although the majority of material released is buoyant and rapidly disperses within the water column (Neff et al., 2011), flocculation within the water column has been reported (Ruddick and Taggert, 2011). This flocculation could potentially lead to delivery of settling material to cold-water coral ecosystems. In this article we will not discuss produced waters further, but refer interested readers to the recently published volume by Neff et al. (2011).

The fourth key hazard, that of acute exposure to large hydrocarbon concentrations following unexpected release, such as experienced by coral communities in the Gulf of Mexico following the 2010 *Deepwater Horizon* disaster (White et al., 2012) is of concern. Though such events are rare globally they cannot be wholly discounted as possible scenarios in European waters. Reducing the likelihood of a repeat of such an event by improving drilling techniques and automated capping systems is an ongoing process within the offshore industry. White et al. (2012) also indicate that the reported negative effects on coral health may have been the result of the deployed flocculation agents in the cleanup operation, rather than the hydrocarbons *per se*. Further research into the best methods of dealing with such releases is clearly needed.

2. One integrated approach to risk assessment and impact monitoring

2.1. The CORAMM project

Given the uncertainties surrounding the responses of key CWC organisms to waste material released during drilling operations, and how this may be transported within the water column, Statoil funded the Coral Risk Assessment, Monitoring and Modeling (CORAMM) project. CORAMM was coordinated by Jacobs University Bremen and run in association with the European Union HERMES and HERMIONE projects.

The project focused on addressing some of the outstanding questions on how *L. pertusa* functions (prey capture rates, growth, mortality rates etc.), both under natural environmental conditions and during/following exposure to elevated concentrations of particles – with reactions to drill cutting exposure being of key interest.

The project gathered together an interdisciplinary international working team from the outset, with representatives from industry, experimental microbiologists, biological oceanographers, image analysis specialists and modelers. A novel concept put into play within the CORAMM project was to solicit the active involvement of all project members during all stages of project planning, experimental design and data analysis. By taking such an interdisciplinary approach the project aimed to ensure the maximum usefulness of results across disciplines, with project output tailored for easy utilization by regulatory bodies and industry.

Remote sensing techniques are useful for locating CWC reef environments (Fosså et al., 2005; Guinan et al., 2009). Without direct observation by dropcam, ROV or submarine however, the health status of particular reef structures cannot be assessed. As discussed in Section 3, where ROV surveys of CWC reefs by the oil and gas industry are conducted, survey plans generally consist of video transects of an area to identify, map and roughly gauge coral reef health in a semi-quantitative fashion. Within the CORAMM project semi-automatic learning algorithms were developed to use vertically captured video images to very rapidly assess the percentage of living *L. pertusa* corals in a given area (Purser et al., 2009). The idea behind using such automated systems was that observer bias could to a large extent be excluded from the analysis of video images (Schoening et al., 2012). A further advantage of such an approach was considered to be that modern computing power would allow a far larger image dataset to be analyzed quantifiably than is commonly the case in such environmental surveys. An additional benefit of using such vertically collected video is that it makes collection of comparable data at a later date easier (thus allowing time series analysis of reef development/decline, prior and post drilling, for example).

The CORAMM group investigated time series variations of oceanographic parameters at CWC reefs. Although throughout the 2000s numbers of measurements of parameters such as salinity, pressure, temperature, flow velocities, chlorophyll concentration, particle flux, turbidity etc., from reefs increased, these datasets have seldom been of more than a few months duration. The ease of access of near shore reefs, such as the Tisler Reef in the Norwegian Skagerrak, allowed the CORAMM group (Wagner et al., 2011) and others (Lavaleye et al., 2009) to deploy and retrieve instruments with some regularity (to cover a 3 year period in the case of CORAMM), thus providing a more extensive time series record than can be obtained from repeated visits by research vessels. From such deployments a host of observations have been made, such as that temperature increases in bottom waters of 3 or 4 °C can occasionally cover such near shore reefs for periods of several weeks (Lavaleye et al., 2009) and indications of the composition and concentration of suspended particulates reefs may be exposed to under natural conditions (Wagner et al., 2011).

