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Resistance of *Lophelia pertusa* to coverage by sediment and petroleum drill cuttings

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ABSTRACT

In laboratory experiments, the cold-water coral *Lophelia pertusa* was exposed to settling particles. The effects of reef sediment, petroleum drill cuttings and a mix of both, on the development of anoxia at the coral surface were studied using O_2, pH and H_2S microsensors and by assessing coral polyp mortality. Due to the branching morphology of *L. pertusa* and the release of coral mucus, accumulation rates of settling material on coral branches were low. Microsensors detected H_2S production in only a few samples, and sulfate reduction rates of natural reef sediment slurries were low (<0.3 nmol S cm^{-3} d^{-1}). While the exposure to sediment clearly reduced the coral's accessibility to oxygen, *L. pertusa* tolerated both partial low-oxygen and anoxic conditions without any visible detrimental short-term effect, such as tissue damage or death. However, complete burial of coral branches for >24 h in reef sediment resulted in suffocation.

1. Introduction

Lophelia pertusa (L. 1758) is the most common reef-building scleractinian deep-water coral (Freiwald et al., 2004). It is reportedly found between 39 m (Rapp and Sneli, 1999) and 3380 m depth (Squires, 1959), between 4 °C and 12 °C (Teichert, 1958), and at densities between 27.35 kg m^{-3} and 27.65 kg m^{-3} (Dullo et al., 2008). In addition to building benthic reefs, *L. pertusa* was also observed to colonize structures of oil and gas platforms in the northern North Sea within the water depth range of 59–132 m (Gass and Roberts, 2006). *L. pertusa* forms bush-like colonies that can reach a height of up to 2 m (Rogers, 1999). Cold-water corals, as sessile filter feeders, require nutrient delivery. Thus, they preferentially settle on elevated features where bottom current speeds are high, such as banks, seamounts and ridges. They are also found in areas where nutrient delivery is enhanced by other hydrodynamic mechanisms, such as internal waves or downwelling events (Frederiksen et al., 1992; Dorschel et al., 2007; White, 2007; Mienis et al., 2009; Wagner et al., 2011). Coral thickets often grow into the prevailing current to optimally benefit from the nutrient supply (Wilson, 1979; Thiem et al., 2006; Buhl-Mortensen et al., 2010).

High current flow generally prevents material from settling and burying corals, especially in the upper, current-exposed zone of living coral reefs (Dowdeswell et al., 1996; Dorschel et al., 2007; Mienis et al., 2007). Within the cold-water coral thickets, however, low energy microenvironments develop, which results in sedimentation of biogenic carbonate debris and allochthonous sediment particles between the coral branches of the thicket (Dorschel et al., 2007; De Haas et al., 2009; Mienis et al., 2009). Exposure of living corals to settling particle material is furthermore facilitated by anthropogenic activities, e.g. resuspension of sediments by fishing (Pilskaln et al., 1998), and following the release of drill cuttings produced during the drilling operations of the offshore oil and gas industry (Lepland and Mortensen, 2008; Trannum et al., 2010). Drill cuttings, drilling waste material from the offshore petroleum industry, are the broken up pieces of rock produced during drilling, combined with a thin layer of drilling fluid. This drilling fluid is used to cool the drill bit and push broken rock

Abbreviations: S, sediment; DC, drill cuttings; S + DC, mix of both sediment and drill cuttings.

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fragments from the drill hole. Although non-toxic, this fluid can contain high percentages of fine particulate material, the 'weighting agent' (commonly the mineral barite), which is added to ensure smooth drilling and to maintain a positive pressure within the well (Neff, 2005). Commonly during a drilling event, these drill cuttings are released to the ocean periodically over a period of 3–5 weeks (Purser and Thomsen, 2012).

The effects of sedimentation on tropical stony corals have been studied for many years (reviewed in Rogers, 1990; Fabricius, 2005; Weber, 2009). Short-term sediment exposure affects these corals by reducing their zooxanthellate symbionts' photosynthetic efficiency whilst increasing their respiration, resulting in bleaching and necrosis (Bak and Elgershuizen, 1976; Riegl and Branch, 1995; Philipp and Fabricius, 2003). Sediment rejection activities, through mucus production and polyp movement, further increase energy expenditure (Bak and Elgershuizen, 1976). In contrast, the effect of sediment coverage on cold-water corals is not very well understood. In a laboratory study on cold-water corals retrieved from the Gulf of Mexico, Brooke et al. (2009) tested the tolerance of two *L. pertusa* morphotypes to different loads of autoclaved sediment, as well as the response to complete short-term sediment coverage. The authors showed that *L. pertusa* was able to tolerate fairly high short-term sediment coverage of 2–4 days before coral mortality sets in and suggested that mortality was most likely due to oxygen deficiency. Sub-lethal effects on *L. pertusa* from exposure to both benthic sediment and drill-cuttings, on the other hand, include loss of tissues (Larsson and Purser, 2011) as well as reduced skeletal growth and reduced larval survival (Larsson et al., 2013). The present study aimed to assess in detail how anoxia develops at the coral surface following sediment coverage and to determine whether this had any impact on coral health. A particular focus of this study was to determine whether anaerobic microbial processes (such as sulfate reduction) on the coral surface would lead to coral damage. Laboratory experiments were carried out with cold-water corals and reef sediments retrieved from the Tisler Reef, Norwegian Skagerrak as well as with drill cuttings supplied by the company Statoil, Norway. Microsensors and ^{35}S-tracer techniques were used to assess the development of anoxia at the coral surface following coverage. The hypothesis tested was that resuspended local material (reef sediments with the associated microbial community), or drill cuttings settling onto the coral would lead to oxygen depletion on the coral surface. Consequently, anaerobic microenvironments on the coral surface would form, with these providing suitable habitats for sulfate-reducing microbial assemblages. The production of H_2S by these assemblages during sulfate reduction would represent a potential danger to the coral tissue as sulfide is a cell toxin (Bagarinao, 1992).