Laboratory work was conducted to investigate respiration, net prey capture, growth, reproduction and surface clearance ability of *L. pertusa* under different environmental conditions and under various levels of exposure to particulate materials. All experimental work was planned with the consideration of actual anthropogenic activity in mind. The group focused on responses by *L. pertusa* to exposures of two broad categories of material: locally derived resuspended sediments (as may be resuspended by bottom trawling or drill rig anchor deployment/retrieval) or drill cuttings.

Given the susceptibility of tropical and temperate corals to damage following particulate exposure (Rogers, 1990; Wesseling et al., 1999; Fabricus, 2005; Weber et al., 2006) the CORAMM project aimed to identify any threshold concentrations above which *L. pertusa* may be negatively affected by exposure. Particle dispersal models, such as the DREAM model (Rye et al., 2008) are commonly in use by the offshore industry to try and predict the dispersal of particles within the marine environment following release. Although these models are often outputting reasonable dispersal predictions (Tenningen et al., 2011) they do not take into account how various suspended or depositional particulate concentrations may negatively impact on CWC marine biota. Such models are in use by the oil industry to assess the environmental impact on soft bottom communities, but to date no comparable models have been developed for the CWC environment. (Durell et al., 2006; Rye et al., 2008; Smit et al., 2008).

Results of the CORAMM project have been published in several peer review journals with other manuscripts currently in preparation. A key conclusion of the project was that *L. pertusa* polyps are seldom killed by short-term exposure environmentally high elevated particulate concentrations, be these derived from the seabed or released from a drilling rig (Larsson and Purser, 2011). The complex branched structure of *L. pertusa*, combined with its azooxanthellate nature render the species more resilient to particle accumulation than species of tabulate tropical corals. In experimental work carried out by the CORAMM group healthy *L. pertusa* polyps were found to be extremely efficient at clearing the majority of their surfaces of material during and following exposures, predominantly via the action of mucus secretion (Larsson and Purser, 2011). However, even following quite low volume exposure pulses, particulate material can build up in the joints between coral polyp cups over time, as observed in the laboratory (Larsson and Purser, 2011; Larsson et al. in review) and in the field following a drilling event (Lepland and Mortensen, 2008). Possibly the periodic high flow velocities of >10 cm s^{-1} often measured at CWC reefs (Wagner et al., 2011), coupled with the mucus release mechanism aids in cleaning. A further key CORAMM experimental observation was the speed at which some fine fractions of drill cuttings may aggregate with naturally occurring phytoplankton and detritus in the water column (Pabortsava et al., 2011). Such aggregation would alter the dispersal patterns of waste material and possibly lead to drill cutting bioaccumulation within the CWC ecosystem. Pabortsava et al. (2011) describe the variability in settling behavior and aggregation rates exhibited by drill cuttings extracted from different depths within a drill well. During the CORAMM experimental work, *L. pertusa* spawned in a number of research aquaria. This spawning allowed the first opportunity (as far as we are aware) for conducting exposure experiments with larvae of the species. The results from this work are currently under review (Larsson et al. in review), but they show indications that mortality in *L. pertusa* larvae may increase following exposure to environmentally low concentrations of suspended material.

Published sediment exposure experiments by other researchers, such as Brooke et al. (2009) report only slightly elevated mortality rates in *L. pertusa* collected from the Gulf of Mexico exposed to high concentrations of suspended sediment than in unexposed comparison populations, provided that total polyp smothering did not occur. These are comparable observations to those made by the CORAMM group.

Adult and juvenile exposure studies have focused on changes in growth rate, polyp budding rates, changes in respiration or mortality rates during and following particulate exposure. At time of writing we are unaware of any studies investigating how exposure impacts on other aspects of *L. pertusa* functioning, such as on reproduction, success in larval settlement and colonisation etc.

Throughout the majority of the CORAMM experimental work drill cuttings from the 17.5 inch section of drill wells were used. These cuttings had a very low petrochemical content (data not shown) and though they may be representative of the majority of material released on the Norwegian margin during drilling operations, the conclusions drawn from exposure studies conducted with these cuttings cannot be extrapolated with great confidence to all drill cutting releases.

3. Currently employed monitoring strategies

There are no international regulations or indeed even an international consensus on how the activities of the offshore oil and gas industry should be monitored. Variations in seabed depth, topography, fauna and ambient oceanographic conditions found at each potential drilling site compound the problem, making it difficult for one set of regulations or guidelines to be applicable for all drilling situations. As one of major drilling nations, Norway has progressively revised its regulations and guidelines over the last three decades (Renaud et al., 2008; Baussant et al., 2011; Iversen et al., 2011). The Norwegian Pollution Control Act of 1981 provides legislation for exploration activities while the Norwegian Climate and Pollution Agency provides general guidelines on how oil and gas companies should plan, report and go about their business, based on years of drilling activity experience and the opinions of independent scientists (Iversen et al., 2011). Some degree of baseline seabed survey is mandatory prior to the granting of drilling licenses within the EEZ of European states. Environmental evaluations and site surveys often commence roughly 1 year prior to drilling. Within Norwegian waters, 'condition' and/or 'impact' reports must be filed and approved by the Norwegian Climate and Pollution Agency (Klif), prior to a drilling agreement being given (Iversen et al. (2011)). Although these reports focus predominantly on water quality they do incorporate a degree of benthic investigation, but do not treat CWC reef regions of the seabed differently.

All these guidelines are necessarily rather vague in some areas for the reasons mentioned above, and there is no provision within current guidelines for the special consideration of areas containing CWCs.

3.1. Seabed characterization

The characteristics of the seabed in the vicinity of a potential drilling operation can be assessed visually by ROV photo or video, and/or by the direct sampling of seabed sediments for grain size and composition analysis. Such surveys are essential if direct physical disruption of sensitive areas of the seabed is to be avoided. There are two key physical hazards posed:

(1) During deployment of both drilling and production well platforms the positioning of large anchor blocks on the seafloor is required. Commonly, these anchor blocks are concrete structures a number of cubic meters in size – with 8 of such blocks regularly used to hold the rig in place. Not only is the region directly below a settled anchor disrupted (wholly smothered), but there is often the chance that individual anchor blocks will be dragged some distance across the seabed during the rig deployment stage.

(2) Direct disturbance at the site of drill bit entry into the seabed. There is a small localized disruption caused by drill entry (less than a meter diameter), surrounded by a larger, though still limited seabed region which becomes covered with the first drill cuttings (those consisting of the unconsolidated seabed sediments drilled through prior to the drill bit reaching the bedrock).

The compositional analysis of seafloor sediments prior and post drilling is important to determine the concentrations and/or sediment depth of released material which may reach the seabed during drilling operation. As described in Section 1, drill cuttings are often rich in barium, from the barite commonly used in the drilling muds as a weighting agent. So, for holes drilled with barite, by measuring the concentrations of barium in the sediment prior and post drilling, the depth and volumes of settled anthropogenically released material at various surveyed sites around a drilling rig may be estimated. Particle size analysis can give an indication of the likelihood of surface material being resuspended by ambient flow conditions. Heavy metal concentrations within sediments are also routinely quantified prior to drilling. Elevations in copper, zinc and cadmium in sediment measurements can be of concern for benthic animals, although again there is little legislation quantifying anthropogenic concentration increases that are acceptable. Offshore in Norwegian waters, guidelines are based on those used inshore (Renaud et al., 2008). Further studies on benthic community structure, species richness etc., is also often required prior to drilling, for comparison with post drilling assessments (Hughes et al., 2010). Seabed characterization measurements are often conducted at various distances radially from the drill hole or point of cutting discharge (Netto et al., 2010).

3.2. Current velocity and oceanographic conditions

It is important to be able to predict the dispersal paths of material following release to the ocean. These predictions are often based on hydrodynamic conditions assessed at the site during the monitoring period before drilling commences. Commonly a small number of Acoustic Doppler Current Profilers (ADCPs) and benthic flow meters record current conditions at a number of heights from the seafloor for a period of time. The data collected is then fed into a hydrodynamic model (such as the DREAM model mentioned previously (Durell et al., 2006; Rye et al., 2008). Predictions on how material released into the water column at a particular height or depth may behave following release can then be generated. Important estimations of parameters such as particle size, material density and oil content can increase the accuracy of predictions. Although often reasonably accurate, unexpected reversals in current direction can occur during discharge periods (Tenningen et al., 2011); rendering predictions based on particular flow conditions invalid.