2. Material and methods

2.1. Site and Sampling

Reef sediment and branches of white *L. pertusa* were collected from Tisler Reef (58°59 N, 10°57 E) located in the Norwegian Skagerrak at a depth of 70–160 m. The material was collected during ROV (Remotely Operated Vehicle) -assisted collection campaigns in April 2007, July 2007, and May 2008. Corals and sediment were kept at *in situ* temperature of approximately 8 °C and transported to the laboratory at the Marine Station of the Sven Lovén Centre for Marine Sciences, Tjärnö, Sweden, within hours of collection. Corals were transferred to aquaria supplied with flow-through of pre-filtered seawater from a depth of 40 m in the adjacent Koster Fjord. Two to seven days after collection, these coral fragments were used in experiments as described below. Drill cuttings for all presented experiments originated from the 17 1/2″ section of a well drilled in the Smørbukk Sør drilling field during November 2006 and were supplied by Statoil. These cuttings came from a 1320 m long section of the drilling hole, which cut predominantly through claystone and occasionally layers of sand.

2.2. Sediment analyses and pre-treatment

A subsample of the reef sediment from the May 2008 campaign was freeze-dried and analyzed for concentration of total carbon (TC), total nitrogen (TN) and total inorganic carbon (TIC). The concentration of total organic carbon (TOC) was calculated following the methods described in Wehrmann et al. (2009). Sediments for all experimental campaigns were sieved through 1 mm mesh size to remove any living macrofauna, the activity of which would bias results of microsensor deployments (bioturbation), and to remove larger fragments, which mostly comprised of biogenic carbonate debris that could break microsensors. Sieved sediments were stored refrigerated until used in experiments. Reef sediments and drill cuttings from the April and July 2007 collection campaigns were analysed for grain size using a Laser *in situ* Scattering and Transmissiometry device (LISST-100X, Sequoia Instruments).

2.3. Measurement of dry weight (dw)/wet weight (ww) ratios

For uniform dosing of sediments and drill cuttings by dry weight, the dry weight/wet weight ratios were determined for each material type. The sediments were stirred and mixed thoroughly, with the wet weights of three replicate samples of each material type measured. Samples were dried at 60 °C until constant weight and the ratios were then calculated.

2.4. Sedimentation experiments

In the first set of flow chamber experiments, the amount of settling sediment required for coverage of coral branches to be sufficiently deep to allow microsensor investigations was determined experimentally. Flow chambers of 10 cm × 20 cm were set up with a water flow of 450 ml min^{-1} and a water temperature of 8–9 °C. Twelve to eighteen fragments of *L. pertusa,* each 3–6 cm long and with at least 4 active polyps, were placed at the bottom of the flow chambers (Fig. 1) and left to recover from the stress of transfer for 24 h. Three sediment concentrations were tested: (i) 66 mg cm^{-2} of sediment (dry weight, dw; designation 1×), (ii) a 3 times higher load of 198 mg cm^{-2} (dw; designation 3×), and *(iii)* a 7 times higher load of 462 mg cm^{-2} (dw; designation 7×) (Fig. 2). These three concentrations were selected to be equivalent to that required to achieve a maximum depositional depth of 6.3 mm (an exposure threshold used by the offshore industry in risk assessment), i.e. 66 mg cm^{-2} (Larsson and Purser, 2011) and exposures 3 and 7 times higher than this (3× and 7× exposures), which represent high levels of exposure, which may result from resuspension or continuous local drill cutting release. In all of the sedimentation load experiments, three different sediment types were studied: (a) Tisler Reef sediment (S), (b) drill cuttings (DC), and (c) a mixture of S and DC (S + DC, 1:1). In the field, these three treatment types would represent (1) typical reef sediments, as may be resuspended by bottom trawl activity in the vicinity of reefs or changes in the bottom water current regime, (2) settling waste drill cuttings released by a drilling rig and (3) waste drilling material mixed with resuspended material, as may be generated as a result of drill anchoring and/or the drilling process (Purser and Thomsen, 2012). This would represent exposure of the corals to drill cuttings amended with the *in situ* microbial community of the reef sediment.

All sediment types were mixed thoroughly with seawater before addition to experimental flow chambers in order to obtain