3.3. Natural sedimentation conditions

Sediment traps can and have been deployed in regions prior to drilling, to assess the natural rates of sedimentation at the seabed. Understanding the natural flux of material, and hence the depositional rates to which the seabed biota are regularly exposed can be useful in tailoring the drill cutting release rates to the environment.

3.4. During drilling operations

At present, there are no standardized methods for monitoring drill cutting transport, deposition or impact on benthic biota in real time required by any regulatory body or put in place by any drilling company. Drill cuttings are assumed to be transported from the point of release in directions as predicted by dispersal models (discussed in Section 3.2), with these predictions based upon drill cutting particle size and density and flow conditions as predicted from measurements taken in advance of drilling.

There have been very few drill cutting release events in the vicinity of CWC reefs to date, with only one attempt made to monitor such a discharge in real time, and to gauge the environmental changes in the vicinity of a CWC reef. During the drilling of four wells at the Morvin field on the Norwegian margin from November 2009 to February 2010 (Block 6506/11, production license 134b/c) in situ, real time monitoring of particulate transport and monitoring of potential environmental impacts on a cold-water coral ecosystem was conducted. The drill hole was situated several hundred meters from the nearest coral structure, and the area was extensively surveyed bathymetrically and via ROV video observation prior to drill platform deployment. Drilling took longer than the average of 1 month, due to poor winter weather conditions. The monitoring project is summarized in Tenningen et al. (2011) and was carried out by Statoil in collaboration with the Institute of Marine Research (IMR) Norway and the EU HERMES project (Weaver and Gunn, 2009).

The monitoring program was organized around a central research Lander equipped with an Anderaa RDCP600 current profiler (connected to surface buoy battery and communication system). From this central lander a cabled camera system was positioned at a reef to video any disturbance which might result from exposure, three sediment traps deployed around the point of drill cutting release to capture particle flux over time, and additional locally positioned flow meters also deployed. The sediment trap data could not be monitored in real time, with flux and particulate composition of collected material only determined following the end of drilling.

The monitoring program was well planned, with instruments deployed in locations to best check the accuracy of the DREAM model dispersal predictions. Unfortunately, the monitoring program suffered from harsh environmental conditions, with several instruments failing during the monitoring period, and severing the Lander from the communications buoy early in the drilling period (Tenningen et al., 2011).

Despite these technical problems, important observations were made. Primarily, the sediment traps collected high concentrations of barite from the water column both upstream and downstream of the point of drill cutting release. This indicated that drill cuttings were not always behaving as predicted by the DREAM model, and that for some period's current flow was not in the predicted direction. Prior to the severing of the communications buoy it was clear that monitoring of reefs visually via remote cameras is possible within the context of a drilling operation, and the response or lack thereof by benthos (gorgonian corals in this instance) to drill cutting exposure is indeed observable in real time.

3.5. Post drilling

In situations where drilling licenses are granted on the proviso of the completion of environmental and faunal analysis of the seabed prior to drilling, the various national legislative bodies usually require a comparable follow up survey to be carried out. The aim of this follow up is to determine whether the risk assessment and drilling plan proposed in advance of drilling adequately predicted the actual impact of drilling on the seabed (and in some cases on the water column). Often these studies will quantify concentrations within sediments of heavy metals, TOC concentrations, THC concentrations etc., with radial distance from a drill point or point of drill cutting discharge. Multivariate analysis of fauna post drilling at various survey points around the drill site are also often required. Aside from some observations on best sampling practice of benthic community structure in the guidelines for offshore environmental monitoring in Norway (Iversen et al., 2011) there are few accommodations in place for the special treatment and monitoring of impacts on CWC reef environments.

4. A suggested best practices model for the cold-water coral environment

The established methodologies for benthic ecosystem impact assessment in use presently in the EEZs of European nations may be effective in monitoring and minimizing the disturbance resulting from activities by the oil and gas industry in regions where the seabed is reasonably uniform. Provisions are in the legislation and guidelines laid down by most nations to modify the standard radial sampling arrays commonly employed for measuring environmental and faunal change in the vicinity of drilling operations on a case by case, site specific basis (Iversen et al., 2011). These provisions however, do not address how to adequately monitor such sampling resistant, biodiverse and biomass dense localized hotspots as CWC reefs.

There are two major difficulties in carrying out the established impact assessments usually carried out around oil and gas drilling operations in the CWC environment.

(1) How to monitor sediment composition change in a CWC reef environment?
Collecting surface seabed samples is routine, with grab samplers commonly used, though multi-cores may be used in some instances (Brion and Pelletier, 2005). Such samplers cannot be operated in the CWC reef environment, as they require a uniform sediment layer into which to penetrate. Within CWC reefs, particulates which fall from suspension are deposited amongst the cracks, fissures and gaps within the coral structure, as a function of local hydrodynamics. The role of a particular drilling event in the modification of the composition of such trapped sediments is therefore difficult to determine. Drill cuttings and suspended sediments can be collected, dated and analyzed from CWC reefs following incorporation within in the growing skeletons of coral polyps, though the collection of such samples would in itself be somewhat damaging to the reef (Lepland and Mortensen, 2008). It is to be noted that corals reported in the Lepland and Mortensen study had not been discovered at time of drilling. From such inclusions it is again difficult to quantify the amount of material which may have been in suspension, or how exposure may have influenced coral growth or ecosystem function.

(2) Can community change be easily monitored in the CWC reef environment?
Many of the techniques used to monitor changes in benthic ecosystems resulting from drilling operations are based on multivariate analysis of seabed population samples, often of meiofauna collected by grab sample (Netto et al., 2010). In the CWC environment, grab samples are undesirable for two key reasons: their destructive impact on coral framework and their inability to capture many of the mobile reef species, which can be important components of reef ecosystems. Projects such as CoralFISH (Grehan et al., 2009), MARIANO, HERMES (Weaver and Gunn, 2009), HERMIONE (Weaver et al., 2009) and CORAMM (Purser et al., 2009) have investigated spatial distribution of species across CWC reefs from videosled, ROV and submarine video footage. All of these projects have focused primarily on quantifying the variation of a limited number of large macrofauna species over environmental or spatial gradients (Orejas et al., 2009; Purser et al., 2009). Such datasets are not sufficient for the multivariate analysis techniques used in community structure assessment of shallower tropical reef communities, where more extensive datasets can be collected (McField et al., 2001) or following drill cutting discharge in other less physically complex environments (Netto et al., 2010).

Given these two difficulties, how can legislative bodies and companies' best monitor and reduce the impact of drilling and drill cutting release on CWC environments? In Norway it is clear from the guidelines provided by the regulatory authority that companies should follow the 'precautionary principle' (Iversen et al., 2011), wherever possible making reasonable effort to minimize impacts on the seafloor. As expressed above and in Section 5, there are difficulties in gauging the level of impacts drill cuttings may have on CWC environments so the precautionary principle here should perhaps focus on minimizing any direct physical interactions between waste drilling products and CWC environments. Although the use of the DREAM model and other dispersal prediction models is aimed at doing just this, unforeseen events can occur (Tenningen et al., 2011). The likelihood of such unexpected events occurring would be greatly reduced if in situ real time monitoring of drilling events was instigated in regions of particular sensitivity (such as in close proximity to numerous coral thickets) or in areas where flow conditions have been shown to vary over time.

The time of year during which drill cuttings are released may also be crucial in determining level of ecosystem impact. As mentioned in Section 2.1 there are preliminary indications that *L. pertusa* larvae may be very susceptible to damage following particulate exposure, and as likely annual broadcast spawning animals' interference with this periodic event should be avoided. The presence of detritus (such as following the spring bloom) within the water column may result in transport pathway change and/or bioaccumulation of drill cuttings. These two points should be considered when planning a drilling campaign, though at time of writing the timing of European *L. pertusa* spawning events is not well known.

4.1. Real time monitoring of the deep sea

Scientific research projects such as NEPTUNE Canada (Taylor, 2009; Thomsen et al., 2011)and the European Seafloor Observatory NETwork (ESONET), (Ruhl et al., 2011) have shown that 24/7 access to sensing equipment over cabled infrastructures is possible, even at several thousands of meters depth. Such scientific cabled observatories can be accessed remotely by researchers over the internet, often with users downloading high volumes of data in seconds, analyzing HD video streams or controlling remote operated equipment. The offshore oil and gas industry likewise monitors activity on and above the seafloor via a host of platforms prior, during and after drilling events. Commonly a number of ROVs are in operation around facilities monitoring anchors; cuttings pile accumulations etc., with a fixed camera often monitoring the outflow of drill cuttings at the seabed during drilling events. These video and data feeds are routinely monitored in real time on drilling platforms, so it is not unfeasible that a selection of monitoring platforms could be attached to those already present network to ensure minimal exposure of CWCs to drill cutting release plumes during drilling events.

4.2. A real time monitoring plan for drill cutting release in the vicinity of CWC ecosystems

We strongly suggest that small instrument platforms containing industry standard flow profilers and turbidity meters be connected by seafloor cables to a monitoring hub. These cables can be of very moderate size, so that they would pose no possible hazard to ROVs in operation. This monitoring hub would itself be linked to the video data feed cable often present at the point of drill cutting discharge (see Section 4.1). Depending on the local situation we would recommend 4 of these instrument platforms to be placed a few hundred meters up, down and at right angles from the drilling rig with respect to the presumed direction of prevalent flow, as shown in Fig. 1. The deployment of even one of these platforms would greatly improve dispersal predictions if the output generated from its instruments is fed in real time into operational dispersal models.

In addition to these instrument platforms, similar platforms with HD video cameras and illumination sources (as shown to be technically feasible during drilling events, see Morvern report, by Tenningen et al. (2011)) should also be deployed at the CWC reefs themselves (Fig. 1). These instrument platforms would not have to be complex pieces of equipment, a simple HD webcam, illumination source and turbidity meter could warn drill operators of waste material reaching a coral reef.

It could be argued that drilling is such an expensive undertaking and that if no negative effects of drill cutting exposure have yet been demonstrated in reef organisms, that there is no reason to change current practices. There are however still many unanswered questions on susceptibility of CWC organisms to drill cutting exposure (see Section 5) and therefore such a response is not really in keeping with the precautionary principle. At present, the outflow point of drill cutting release can be some distance from the riser return, and drill cuttings piped some distance via seabed transportation systems prior to release. For a minimum financial outlay a junction box may be placed within these transportation systems to allow two (or more) possible release points for drill cuttings. By using such a junction in the discharge system, these discharge outlet pipes could be laid in different directions from the site of drilling, and operational discharge pipe selected or changed as required in real time, in response to change in oceanographic conditions. By careful placement of these two outlets, and by monitoring flow and turbidity conditions in the area, the precautionary principle could be followed relatively cheaply, with large-scale exposures of sensitive ecosystems (such as small isolated CWC reefs) to drill cuttings in suspension avoided by simply shifting drill cutting release between the two proposed outlet pipes. The real time instrument platforms, particularly the video platforms positioned close the reefs themselves, would indicate the success of such a strategy.

In addition to demonstrating an adherence to the precautionary principle by drilling companies, costs associated with post-drilling seabed surveys may be reduced. By recording instrument data

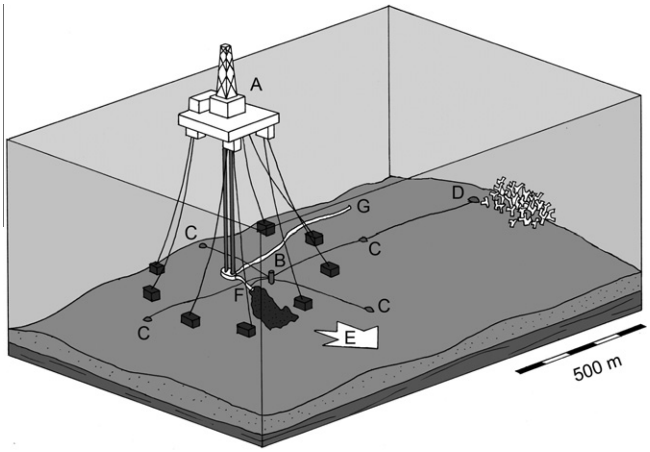

Fig. 1. Idealised depiction of drilling rig deployed within 1 km of a cold-water coral reef, following the best practices protocol outlined in this article. (A) Drilling rig; (B) Central monitoring hub, connected to rig drill cutting release monitoring infrastructure; (C) Real-time flow meters and turbidity sensors; (D) Video and turbidity monitoring platform at reef; (E) Direction of prevalent flow; (F) Primary drill cutting release outlet; (G) Secondary drill cutting release outlet (Scale bar only applicable for cable lengths between infrastructure nodes).

throughout the drilling operation and ideally making this data available to regulatory bodies in real time (much larger datasets are routinely collected, archived and made publicly available within minutes by the NEPTUNE Canada project, (Taylor, 2009)) drilling companies could ensure and show that no large scale disturbance of CWC reefs resulted from their activities, with no smothering events or extended periods of high suspended particulate exposure. Although the standard seabed monitoring of post drilling THC, heavy metals content, macrofauna abundances etc., would still be required (cheap grab sample and push core sampling) for off reef locations, extensive ROV studies of CWCs would not be required, provided demonstrated exposure throughout the drilling event was marginal.

5. Outstanding research questions

The resilience of *L. pertusa* to particulate exposure has only been assessed in terms of coral polyp mortalities, growth rate change or change in respiration. The impact such exposures may have on reproduction, both in terms of fecundity or larval health during exposure events – is much understudied. Pabortsava et al. (2011) show that the behavior of drill cuttings in the water column varies with phytodetrital concentration, and therefore there is the possibility that drill cutting discharge at certain times of the year, such as following an algal bloom, may lead to bioaccumulation within corals directly or within the zooplankton on which they preferentially feed in some locations (Dodds et al., 2009). There has been no research carried out to date to investigate this possibility.

Whether the resilience shown by *L. pertusa* holds true for other scleractinians is not known. At reefs elsewhere in the world ocean, species such as *Solensomilia variabilis* may take on the role of key engineer species, such as within the EEZ of New Zealand (Tracey et al., 2011), an area also of interest to oil and gas companies.

In European waters the limited research that has been conducted on susceptibility of CWC reef organisms to drill cuttings has not focused on reef community members other than *L. pertusa.* A species rich/high biomass community of sponges is often present within the living coral region of reefs (van Oevelen et al., 2009) and in the surrounding rubble zones (Purser et al., 2009). As filter feeding organisms which pump large volumes of water through themselves they may be susceptible to damage from increased suspended particulate concentrations, as has been observed in some shallow sponge species (Bannister et al., 2011).

A further drawback in using results of exposure studies published to date in guiding drill cutting release strategies in European CWC environments is the fact that all research work has been carried out with drill cuttings released to the ocean with zero or close to zero THC content. Drill cuttings, even if produced with water based drilling muds, can become contaminated with hydrocarbons which have escaped from the reservoir rock into overlying sediments, or from the cap rocks. Although in Norwegian waters, only 1% of drill cutting content discharged can be THCs, the possible negative impacts of such concentrations on *L. pertusa*, or indeed other CWC organisms, is unknown. Recent publications indicate that the glycol concentrations within water based drilling mud may lead to oxygen depletion and associated impacts on soft bottom communities (Schaanning et al., 2008; Trannum et al., 2010, 2011). Whether comparable impacts would be felt by the communities associated with some of the more horizontal CWC ecosystem niches, such as the rubble zones, is wholly unknown.

Not addressed in this overview were the potential negative impacts on CWC reef ecosystems which may result from produced water exposure when production is underway.

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